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## Abstract

During the strong 1999 Izmit (Kocaeli) earthquake, 100 km long east-west-striking (N80°–100°), right-lateral, fault traces were formed. In the epicentral area the seismic ruptures did not follow any known or mapped fault traces, but morphology and tectonostratigraphic evidence from trenches reveal

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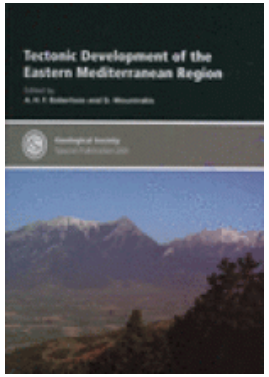


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pre-existing earthquake-related features, e.g. elongated valleys, shutter ridges, high-angle slopes, scarplets and stream offsets. In the Gölcuk Peninsula a characteristic NW-SE-trending extensional fault segment emerged at the surface with a 1.5–2 m maximum vertical displacement and a 0.30 m right-lateral component. The resulting coseismic fault scarp was mapped in detail, and two trenches were excavated at the Dëniz Evler site. The 1999 displacement at this site was 1.50 m, whereas the penultimate event displaced the same sediments by 0.70 m, and a previous event by 0.20 m. Displacement is not characteristic, as fault-associated soft (recent) deltaic deposits, and the fault itself, are typically not coseismic, but rather a secondary accommodation structure in geometric consistency with the right-lateral main displacement zone. The data were compared with similar results from the Aşağı Yuvacik, Kular Yaylacik and Acisu sites between Izmit and Sapanca Lake. The same fault segment seems to have been activated and produced surface ruptures including during the earthquakes of AD 1509, AD 989 and AD 554, plus two prehistoric events. The palaeoseismological results provide clear evidence for repeated reactivation of the same fault or fault segments during historical seismic events.

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# Evidence for late Holocene activity along the seismogenic fault of the 1999 Izmit earthquake, NW Turkey

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**Abstract:** During the strong 1999 Izmit (Kocaeli) earthquake, 100 km long east–west-striking (N80°–100°), right-lateral, fault traces were formed. In the epicentral area the seismic ruptures did not follow any known or mapped fault traces, but morphology and tectonostratigraphic evidence from trenches reveal pre-existing earthquake-related features, e.g. elongated valleys, shutter ridges, high-angle slopes, scarplets and stream offsets. In the Gölcuk Peninsula a characteristic NW–SE-trending extensional fault segment emerged at the surface with a 1.5–2 m maximum vertical displacement and a 0.30 m right-lateral component. The resulting coseismic fault scarp was mapped in detail, and two trenches were excavated at the Dëniz Evler site. The 1999 displacement at this site was 1.50 m, whereas the penultimate event displaced the same sediments by 0.70 m, and a previous event by 0.20 m. Displacement is not characteristic, as fault-associated soft (recent) deltaic deposits, and the fault itself, are typically not coseismic, but rather a secondary accommodation structure in geometric consistency with the right-lateral main displacement zone. The data were compared with similar results from the Aşağı Yuvacik, Kular Yaylacik and Acisu sites between Izmit and Sapanca Lake. The same fault segment seems to have been activated and produced surface ruptures including during the earthquakes of AD 1509, AD 989 and AD 554, plus two prehistoric events. The palaeoseismological results provide clear evidence for repeated reactivation of the same fault or fault segments during historical seismic events.

On 17 August 1999 an $M_w = 7.4$ earthquake occurred along the western part of the North Anatolian Fault Zone (NAFZ) (Fig. 1). Its epicentre was located in the Gulf of Izmit. This was a multiple event, which ruptured a sequence of segments with typical right-lateral displacements (0.2–5 m). During this strong earthquake, a series of east–west-striking (N80°–100°), right-lateral, fault traces appeared, their length being 100 km in total. At a small scale they show typical strike-slip displacements (2–5 m), pop-ups and pressure ridges (N 40–70°), P (N80°), R (N100–110°) and R′ (*c.* N350°) Riedel shears, extensional cracks (N115°–135°), restraining and releasing bends, and small pull-apart structures (Tutkun & Pavlides 2001).

Although the earthquake ruptures are generally linear (Fig. 2), and east–west-striking (N80°–100°), they can be divided into branches (or segments) on the basis of geometry. The Karadere 'segment' (or branch) is an ENE–WSW-striking (N75–85°), 20–25 km long fault from Eften Lake to Akyazi town. This fault overlapped the 12 November, 1999 Duzce earthquake ruptures of the Aksu segment (e.g. Tutkun & Pavlides 2001; Emre *et al.* 2003*a*); the maximum observed displacement is about 2 m, and the average is 1 m.

The Arifiye segment is a 25 km long linear and continuous seismic trace from Arifiye village to the east shore of Sapanca Lake. Between Arifiye and the town of Akyazi, there is a 5 km gap in the surface seismic traces. The maximum right-lateral displacement (4.8 m) was observed close to Arifiye village. The displacement gradually decreases toward the east (0.3 m), and the average displacement on this segment is about 2–2.5 m. The Karadere and Arifiye fault branches are close to the western edge of the 1967 Mudurnu seismic fault traces (Ambraseys & Zatopec 1969; Barka & Kadinsky-Cade 1988). This segment is separated from the Tepetarla one by the Sapanca Lake stepover and by a NW–SE-trending normal fault (Gölcük Peninsula–Kavakli area).

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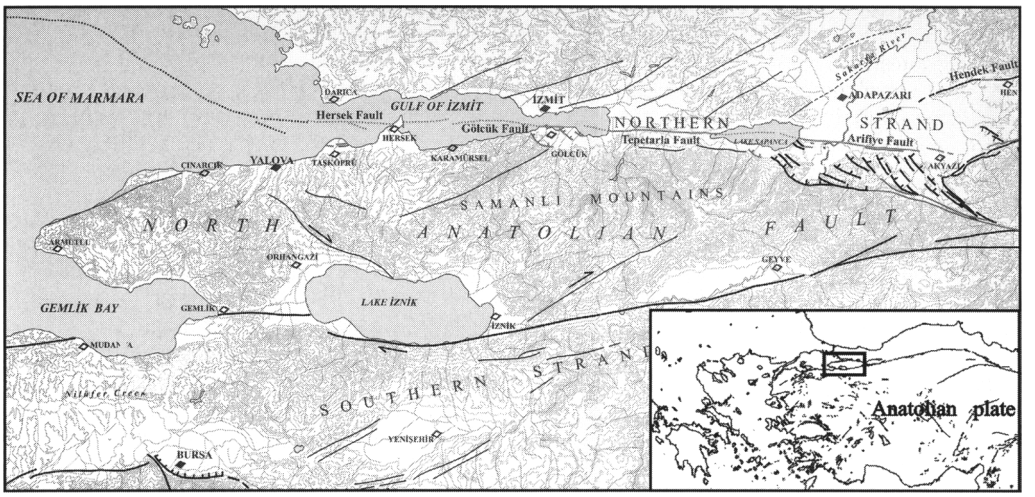


**Fig. 1.** Regional structural map, after Emre *et al.* (2003*a*). The North Anatolian Fault Zone is divided into two main strands, a northern strand, activated during the 1999 Izmit earthquake, and a southern strand. Inset: the study area in relation to the broader geodynamic setting of the area.

The Tepetarla segment is east–west-striking (90°), 35 km long, and extends from the north-western shore of Lake Sapanca to the Gölcük Peninsula; for about 4 km the fault runs beneath the Izmit Gulf near its southern shoreline. The maximum displacement of this fault segment is 4 m, and the average is $2.5 \pm 0.5$ m. The western edge of the segment in the Kavakli–Denizevler–Yeniköy area is a typical normal fault 4 km long, striking NW–SE (120–130°), with a maximum vertical offset of 2.10 m and a right-lateral component of 0.2–0.3 m.

The westernmost Hersek and Gölcük segments are two probable submarine east–west structures that extend from Gölcük to Yalova; they are about 50 km long, based on the distribution of aftershocks. The seismicity pattern defines two major segments that extend about 80 km east and 75 km west of the main shock epicentre (40.8°N, 29.9°E, Gölcük–Izmit, Fig. 1) (Barka 1999, 2000; Awata *et al.* 2000; Lettis *et al.* 2002; Emre *et al.* 2003*a*).

## Palaeoseismology of the westernmost edge of the North Anatolian Fault

The broader Aegean region, including western Anatolia, is mainly the result of Late Mesozoic and Early Tertiary deformation, with collisional shortening and an inherited fabric of folds, reverse faults and thrusts, nappes, sutures and strike-slip structures. It is also the result of post-orogenic and lithospheric extension during the last 25 Ma, and especially during the youngest, Mid–Late Quaternary extensional deformation, which is locally associated with important strike-slip motion. From the neotectonic point of view, Anatolia is a post-Alpine collisional intracontinental convergence zone affected by tectonic escape, and where typical active normal faults and important strike-slip faults dominate the region, e.g. the right-lateral North Anatolian Fault Zone (e.g. Bozkurt 2001). Indeed, it was only during the Quaternary that the North Anatolian Fault propagated westwards to merge with the North Aegean Trough (Şengör 1979; Saroğlu 1988; Jackson 1994). The North Anatolia Fault Zone is the northern boundary of the Anatolian 'microplate' or 'megablock', which accommodates the westward motion of Anatolia relative to Eurasia (Şengör *et al.* 1985; Taymaz *et al.* 1991; Gautier *et al.* 1999). This fault is an intracontinental strike-slip structure, with a slip rate of about 20–25 mm $a^{-1}$, a well-developed topographic expression and remarkable seismic activity.

As a result of continuing tectonic activity, the broader Aegean region has been affected by many active faults (e.g. Jackson 1994; Bozkurt 2001). Many segments were reactivated during recent and historical earthquakes, associated with surface ruptures and other ground deformation (Pavlides & Caputo 2004). In geological terms, active faults are theoretically in constant motion, with episodic events or creep, for relatively long periods of time. The western segments of the North Anatolian Fault have been investigated for a better understanding of their seismogenic behaviour (e.g. Hancock & Barka

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1987; Barka & Kadinsky-Cade 1988; Bozkurt 2001). By analysing the geometry, kinematics and seismotectonic characteristics, several common features of these faults can be emphasized: they are commonly active since the early Pleistocene, are characterized by strong earthquakes ($M \approx 7$), have maximum vertical displacements of some tens to a few hundreds of centimetres and exhibit return periods of hundreds to thousands of years. Strike-slip faults associated with the North Anatolia–North Aegean Trough system are associated with very strong, devastating earthquakes, with horizontal displacements up to 5 m (Barka & Kadinsky-Cade 1988).

Palaeoseismological studies based on investigation of fault colluvium in trenches extends the chronology of historical seismological information and can thus provide crucial data regarding the occurrence of destructive prehistoric earthquakes (e.g. Sieh 1978; McCalpin 1996; Pavlides 1996; Yeats *et al.* 1997; Pavlides *et al.* 1999). Knowledge of the spatial and temporal complexity of earthquake recurrence is essential for reliable seismic hazard evaluation and the development of important new concepts concerning earthquake generation (Yeats *et al.* 1997).

In an early attempt to study the palaeoseimicity of the Iznik–Mekece and Izmit–Sapanca fault segments, Ikeda *et al.* (1991) determined the eastern extent of the Iznik–Mekece fault. Two seismic events that have taken place between 200 and 500 years BP and the 1967 Mudurnu Valley earthquake ruptures have been identified. Demirtaş (1996) excavated and interpreted four trenches across the surface ruptures of the 1957 and 1967 earthquakes in the Mudurnu Valley segment, and suggested that at least three or four previous large earthquake events have produced surface faulting on the same fault prior to the last two earthquakes of 1957 and 1967. Radiocarbon dates show that all the faulting events in the Mudurnu Valley, prior to the last two earthquakes, occurred at some time between 4335 BC and 2500 years BP. The excavation demonstrated an average recurrence interval of this segment of 150 years.

Palaeoseismological research by Rockwell *et al.* (2001) along the Ganos segment, which was last activated during 1912, has shown that recent sediments affected by the fault activity range in age from less than a few hundred years to about 6000 years. They were also affected by repeated coseismic fault behaviour, at least four times during the historical period and even more during the last 4000 years.

The August 1999 Izmit–Kocaeli seismogenic fault comprises two major segments, east and west of Sapanca Lake; these in turn can be divided into six smaller segments. The western segment, according to Sugai *et al.* (2000) and Emre *et al.* (2003*b*), produced surface ruptures at least three times during the last millennium. There is palaeoseismological evidence for at least three or possibly four surface-rupturing events since the 17th century, according to Toda *et al.* (2003). The historical record suggests that the Izmit–Sapanza area experienced strong

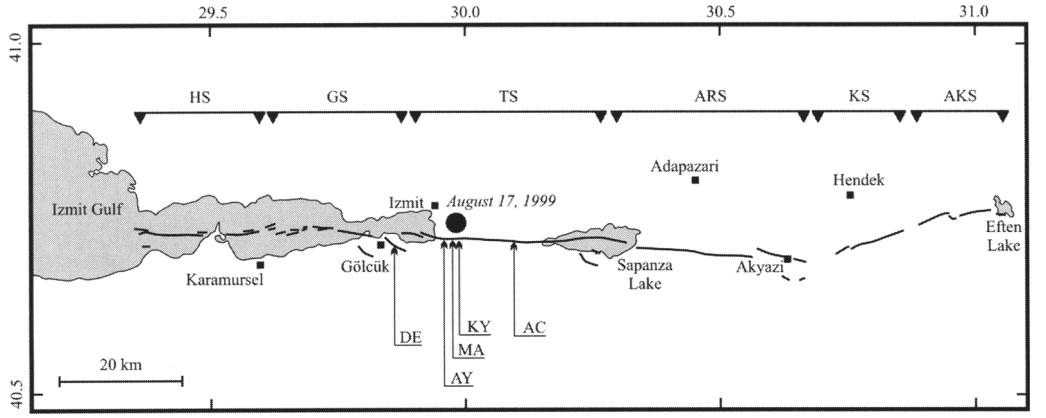


**Fig. 2.** Map of the 1999 Izmit earthquake ruptures (modified from Emre *et al.* 2003). ●, epicentre of the main shock. Ruptures have been divided into the following segments: HS, Hersek segment; GS, Gölcük segment; TS, Tepetarla segment; ARS, Arifiye segment; KS, Karadere segment; AKS, Aksu segment. Trenching sites discussed in this paper are indicated by arrows: DE, Dëniz Evler; AY, Aşağı Yuvacık; MA, Mahmutpaşaçiftliği; KY, Kullar-Yaylacik; AC, Acisu.

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earthquakes during 1509, 1719, 1754 and 1894 (Ambraseys & Finkel 1995; Ambraseys 2002). Three seismic events were also defined during the last 1000 years in the eastern segment and the Duzce fault. Emre *et al.*'s (2003*b*) data indicate that the eastern Izmit segment exhibits a synchronous recurrence interval with the Duzce fault, unlike the western part of the Izmit segment. Dating results show that the penultimate event occurred some time between 200 and 300 years

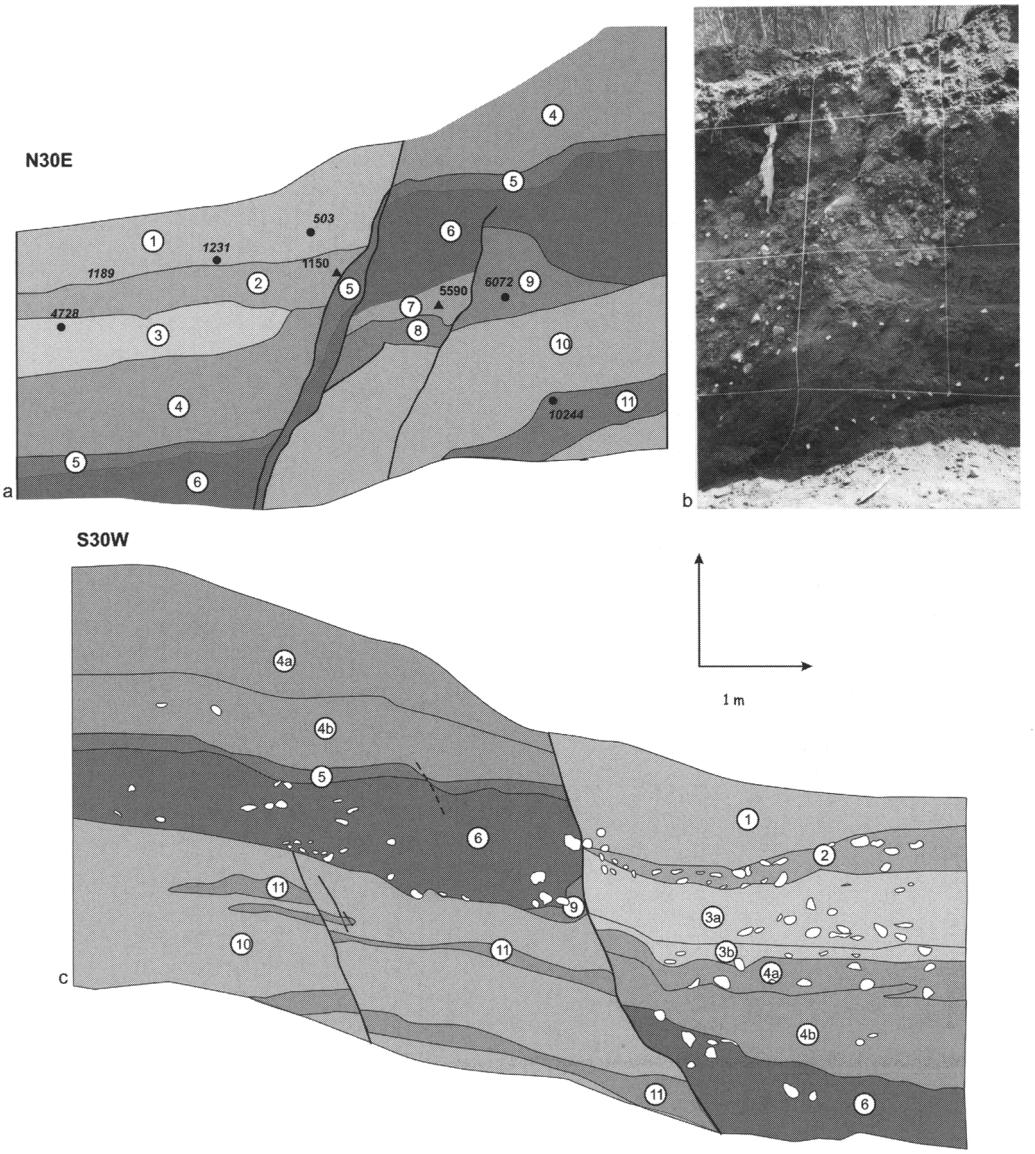


**Fig. 3.** (**a**) Log of the SE wall of DE-1 trench at Dëniz Evler site. The detailed stratigraphy of Holocene sediments is shown in Figure 4 and described in the text. ●, sampling points for OSL dating (results in italics); ▲, sampling points for $^{14}C$ dating. Results are shown in Tables 3 and 4. (**b**) Photograph showing part of the southeastern wall of DE-1 trench and details of the main fault zone (faults and layer boundaries are shown by a series of colour-coded flags; grid is 1 m × 1 m). (**c**) Log of the NW wall of DE-1 trench. Although there are some differences in the logs of the two walls, the main stratigraphic and structural features are consistent.

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BP, and possibly correlates with the well-known 1719 earthquake. Palaeoseismological results from both segments indicate that the 1719 event had a similar triggering process to the 1999 events (19 August, Izmit; 14 November, Duzce).

Klinger *et al.* (2003) studied the NW–SE-trending Gölcük normal fault, part of the western segment, known as Dëniz Evler, which also produced surface ruptures during the 1999 Izmit earthquake. The same fault segment was studied in the present work. The results of Klinger *et al.* were based on anisotropy of magnetic susceptibility (AMS) dating of colluvial wedges in two trenches, as well as on the total vertical displacement of two palaeoscarps, and they concluded that two possible earthquakes (1509 and 1719) were associated with the Gölcük fault.

## Historical seismicity

Prior to the 1999 earthquake the well-known strong 1894 earthquake seismic event probably ruptured the segments that were listed activated by the 1999 event (Ambraseys 2001). Several other large earthquakes (e.g. those of 1719 and 1754), as documented by Ambraseys & Finkel (1987) and Ambraseys (2002), could potentially be associated with the western branch of the NAFZ, especially in the Izmit region. Other earthquakes of similar size include the events of AD 1766, 1754, 1719, 1509 and 989 (Ambraseys & Finkel 1991), and the less well-documented events of AD 554, 447(?), 362(?), 358(?), 268(?) and 268(?) and 68 (Ambraseys 2002). Thus, there is a strong possibility that some of these earthquakes, or possibly other unknown ones, have ruptured segments of the 1999 seismogenic fault.

## Trenching sites

In the present study, five palaeoseismological trenches were excavated during September 2001 at four sites along the 1999 fault ruptures (Fig. 2): (1) Dëniz Evler (Gölcuk–Kavakli area); (2) Aşağı Yuvaclk (Kocaeli, south of Izmit); (3) Kullar–Yaylaclk (Kocaeli, SE of Izmit); (4) Acisu (Kocaeli, west of Sapanza Lake). Previous work included preliminary palaeoseismological trenching at Mahmutpaşaçiftliği (in May 2000, Tutkun & Pavlides 2001; Buluş-Kırıkkaya *et al.* 2006). All these sites were selected on the basis of the existence of surface ruptures, as well as on the basis of surface morphology. The objective during the data selection was to examine the 1999 surface ruptures, and also to try to establish a link between current and past faulting.

### *Dëniz Evler site*

This site is located east of Gölcuk city, close to Kavakli and Yeniköy villages (Fig. 2). The east–west-trending Gölcuk fault segment extends eastwards marked by a NW–SE normal fault about 3 km long on land, where seismic ruptures emerge at the surface, with a maximum vertical displacement of 1.5–2 m and a right-lateral component of 0.30 m. This fault affects recent deltaic deposits, i.e. sandy clays, sands, gravel, conglomerates and soil. It has a typical extensional structure perpendicular to the $\sigma_3$ main principal

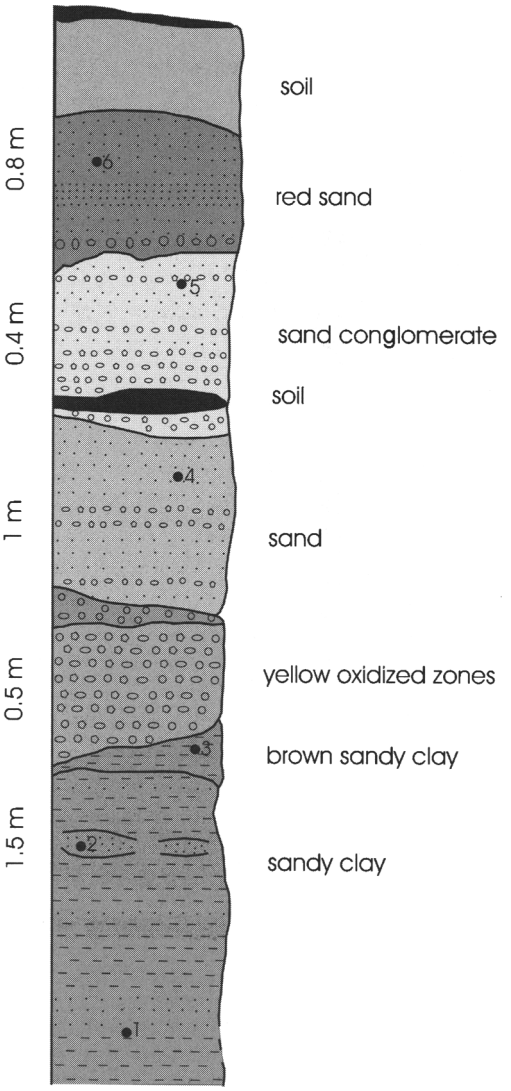


**Fig 4.** Synthetic stratigraphic column of the layers observed in DE-1 trench (both walls). Numbers refer to sampling points for OSL dating.

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stress axis. Extensional features, i.e. mode I cracks (see Scholz 1990) form in strike-slip systems, in response to simple shear at about 45° to the master fault, e.g. the Gölcük–Kavakli normal fault. This fault is believed to have been activated during, or just after, the main shock of 1999 in the form of a gravitational slip, following a pre-existing structure, rather than as a typical coseismic rupture. This normal fault could possibly be a visible strand of a pull-apart structure, located close to the epicentre of the main shock where the rupture propagation began.

The seismic ruptures did not follow any known or mapped fault traces. The round,

**Table 1.** *Events and displacements observed at the DE-1 trench at the Dĕniz Evler site*

| Event | Timing | Displacement (m) |
|---|---|---|
| 1 | 1999; associated with activity of the main fault zone; cuts through the surface, causing significant ground distortion | 1.5–1.6 |
| 2 | Before deposition of layer 2 and after deposition of layer 4; associated with activity on the main fault zone | 0.7 |
| 3 | Before deposition of layers 6 and 7, and after deposition of layers 8 and 9; associated with an erosional surface and activity on a secondary fault | At least 0.2 |
| 4? | Before the deposition of layers 8 and 9; not associated with any faults, but assumed to be due to the abrupt change of depositional facies | Unknown |

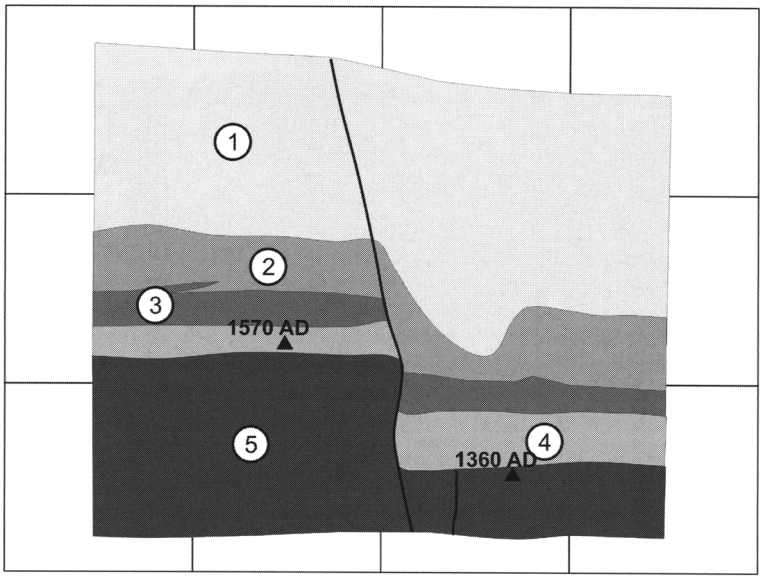


**Fig 5.** Log of part of the western wall of AY-1 trench. ▲, sampling points for $^{14}C$ dating (Table 6). Grid is 1 m × 1 m. Number indicate layers described in the text.

**Table 2.** *Events and displacements observed at the AY-1 trench at the Aşağı Yuvacık site*

| Event | Timing | Displacement (m) |
|---|---|---|
| 1 | 1999; associated with the activity of the main fault zone and cuts the surface | 0.25–30 |
| 2 | After deposition of layer 5 and immediately before deposition of layer 4; associated with a secondary fault that stops at the base of layer 4 | 0.7 |

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eroded pre-seismic topographic scarp height is similar to or slightly higher than the 1999 one. The 1999 fault rupture formed a NW–SE-trending, NE-dipping, typical normal fault scarp with up to 2 m of normal displacement.

The Dëniz Evler excavation site is located in the middle of the Gölcük normal fault, east of Kavakli village. At this site the fault scarp had a vertical throw of 1.5–1.6 m. However, the morphology of the area indicates a pre-existing fault scarp, indicating previous reactivation. Such reactivations were traced during the process of trench logging, as described below. Surface effects along this scarp were associated with marsh subsidence, tilting of trees, etc. Trenching at this site (DE-1 trench) revealed that the stratigraphy consists of fluvial sediments at the top, changing to lake deposits at the bottom of the trench (Fig. 3). This was the largest and deepest trench (12 m × 8 m, 4–5 m deep). The stratigraphy includes the following layers from the top to the bottom (Fig. 4):

(1) Modern red–brown fine-grained soil, with few pebbles.
(2) Alluvium with multicoloured bedrock pebbles, of up to 10–12 cm diameter.
(3) Coarse-grained sand with weak lamination towards the north and a very few pebbles (up to 2 cm in diameter).
(4) As (2), but with a larger proportion of coarse-grained sand. The lower part of this layer is slightly Fe-oxidized (red–brown coloured).
(5) Pebbles with black Mn-oxides; these are arranged roughly parallel to the general bedding.
(6) Red–brown conglomerate with pebbles of various sizes (up to 15 cm in diameter).
(7) Grey colluvium with a few large pebbles (up to 12 cm) and many smaller ones (2–5 cm), without bedding.
(8) Red–brown conglomerate (large pebbles, up to 15 cm).
(9) Brown–green fine-grained sand with a very few small pebbles, mainly near its southern edge.
(10) Olive green clay with lenses of fine-grained sand.
(11) Coarse-grained green sand.

According to an analysis of the microstratigraphy and fault geometry, the events listed in Table 1 may be distinguished.




**Fig 6.** (**a**) View of the KY-1 trenching site. Dextral displacement, as documented in displaced walls, is of the order of 3 m. (**b**) Detail of the 1999 shear zone. Slickenlines indicate a pure strike-slip movement at this site. (**c**) Liquefaction structures are associated with a previous event in KY-1 trench. Dating of this event was not possible because of lack of organic material.

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Evidence for three prior events is, therefore, present in the trench, each displacing layers by less than the 1999 event. Most of the displacement took place along the main fault zone, which is the same one that produced the 1999 event, but there is also another fault that dies out upwards, indicating that it was activated only once. Analysis of the microstratigraphy shows that there is an abrupt change of facies in the footwall (lacustrine to fluvial), possibly connected with a single earthquake or several events closely spaced in time on the main fault.

### *Aşağı Yuvacık site*

Seismic fault fractures at this site appeared in two separate roughly east–west-trending parallel strands, about 40 m apart; the displacement was predominantly normal, while the strike-slip vector was very small. Two north–south-trending trenches were excavated at this site (AY-1 and AY-2) in both fault strands.

AY-1 trench, located on the southern strand, was 12 m long and 3 m deep. Its stratigraphy consists of the following layers from the top to the bottom (Fig. 5):

(1) Well-rounded pebbles (5–15 cm) containing abundant gravels and sand lenses. Towards the surface this changes to poorly developed reddish brown soil.
(2) Coarse sand laminations with occasional fine gravels; greyish brown.
(3) Clay with occasional small to medium-sized pebbles; reddish brown.
(4) Dark grey organic silty material, probably associated with a periodic sag pond or swamp bed.
(5) Coarse sand with occasional gravels.

Analysis of the microstratigraphy shows that there was one event prior to the 1999 earthquake (Table 2).

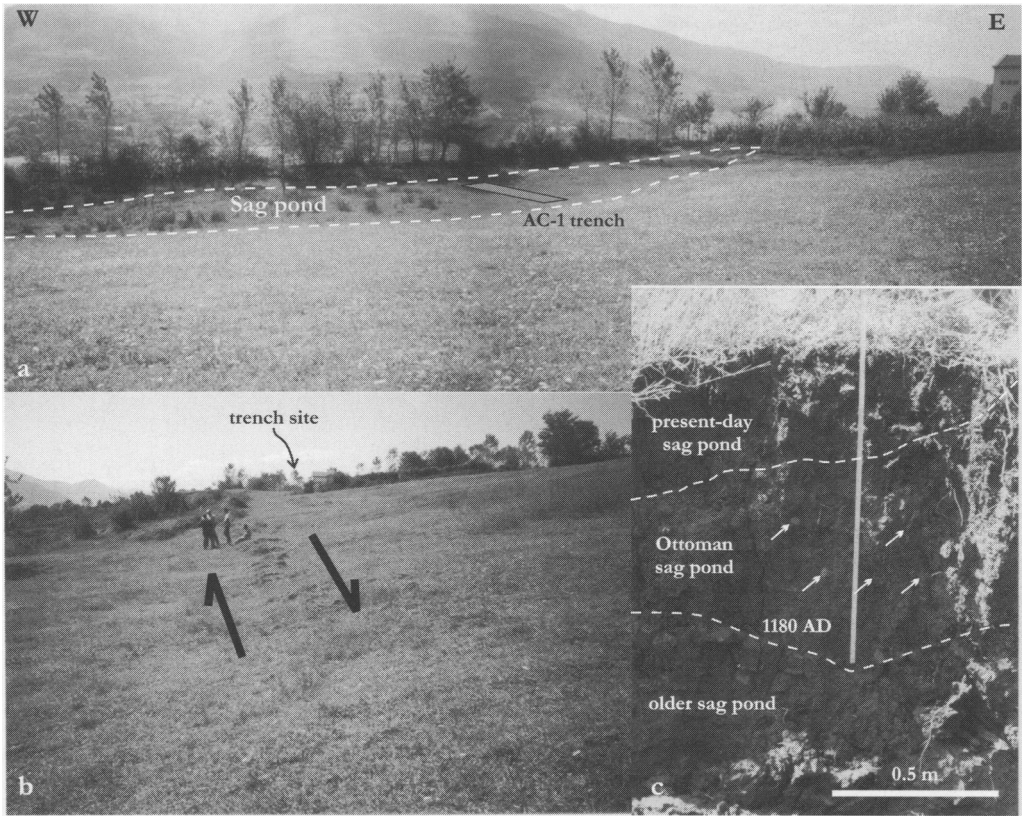


**Fig 7.** (**a**) General view of the trenching site at Acisu. A sag pond is formed parallel to the main fault line. (**b**) The 1999 surface ruptures 100 m west of the trenching site. The sag pond is formed in a relief inversion, in which the trench AC-1 was excavated (arrow). (**c**) Detail of the eastern wall of AC-1 trench. Three successive palaeo-sag ponds are visible in the trench; Ottoman ceramic shards are visible in the middle one (arrows). (For dating see Table 7.)

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AY-2 trench was excavated on the northern strand, where it crossed a sag pond, indicative of active strike-slip displacement. However, no evidence of previous events was found in this trench.

### *Kullar–Yaylacık site*

This trench (KY-1) was excavated in the Yaylacik area, *c.* 1 km west of Kullar. A block of flats was demolished during the earthquake, which produced a right-lateral displacement of *c.* 3 m (Fig. 6a). Two main fault zones were detected in the trench, in contrast to the 1999 rupture, which was confined to just one. The sedimentary structure is chaotic; there are also multiple shear zones and older liquefaction phenomena (Fig. 6b). Liquefaction at this site directly relates to older earthquakes; however, dating of these earthquakes is difficult, because of the lack of suitable material. It seems that the intensity of at least one of the palaeoearthquakes was large enough to cause ejection of underlying material (Fig. 6c).

### *Acisu site*

This trenching site is located east of Acisu village. The site was selected because of the morphology of the area, as well as its proximity to 1999 earthquake fractures. This was the only site where the trench did not cut exposed fault ruptures. The site is located in an elongated sag pond that forms a relief inversion, as it is located on the slope of a 'host' hill, not at its base (Fig. 7a and b). The sag pond is about 80 m long by 20 m wide, and strikes east–west, parallel to the NAFZ at this point. The trench was excavated perpendicular to the major axis of the sag pond, to detect variations in deposits that could be associated with subsequent faulting events.

Trench AC-1 was about 10 m long and 2.5 m deep; it was excavated entirely in dark-coloured organic material, indicating that it operated as a sag pond for a long period of time. Two older sag ponds were detected, associated with earlier development phases, the uppermost one being rich in ceramic fragments of the Ottoman period (Fig. 7c). A log of this trench shows that the sag ponds did not form along the same axis, but that their axes are migrating towards the south, thus indicating possible tilting.

## Dating

Dating of samples from the trenches was performed by $^{14}C$ with anisotropy of magnetic susceptibility (AMS) and by optically stimulated luminescence (OSL). The most suitable method for each case was defined mainly by the amount of organic material present in samples. Samples dated by $^{14}C$ were analysed at the Center for Applied Isotope Studies, University of Georgia, USA (CAIS-UGA), and the OSL dating was performed by E. Buluş-Kırıkkaya at the University from Kocaeli (Turkey). The following paragraphs describe the dating results from the trenches.

### *Döniz Evler site*

Several samples were dated in this trench by both $^{14}C$ and OSL methods. Table 3 summarizes the corrected $^{14}C$ dates, and Table 4 the OSL ones. Based on these results, as well as the description in Table 1, Table 5 summarizes the palaeoseismic history observed in trench DE-1.

**Table 3.** *Corrected $^{14}C$ ages of the samples from the DE-1 trench at the Döniz Evler site*

| UGA no. | Sample no. | Date (years BP ± 1) | Corrected date | $^{13}C$ (‰) | Years |
|---|---|---|---|---|---|
| 10113 | Sand 7C | 5580 ± 40 | 5590 | −24.51 | +8 |
| 10115 | Sand 9C | 1080 ± 50 | 1150 | −20.75 | +69 |

**Table 4.** *The palaeodose (De), annual dose and OSL ages obtained from six samples from the DE-1 trench (Buluş-Kırıkkaya et al. 2006)*

| Sample no. | *De* (Gy) | Dose rate (Gy ka$^{-1}$) | Additive-dose age (years) |
|---|---|---|---|
| 8T | 25.293 | 2.469 | 10244 ± 764 |
| 3T | 15.211 | 2.505 | 6072 ± 453 |
| 5T | 11.939 | 2.525 | 4728 ± 353 |
| 6T | 3.120 | 2.534 | 1231 ± 92 |
| $6T_1$ | 2.938 | 2.470 | 1189 ± 89 |
| 7T | 1.303 | 2.590 | 503 ± 37 |

**Table 5.** *The timing of the events observed at DE-1 trench at Döniz Evler site*

| Event | Date of the event |
|---|---|
| 1 | 1999 |
| 2 | Prior to AD 800, younger than 2778 BC; because of the geometry of the fault zone and the stratigraphic relations, probably the uppermost time limit rather than the lowermost one |
| 3 | Between 3640 BC and 4122 BC |
| 4? | Between 4122 BC and 8294 BC |

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**Table 6.** *Corrected $^{14}C$ ages of the samples from the AY-1 trench at the Aşağı Yuvacık site*

| UGA no. | Sample no. | Date (years BP ± 1) | Corrected date | $^{13}C$ (‰) | Years |
|---|---|---|---|---|---|
| 11472 | Soil AY-1/1 | 590 ± 70 | 590 | −25.18 | −3 |
| 11473 | Soil AY-1/2 | 370 ± 50 | 380 | −24.12 | +14 |

**Table 7.** *Corrected $^{14}C$ ages of the samples from the AC-1 trench at the Acisu site*

| UGA no. | Sample no. | Date (years BP ± 1) | Corrected date | $^{13}C$ (‰) | Years |
|---|---|---|---|---|---|
| 11471 | Soil AC-1 | 750 ± 80 | 770 | −23.80 | +19 |

### *Aşağı Yuvacık site*

Two samples from characteristic spots were dated in this trench (Fig. 5), as shown in Table 6. Based on these results, as well as the interpretation of Table 2, we conclude that, apart from the 1999 event, the previous large event occurred between AD 1360 and 1570.

### *Acisu site*

The trench at this site did not cut the 1999 rupture; therefore, this earthquake is not documented in the trench. Based on the stratigraphical relationships observed in the trench, we can relate the evolution of older sag ponds to previous earthquakes, which caused tilting of the surface at the site. One sample was taken from the bottom of the penultimate sag pond (Table 7). In

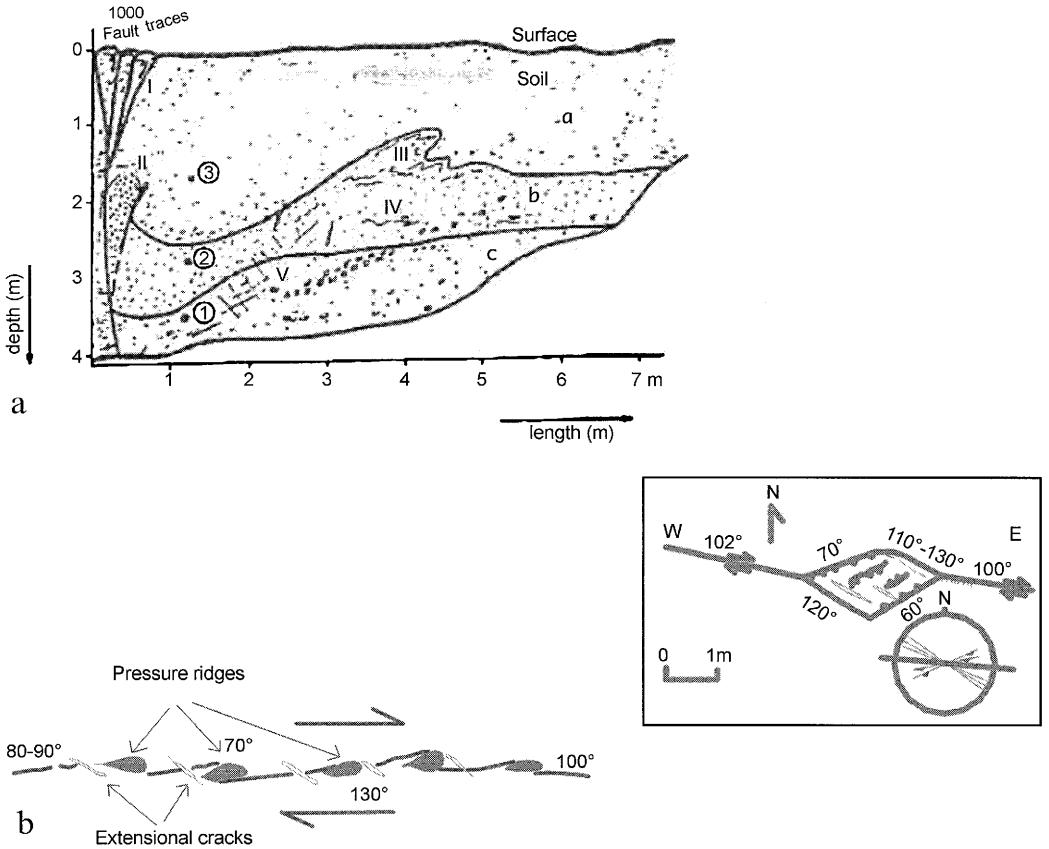


**Fig 8.** (**a**) Stratigraphy of the Mahmutpaşaçiftliği trench. Distinct layers are shown (a, soil; b, sandy mud; c, soil, possibly of palaeo-sag -pond origin). The 1999 fault (contractional) is marked by the small-scale flower structure (I), liquefaction (II and III), seismites (IV) and cracks (V). Numbers 1–3 indicate layers described in the text. (**b**) Sketch of a series of pressure ridges along the right-stepping linear fault traces at Mahmutpaşaçiftliği in the Kocaeli district (Aşağı Yuvacık–Yailacik) where the trenches were excavated. In general, the orientation and movement along stepping small fault branches resulted in local compression; this caused shortening and uplift of *c.* 5–10 m long (grey areas), accompanied by extensional fractures (120–130°). Inset: the structure of a typical pressure ridge, where the main displacement zone is oriented at 100° and the contractional structures at 70°.

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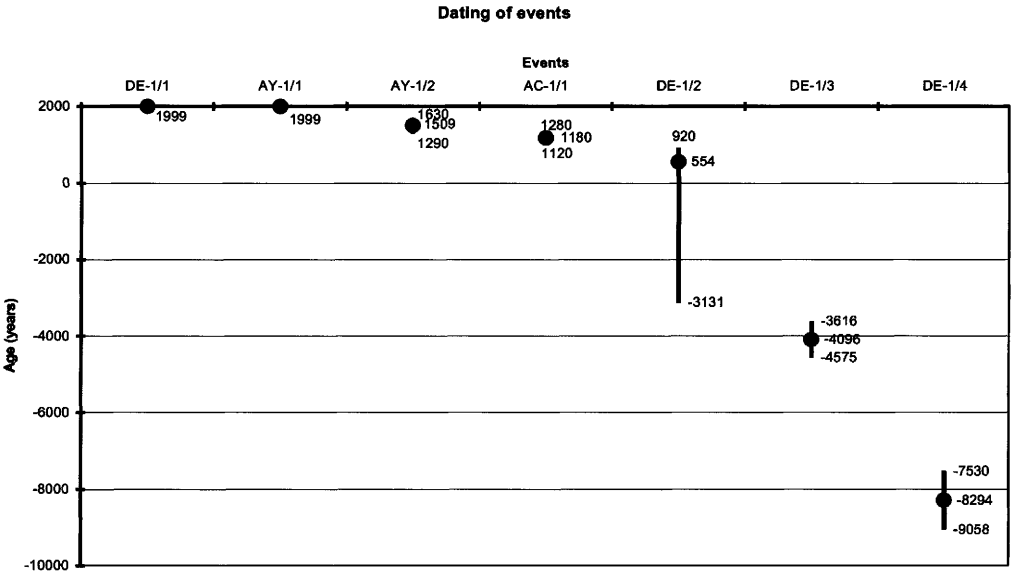


**Fig 9.** Synthetic graph of the events detected in palaeoseismological trenches in this study. Most of the events dated in the AD period are associated with known historical events.

the absence of other obvious factors, the creation of the sag ponds can be attributed to alterations in the morphology associated with earthquake events. In this case, the last event that produced enough ground distortion to modify the sag pond would be around AD 1180.

### *Mahmutpaşaçiftliği site*

Our interpretation of a previously excavated trench was also used. Although results from this trench (Fig. 8a) were already published (Tutkun & Pavlides 2001) based on two samples of $^{14}C$ dating, new results show that there were subsequent activations of the same fault zone throughout the Holocene (Table 8).

The Mahmutpaşaçiftliği area is located in the middle of a shallow linear valley with a flat floor. Two trenches, 8 m long and 4 m deep, were excavated across the 1999 fault traces on a small pressure ridge (Fig. 8b), to look for fossilized palaeoseismic structures or palaeoearthquakes (Fig. 8a). The trench walls display a record of Holocene (historical) sedimentation. These sediments can be broadly divided into at least three layers plus superficial recent soil; (1) 2 m dark soil; (2) 1 m yellow sandy mud, possibly of palaeo-sag pond deposits; (3) 1 m dark palaeo-soil with a few pebbles. The pebbles are typically in horizontal position, but disseminated. Structural features, i.e. joints (cracks), seismites and

**Table 8.** *De: the annual dose rate and OSL ages obtained from the three samples from the Mahmutpaşaçiftliği trench (Buluş-Kırıkkaya et al. 2006)*

| Sample no | *De* (Gy) | Dose rate (Gy ka$^{-1}$) | OSL age (years) |
|---|---|---|---|
| c | 28.607 | 2.529 | 11311 ± 843 |
| b | 23.055 | 2.489 | 9263 ± 691 |
| a | 22.650 | 2.756 | 8218 ± 613 |

**Table 9.** *Summary of palaeoseismic events in chronological order traced at the excavated sites*

| Event | Minimum age | Maximum age | Probable age |
|---|---|---|---|
| DE-1/1 | | | AD 1999 |
| AY-1/1 | | | AD 1999 |
| AY-1/2 | AD 1290 | 1630 AD | AD 1509 |
| AC-1/1 | AD 1120 | 1280 AD | AD 1180(?) |
| DE-1/2 | 3131 BC | 920 AD | AD 554 |
| DE-1/3 | 4575 BC | 3616 BC | 4096 BC |
| DE-1/4 | 9058 BC | 7530 BC | 8294 BC |

DE, Dëniz Evler site; AY, Aşağı Yuvacık site; AC, Acisu site.

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**Table 10.** *Summary table of palaeoseismic events traced in various locations along the NAFZ within the wider study area*

| | Events | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | AD | | | | | BC | | |
| Location | 1999 | 1719 | 1509 | 989 | 554 | 4096 | 8294 | References |
| Dëniz Evler | X | | | | x | x | x | This paper |
| Dëniz Evler | X | x | x | | | | | Klinger *et al.* (2003) |
| Aşağı Yuvacık | X | | x | | | | | This paper |
| Acisu | | | | x | | | | This paper |
| Eastern segment | X | x | | | | | | Emre *et al.* (2003) |

palaeo-liquefaction, are associated with the fault. These features are consistent with morphotectonic observations showing that a large-scale dextral movement is documented by 'blind' streams and truncated elongated hills (Tutkun & Pavlides 2001).

## Discussion and conclusion

The trenches excavated at various sites along the 1999 surface rupture lines show that the same faults were reactivated several times during the late Holocene. Indeed, as shown in Table 9, a number of events were identified during this period. The results in Table 9, as well as their projection as a graph (Fig. 9), are associated with known historical earthquake activity, with the exception of the AD 1180 event, detected in trench AC-1, which does not coincide with any known historical earthquake. The closest event is that of AD 989. A possible explanation for this discrepancy is that it is associated with the lower part of the middle sag pond at this site, which could have taken some time before it is formed. It is, therefore, assumed that the *c.* 100 year gap was associated with geomorphological processes, and that the palaeoseismologically derived age is linked to this event. Several of the above-mentioned events are comparable with findings in other trenches, as discussed above. Table 10 presents the recent seismic history of several sites along the NAFZ in the broader study area, as derived from palaeoseismological research. It is, therefore, concluded that the 1999 earthquake fault was indeed reactivated during the past, during several historical earthquakes. Of those, the 1719 event seems to have extended across both major segments of the 1999 fracture, whereas the 1509, 989 and 554 events were most probably confined to its western segment.

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