Archeological sites (Tell and Road) offset by the Dead Sea Fault in the Amik Basin, Southern Turkey

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SUMMARY
The northern end of the Dead Sea Fault (DSF) in the Amik Basin (Southern Turkey) is investigated using palaeoseismology, archaeoseismology and geophysical prospecting to understand the fault activity during the Holocene. Archeological sites are largely spread in the area and the fault crosses at least two of them: the ∼5000 BC Tell Sıçantarla and ∼2000 BC ancient road. Detailed field investigations and geophysical surveys of the tell, an ancient road and a Roman wall reveal 42.4 ± 1.5, 25 ± 3.5 and 9 ± 0.5 m cumulative left-lateral movement along the fault and yield an average 6.07 mm yr⁻¹ slip rate. In addition, palaeoseismic trenching across the fault supports both the exact location of the fault that cut tell and ancient road and recent faulting events related with the 1408 and 1872 large historical earthquakes. This work shows the value of faulted archeological sites that document past earthquakes and may contribute to a better seismic hazard assessment along the northern DSF.

Key words: Geomorphology; Palaeoseismology; Seismicity and tectonics; Transform faults; Continental tectonics: strike slip and transform; Neotectonics.

1 INTRODUCTION
Large earthquakes, involving surface rupture, leave record in geological deposits and damage man-made structures as a result of rupturing. The simultaneous record in geological deposits and archeological sites is a valuable source of information for seismic catalogues, earthquake deformation, related seismic-hazard evaluation and human history. Areas of rich cultural heritage like the Mediterranean region are regularly affected by past earthquakes with large surface slip along major continental faults (Guidoboni et al. 1994; Stiros 1996; Ambraseys & Jackson 1998; Nur & Cline 2000). One such fault is the Dead Sea Fault (DSF) trending north-south as a plate boundary between the Arabia and Africa plates (Fig. 1a) which shows 4–7.5 mm yr⁻¹ of left-lateral slip rate (Klinger et al. 2000; Niemi et al. 2001; Gomez et al. 2003; McClusky et al. 2003; Meghraoui et al. 2003; Daeron et al. 2004; Marco et al. 2005; Reilinger et al. 2006; Ferry et al. 2007; Gomez et al. 2007; LeBeon et al. 2008). The environs of the DSF are rich in well exposed archeological sites which are regularly affected by past earthquakes with large surface slip along the fault (e.g. Marco et al. 1997; Ellenblum et al. 1998; Klinger et al. 2000; Galli & Galadini 2001; Gomez et al. 2003; Meghraoui et al. 2003; Daeron et al. 2005; Marco et al. 2005; Haynes et al. 2006; Nemer et al. 2008). The richness of the historical catalogue and numerous archeological sites may significantly help in improving the constraint of the Holocene activity of the DSF and timing of past earthquakes. Large historical earthquakes occurred on the northernmost DSF (Ergin et al. 1967; Ambraseys 1989; Guidoboni et al. 1994; Sheinati et al. 2005) and some of them involved surface rupture (Ambraseys & Melville 1995; Sheinati et al. 2005; Akyüz et al. 2006). The vicinity of northern DSF is rich in archeological sites (Fig. 1b) and the age of ancient sites goes back to ∼6000 BC (Demir 1996; Yener et al. 2000). For example, there are more than 200 tells in the Amik Quaternary Basin (Yener 2005, Fig. 1). (A Tell is an archeological settlement in the Middle-East regions that consists on a hill built on a flat plain with a circular shape and made of a succession of layers of different periods of settlements.) In addition, there are main roads between major ancient sites such as Antioch (modern Antakya) in Turkey and Aleppo in Syria (Fig. 1a). Considering the existence of archeological sites (e.g. tells, roads, aqueducts, castles and walls) and seismic activity of the DSF, it is possible that some of those archeological features are located along the fault and they have been displaced by the surface ruptures of large earthquakes. Detailed field investigations in the Amik Basin showed that one of those tells called Tell Sıçantarla [also called Tell al-Fa’r by Braidwood (1937)] and an ancient road are located on the segment of the northern DSF where we focused our field investigations.

This paper presents field observations, trenching, total station measurements and geophysical prospecting of the northernmost section of the DSF and shows important implications in terms of earthquake faulting. The integration of results from different disciplines shows that archeological sites are left-laterally faulted.
Because offsets are interpreted as resulting from a succession of large seismic events that occurred along the DSF, the Sıçantarla Tell and the ancient road sites provide a rare opportunity to establish a long record of earthquakes along this major plate boundary. Our results provide field data for earthquake timing and slip rate for the northern DSF which was poorly known as compared to the southern part of the fault.

2 NEOTECTONIC AND HISTORICAL SEISMICITY SETTING OF THE AMIK BASIN

The Amik Basin is a roughly round depression of about 40-km-long diameter (Fig. 1b) located in the northern termination of the DSF. This basin is surrounded by Amanos Mountains to the west, Akra...
Mountain to the south, Kurt Mountains to the east and NE–SW-trending Karasu Valley to the north (Fig. 1b). The bottom of the basin is blanketed by Quaternary deposits. Earlier works based on field observations, subsurface geophysical data and GPS data suggest that the DSF splays into a complex parallel fault strand in south Turkey and slip is partitioned (e.g. Muehlienger & Gordon 1987; Perincek & Čemen 1990; Şaroğlu et al. 1992; McClusky et al. 2000, 2003; Adiyaman & Chorowicz 2002; Yurtmen et al. 2002; Westaway 2003). However, some recent studies (e.g. Rojay et al. 2000, 2003; Adıyaman & Chorowicz 2002; Yurtmen 1987; Perincek & Cemen 1990; Şaroğlu 1992; Muehlienger & Gordon 2001; Akyüz et al. 2006; Karabacak 2007) propose that the main strand of the DSF extends throughout the Amik Basin and the significant amount of slip is transferred by the Karasu Fault to the East Anatolian Fault (Fig. 1b).

Large historical earthquakes have been documented along the DSF (Willis 1928; Ergin et al. 1967; Poirier & Tahir 1980; Ambraseys 1989; Guidoboni et al. 1994; Ambraseys & White 1997). The detailed studies in southern part of the DSF showed that some of them were associated with left-lateral surface ruptures (e.g. Marco et al. 1997; Ellenblum et al. 1998; Klinger et al. 2000; Galli and Galadini 2001; Gomez et al. 2003; Meghraoui et al. 2003; Marco et al. 2005; Haynes et al. 2006). For example, Meghraoui et al. (2003) made palaeoseismological and archaeoseismological studies on the northern DSF at about 130 km south of the Amik Basin and their results show that a Roman aqueduct (younger than 30 AD) is sinistrally offset by about 13.6 m.

Historical sources interpreted by several workers (e.g. Willis 1928; Ergin et al. 1967; Poirier & Tahir 1980; Ambraseys 1989; Guidoboni et al. 1994; Sbeinati et al. 2005) report more than 30 macroseismic events recorded on the northern part of the DSF since 184 BC. However, the only historical account that refers to earthquakes with observed surface ruptures in this part of the fault zone is that of the 1408 earthquake ($M = 7.5$) associated with about 20-km-long surface rupture (Ambraseys & Melville 1995; Sbeinati et al. 2005). More recent earthquakes took place along the northern DSF and according to Ambraseys (1989), the 1822 August 13 event ($M = 7.4$) occurred in the Karasu Valley (Fig. 1b). Furthermore, Ambraseys (1989) reports that the 1872 April 3 earthquake ($M = 7.2$) occurred in the Amik Basin and generated heavy damage around the former Amik Lake (Fig. 1b). He stated that damage was very heavy to north and south of the former Amik Lake, particularly around Qilliq (ancient Tell Kardu, modern Kumlu, Fig. 1b). He also reports that the earthquake splaid the ground in places but he interpreted them as widespread liquefaction. Examination of the 20th century earthquake catalogue shows no records of large earthquakes on the northern DSF.

### 3 ANALYSIS OF FIELD OBSERVATIONS

The main purpose of this study is to use palaeoseismology, archaeoseismology and geophysical prospecting to investigate the northern end of the DSF in the Amik Basin. The late Quaternary DSF activity south of the Amik Basin is characterized by faulted alluvial and colluvial deposits, left-lateral offset of stream beds, roads and, and a N–S trending morphologic scarp affecting Holocene lacustrine deposits (Akyüz et al. 2006, Fig. 2). Following the fault trace further north in the Amik Basin, it is clearly noticeable that the fault crosses the ancient road and the Tell Şıchantarla (Fig. 1b).

Each site is investigated using a total station or differential GPS in order to obtain an accurate estimate of fault offsets. Field studies include a detailed mapping of the fault zone coupled with detailed topographic surveys, ground penetrating radar profiles, magnetic profiles and trenching. The uncertainties on fault offsets are deduced from the combined microtopographic, GPR and magnetic surveys and their consistency in the identification of piercing points.

#### 3.1 The ancient road

One of the main archaeological features of the Amik Basin is the nearly E-W trending ancient road between the ancient cities of Antioch and Aleppo (Buschmann & Högemann 1989; Roat 1991, Fig. 1). The mapped ancient road was an important way of travel probably since the pre-Hittite time (~2000 BC) and until the Roman period (Roat 1991). The road goes over the bridge called Gyphra in Hellenistic time and Jisr Hadid in the Islamic period (modern Demirköprü, Fig. 3a) which used to be the only passage across the Orontes River (now Asi River). The ancient road had to cross the
N–S trending DSF immediately east of the bridge where we have focused our investigations (Fig. 3b).

We use a total station to map the river edges, ancient bridge and related nearby ancient and modern roads (Fig. 3b). The width of the bridge is $7.0 \pm 0.20$ m and after its eastern exit the ancient road disappears but it becomes again visible a few tens of metres further east (Figs 3a and b). The detailed investigation of the eastern bridge exit shows that the pavement and related stone-arch building below make a sharp turn and show a N110E trend (Fig. 3). Further east, the N80E trending ancient road located on maps and recognized in the field from the remaining archaeological stones-pavements and artefacts do not match the bridge road section further west (Fig. 3a). Although discontinuous when getting close to the bridge, the detailed mapping indicates that the road intersects the fault a few tens of metres east of the bridge.

According to French (1981), the width of the main Roman road in normal circumstances was about 6.5 m (Figs 4a and b). Considering that such road lays on fine sediments of the Amik Basin, it is possible to get reflectors of the road pavements in GPR (Ground Penetrating Radar) profiles (e.g. Vaughan 1986; Conyers 2004). The GPR method provides useful information for buried features. For example, the application of GPR method to measure offset medieval (Ottoman) canal helped in constraining offset features and the slip rate along the North Anatolian fault (e.g. Ferry et al. 2004).

Location of a buried temple in Nysa (western Turkey) was also identified by GPR (Yalçın et al. 2009). Thus, possible extent of the ancient road (Fig. 3b) was surveyed using total station and ground penetrating radar (GPR) surveys with 500 MHz shielded antenna. GPR profiles display high contrast reflectors forming an ellipsoid shape in $7.0 \pm 0.50$ m wide (Fig. 5a). Considering that the width of high contrast reflectors is comparable to the width of the bridge, and the shape of anomaly (Fig. 5a) resembles a cross-section of the Roman road (Fig. 4b,) it is interpreted that GPR reflectors in profiles indicate the ancient road. Both edges of the high contrast reflectors in GPR profiles were projected onto the surface and marked to map the extent of the buried part of the ancient road (Fig. 3b). In addition, four east–west trending GPR profiles were performed across the fault zone (Fig. 3b) and show about 3-m-wide discontinuity zone with offset reflectors (Fig. 5b).

3.2 Tell Sıçantarla

Tells in the Amik Basin (Fig. 1b) have been the subject of numerous studies (Braidwood 1937; Yener 2005) and characteristically, most tells are considerably high and circular in map view (Fig. 6a). However, the Sıçantarla Tell is noticeably lower than most tells in the basin (Fig. 6b) and its plan view is not round (Fig. 6c). According to Braidwood (1937) and Yener (2005) the lower height of the tell is probably due to successive abandonments, the most recent being during the late Roman period. A microtopographic survey provides a detailed morphology which shows a N–S-trending scarp facing west in the northern part of the Tell and east in the southern part (Fig. 7a). An S shaped of symmetrical hills exists on both sides of the scarp which implies that the original circular shape has been twisted as a result of left-lateral fault slip (Figs 6c and 7a).
Figure 3. (a) Google view of the ancient bridge site and locations of trenches. East–west road is the modern road, it was built on the ancient road in western side of the bridge (yellow dashed lines) but it is located further south of the ancient road in the eastern side. Blue dashed lines indicate the visible part of the ancient road, green dashed lines indicate buried part of the ancient road revealed by GPR. Note that the eastern exit of the bridge does not match with the continuation of the ancient road. (b) Plan of the bridge and ancient road as surveyed by total station. Arrows indicate locations of GPR profiles on the road and fault. Dashed red line indicates the location of the fault in both figures. Small rectangular indicated by arrow shows location of the Hittite stone in Fig. 10(c). Yellow dots alongside the revealed part of the road are the projection of sides of high contrast reflectors in GPR profiles.

retrodeforming the tell morphology of Fig. 6(c) to reach a circular shape we observe that the tell has been left-laterally offset. If we adjust the northern and southern tell edges, only a rough estimate of 45 ± 5 m left-lateral offset can be obtained from the morphology alone, the large uncertainty being inferred from the approximate tell edges probably resulting from natural and man-made erosion.

Archaeological excavations in nearby tells (e.g. Tell Atchana and Tell Kurdu) showed well-developed man-made buildings such as walls and streets. Similarly, walls and streets may exist in the Şıantarla Tell and it is possible that they are displaced as a result of faulting. Studies of archaeological sites with integrated shallow geophysical prospecting (magnetic and GPR) were successfully conducted for the identification of ancient buried structures (e.g. Chianese et al. 2004). The S shaped microtopography of the tell being located on the N–S trending fault zone, our aim is to identify offset features from geophysical profiles that may coincide with the offset morphology. Thus, we image the subsurface using a magnetic survey and GPR profiles in order to identify the precise location of the fault and subsurface offset of man-made structures (mainly walls).
3.2.1 Magnetic survey

A magnetic field survey was conducted on the Tell Scantarla (Fig. 7a) in order to identify buried archaeological features. Our equipment consists of four three-axis fluxgate magnetic sensors (Bartington Instruments MAG-03MC) fixed in a plastic tube and spaced horizontally of 0.5 m (Munsch et al. 2007). This tube is horizontal and fixed to a 1.5 m long pole attached to a rigid non-magnetic backpack. A Trimble Ag114 GPS electronics and antenna is fixed at the top of the backpack which contains the electronics and battery. This GPS system calculates submetre positions in real time (±0.10 m), which are stored in the memory of the electronics. We define 50 × 50 m grids surveyed in a zigzag configuration with spacing of 2 m between each profiles. Three transverse profiles are generally performed to show magnetic anomalies at 0.5–1.0 m depth. At the beginning and the end of each cartography a reference value is measured (same location and same attitude of the magnetometer), to check for the drift of each sensor. Generally, the drift measured is less than 1 nT and is neglected.

The goal of magnetic data processing is to obtain a magnetic anomaly map where the data of each profile are geo-referenced using GPS. Each magnetic profile is inspected and possible spikes

Figure 4. Schematic plan (a) and section (b) of a Roman road (from French 1981).

Figure 5. Processed GPR profiles across the possible extent of the ancient road and probable fault. Profiles were taken with 500 MHz shielded antenna and processed with ReflexW. (a) (i) A 19-m-long profile across the ancient road (see Fig. 3c for the location). (ii) Close up view between 9 and 19 m. (iii) Interpretation of the close up part (9–19 m). High contrast reflectors represent the ancient road in cross-section (compare with Fig. 4b). (b) (i) A 46-m-long profile across the fault (see Fig. 3b for the location). (ii) Close up view between 14 and 28 m. (iii) Interpretation of the close up part (14–28 m). Vertical discontinuities in a 3-m-wide zone are interpreted as subparallel faults.
are removed and the magnetic anomaly is computed by removing a constant value for each profile. A regular grid is defined with 0.5 m spacing between the nodes and data are interpolated to obtain the node values. Finally, the east–west horizontal derivative of the magnetic anomaly map was also computed.

The magnetized structures and corresponding anomalies are observed on the high-resolution map of the magnetic field (Fig. 7b). The surveyed area shows: (1) a clear lineament in north-south direction probably reflecting the fault location which coincides with the north-south trending morphological scarp; (2) almost no high magnetic anomaly (in red) crosses the middle magnetic lineament; (3) a clearly visible ~42 m left-lateral offset obtained from the north-

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3.2.2 Ground Penetrating Radar (GPR)

A GPR coupled with total station surveys of more than 10 profiles were performed on the Tell Şançantarla with 250 MHz shielded antenna in order to complement the magnetic survey, locate the fault and detail the offset features (Fig. 8a). Shielded antenna is a rigid system with no capacity to follow a rough surface like an intensively plowed field and uncorrected 20 to 30-cm topographic errors would have affected the quality of the data set. Therefore, GPR surveys were limited by the existence of smooth topography.

The GPR prospecting is located in approximately the centre of tell (Fig. 8a), a zone where Roman stones are visible at the surface and magnetic anomalies revealed a \( \sim 10 \) m left lateral offset (Fig. 7b). N–S profiles show the offset buried magnetized structures across the fault while E–W GPR profiles show the fault zone in cross section. The 9 N–S profiles are spaced by 1-m intervals to determine the geometry and extent of buried wall and related offset across the fault (Figs 8b and c). The results indicate high contrast reflectors near the surface which are about 80 cm in width and about 1.5 m in height (Fig. 8b). The depth of the upper surface of the high contrast reflectors changes between 80 and 90 cm (Fig. 8d). Similarities between width, height and depth of the high contrast reflectors in all GPR profiles probably reflect the same structure. Thus, the high contrast reflectors are interpreted as a piece of near surface wall also recognized as the remaining of a Roman wall (Fig. 8e).

The three E–W trending GPR profiles of Fig. 8a showing up to 2-m-wide discontinuity zone with vertically offset reflectors (Fig. 8c) indicate the fault zone. We observe that the high contrast reflectors are displaced to the left in all profiles when crossing the discontinuity zone (Fig. 8b). The GPR profiles suggest that the near surface wall is left-laterally offset by 9.0 \( \pm \) 0.5 m across the fault scarp, in agreement with the location of the \( \sim 10 \) m offset magnetic lineament. The 0.5 m uncertainty is here obtained taking into account the total station measurements of GPR profiles spacing, depth and space resolution as determined from the 250 MHz antenna. The offset Roman wall probably corresponds to the last occupation level. Other similar signatures were identified in most GPR profiles but reconstructions are difficult due to probably toppled walls, spread rock pieces and other chaotic artefacts.

3.3 Palaeoseismological trenching

Two palaeoseismological trenches were dug south of the tell to complement the archeoseismic study and document the fault zone and related past large earthquakes which involved surface rupturing. A selection of convenient locations for trenching were prospected using GPR profiles spaced by 5-m intervals in E–W direction to decide the exact digging places and trenches length. The palaeoseismic study is added here at the tell and bridge sites. Although some secondary fault branches may have been disregarded, our detail survey shows that main faults exposed in trenches.

Trench 1 is 14-m-long, up to 2 m deep and located about 100 m south of the offset ancient road (Fig. 3a). Horizontal alluvial deposits including clay, silt and fine sand from the nearby Ası River are exposed in the trench wall (Fig. 9a). The exposed fault zone consists of several subparallel vertical ruptures with negligible offset probably due to lateral slip of horizontal units. Vertical faults were identified cutting horizontal deposits in a 6-m-wide zone of rupture strands (Fig. 9a). The trench wall displays buried fault traces.
Offset archaeological sites in the Amik Basin

Figure 8. (a) Locations of GPR profiles (with 250 MHz shielded antenna) on the tell. Profiles numbered with 1–9 are parallel to the fault and I–III are across the fault. (b) Processed (with ReflexW) profiles, note that about 80 cm wide high contrast reflectors (pale brown) exist in all profiles at a depth of about 80–90 cm. These high contrast reflectors are interpreted as a near surface wall which shows ∼9 m left-lateral displacement. Red arrows indicate location of the fault. (c) Processed GPR profiles across the fault. (i) A 52-m-long GPR profile (profile I in Fig. 8a) across the fault, (ii) close up view between 10 and 25 m, (iii) interpretation of the close up part of the profile Red vertical lines are subparallel faults, brown filled boxes probably reflect pieces of walls. (d) Excerpt of GPR profile wall1 showing the conspicuous signature of a buried limestone block. Interpretation sketch shows the origin of bounding half hyperbolas. (e) Field photographs of limestone blocks cropping out at the surface of the tell and at the site of GPR profiles. An excavated block (lower right-hand side) shows features typical of a main door hinge of Roman epoch (Yener 2004, personal communication).
(Fig. 9a, i and ii) with clear evidence for three faulting events. Event E1 is visible with two fault branches between 1st and 4th metres covered by the thin pink clay unit c overlain by brown clay unit b. Fault branches related to event E2 between 4th and 8th metres affects all units below unit e. The presence of buried fissure fills in unit j (Fig. 9a) also evidences an older (E3) earthquake. The youngest faulting event identified in trench log occurred after the deposition of unit d and before units c and b. Charcoal samples D2 and D5 (see Table 1) collected to date the most recent event yielded calibrated ages ($2\sigma$ interval, Stuiver et al. 1998) of about 1801–1940 and 1801–1888 AD, respectively, suggesting that the last earthquake occurred sometime between 1801 and 1940 AD. The obtained age for the most recent event in trench 1 is consistent with the 1872 April 3 large seismic event ($M \geq 7.2$) in the Amik Basin (Ambraseys 1989; Sbeinati et al. 2005). Unfortunately, we were unable to bracket the ages of events E2 and E3 because no
Figure 9. (a) Log of Trench 1 (southern wall). (i) A buried fault in the base of trench 1, (ii) A close up view of the southern wall showing sand boil (b) and a fault trace (red arrows). Note that the eastern side of erupted sand is limited by the fault. (c) Log of Trench 2 (southern wall). E indicates event rupture.

Table 1. Radiocarbon dates from trenches across the northern Dead Sea Fault.

| Trench name | Sample number | Unit            | Laboratory ID no | Material type and weight (mg) | Radiocarbon age (BP) | Calibrated age (AD) | Two sigma (AD) |
|-------------|---------------|-----------------|------------------|-------------------------------|----------------------|---------------------|---------------|
| Demirköprü  | D-2           | Brown clay      | KIA28230         | Charcoal (0.2)                | 31 ± 77              | No intercept         | 1801–1940     |
| Demirköprü  | D-5           | Light brown clay| KIA28233         | Charcoal (3.0)                | 134 ± 24             | 1687, 1730, 1810, 1924, 1954 | 1801–1888     |
| Demirköprü  | D-8           | Sand boil       | KIA28236         | Charcoal (0.4)                | 3268 ± 52            | 1522 BC             | 1641–1432 BC   |
| Hanımağa    | HC-5          | Dark brown clay | KIA28224         | Charcoal (0.7)                | 325 ± 29             | 1524, 1562, 1629    | 1487–1605     |
| Hanımağa    | HC-6          | Dark brown clay | KIA28225         | Charcoal (0.2)                | 274 ± 59             | 1644               | 1470–1681     |
| Hanımağa    | HC-8          | Dark brown clay | KIA28227         | Charcoal (1.9)                | 493 ± 23             | 1429               | 1408–1442     |
| Hanımağa    | HC-9          | Dark brown clay | KIA28228         | Charcoal (3.6)                | 546 ± 23             | 1407               | 1391–1432     |

Note: The calibrated age is according to ‘CALIB rev 43’ (Data set 2) (Stuiver et al. 1998).
3.4 Earthquake events from archaeoseismology and palaeoseismology

The mapping of offset streams south of the Amik Basin, morphological scarp affecting Holocene lacustrine deposits in the Amik Basin, offset ancient road and the offset tell indicate a consistent displacements on a nearly N–S trending fault (Fig. 2a). Palaeoseismological studies in trenches show that repeated surface faulting and slip events occurred on the fault. Detailed mapping, morphological, magnetic survey and GPR studies of the ~7000-yr-old tell, ~4000-yr-old road and late Roman wall reveal 42.4 ± 1.5, 25 ± 3.5 and 9.0 ± 0.5 m cumulative left-lateral offset, respectively. The palaeoseismic study from trench 1 and trench 2 provide evidence for at least three surface rupturing earthquakes. Trench 2 suggests that the last activation of the fault was after 1470 AD (samples HC-5 and HC-6). However, Trench 1 provides quite tight time span for the last reactivation of the fault and indicates that the last surface rupturing event took place sometime between 1801 and 1940 AD (samples D-2 and D-5). The penultimate event (E2) is recognized in the wall of Trench 1 (Fig. 9a) but no dating is available for the event. However, samples HC-8 and HC-9 from Trench 2 suggest that the penultimate event (E2) occurred before 1442 AD. Examination of the historical earthquake catalogue (e.g. Ambroseys & Melville 1989; Sbeanati et al. 2005) shows that recent earthquakes occurred in 1822 and 1872 in the Amik Basin. Palaeoseismic results indicate that the last surface rupturing event (E1) occurred after 1470 AD which could be related either 1822 or 1872 earthquakes. On the other hand, Ambroseys (1989) reported that the 1822 earthquake was responsible for heavy damage north and south of the former Amik Lake, and in particular in the eastern side of the Asi River around Qillig and Armenez (Fig. 1b). On the basis of both palaeoseismic results and historical accounts, we suggest that event E1 in trenches is related to the 1872 earthquake.

Ambraseys & Melville (1995) report that before the 1872 event, the 1408 earthquake was associated with surface rupture along the DSF at Jisr-Al-Shuggur in northern Syria. In addition, Akyüz et al. (2006) provided palaeoseismological evidence suggesting that the 1408 earthquake involved surface rupture along the DSF immediately south of the Amik Basin. Here again, the historical accounts combined with trench results indicate that the penultimate event (event E2) can be attributed to the 1408 earthquake.

4 DISCUSSION

Detailed field investigations in the Amik Basin showed that the Şıncarlar Tell and an ancient road, probably pre-Hittite, are located on the northernmost DSF segment. Thus, the tell and ancient road have important implications in terms of historical faulting and slip rate for this part of the DSF. However, before discussing historical faulting and slip rate, it is essential to argue on the age of the ancient road and tell.

4.1 Historical background of the ancient road and tell

The ancient road that goes over the bridge is clearly indicated both on Roman (Fig. 10a) and pre-Roman (Fig. 10b) archaeological maps of the region (Buschmann & Högemann 1989; Roat 1991). Yener et al. (2000) state that this major east–west route existed between Yamkud (centred on Aleppo) and the Mediterranean Sea in the second-millennium BC. Several stone blocks with Hittite inscriptions were found next to the road about 50 m east of the bridge (Fig. 10c). As Braidwood (1937) pointed out, since the Amik Plain’s topographic possibilities of entrance and exit are restricted and must in the past have determined the courses of the roads, it is probable that the more important ancient routes were always more or less the same. Thus, the existence of the road on archaeological maps, Hittite writings on a stone near the road and archaeological accounts suggest that this road has been used at least for the last 4000 yr.

Archaeological investigations report that the Şıncarlar Tell was abandoned in late Roman/Byzantine time (around 500 AD; Braidwood 1937; Yener 2005). Since there is no archaeological excavation on the Şıncarlar Tell, the geophysical prospecting (magnetometry and GPR) helped in the identification of archaeological remains; however, the precise age of the mound remains to be established. The history of human settlements in the Amik Basin goes back at least 6000 BC (Demir 1996; Yener et al. 2000; Bressy et al. 2005) and Yener et al. (2000) report that there has been significant change in settlement locations over the past 8000 yr. They report that during the period of about 6000–3500 BC, the major settlements in the Amik Basin were Tell Kurdu (Kiliq, modern name Kumlu) and neighbouring Tells Imar and Hijar located near the centre of the basin (Figs 1b and 10a). The main settlements shifted first towards the southern edge of the basin where Tells Tayinat and Atchana grew up (Fig. 1b), then there followed another dramatic shift towards west in the 3rd or 2nd century BC when Antioch was established. On the basis of archaeological account, it is clear that there is a progressive shift of the main settlements first to the south and then out of the Amik Basin. The Şıncarlar Tell is located near the centre of the

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basin (Fig. 1b) and taking into account that the first settlements were established near the centre around 6000 BC, the estimated age of the Sıcantarla Tell around 5000 BC can be considered in comparison with the more developed neighbouring tells (Tell Kuru, Tell İmar and Tell Atchana).

4.2 Historical faulting and archeoseismology: their impact on the cultural heritage

Although the history of the settlements in the Amik Basin goes back to six thousands years BP (Demir 1996; Yener et al. 2000), reliable information about macroseismic events come only from historical sources postdating the foundation of the ancient city of Antioch (modern Antakya) in the third century BC. Interpretation of the historical earthquake catalogue by several workers (Willis 1928; Ergin et al. 1995; Ambraseys 1989; Guidoboni et al. 1994; Ambraseys & White 1997; Sbeinati et al. 2005) indicates that the ancient Antioch was damaged by more than 30 earthquakes in the last 2200 yr. Considering the nature of large earthquakes and based on our up to date knowledge about surface rupturing events, it can be said that not all of these large seismic events involved surface ruptures along the northern section of the DSF. Nonetheless, Ambraseys & Melville (1995) report that the 1408 December 29 earthquake ($M_w 7.5$) generated surface rupture along the northern DSF for a length of about 20 km. Additional support comes from Akyüz et al. (2006), who present palaeoseismic evidence of fault ruptures in trenches dug across the DSF south of the Amik Basin (see Fig. 2a for locations) that is most likely to be attributed to the large earthquakes of 1872, 1408 and one prior earthquake. Our palaeoseismological studies also show that historical earthquakes involved surface ruptures in the Amik Basin (Fig. 9). Trenches 1 and 2 reveal the possible occurrence of two large earthquakes in the last 600 yr (according to the dating of unit c in trench 2). The palaeoseismic record seems to be consistent with the historical seismic catalogue that includes large events of 1408 and 1872 (Ambraseys 1989; Ambraseys & Melville 1995; Sbeinati et al. 2005). Ambraseys & Melville (1995) state that the 1408 earthquake ($M = 7.5$) associated with about 20-km-long surface rupture in northern Syria. However, considering that the comparable size of the 1999 Izmit earthquake ($M = 7.4$) involved in about 130-km-long surface rupture (Barka et al. 2002), it is most likely that the rupture of the 1408 event was more than 20 km. Akyüz et al. (2006) provide palaeoseismological evidence for the rupture of 1408 event in south of the Amik Basin. Trench 2 suggests that an earthquake occurred sometimes between 1391 and 1442 AD. Thus, it is possible to interpret that the rupture of the 1408 earthquake extended to the Amik Basin and contributed to the cumulative sinistral offset on the ancient road, late Roman wall and tell.

The 1872 April 3 earthquake ($M_w 7.2$) is the most recent destructive event in the Amik Basin (Ambraseys 1989) and contemporaneous documents report that damage was very intense north and south of the Tell Sıcantarla and particularly east of the Asi River, around the village of Armenez (Fig. 1b; Ambraseys & White 1997; Sbeinati et al. 2005). Ground breaks are not mentioned in historical documents, but taking into account the required fault dimensions for large seismic events (Wells & Coppersmith 1994), it is likely that the 1872 ($M_w 7.2$) earthquake produced surface ruptures. Indeed, the comparable size of the 1999 Duzce earthquake ($M_w 7.1$) displayed surface ruptures extending for 50 km along the North Anatolian Fault (Akyüz et al. 2002). Therefore, it is likely that the most recent earthquakes of 1408 and 1872 generated surface slip and have affected Tell Sıcantarla and the ancient road along the northern section of the DSF. Support for this inference comes from the radiocarbon dating of the faulting events inferred from our trenches (Fig. 9) that can be correlated with these recent historical earthquakes.

The progressive shifting of settlements from the centre of the Amik Basin to outside of the basin (Yener et al. 2000) is a striking archaeological account. According to Yener et al. (2000), this change in settlement locations may result from periodic environmental events and socio-economic factors. However, it is noteworthy that Ambraseys (1989) reports that the 1872 April 3 earthquake produced heavy damage around the former Amik Lake, especially in Qilliq (Tell Kuru) (Fig. 1b). In addition, Braidwood (1937) mention seismological disturbances (seismites) in the Amik Basin. Furthermore, according to Yener (personal communication in the excavation site, 2003), level IV or V (dated to ~2nd millennium BC) of the Tell Atchana was damaged by earthquakes. Furthermore, it...
is well documented by both historical and modern records (e.g. Bean 1971; Stiros 1996; Hancock & Altunel 1997; Altunel 1998) that earthquakes play a certain historical role in tectonically active regions. For example, the catastrophic earthquake of 526 May 29 (Sbeinati et al. 2005) severely destroyed the Saint Simeon sanctuary and the city of Antioch and provoked the abandonment of several villages in northern Syria and southern Turkey during the Byzantine times. The abandonment of the Şcantarla Tell around this time is either a coincidence or is possibly due to heavy damage by surface rupture. Thus, in view of these information, it is important not to neglect the earthquake factor in such progressive shifts of settlements from the centre (where the offset tell is located) to the outer regions of the basin.

4.3 Measured offsets, uncertainties and related slip rate

Detailed field investigations in archaeoseismology combined with geophysical prospecting (magnetic and GPR surveys) reveal that the DSF extends into the Amik Basin (Fig. 1b). Archeoseismic investigations coupled with microtopographic surveys and shallow geophysics document the ~9, ~25 and ~42 m left-lateral offset of the tell and ancient road. Palaeoseismic studies verify the extension of the fault in the Amik Basin and suggest the occurrence of at least three surface rupturing that may correspond to the occurrence of historical large earthquakes on this fault section. Although some secondary fault branches may have been disregarded because of the limited trench length, the palaeoseismic study is added here to complement the archeoseismic study at the tell and bridge sites.

The measured ~9, ~25 and ~42 m left-lateral offset are based on combined microtopographic surveys, magnetic and GPR prospecting added with field observations and fault mapping. The tell topography taken alone may suggest a larger fault offset if we correlate the northern tell edge. However, we cannot rely on the topography alone since the surface farming (plough and possible landform change) may greatly influence surface observations. The shallow geophysics are here decisive to infer the accurate left-lateral offsets and the topographic landform alone cannot determine the amount of fault offset. On the other hand, the microtopographic survey combined with the geophysical prospecting reduces the uncertainties of our offset measurements ±1.5 m for the magnetic survey (Figs 7a and b) and to ±0.5 m for the GPR prospecting on the tell (Figs 8a and b). The precise road offset is inferred from the road trend projection to the fault and although the total station surveying provide accurate measurements we admit 3.5 m uncertainty (equivalent to half the road width, Fig. 3b).

The cumulative offset at Tell Şcantarla and ancient road has important implication in terms of slip rate for this part of the DSF which is poorly known in comparison with the southern sections of the fault. Although it is difficult to directly correlate individual slip to a given historical seismic event, it is possible to extract an average displacement rate from the cumulative offset. About 9 m left-lateral slip observed on a near surface wall in magnetic anomaly map and GPR profiles (Figs 7b and 8b). Considering that the wall corresponds to the last occupation level of the tell (late Roman) it implies that the 9.0 ± 0.5 m-slip occurred in the last 1500 yr and an average 6.0 ± 0.3 mm yr⁻¹ slip rate can be estimated. Magnetic surveys show 42.4 ± 1.5 m of left-lateral slip since the establishment of the Tell Şcantarla. Indeed, the northern tell sharp contrast of anomalies reduces the uncertainties of measurements and leave not much possibilities for alternative interpretations of this offset. The age of the tell, presumed around 5000 BC, implies an average slip rate of 6.06 ± 0.25 mm yr⁻¹. Assuming that the ancient road has been used since ~2000 BC, the 25 ± 3.5 m total horizontal offset of the ancient road results from successive displacements in the last 4000 yr. The age of the road implies an average slip rate of 6.25 ± 0.8 mm yr⁻¹.

We contend that offsets on tell, road and wall include the surface slip increments of the two most recent large earthquakes (1408 and 1872). Although trenches expose confirmation for the recent activity of the fault, they do not provide evidence to determine slip rate. The cumulative slip measured on offset archaeological features implies that an average slip rate for the fault varies between 6.0 ± 0.3 and 6.25 ± 0.8 mm yr⁻¹. This implies that the average slip rate for the DSF is under discussion and a wide variety of techniques, geological, geomorphological, seismic, geodetic, kinematic modeling and archaeoseismological have been employed to determine values for either along the whole DSF or parts of it. Using geological (e.g. Quennell 1958; McKenzie 1970; Daeron et al. 2004),

| Offset feature | Total slip (m) | Evidence | Age of the feature | Slip rate | References and remarks |
|----------------|---------------|----------|-------------------|-----------|-----------------------|
| Tell Şcantarla | 42.4 ± 1.5    | Direct observations, Low height, Elongation in NE-SW, Magnetometry, offset edge of the tell, offset walls in tell (see below), Microtopography, scarp offset morphology | 5000 BC (obtained from archaeological investigations; see references and text) | 6.06 ± 0.25 | Considering that the tell is ~5000 BC, Dating of tells is from Demir (1996), Yener et al. (2000), Bressy et al. (2005). |
| Road          | 25.0 ± 3.5    | GPR survey reveals burried part of the road locates fault, Total station measurement Position of the road and bridge | ~2000 BC (see old maps and references) | 6.25 ± 0.88 | Braiding (1937), Yener et al. (2000): Old Assyrian Map (~2000 BC) and Hittite stones (~1300 B.C.) next to the road supports that the road was in use at that period. |
| Wall in the Tell | 9.0 ± 0.5     | GPR survey Total station measurement reveals offset wall | Roman (Yener 2005 & personal communication) | 6.00 ± 0.33 | (AD 526?), 1408 and 1872 large earthquakes (see references in text) affected the wall. |
Offset archaeological sites in the Amik Basin

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Figure 11. Cumulative offset on faulted archaeological relics versus approximate age of structures. Average 6.07 mm yr$^{-1}$ slip rate obtained from fault offsets at different locations along the northern section of the Dead Sea Fault.

geomorphological (e.g. Enzel et al. 2000; Ginat et al. 1998), seismic (e.g. Garfunkel et al. 1981) and archaeoseismological (e.g. Ellenblum et al. 1998; Klinger et al. 2000; Meghraoui et al. 2003) data, an average slip rate of 1.5–10 mm yr$^{-1}$ was determined but the estimated slip rate is local and does not represent the whole fault zone. Knowing that parallel fault branches may exist along the northern end of the DSF (Fig. 1a), the average 6.1 mm yr$^{-1}$ slip rate obtained in this study is consistent with the average 6.9 mm yr$^{-1}$ obtained further south by Meghraoui et al. (2003) from a faulted Roman aqueduct located along the Missyaf segment and single fault branch of the DSF in Syria. Geodetic (GPS) technique has been used to estimate a slip rate along the DSF but different values obtained from GPS studies. For example, McClusky et al. (2003) suggest that the slip rate changes between 5.6 and 7.5 ± 1 mm yr$^{-1}$ along the DSF and the slip increases towards north. Wdowinski et al. (2004) estimated an average slip rate of 3.3 ± 0.4 mm yr$^{-1}$ for the DSF. Mahmoud et al. (2005) and Reilinger et al. (2006) estimated up to 4.8 mm yr$^{-1}$ slip rate along the DSF and they suggest that it increases towards north. According to Gomez et al. (2007), the GPS velocity field indicates 4–5 mm yr$^{-1}$ of relative motion is transferred to the northern continuation of the DSF in northwestern Syria. Recently, LeBeon et al. (2008) estimated a slip rate of 4.9 ± 1 mm yr$^{-1}$ across the southern DSF. GPS measurements complemented by different teams indicate that the slip rate is 4–5 mm yr$^{-1}$ across the southern DSF but it increases towards north. Based on kinematic modelling, Westaway (2004) also suggested that the rate of relative plate motion between the African and Arabian plates increases from 5.5 mm yr$^{-1}$ in the south to 8.7 mm yr$^{-1}$ in the north.

The average slip rate deduced from the displaced archaeo-

development at the site, and related palaeoearthquakes. Faulted ancient man-made structures (i.e. ancient road, wall and tell) in the Amik Basin are clear indications for the occurrence of the large earthquakes along the northern DSF (e.g. AD 526, 1408 and 1872 earthquakes). The heavy buildings of large stone masonry in several Byzantine villages did not resist the AD 526 large earthquake (Sbeinati et al. 2005). A paleoearthseismological analysis with extensive shallow geophysics and trenching is needed to document the earthquake cycles during the Holocene. It is now clear that a repetition of large historical earthquakes on the northern DSF would badly affect the large urban areas of Aleppo and Antioch and surrounding villages where modern buildings and related lifelines do not comply with standard seismic hazard and risk regulations and codes.

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