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# Historical earthquake activity of the northern part of the Dead Sea Fault Zone, southern Turkey

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**Abstract**

The northern part of the Dead Sea Fault Zone is one of the major active neotectonic structures of Turkey. The main trace of the fault zone (called Hacıpaşa fault) is mapped in detail in Turkey on the basis of morphological and geological evidence such as offset creeks, fault surfaces, shutter ridges and linear escarpments. Three trenches were opened on the investigated part of the fault zone. Trench studies provided evidence for 3 historical earthquakes and comparing trench data with historical earthquake records showed that these earthquakes occurred in 859 AD, 1408 and 1872. Field evidence, palaeoseismological studies and historical earthquake records indicate that the Hacıpaşa fault takes the significant amount of slip in the northern part of the Dead Sea Fault Zone in Turkey. On the basis of palaeoseismological evidence, it is suggested that the recurrence interval for surface faulting event is 506±42 years on the Hacıpaşa fault.


*Keywords:* Historical earthquake; Dead Sea Fault Zone; Palaeoseismology; Southern Turkey; Trench

## 1. Introduction

The left-lateral Dead Sea Fault Zone (DSFZ) extends from the Red Sea in south to the East Anatolian fault zone in north (Fig. 1a). Large historical earthquakes have been documented along the DSFZ and detailed studies showed that some of them were associated with left-lateral surface ruptures (e.g. Marco et al., 1997; Al-Tarazi, 1999; Klinger et al., 2000; Galli and Galadini, 2001; Gomez et al., 2003; Marco et al., 2003; Meghraoui et al., 2003; Daëron et al., 2005). For example, Marco et al. (1997) reported that E–W-trending walls were displaced sinistrally up to 2.1 m by the DSFZ near the Jordan River. Gomez et al. (2003) identified five surface-rupturing events in the last 6500 years based on palaeoseismological evidence in Syria and Lebanon and concluded that the last event occurred in the 18th century and involved 2–2.5 m left-lateral displacement. Meghraoui et al. (2003) made palaeoseismological and archaeoseismological studies on the DSFZ in Syria and their results showed that a Roman aqueduct (older than 70 A.D. and younger than 30 A.D.) is offset sinistrally by about 13 m.

Large historical earthquakes have also been documented (Table 1) along the northern part of the DSFZ (e.g. Ergin et al., 1967; Soysal et al., 1981; Ambraseys, 1989;

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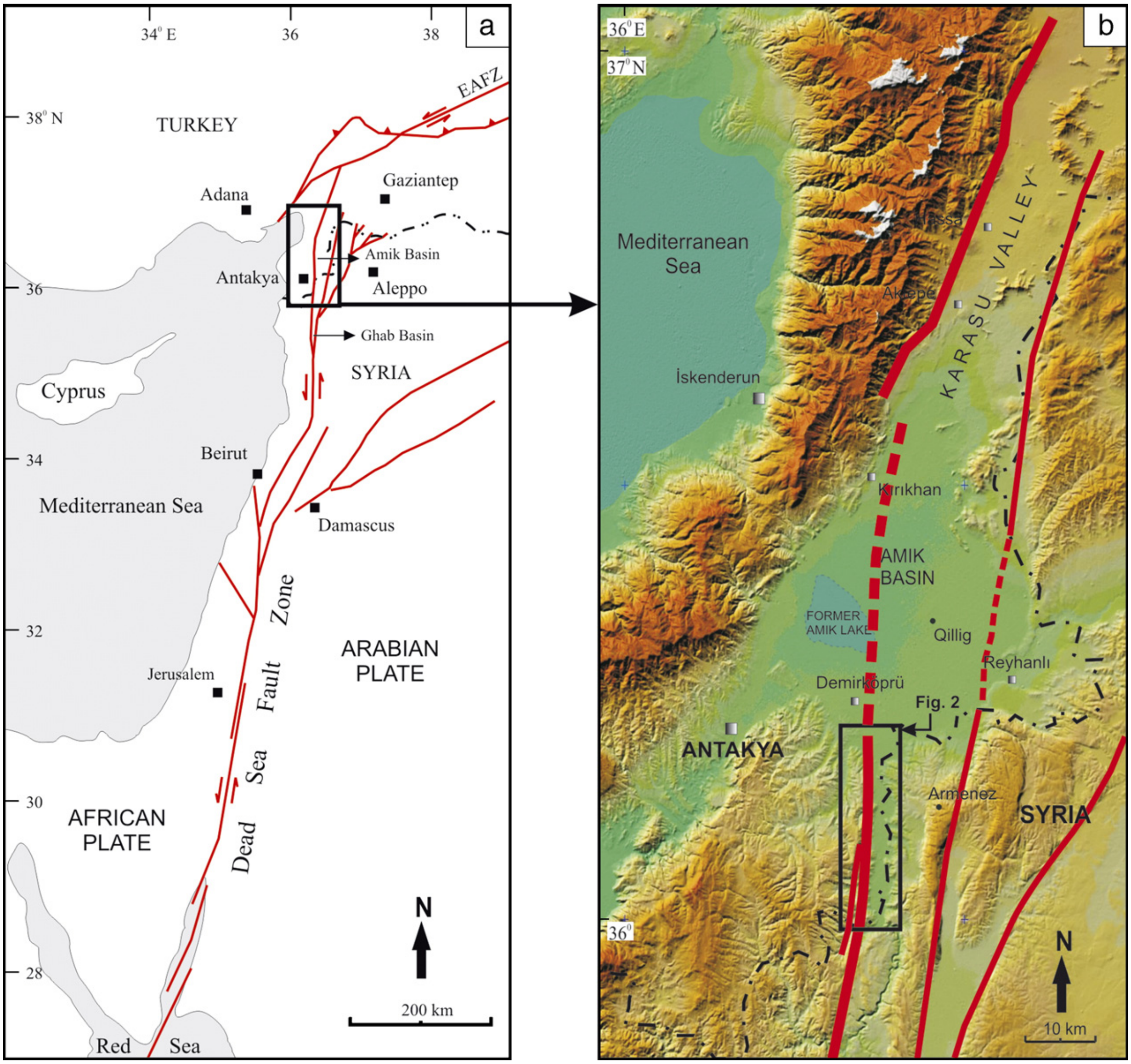


Fig. 1. a) General map of the Dead Sea Fault Zone between the Red Sea in south and East Anatolian Fault Zone (EAFZ) in north. Simplified from Zilberman et al. (2000), Meghraoui et al. (2003) and Westaway (2003). b) DEM of the northern part of the Dead Sea Fault Zone. The Hacıpaşa fault (red line) was drawn on the basis of authors' field observations; other faults (black lines) are taken from Perinçek and Çemen (1990), Lyberis et al. (1992), Yürür and Chorowicz (1998), Rojay et al. (2001) and Westaway (2003).

Guidoboni et al., 1994; Ambraseys and Melville, 1995; Ambraseys and White, 1997; Guidoboni et al., 2004). Historical records report that earthquakes destroyed the nearby ancient city of Antioch (modern Antakya, see Fig. 1 for location) which was founded in the 3rd century B.C. (Demir, 1996). Since Antioch was an important ancient city, historical earthquake records are long and extend back at least 2300 years, thus, it provides opportunity to correlate macroseismicity with field investigations in active tectonics and palaeoseismology.

The DSFZ expresses clear trace in the south (Fig. 1a) but splays into branches in southern Turkey (Fig. 1b). Surface ruptures associated with historical earthquakes and basic kinematic parameters are well documented with palaeoseismological investigations along the southern DSFZ (e.g. Marco et al., 1996, 1997; Ellenblum et al., 1998; Klinger et al., 1999, 2000; Meghraoui et al., 2003; Marco et al., 2003, 2005). However, although southern Turkey presents a good opportunity to integrate historical records of large

Table 1
List of recorded historical earthquakes on the northern part of the Dead Sea Fault Zone

| N | Date | Coordinate<br>Lat. (N)–Long. (E) | Location | Life missing | *I* | *M* | Reference |
|---|---|---|---|---|---|---|---|
| 1 | BC 140 (9) or 148 | 36.25–36.10 (3) | Antakya, Karasu Valley (9) | ? | 8 (3) | 7 (9) | 3, 6, 7, 8, 9 |
| 2 | BC 64 (9) or 65–66 | 36.20–36.10 (9) | Karasu Valley (9) | ? | ? | 7.5 (9) | 7, 8, 9 |
| 3 | December 13 115 | 36.10–36.10 | Antakya, Karasu Valley (9) | 250000 (6) or 260000 (4) | 9 or 6 (1) | 7.3 (9) or 7.5 (4) | 1, 3, 4, 6, 7, 8, 9 |
| 4 | 499 or 500 (4) | 36.20–36.10<br>37.00–37.00 (4) | Karasu Valley, Antakya (4) | ? | ? | 7.2 or 7 (4) | 4, 9 |
| 5 | May 29 526 or 525 (4) | 36.25–36.10 | Antakya, Samandag | 250000–300000 | 9 | 7 (4) | 1, 3, 4, 7, 8 |
| 6 | November 29 528 or 529 | 36.25–36.10<br>37.00–38.00 (4)<br>36.50–36.15 (2) | Antakya, Karasu Valley (9) | 4870 | 9 or 10–11 (2) | 7.1 (9) or 6.5 (4) | 1, 2, 3, 4, 7, 8, 9 |
| 7 | September 30 587 | 36.25–36.10 | Antakya | 60000 | 9 | ? | 3, 7, 8 |
| 8 | March 713 | 36.25–36.10 | Antakya, Karasu Valley (9) | ? | 6, 9 (2) | 6.8 (9) or 6.5 (4) | 1, 2, 4, 7, 8, 9 |
| 9 | April 8 859 | 36.25–36.10 | Antakya, Lattakia, Homs, Sergilla, Karasu Valley (9, 2) | ? | 9 or 6 (1) or 10–11 (2) | 7–7.5 or 7.9 (9) | 1, 2, 3, 7, 8, 9, 10 |
| 10 | July 15 (9) or August 1157 | 35.10–36.30 (9) | Apamea, Hama, Aleppo, Ghab Valley (9) | ? | ? | 7–7.5 (9, 10) | 9, 10, 11 |
| 11 | June 29 1169 or 1170 (4) | 35.90–36.40<br>36.50–37.00 (4)<br>36.50–36.15 (2)<br>34.40–35.80 (3) | Missyaf, Shaizar, Homs, Hama, Missyaf, Karasu Valley, Halep (4) | 80000 | 9 | ~7.5 or 7.4 (9) | 2, 3, 4, 9, 10 |
| 12 | December 29 (9) 1408 | 35.90–36.30 (9)<br>36.50–36.15 (2) | Qalaat Blatnes, West of Aleppo, Lattakia, Karasu Valley (9), Antakya (5) | ? | 10–11 (2) | >7.5 or 7.2 (9) | 2, 5, 9, 10 |
| 13 | August 13 1822 | 36.40–36.20<br>36.70–36.90 (6, 9)<br>36.00–36.50 (4) | Antakya, Samandag (6), Karasu Valley (9), Ýskenderun-Kilis (3) | 1800–60000 (6), 20000 (3) | 10 or 9 (3) or 6 (1) | 7.4 (6, 9) or 7 (4) | 1, 3, 4, 6, 9 |
| 14 | April 2 1872 | 36.25–36.10 | Antakya, Samandag Amik Lake (4), Karasu Valley (9) | 1800 (4) | 8 or 9 (3) | 7.2 or 6.5 (4) | 1, 3, 4, 6, 9 |

(1) Ergin et al., 1967; (2) Poirier and Taher, 1980; (3) Soysal et al., 1981; (4) Karaki, 1987; (5) Ambraseys and Melville, 1995; (6) Ambraseys, 1989; (7) Guidoboni et al., 1994; (8) Ambraseys and White, 1997; (9) Khair et al., 2000; (10) Meghraoui et al., 2003; (11) Guidoboni et al., 2004.

earthquakes with palaeoseismological investigations in order to understand the processes of earthquake recurrence, similar studies are lacking for the Turkish part of the DSFZ. In addition, basic kinematic parameters such as slip rate are not well documented for the northern part of the DSFZ. Furthermore, the structural and kinematic connection between the northern part of the DSFZ and East Anatolian fault zone is uncertain. Thus, it is essential to unravelling on which structures large historical earthquakes occurred.

This study examines the northern part of the DSFZ located between the Syrian-Turkish border in south and Amik Basin in north (Fig. 2). This paper presents geological and geomorphological field evidence for significant left-lateral faulting on the DSFZ in southern Turkey. Results of palaeoseismological investigations accord with historical records and provide reliable information about the slip rate for this part of the fault zone. Palaeoseismological evidence demonstrates that this branch of the DSFZ has important implications in terms of regional tectonics and earthquake activity. Furthermore, it is believed that field observations in this study would make a significant contribution to understand the extent of the main strand of the DSFZ in southern Turkey.

## 2. Seismotectonic setting

### 2.1. Tectonic framework of the study area

The Dead Sea Fault is a left-lateral strike-slip fault that extends northward from the Red Sea spreading center to the East Anatolian fault zone, in Turkey. The fault is oriented N–S on average, bounding the African and Arabian plates (Fig. 1a). Age of the DSFZ and the total left-lateral offset on the fault zone have been the subject of debate. However, it is agreed that the tectonic

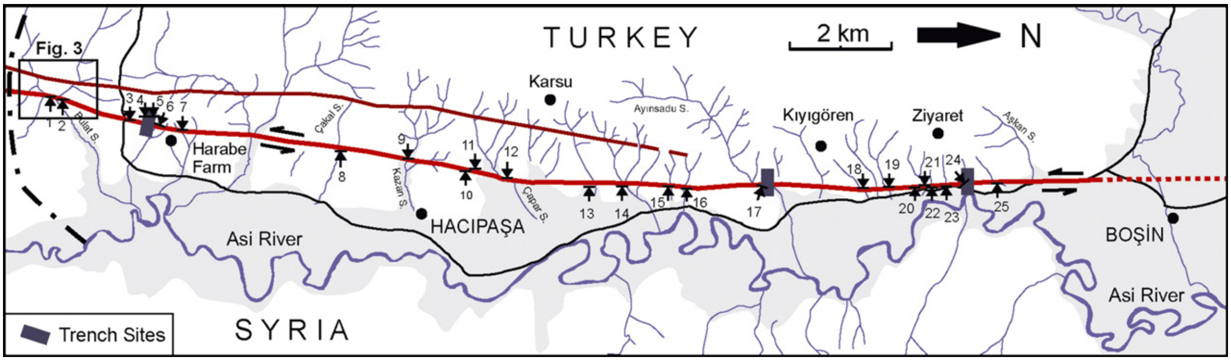


Fig. 2. Simplified map of the offset stream beds between the Syrian-Turkish border in south and Amik Basin in north. Note that the western fault does not extend further north of Hacıpaşa town and it does not offset any stream bed. The border between Turkey and Syria is the dashed bold line in south and Asi River. Numbers indicate locations of offset measurements given in Table 2. Map also shows trench locations.

deformation associated with the DSFZ began with initiation of sea-floor spreading in the Red Sea and the total slip on the DSFZ has been estimated up to 110 km for the southern section (e.g. Quennell, 1956; Garfunkel, 1981) and about 65 km for the northern section (Dubertet, 1966). The extent of the northern part of the DSFZ in Turkey is under discussion. Previous studies based on field observations (e.g. Şaroğlu et al., 1992; Rojay et al., 2001; Yurtmen et al., 2002), subsurface geophysical data (e.g. Perinçek and Çemen, 1990; Perinçek and Eren, 1990), GPS data (e.g. McClusky et al., 2000, 2003) and DEM of the area (Adiyaman and Chorowicz, 2002) suggested that the DSFZ splays into branches towards north and slip is partitioned. Westaway (2003, 2004) claims that the slip rate in Turkey is not more than 2 mm$^{yr-1}$ but his conclusion is based on general kinematic model of the region. Our field observations suggest that the main branch of the DSFZ, which takes the significant amount of the slip, extends approximately N–S from the Syrian-Turkish border into the Amik Basin (Fig. 2).

### 2.2. Historical seismicity

Large historical earthquakes, including the well documented 1822 and 1872 events, are reported along the

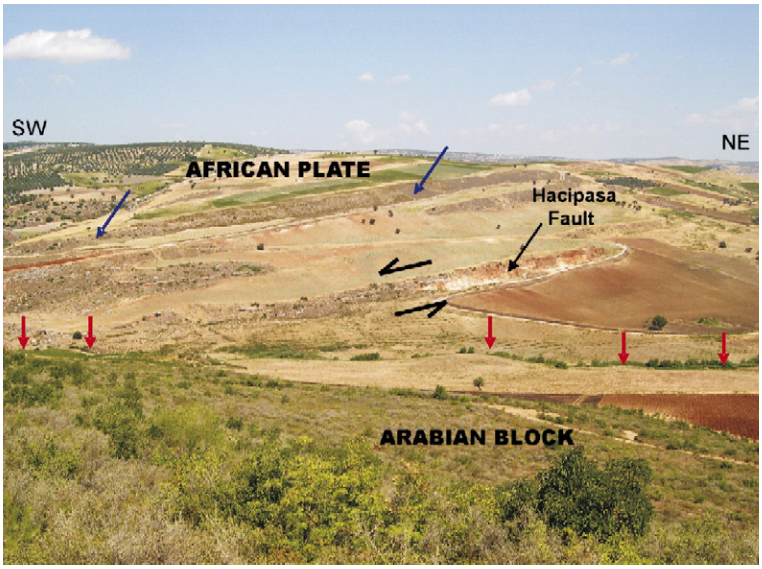


Fig. 3. A view towards northwest from the Syrian-Turkish border in south. Red arrows indicate Bulat Stream (see Fig. 2 for location), black arrow indicate a nearly vertical fault plane in limestone. Note that Bulat Stream (red arrows) is sinistrally offset by the fault (black arrow). Blue arrows indicate linear scarp in limestone on inactive fault branch.

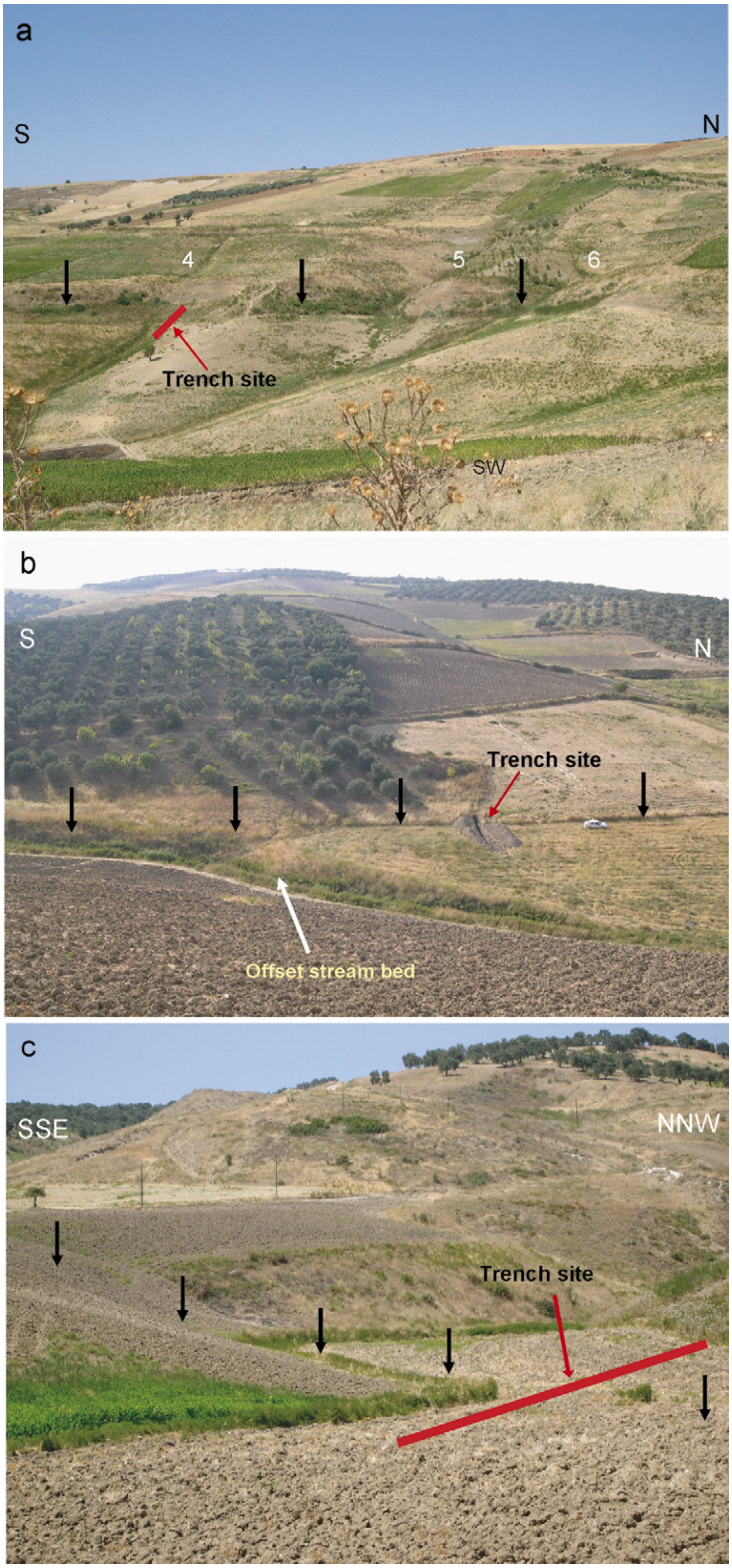


Fig. 4. a) A view from south of the Harabe Farm (locations 4, 5 and 6 in Fig. 2) showing offset small gullies and colluvial deposits on the east facing slope. View towards west. Numbers refer to location numbers in Fig. 2 and Table 2. Black arrows indicate fault trace and red line is the trench site. b) A general view of Yazlık trench site. View towards west. c) The offset stream bed in Ziyaret trench site. View towards southwest.

Table 2
Measured cumulative displacements from offset stream beds along the Hacıpaşa segment of the DSFZ

| Location number | Stream name | Cumulative offset (m) | GPS coordinates (±10,0) E–N |
|---|---|---|---|
| 1 | Bulat | 263±10,0 [a] | 0260746–3987981 |
| 2 | – | 18±0,5 [b] | 0260790–3988191 |
| 3 | – | 100±10,0 [a] | 0261286–3989425 |
| 4 | – | 14±0,5 [b] | 0261352–3989867 |
| 5 | – | 20±0,5 [b] | 0261349–3989989 |
| 6 | – | 20±0,5 [b] | 0261347–3990066 |
| 7 | – | 16±2,0 [c] | 0261450–3989500 |
| 8 | Çakal | 100±10,0 [a] | 0261830–3993550 |
| 9 | Kazan | 31±2,0 [c] | 0262070–3994920 |
| 10 | – | 21±2,0 [c] | 0262326–3995952 |
| 11 | – | 30±2,0 [c] | 0262326–3995972 |
| 12 | Çapar | 29±5,0 [d] | 0262550–3996750 |
| 13 | Çesme | 125±10,0 [a] | 0262680–3998500 |
| 14 | Killi | 437±10,0 [a] | 0262690–3999100 |
| 15 | – | 42±2,0 [c] (60±10,0 [a]) | 0262750–4000000 |
| 16 | – | 100±10,0 [a] | 0262755–4000200 |
| 17 | Ayınsadu | 650±10,0 [a] | 0262755–4001800 |
| 18 | – | 125±10,0 [a] | 0262875–4003750 |
| 19 | – | 140±10,0 [a] | 0262890–4004250 |
| 20 | – | 24±5,0 [d] | 0262890–4004840 |
| 21 | – | 46±1,0 [b] | 0262867–4004944 |
| 22 | – | 30±5,0 [d] | 0262890–4005090 |
| 23 | – | 48±1,0 [b] | 0262881–4005150 |
| 24 | – | 68±1,0 [b] | 0262885–4005376 |
| 25 | – | 75±1,0 [b] | 0262891 – 4006354 |

See Fig. 2 for locations.
[a] Measured from map.
[b] Measured with total station.
[c] Measured with GPS.
[d] Measured with tape-meter on field.

northern end of the DSFZ (Ergin et al., 1967; Poirier and Taher, 1980; Soysal et al., 1981; Karaki, 1987; Ambraseys, 1989; Guidoboni et al., 1994; Ambraseys and Melville, 1995; Ambraseys and White, 1997; Khair et al., 2000; Meghraoui et al., 2003; Guidoboni et al., 2004). Table 1 summarizes macroseismic descriptions of large historical earthquakes which affected the region. According to Ambraseys (1989), the 1822 event ($M$=7.4) took place in the Karasu valley further north of the Amik Basin and the 1872 earthquake ($M$=7.2) occurred in the Amik Basin. The April 3, 1872 earthquake was responsible for heavy damage around the former Amik Lake, especially both north and south of the lake. The eastern side of the Asi River, around Armenez, seems to have been particularly affected (Ambraseys, 1989) (Fig. 1b). These accounts indicate a probable N–S trending of the fault. There is no statement that the 1872 event was associated with surface rupture. However, considering magnitude 7.2 earthquake usually involves surface faulting (e.g. $M$=7.2, 1999 Duzce earthquake, Akyuz et al., 2002), it is very likely that the 1872 earthquake was associated with a N–S-trending surface rupture. Ambraseys (1989) also reports that the earthquake split the ground around Qilliq (Fig. 1b) but he interpreted them as widespread liquefaction. Examination of the 20th century earthquakes shows no records of large earthquakes on the northern part of the DSFZ.

## 3. Field observations for active faulting

The northern section of the DSFZ roughly trends N–S in Syria and bounds the western side of the Ghab Basin in northern Syria (Fig. 1a). Towards north, it enters Turkey and extends along the western side of the Asi River up to the Amik Basin (Figs. 1b and 2). The Turkish part of this segment of the DSFZ is called Hacıpaşa fault since the town of Hacıpaşa is the major settlement on the fault zone (Fig. 2). The late Quaternary tectonic activity of the Hacıpaşa fault is characterised by faulted alluvial and colluvial deposits, shutter ridges and sinistrally offset streams from tens to hundred of meters.

Table 3
Radiocarbon dates from trenches across the Hacıpaşa fault

| Trench name | Sample number | Unit | Laboratory ID no | Material type and weight (mg) | Radiocarbon age (BP) | Calibrated age (AD) | Two sigma range (AD) |
|---|---|---|---|---|---|---|---|
| Harabe | H5 | IV | KIA22526 | Charcoal (0.2) | 1012±42 | 1019 | 960–1039 |
| Yazlik | Y5 | IV | KIA22520 | Charcoal (0.6) | 609±72 | 1324–1390 | 1284–1428 |
| Yazlik | Y7 | IV | KIA22521 | Charcoal (0.5) | 621±39 | 1312–1387 | 1296–1401 |
| Yazlik | Y9 | V | KIA22523 | Charcoal (0.2) | 505±84 | 1423 | 1294–1522 |
| Ziyaret | Z19 | III | KIA26960 | Charcoal (0.3) | 264±61 | 1647 | 1468–1689 |
| Ziyaret | Z24 | IV | KIA26965 | Charcoal (1.5) | 249±22 | 1653 | 1637–1669 |
| Ziyaret | Z26 | III | KIA26967 | Charcoal (1.3) | 445±23 | 1442 | 1424–1478 |
| Ziyaret | Z27 | II | KIA26968 | Charcoal (1.5) | 1074±24 | 983 | 943–1018 |
| Ziyaret | Z31 | III | KIA26970 | Charcoal (0.2) | 165±76 | 1760 | 1637–1955 |

The calibrated age is according to “CALIB rev 4.3” (Data set 2) (Stuiver et al., 1998).

Nearly vertical faults cut pre-Pliocene limestone just north of the Syrian-Turkish border. A N5E-trending striated surface has formed in the bedded limestone and horizontal slickensides in limestone are visible that indicate horizontal motion. The lineation shows risers of steps facing south on a vertical W-facing surface, suggests that the sense of movement was sinistral. Further north, a cemented limestone breccia surface, a few hundreds of meters long, is exposed as a result of quarrying (Fig. 3). The lineation on this east facing surface is also horizontal. To the west, there is another N–S-trending linear scarp in limestone (Fig. 3) which extends about 12 km in the study area (Fig. 2). This scarp in limestone and escarpment probably reflects the location of a parallel fault but it does not continue further north because there is no morphological evidence (such as offset streams and shutter ridges) for active faulting. Thus, this linear scarp and escarpment most likely express an inactive fault.

The trace of the Hacıpaşa fault extends along the western side of the Asi River which has a low slope facing east (Fig. 2). Several east-flowing steams are offset left-laterally by various amounts by the Hacıpaşa fault (Figs. 2 and 4, Table 2). Table 2 presents the amount of cumulative left lateral displacements on stream beds at different locations between the Syrian-Turkish border in south and Amik Basin in north. The amount of cumulative sinistral displacement on offset stream beds varies between 14 m and 650 m (Table 2).

## 4. Results of palaeoseismological trenching

In order to obtain detailed information on the frequency of surface faulting earthquakes, we excavated palaeoseismological trenches on the northern part of the DSFZ (Fig. 2). The palaeoseismological sites are located between the Syrian-Turkish border and Amik

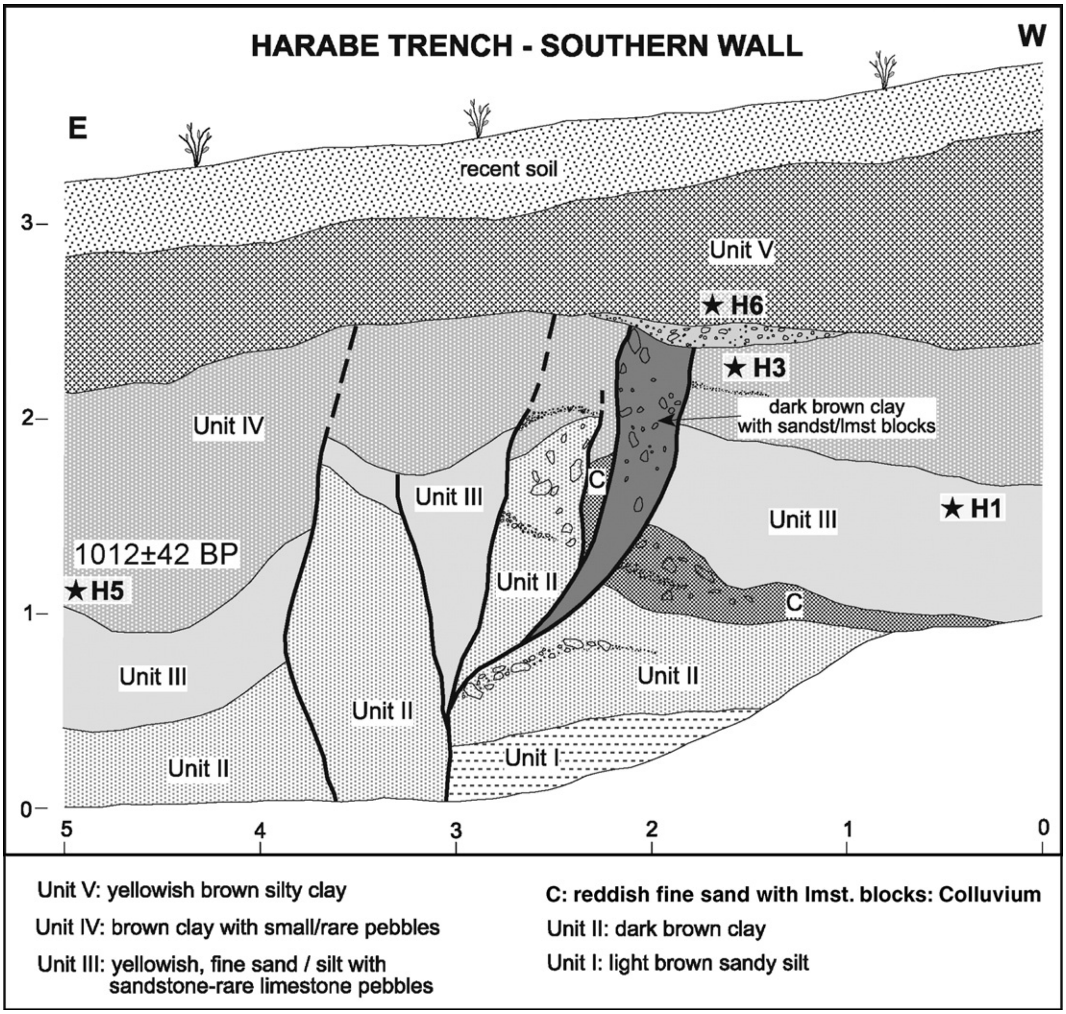


Fig. 5. Log of Harabe trench, southern wall.

Basin where the fault trace is unusually simple (Fig. 4). The trenches were dug in colluvial and alluvial sediments deposited by nearby streams (Figs. 2 and 4). Age estimates of the deposits exposed within the trenches are based on selected charcoal fragments collected from deposits (calibrated age is according to Stuiver et al., 1998 and atmospheric data is taken from Reimer et al., 2004). Results of the age dating are given in Table 3.

### 4.1. Harabe trench

The Harabe trench is located about 4 km north of the Syrian border (Fig. 2). The fault at this location is characterised by faulted colluvial deposits and deflected stream beds on an east facing slope (Fig. 4a). Eastward-flowing gullies are sinistrally diverted in this location and the cumulative offset ranges from 14±0.5 m to 20±0.5 m. The trench was excavated in the northern side of the southernmost stream bed (Fig. 4a).

Fig. 5 depicts the strata and fault zone that were exposed in Harabe trench. Trench crosses a 2-m-wide fault zone characterised by nearly vertical fault traces and an associated 30-cm-wide fissure fill. Unit C includes reddish sand with limestone blocks which is derived from upper hillside. Since its eastern side is bounded by the fault, it is likely that this unit is a colluvial wedge. Fissure fill and faults which offset the colluvial wedge are overlain by channel deposits. The significance of the stratigraphic relations exposed in Harabe trench includes documentation of two or possibly three surface rupture events. Considering that Unit C is a colluvial wedge, it represents the oldest event which occurred after the deposition of Unit II and before the deposition of Unit III. Fault cutting Unit III (at 3rd m in the trench log) is evidence for the second event which took place before the deposition of Unit IV. The youngest event cuts Unit IV and overlain by the channel deposits. Charcoal samples were collected and analysed to bracket the age of events (Fig. 5). Unfortunately, we were unable to bracket the age of the oldest and youngest events because charcoal samples H1, H3 and H6 have no sufficient amount of carbon for reliable dating. Sample H5 yielded calibrated age of about 1019 A.D., suggesting that the penultimate earthquake occurred before 1019 A.D.

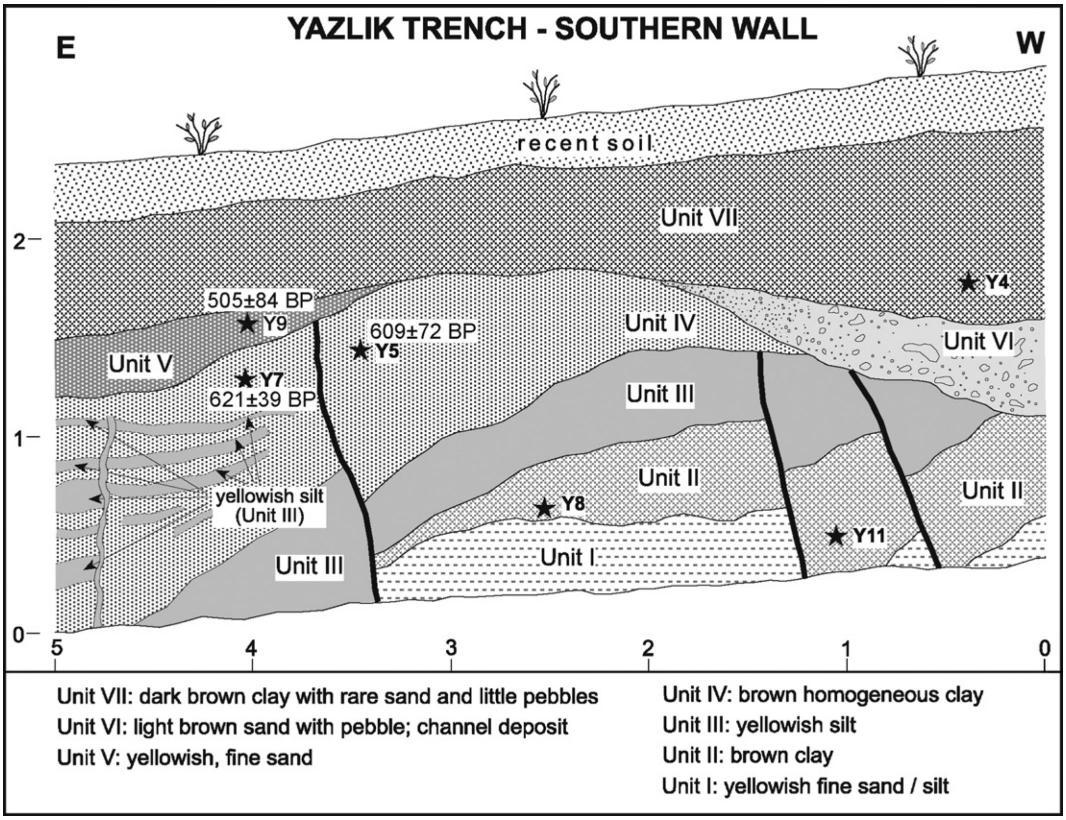


Fig. 6. Log of Yazlık trench, southern wall.

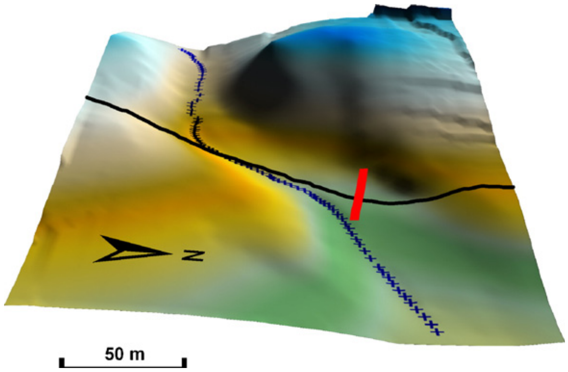


Fig. 7. Microtopography of the Ziyaret trench site showing diversion on the stream course. As a result of faulting, the hill obstructs the stream bed. A 68-m-left-lateral-offset measured with total station. Black solid line is the fault, red line shows trench site.

### 4.2. Yazlık trench

Hacıpaşa fault cuts an E–W-trending ridge in north of Hacıpaşa and forms a neck on the ridge. The Ayınsadu Stream flows eastward in the northern side of the ridge and the amount of cumulative sinistral displacement is measured as 650 m (Fig. 2 and Table 2). The trench was excavated in the northern side of the stream on a N–S-trending scarp which is about 1 km in length (Fig. 4b).

The trench wall clearly shows seven different units (Fig. 6). There is conformity between units I, II and III and two faults cut these units but they do not affect Unit IV which overlies Unit III. Units II, III and IV are blanked by channel deposits (unit VI) in the western side of the trench wall. Unit IV, which is cut by a fault, is overlain by Unit V in the eastern side. Unit VII covers units IV, V and VI. Horizontal and vertical yellowish silt take place within Unit IV. One of the possible interpretations is that they injected into unit IV as a result of liquefaction from Unit III.

Yazlık trench provides direct stratigraphical evidence for two past earthquakes. Rupture of the older event cuts units I, II and III and these faults, possibly represent the same event, are covered by units IV and VI in the western side of the trench wall. Younger fault cuts units I to IV and it is blanked by unit V. Samples were collected from stratified units in trench wall in order to determine precise ages of events but only four samples were sufficient for dating. Samples Y5 and Y7, analysed from unit IV and yielded calibrated ages between 1312 and 1390 A.D., are the upper boundary for the older event and lower boundary for the younger event. Sample Y9 analysed from unit V which is covering the younger event gave a calibrated age of 1423 A.D. Thus, the stratigraphical relationships and age results suggest that the older event occurred before 1350±40 A.D. and the younger event took place sometime between 1350±40 A.D. and 1423 A.D. Liquefaction structures within Unit IV are most likely the result of younger event.

### 4.3. Ziyaret trench

The Ziyaret trench site is located close to the southern margin of the Amik Basin (Fig. 2). The trench was dug in the northern side of an eastward flowing stream bed which is sinistrally offset 68±1 m (Figs. 4c, 7). The most distinctive topographic feature in this location is that a hill obstructs the stream as a result of faulting and forms a shutter ridge (Fig. 7).

Fig. 8 shows the log of Ziyaret trench. Pre-Quaternary siltstone exposes at the base in the western side of the trench. The trench wall shows four different units in Holocene age, Units I, II, III and IV. The contact between Unit I and Unit IV is vertical and characterised by sub-parallel fault traces which may reflect more than one event. The total width of the deformation zone exposed in the trench wall is about 9 m (Fig. 8).

The Ziyaret trench wall displays clear evidence for three earthquakes. The older event cuts Unit I and overlain by Unit II. Three faults cut both Units I and II but they do not affect Unit III and thus they represent the

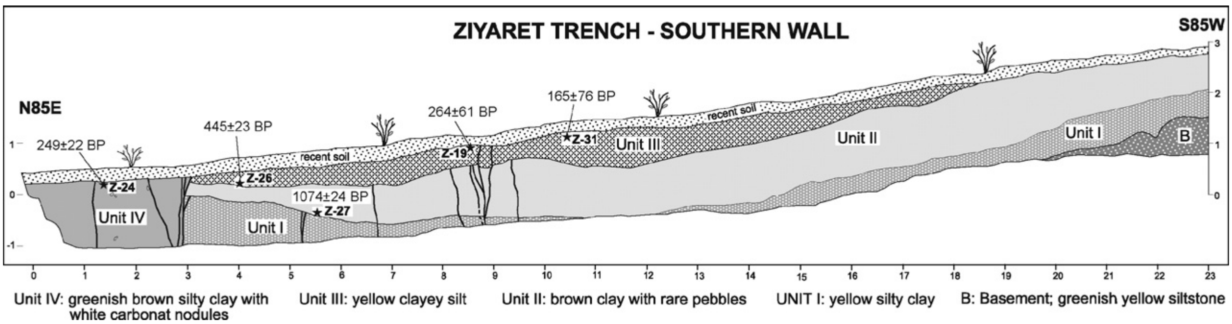


Fig. 8. Log of Ziyaret trench, southern wall.

penultimate event. The youngest event corresponds with a wide deformation zone which is blanked by recent soil. Samples for precise dating were collected from different levels but only four samples gave sufficient results. Sample Z27 gave a calibrated age of 983 A.D. which indicates that the older event occurred before 983 A.D. Sample Z26 was taken near the base of Unit III and gave a calibrated age of 1442 A.D. This sample gives the upper limit for the penultimate event. Samples Z19, Z31 and Z24 were taken from the upper parts of Unit III and Unit IV, and gave calibrated ages of 1647 A.D., 1677 A.D. and 1653 A.D., respectively. Although Z24 was taken from different unit (Unit IV), these three samples gave similar ages; Z24 probably deposited simultaneously in a different environment and juxtaposed with Unit I, II and III as a result of faulting. These ages suggest that the youngest event took place after about 1650 A.D.

## 5. Discussion and conclusions

The DSFZ enters Turkey along the western side of the Asi River and it provides geological and morphological evidence up to Amik Basin in north (Figs. 1b and 2). This part of the fault zone between the Syrian-Turkish border in south and Amik Basin in north is named as Hacıpaşa fault. Detailed field investigations on the Hacıpaşa fault showed sinistrally offset stream beds up to 650 m (Figs. 2 and 4, Table 2), and faulted alluvial and colluvial deposits which indicate evidence for its activity.

Historical records listed in Table 1 indicate that there were large earthquakes on the northern part of DSFZ (Ergin et al., 1967; Poirier and Taher, 1980; Soysal et al., 1981; Karaki, 1987; Ambraseys, 1989; Guidoboni et al., 1994; Ambraseys and Melville, 1995; Ambraseys and White, 1997; Khair et al., 2000; Meghraoui et al., 2003; Guidoboni et al., 2004). However, there was no enough historical account about their locations and whether they involved surface rupture or not. Only Ambraseys and Melville (1995) reported that the 1408 earthquake was associated with surface rupture in northern Syria but they claim that the northern end of the rupture should be south of Antioch (modern Antakya).

Results of palaeoseismological studies show that repeated surface faulting earthquakes occurred on the Hacıpaşa fault (Fig. 9). The trench sites across the fault provided evidence of three events. Samples H5 (from Harabe Trench) and Z27 (from Ziyaret Trench) suggest an earthquake before 1019 A.D. and 983 A.D., respectively. Samples Y5 and Y7 (from Yazlık trench) indicate that there was an event before 1350±40 A.D. These ages are the upper boundary for the oldest event in trenches and they probably reflect the same earthquake. Considering historical records, there were some large earthquakes in 859, 1157 and 1169 (or 1170) in the area (Table 1). According to Meghraoui et al. (2003), the 1157 earthquake took place in south of Ghab basin and the 1169 (or 1170) event occurred further south, in the Misyaf segment. Thus, on the basis of above account and our palaeoseismological evidence, it is possible that the oldest event observed in trenches corresponds with the 859 A.D. earthquake.

Trench data in Harabe site provides evidence for an event after 1019 A.D. (H5) but there is no date for its upper boundary. Palaeoseismological evidence in Yazlık and Ziyaret trenches suggests that the penultimate event took place sometime between 1350±40 A.D. and 1423 A.D., and before 1442 A.D., respectively. The recorded historical earthquake was the 1408 event in this period (Table 1) and according to Ambraseys and Melville (1995), this earthquake involved about 20 km surface rupture. In view of the historical records and of palaeoseismological evidence, it is concluded that the last event in Harabe and Yazlık trenches, and the penultimate event in Ziyaret trench occurred in 1408 A.D. Ambraseys and Melville (1995) suggest that the northern end of the 1408 event surface rupture terminated in south of Antioch (modern Antakya) but palaeoseismological studies suggest that the Hacıpaşa fault also ruptured in 1408 and the rupture extended up to Amik Basin in north.

Ziyaret trench suggests that the last reactivation of the Hacıpaşa fault took place after 1650 A.D. (samples Z19 and Z24). Taking into account historical records, the only recorded large event on the northern part of the DSFZ is the 1872 event after 1650 A.D. (Table 1). In addition, Ambraseys (1989) reports that the April 3, 1872 earthquake gave heavy damage in north and south of the former Amik Lake, particularly in the eastern side of the Asi River around Armenez (Fig. 1b). Harabe and Yazlık trenches do not provide any evidence about the 1872 event and the last earthquake in these trenches is the 1408 earthquake. There are two possible explanations for the absence of 1872 rupture in Harabe and Yazlık trenches: either the 1872 rupture is out of the trench and could not be observed or the 1872 earthquake took place in the Amik Basin and its rupture did not extend up to the southern part of the Hacıpaşa fault. Taking into account the second explanation, it is clear that there has been a significant amount of slip deficit since 1408.

Although there is a limited number of radiocarbon dates, the recurrence interval for surface-faulting events appears to range from 464 to 549 years (Fig. 9). This

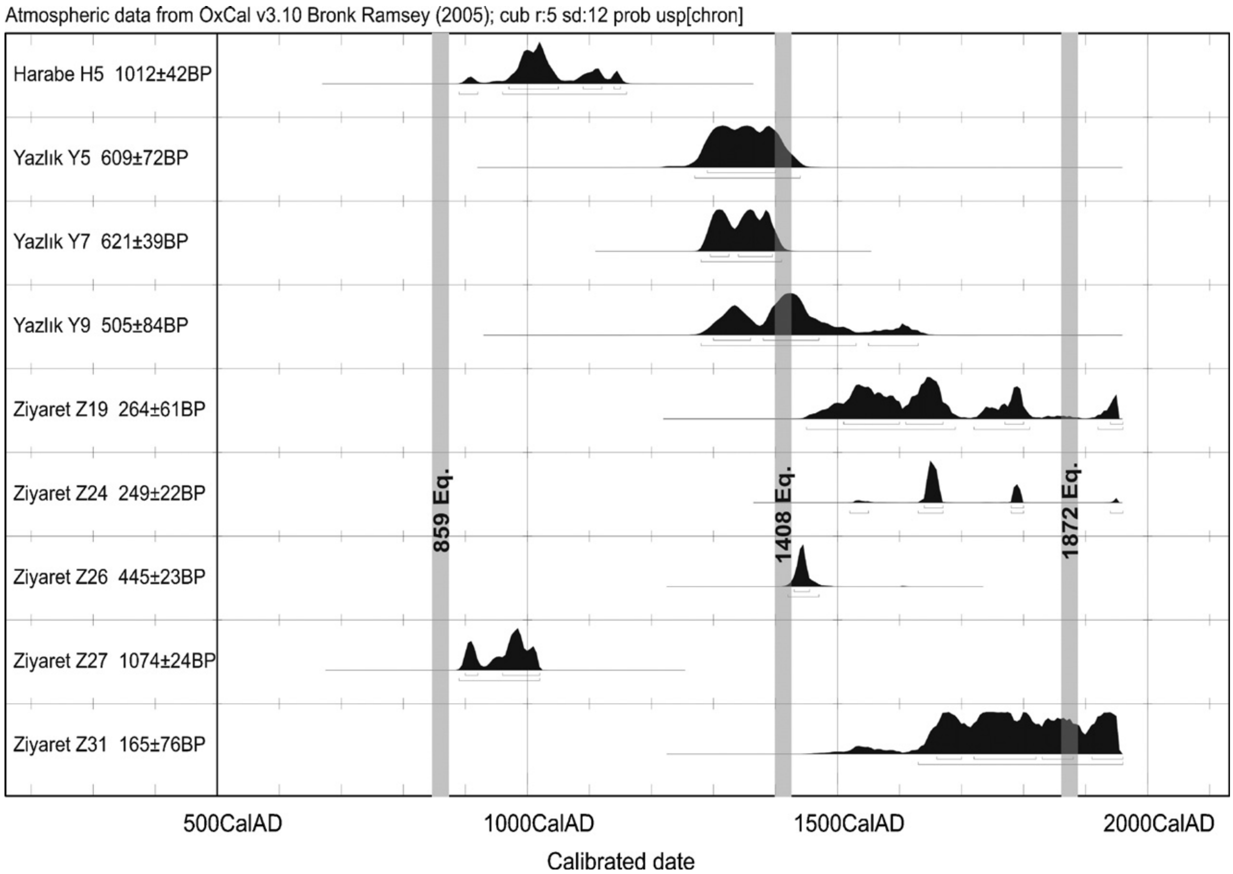


Fig. 9. Probability distribution of calibrated 14C ages obtained from sequential radiocarbon dates.

interval is not well constrained but at least it gives an idea about the basic kinematic parameters (such as slip rate) which are not documented for the northern part of the DSFZ. Meghraoui et al. (2003) and Westaway (2003) suggested that the average slip rate for the DSFZ in Syria is about 6–7 mm$^{yr-1}$. Previous studies (e.g. Perinçek and Çemen, 1990; Perinçek and Eren, 1990; McClusky et al., 2000; Yurtmen et al., 2002; Adiyaman and Chorowicz, 2002; Westaway, 2003, 2004) suggest that the DSFZ branches in southern Turkey and, thus the slip rate is partitioned. For example, Westaway (2004) claims that the average slip rate is not more than 2 mm $^{yr-1}$ for each branch of the DSFZ in Turkey. Although our palaeoseismological studies did not provide any evidence for the amount of lateral offset for each event, the recurrence time of large earthquakes suggests that there is a considerable slip on the Hacıpaşa fault. Three surface rupturing events are interpreted to have occurred on the Hacıpaşa fault at least in the last 1200 years. Although there is no reliable information about the magnitude of these earthquakes in historical catalogues, Ambraseys (1989) suggests 7.2 magnitude for the 1872 earthquake. Meghraoui et al. (2003) suggest that the 1408 earthquake was larger than 7.5. Furthermore, detailed studies on other fault zones showed that $M=7$ or larger earthquakes were associated with surface rupture and average offset of 2–3 m. For example it was 3 m for the 1912 Mürefte-Sarköy, $M=7.4$, earthquake (Altunel et al., 2004), 2–4 m for the 1944 Bolu-Gerede, $M=7.3$, earthquake (Kondo et al., 2005), 2.5–3 m for the 1999 Düzce earthquake (Akyuz et al., 2002) and 3 m for the Izmit, $M=7.4$, earthquake (Barka et al., 2002). Considering that historical earthquakes revealed from trenches involved surface faulting, it can be assumed that they were at least magnitude 7 or more and were associated with an average offset of 2–3 m. Based on above accounts, it is clear that the Hacıpaşa fault takes the significant amount of slip in the northern part of the DSFZ. A remarkable observation from the present trenches is that the southern trenches (Harabe and Yazlik) do not provide evidence for the 1872 earthquake. This situation needs further detailed investigations because if the 1872 earthquake did not take place along the Hacıpaşa fault, there has been a significant amount of slip deficit since 1408 which constrains the size of the future earthquake more than magnitude 7 on this part of the DSFZ.

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