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SPECIAL

Coseismic displacements along the Serghaya Fault: an active branch of the Dead Sea Fault System in Syria and Lebanon

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Examination of the Serghaya fault, a branch of the Dead Sea Fault System in western Syria and eastern Lebanon, documents Late Quaternary and Recent left-lateral fault movements including the probable remnant of a historic coseismic surface rupture. Carbon-14 dating and the presence of fault-scarp free faces in soft, late Pleistocene lake deposits suggest coseismic slip during the past two or three centuries, possibly corresponding with one of the well-documented earthquakes of 1705 or 1759. With an estimated Holocene slip rate of 1–2 mm a^{-1}, the Serghaya Fault accommodates a significant part of the active deformation along the Arabian–African plate boundary. These results suggest that multiple active fault branches are involved in the transfer of strain through the 'Lebanese' restraining bend.

Keywords: Dead Sea Transform, Syria, Lebanon, neotectonics, earthquakes.

The Dead Sea Fault System is a key element in the eastern Mediterranean tectonic framework as it accommodates 5–10 mm a^{-1} of left-lateral motion between the Arabian and African plates (Joffe & Garfunkel 1987). Although historical records report earthquakes in the region over a period of at least 2000 years, our understanding of the Dead Sea Fault System as an active, seismogenic structure is relatively limited. This is particularly true for the northern *c.* 500 km of the Dead Sea Fault System in western Syria, Lebanon, and southern Turkey where instrumentally recorded seismicity appears minimal (Fig. 1). In particular, there has been debate about whether the active plate boundary is represented by the northern Dead Sea Fault System (e.g. Garfunkel *et al.* 1981; Quennell 1984) or whether active deformation is concentrated offshore to the west (e.g. Girdler 1990; Butler *et al.* 1997). Distinguishing between these two hypotheses has important implications for regional earthquake hazard assessment, as well as regional tectonic models.

This study focuses on the central section of the Dead Sea Fault System, where it consists of several prominent branches (e.g. Quennell 1984; Walley 1988), including the Yammouneh, Serghaya, and Roum Faults (Fig. 1b). The results of a field investigation of the Serghaya Fault Zone, a branch of the Dead Sea Fault System cutting through the Anti-Lebanon Mountains along the Syrian–Lebanese border (Fig. 1b), challenge suggestions that the NE–SW-striking faults within the 'Lebanese' restraining bend are inactive as a result of an

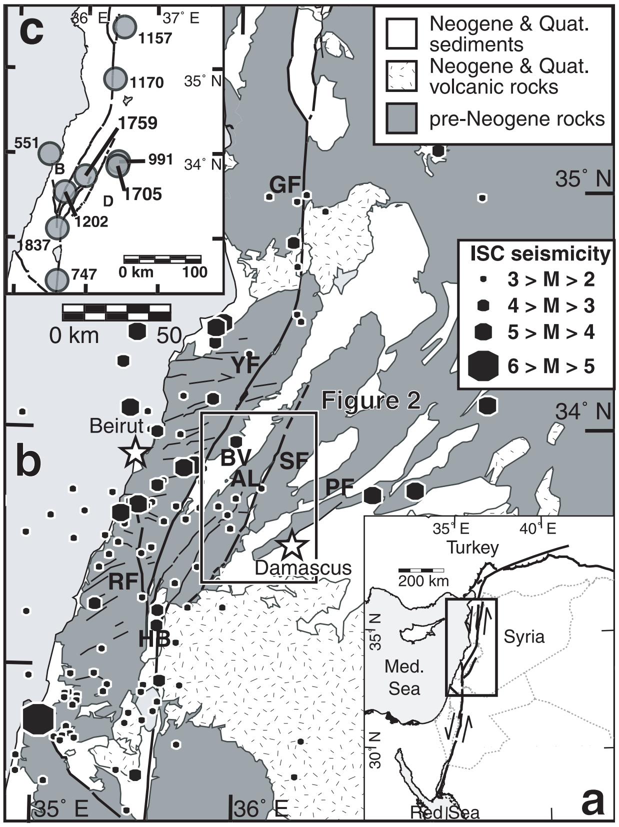

Fig. 1. (**a**) Regional tectonic setting of the Dead Sea Fault System (DSFS). (**b**) Simplified geology of the central and northern DSFS, after Dubertret (1949). AL, Anti-Lebanon Mountains; BV, Bekaa Valley; GF, Ghab Fault; HB, Hula Basin; RF, Roum Fault; SF, Serghaya Fault; YF, Yammouneh Fault; PF, Palmyride Fold Belt. Black discs depict earthquake locations (magnitude >2) from the catalogue of the International Seismological Centre (ISC) (1963–1997). (**c**) Map of approximate locations of historical earthquakes within the restraining bend region (latitude 32.5°N–35°N) with estimated $M>7$ (based on Mouty *et al.* 1998). B, Beirut; D, Damascus.

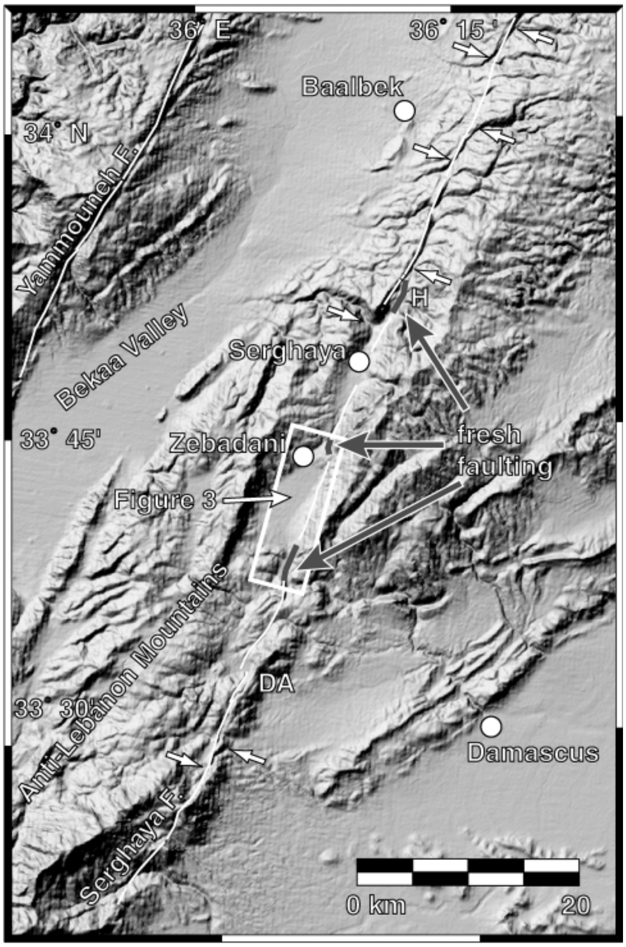

Fig. 2. Map showing shaded relief from a digital elevation model (produced from SAR interferometry) of the Serghaya Fault Zone (SFZ) depicting the large scale geomorphology (see Fig. 1 for location). Note the consistent left-lateral stream valley deflections that are particularly well expressed along the northern segment of the SFZ (small white arrows). Locations of fresh faulting observed in the field are marked by large grey arrows (see text for details). Other abbreviated locations: DA, Deir el Acheir; H, Ham.

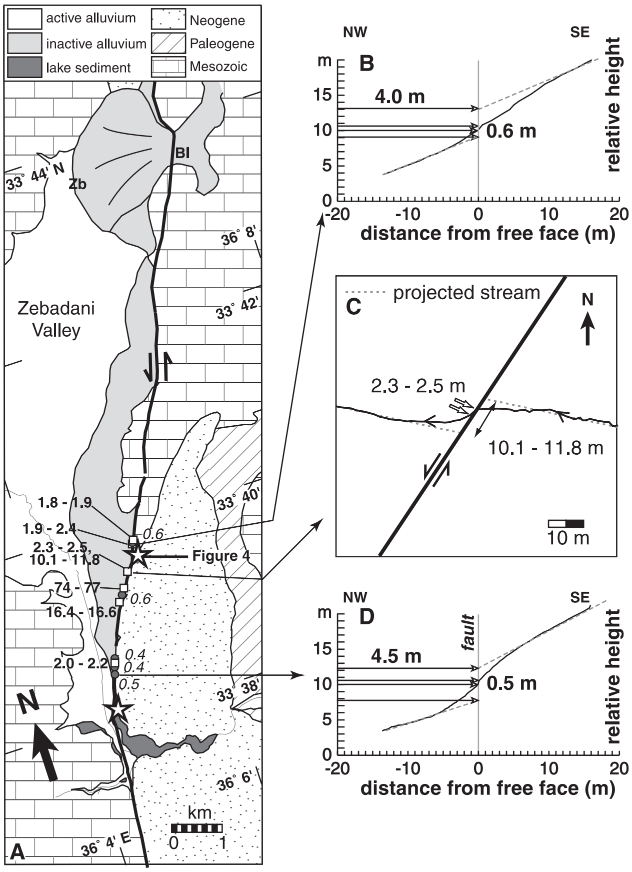

Fig. 3. (**a**) Detailed map of the Serghaya Fault Zone through the Zebadani Valley (see Fig. 2 for location). Numbers denote free face heights (black circles) and small stream offsets (white squares), both in metres, surveyed in the southern Zebadani Valley. White stars denote the locations of the fault zone excavations. Towns: Zb, Zebadani; Bl, Bloudan. (**b**)–(**d**) Examples of landforms along the SFZ surveyed using a total station. Arrows on scarp profiles (b and d) depict free face heights. In addition, a composite scarp of 4.5 m is evident in (d).

evolving regional stress field (e.g. Butler *et al.* 1997). Our research indicates that the Serghaya Fault Zone, which has been previously regarded as inactive since the Pliocene (e.g. Walley 1988), is active and appears capable of generating large earthquakes.

Evidence for active tectonics of the Serghaya Fault Zone. At a regional scale, the Serghaya Fault Zone is characterized as a *c.* 150 km lineament with a strong physiographic expression including large stream valley deflections and pull-apart basins (Fig. 2). 29 of the 34 large stream valleys crossing the Serghaya Fault Zone from the Golan Heights to the NE of Baalbek show distinct left-lateral deflections, suggesting a tectonic influence on the drainage system. Left-stepping fault geometries are regularly observed at the elongate basins along the Zone suggesting a pull-apart mechanism for basin formation. The largest examples are the fault step-overs at Deir el Acheir and Ham (Fig. 2).

The Serghaya Fault Zone interacts with geologically young deposits and landforms in the Serghaya and Zebadani Valleys (Figs 1 & 2). It traces along the eastern side of the Zebadani Valley with a pronounced geomorphic expression (Fig. 3a). In the southern part of the valley, the Serghaya Fault Zone follows the mountain front juxtaposing recent alluvium and colluvium against late Quaternary lake sediments, Neogene conglomerates, and Cretaceous carbonates (Dubertret 1949). Recent faulting has produced a prominent linear scarp corresponding with left-lateral deflections of small drainages (discussed in more detail below). In the southern Zebadani Valley, the fault scarp still preserves a free face in the soft lacustrine deposits. This free face suggests very recent fault movement as such features typically erode quickly and disappear after *c.* 1000 years (e.g. Wallace 1977). At several locations, left-lateral striations on sub-vertical fault planes in the lake sediments depict a predominant rake of 10–15° implying a dip-slip component of about 20–25%. At the northern end of the Zebadani Valley, the Serghaya Fault is expressed as a north–south-striking, striated bedrock fault scarp approximately 15 m high. Recent fault movement is suggested by a lesser degree of weathering of the lower 1.5–2 m of the fault scarp compared with the fault surface above.

To the north in the Serghaya Valley, the Serghaya Fault Zone follows the mountain front briefly, and then deviates through the bedrock. In the southern part of the valley, shutter ridges composed of Jurassic limestone have been faulted in front of drainage valleys with left-lateral senses of motion. Farther north, across the Lebanese border near the village of Ham (Fig. 2), the Serghaya Fault Zone cuts through the colluvial apron at the base of abrupt and steep slopes on the east side of the narrow valley. Recent faulting is expressed as freshly exposed soil within the colluvial apron visible by its light tan colour. Thus, expressions of very recent faulting span a length of at least 35 km from the southern Zebadani Valley to Ham.

Small stream deflections and fault scarp profiles in the southern Zebadani Valley (Fig. 3) were measured using a total station in order to quantify recent fault movements. This region was chosen for its lack of anthropogenic modification and contained 6 small streams. All drainages show consistent left-lateral deflections interpreted to be true offsets. Qualitatively, more shallowly incised drainages (and thus presumably younger) demonstrated smaller offsets. Minimum stream offsets of 1.8–2.5 m were measured (Fig. 3). Larger drainages depict offsets of up to 77 m, and some streams present both the minimum offset and a larger, composite offset (Fig. 3c).

Profiles were also surveyed perpendicular to the fault scarp across generally planar surfaces away from drainages, with direct measurement of the free face heights. Heights of scarplets containing free faces measured 0.4–0.6 m (Fig. 3). The proportions of these heights to the minimum small stream displacements are consistent with the striations in the main fault zone observed nearby (20% to 25% dip-slip). It therefore seems probable that the minimum stream offsets and the most recent portions of the fault scarps are contemporary, and the resultant displacement is 1.8–2.6 m.

Furthermore, a 4.0–4.5 m composite scarp is visible in some of the topographic profiles (Fig. 3b & d), including the southern three profiles in which Quaternary lake sediments are faulted against young deposits of the inactive and incised alluvial apron. The surface measured in the profiles is roughly planar, so the relief across the fault scarp probably reflects true tectonic uplift with minimal relief effects from horizontal translation of geomorphic features. We interpret the aggradation of this alluvial surface as a probable response to climate change at the end of the Late Pleistocene. At that time, the arid climate of Lebanon and western Syria was followed by considerably more humid conditions (Rossignol-Strick 1993); increased slope erosion and aggradation in the Zebadani Valley would have resulted from the combination of increased stream power and lack of vegetation to stabilize slopes. Without better constraints, it seems reasonable to assume that this surface probably aggraded with this climate change approximately 9–10 ka BP (Rossignol-Strick 1993). Alternatively, and as a maximum age constraint, the surface may have been active at the end of the main glaciation approximately 17 ka BP. These assumptions imply a vertical slip rate 0.25–0.45 mm a^{-1} for the Late Pleistocene and Holocene. If the proportions of horizontal and vertical slip have been maintained (*c.* 4:1, or 5:1), this suggests a long term slip rate of 1–2 mm a^{-1} for the Serghaya Fault Zone.

The last surface-rupturing event. Two fault-zone excavations (originally created for groundwater exploration) in the southern Zebadani Valley (Fig. 3) exposed the fault rupture with sheared colluvium, palaeosols, and lake sediment. From one of these excavations, three samples of charcoal and plant remains were collected from the uppermost, faulted colluvium at depths between 0.5 and 1.0 m below the present soil horizon (Fig. 4). Conventional radiocarbon ages for all three samples were measured by Beta Analytic, Inc., and the ages were reported as Modern (i.e., conventional radiocarbaon age of 200 years or less). After correction, these correspond with calendar dates of AD 1650 or younger (Trumbore 2000) for the deposits and, thus, provide a maximum age limit for the last surface-faulting event.

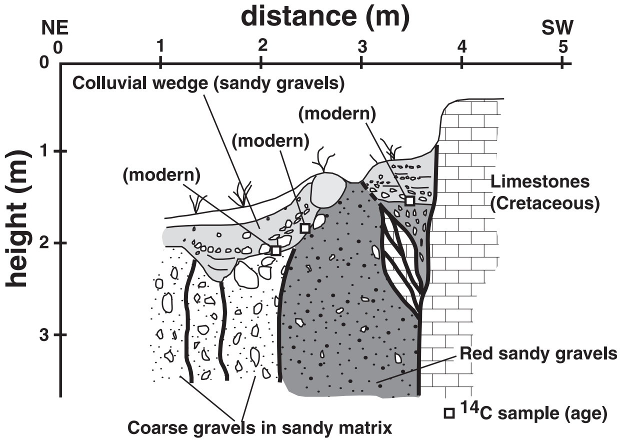

Fig. 4. Schematic cross-section of the excavation along the Serghaya Fault Zone with faulted colluvial deposits and positions of radiocarbon samples (white squares). See Fig. 3 for location.

Assuming the 1.8–2.6 m displacements observed in the southern Zebadani Valley reflect the average displacement of the last surface-rupturing event, an earthquake of M_w 6.9–7.2 involving 60–90 km of total fault length can be estimated using the empirical relationships obtained by Wells & Coppersmith (1994) and Ambraseys & Jackson (1998).

A large earthquake along the Serghaya Fault Zone within the past two or three centuries should be documented in historical records. Only three historical earthquakes (1705, 1759 and 1837) occurred within the time limits imposed by the ^{14}C dates from the faulted colluvium. Detailed accounts of damage distribution during the Ottoman period report that the 1705 and 1759 events strongly affected the Anti-Lebanon region, and thus they may be candidates for earthquakes along the Serghaya Fault. A reappraisal of the 1705 event indicates that effects were more intense in the Anti-Lebanon region and western Palmyrides, causing damage to Damascus and other towns in the vicinity (Poirier & Taher 1980; Mouty *et al.* 1998).

The earthquake sequence of October and November 1759 is one of the best documented examples of historical seismicity along the Dead Sea Fault System (e.g. Ambraseys & Barazangi 1989). The larger event (November) was associated with a possible fault rupture of up to *c.* 100 km (Ambraseys & Barazangi 1989), and although it was originally attributed to the Yammouneh Fault, its location has not been successfully confirmed with field evidence. Of the locations for which macroseismic data were reported by Ambraseys & Barazangi (1989), the towns of Baalbek, Serghaya, Zebadani, and Quneitra were most intensely affected. All of these locations are closer to the Serghaya Fault Zone than any other fault zone. We therefore suggest that either the 1705 or 1759 earthquakes may have occurred along the Serghaya Fault and may represent the coseismic displacements documented here.

Tectonic implications. Holocene movements and historical earthquakes along the NW–SE-striking Serghaya Fault imply that the 'Lebanese' restraining bend is an active feature. Our results suggest that the Serghaya Fault Zone accommodates a significant portion of the total expected slip of the Dead Sea Fault System. The estimated long-term slip rate along the Serghaya Fault Zone of *c.* 1–2 mm a^{-1} leaves 3–8 mm a^{-1} of motion along the Dead Sea Fault System to be accommodated by different structures such as the Yammouneh or the Roum Faults. In contrast, activity of the Serghaya Fault Zone is not readily explained by the hypothesis that an evolving regional stress field has moved the locus of active faulting offshore to the west of Lebanon and Syria and rendered the northeast-southwest striking restraining bend inactive (e.g. Butler *et al.* 1997).

Although the reported fossilization of the Yammouneh Fault by Pliocene lava in northern Lebanon (Butler *et al.* 1997) cannot at present be discounted, there is ample geomorphic evidence of active faulting along the northern Dead Sea Fault System along the Ghab Fault of northwestern Syria (Fig. 1b) (e.g. Trifonov *et al.* 1991), and this is consistent with GPS observations along the Dead Sea Fault System in southern Turkey (McClusky *et al.* 2000). It seems peculiar that the Yammouneh fault, which links to the northern section of the Dead Sea Fault System, would not also be active. Hence, we draw a similar conclusion to the recent study of Griffiths *et al.* (2000) that it seems unlikely that the Roum Fault constitutes the present-day plate boundary.

Conclusions. Our results from the Serghaya Fault Zone demonstrate that the large restraining bend of the Dead Sea Fault System involves active strike-slip faulting. The Serghaya Fault Zone appears capable of generating large earthquakes, and it should be an essential element in any regional earthquake hazard assessment, particularly with its close proximity to Damascus (25 km) and Beirut (60 km), two cities with more than 4 million and 2 million people, respectively. Integration of historical earthquake records with field studies suggests probable candidates for a recent (1705 or 1759) surface-rupturing earthquake along the Serghaya Fault Zone, and segmented fault scarps and larger stream offsets suggest the occurrence of multiple events. A comprehensive assessment of the earthquake hazard definitely requires further studies of earthquake and faulting behaviour through future endeavors including palaeoseismic analyses and GPS geodesy.

These results represent an ongoing collaboration between Damascus University, the Lebanese National Remote Sensing Center, IPG Strasbourg, and Cornell University to study active tectonics in Syria and Lebanon. We thank our Syrian colleagues, particularly F. Dahan, K. Al Maleh, W. Rasool Agha, M. Mouty, M. Daoud, and R. Mohamad for their support. D. Seber, E. Sandvol, and G. Brew provided helpful suggestions. Constructive reviews were provided by Y. Klinger and R. England. This research was partially supported by NSF grant INT-9810510. INSTOC contribution 263.

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