Prehistoric earthquake deformations near Masada, Dead Sea graben

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ABSTRACT

Earthquake-induced fluidizations and suspensions of lake sediments, associated with syndepositional faults, form a paleoseismic record in the Dead Sea graben. The association of fluidized beds with surface faulting supports the recognition of mixed layers as reliable earthquake indicators and provides a tool for the study of very long term (>70 kar) seismicity along the Dead Sea transform. The faults compose a fault zone that offsets laminated sediments of the late Pleistocene Lake Lisan. They exhibit displacements of as much as 2 m. Layers of massive mixtures of laminated fragments are interpreted as disturbed beds, each formed by an earthquake. The undisturbed laminated layers between these mixed layers represent the interseismic interval. A typical vertical slip of about 0.5 m per event is separated by several hundred years of quiescence. The fault zone lies within the Dead Sea graben, 2 km east of Masada, where archaeology and historical accounts indicate repeated strong earthquake damage. The distribution of strikes in the fault zone resembles that of the faults exposed in and around the graben, including the seismogenic ones. The excellent exposures over hundreds of metres allow an unprecedented temporal and spatial resolution of slip events on faults.

INTRODUCTION

Paleoseismic records in active regions are valuable in estimating past activity and associated seismic hazard. An ideal record consists of reliable, clear, and datable earthquake indicators that span a long time. We show that the laminated sediments of Lake Lisan (paleo–Dead Sea) provide an excellent opportunity to study the paleoseismicity along the Dead Sea transform.

The Lisan Formation was deposited continuously along a 220-km-long tectonic depression that is part of the Dead Sea transform (Fig. 1). U-series ages range from 72 to 18 ka; the sedimentation rate has averaged 0.8–0.9 mm/yr (Kaufman et al., 1992; Marco et al., 1994). Most of the Lisan Formation in the study area is composed of alternating laminae of aragonite and detritus; the latter consists of fine-grained calcite, dolomite, quartz, and clay. Because of the absence of bioturbation in Lake Lisan, fine and clearly visible ~1-mm-thick laminae were preserved. The paired laminae resemble present deposits of the Dead Sea; they are interpreted as annual varves. Winter floods supplied detritus and carbonate, and evaporation during summer deposited aragonite (Begin et al., 1974; Katz et al., 1977). The Lisan deposits postdate the major landscaping of the current topography. In places, they are overlain by the Dead Sea highstand deposits that exhibit similar features. The retreat of the modern Dead Sea enables ongoing incision of canyons into the Lisan, creating vertical exposures of more than 40 m.

Post-Lisan faulting, historical earthquakes, and current seismic activity near the

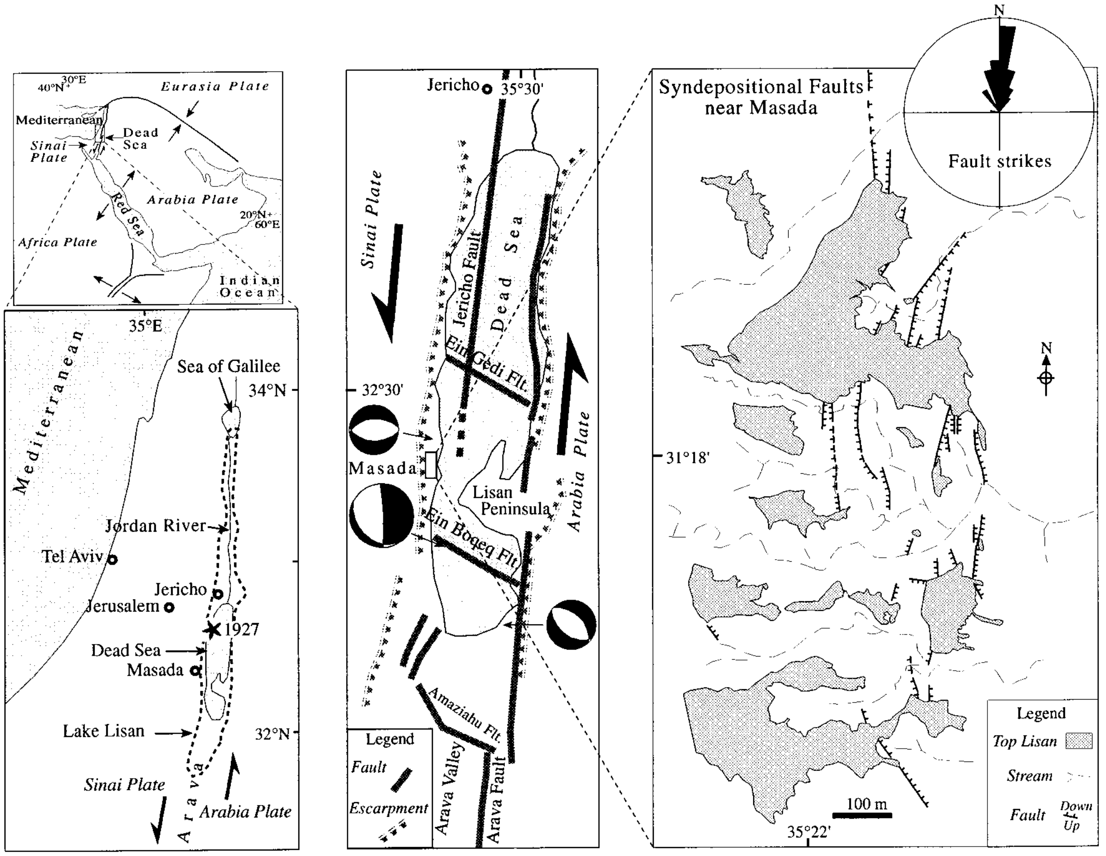

Figure 1. Right: Syndepositional fault zone near Masada. General north trend parallels Dead Sea transform in area and principal morphotectonic features to east and west of fault zone. Most fault planes similarly strike north, and a few strike northeast or southeast. Dips are 40°–70° eastward as well as westward. Rose diagram shows strike distribution weighted by fault length; largest petal is 28%. Upper left: Plate-tectonic setting of Middle East. Lower left: Extent of Lake Lisan. Star denotes epicenter of 1927 M 6.2 damaging earthquake (Shapira et al., 1993). Center: Active faults in Dead Sea region (Garfunkel et al., 1981; ten Brink and Ben-Avraham, 1989). In addition to left-lateral motion on north-striking faults, focal mechanisms of M_L 2–4 earthquakes (van Eck and Hofstetter, 1990) show normal faulting on planes parallel to syndepositional faults near Masada.

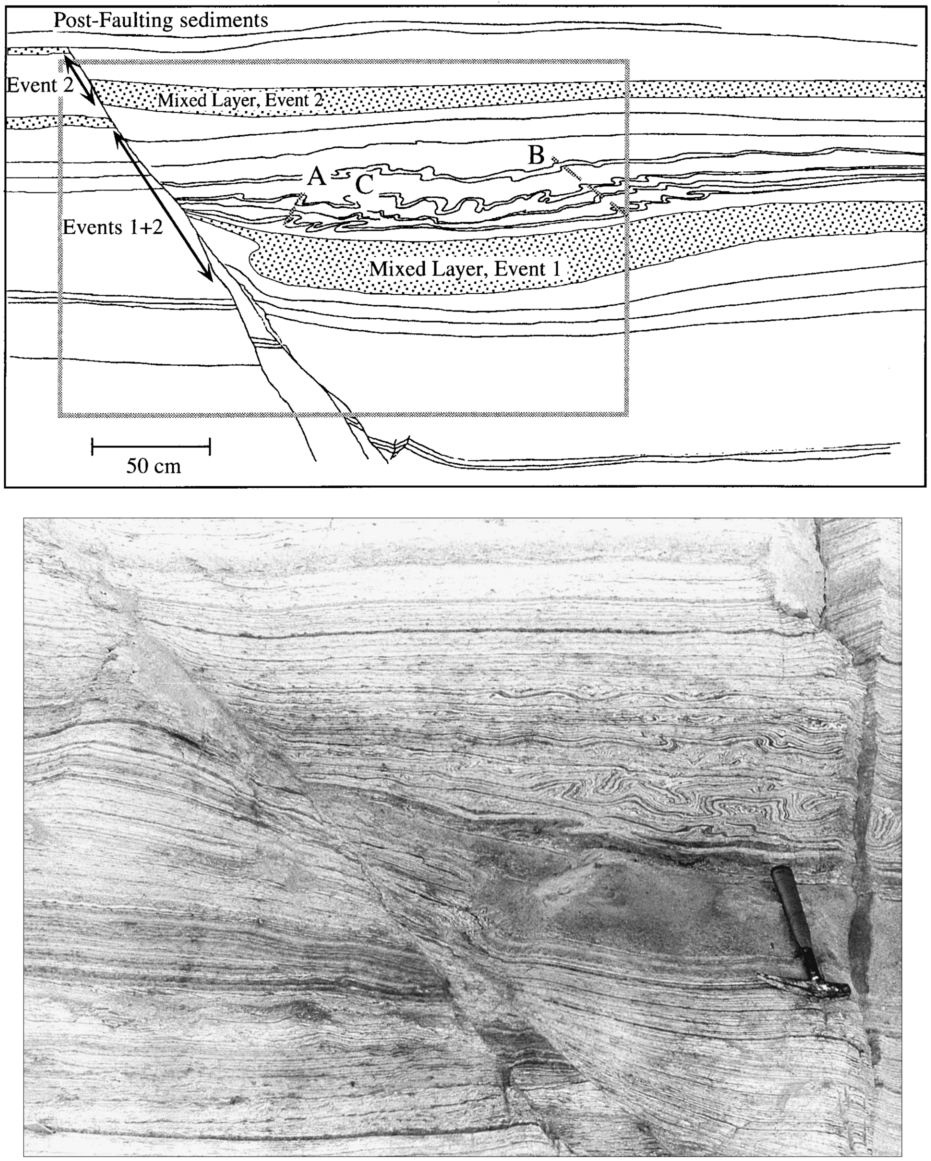

Figure 2. Syndepositional normal fault in Lisan Formation near Masada unconformably overlain by undisturbed layers. Two mixed layers terminate at fault in each block, indicating repetitive seismic faulting on same plane. They are thicker in downthrown block, filling 10–30-cm-deep troughs. Lower mixed layer in downthrown block is also bent and overlain by folded layers. These folds show local downdip transport; dips of axial planes change from toward fault plane near fault (line A) to away from fault on far end of folded strata (line B). Box folds with two axial planes are common at bottom of trough (C). This folding formed because of local slumping of soft layers into trough. Lithologic markers indicate that mixed layers across fault correlate. They formed during two events when fault slipped abruptly and ruptured surface, creating subaqueous scarp. Because of this scarp, subsequent accumulation above mixed layers in downthrown block is thicker than in footwall. Photograph shows area outlined in drawing. Figure 4 gives interpreted sequence of events recorded in outcrop.

Dead Sea have been reported in previous studies (Garfunkel et al., 1981; Reches and Hoexter, 1981; Institute for Petroleum Research and Geophysics, 1983–1995; Ben-Menahem, 1991). We discovered a syndepositional fault zone in the Lisan outcrops, 2 km east of Masada, the Jewish rebel stronghold where strong earthquake damage occurred in the first century B.C. (Karcz et al., 1977); at Masada, disturbed floors, tilted walls, aligned fallen masonry, cracks, and collapsed walls are preserved. Later shocks have been reported in the Dead Sea area after Masada was abandoned, e.g., in A.D. 362, 746, 1546, and 1834. Accounts of their effects in the Dead Sea include giant waves and appearance of large asphalt blocks that seep out through faults and fissures at the bottom of the lake (Ben-Menahem, 1991). The last damaging earthquake ($M_L = 6.2$) struck the Dead Sea area in 1927 (Fig. 1), causing severe damage and hundreds of casualties in Jericho, Jerusalem, Bethlehem, and other settlements in the region. The identification of disrupted layers as deformations due to earthquakes provides the tool for expansion of the 4 kyr historical record. In the Masada area, these deformations are associated with repetitive surface ruptures, but the same deformed layers are found also away from observed faults throughout Lisan and post-Lisan outcrops by the Dead Sea. This widespread distribution of earthquake-caused deformations yields a ~70 kar paleoseismic record.

SYNDEPOSITIONAL FAULTS AND MIXED LAYERS

A north-trending fault zone was found near Masada. Most of the fault planes strike north, paralleling the main graben faults and morphological trends. The faults are overlain by undisturbed layers (Figs. 1, 2), indicating that they are syndepositional. Dips are 40° to 70° eastward as well as westward, with normal displacements as much as 2 m. Average strike is 360° (weighted by length; $\alpha_{95} = 3.4°$) with distribution pattern resembling the active graben faults (Fig. 1). Gouges, consisting of fine aragonite and detrital breccia, calcite, and some gypsum, are commonly limited to narrow zones (1–10 cm).

Layers that exhibit unusual thickness, structure, and fabric are associated with the faults. They are composed of massive mixtures of fine-grained matrix and tabular laminated fragments (Figs. 2, 3). Graded bedding is common where fragment-supported texture shows a gradual upward transition to a matrix-supported texture. Fragments are several millimetres to centimetres long. No imbrication, lateral grading, or other transport indicators were found. In many cases, the lower fragments can be restored to their original place in the underlying layers, indicating negligible transport. In contrast to the common ~1-mm-thick laminae of the Lisan, these layers, here referred to as “mixed layers,” are locally up to 1 m thick. The lower contact of many mixed layers is folded (Fig. 3). Each sequence of mixed layer and its folded lower contact is restricted to a single stratigraphic horizon enclosed between undeformed beds. Such sequences can be traced over large distances on the order of hundreds of metres, limited only by the continuity of the outcrop.

The layers are thicker in the downthrown block, partly filling the new relief. Additional thickness near the fault is due to the 20–40-cm-deep troughs that formed by bending of that block. Detailed sections across the faults show thicker accumulation of subsequent sediments above the mixed layers in the downthrown block (Fig. 2).

DISCUSSION

The mixed layers terminate at faults that ruptured the lake bed, forming subaqueous fault scarps. Thicker accumulation above the mixed layers in the downthrown block is considered as evidence for a fault scarp. We suggest that the mixed layers formed because of shaking of the top of the sediment simultaneously with slip on the faults. The graded deformation shows that the sediment responded to shaking according to its degree of consolidation with depth. The top of the sediment was fluidized and partly resuspended. Cohesive beds ruptured and brecciated (fluidization). Deeper beds deformed hydroplastically and folded (Lowe, 1975), accommodating local shear between underlying consolidated, undeformed beds, and water-saturated sediment (liquefaction). A mixed layer formed at the water-sediment interface on both sides of the subaqueous scarp together with the fault slip (Fig. 4). Some local mass transport near the scarp produced thicker mixed layers in the lower block.

Slope failure that involves mass transport is considered an unlikely mechanism because (1) the mixed layers are related to faults, (2) they are flat lying, (3) the extremely friable laminated fragments are expected to be pulverized completely during turbulent transport, (4) the fragments at the bottom can be restored to their original place, and (5) imbrication and lateral grading are absent. Dipping beds are found in the vicinity of faults, and in those places, slope failure shows a distinct behavior: these layers are folded strata that fill the troughs in the downthrown blocks near the faults, show downdip transport, and change thickness within only a few metres of the faults. These folded strata are interpreted as local slumps on the order of up to several metres, controlled by bottom topography (Fig. 2). Folded Lisan layers have been interpreted as “seismites” (Seilacher, 1984; El-Isa and Mustafa, 1986) although no association with faults was reported. Our observations indicate that such folds are areally limited by local topography. Their formation may have been triggered by earthquakes, but the limited distribution and lack of robustness of these features restrict their use as paleoseismic indicators. Such earthquakes could be significantly weaker than those that triggered the formation of the widespread mixed layers.

Deformed layers of soft sediment akin to the mixed layers are described around the world and attributed to earthquakes (e.g., Davenport and Ringrose, 1987; Doig, 1991; Vittori et al., 1991; Guiraud and Plaziat, 1993, and references therein). The association of such layer deformations with strong earthquakes is also backed by observations of recent events (Sims, 1975; C. R. Allen, 1986). Resuspension of sediments was directly observed in bottoms of lakes less than 10 km from the epicenter of the 1935 Timiskaming, Canada, M 6.3 earthquake. Independently, piston cores recovered a 20-cm-thick chaotic layer, composed of tabular fragments of a previously formed silt layer (Doig, 1991). What makes the mixed layers in the Masada area special is their juxtaposition with surface ruptures (Fig. 2).

The direct association of the mixed layers with syndepositional fault scarps, their distribution over large areas, and their texture lead us to conclude that each mixed layer formed during an individual earthquake. Its timing is constrained by the first overlying undisturbed lamina (Fig. 4).

Cyclic liquefaction of loose, water-saturated, clastic sediments is commonly attributed to seismic waves that subject the sediment to repeated shaking. Direct observations and experiments indicate that cyclic liquefaction related to earthquakes occurs mainly during those of magnitude 6 and more (Allen, 1982). Liquefaction of sand

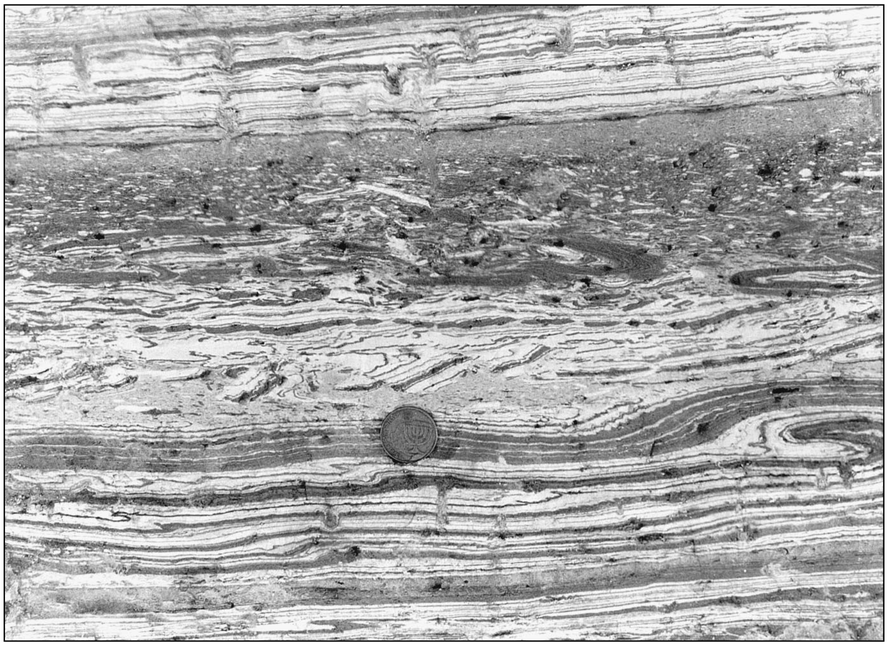

Figure 3. Typical mixed layer overlying laminated layers shows gradual upward transition from folded strata, through fragment-supported texture, to matrix-supported texture at top. Underlying folds are asymmetrical and recumbent, and in places they have box shapes. Undisturbed, postseismic layers overlie mixed layer. Such mixed layers abut syndepositional faults (Fig. 2) and are interpreted as earthquake deformations. Each formed at sediment-water interface when top of sediment was fluidized and partly resuspended during an earthquake. Coin is 22 mm diameter.

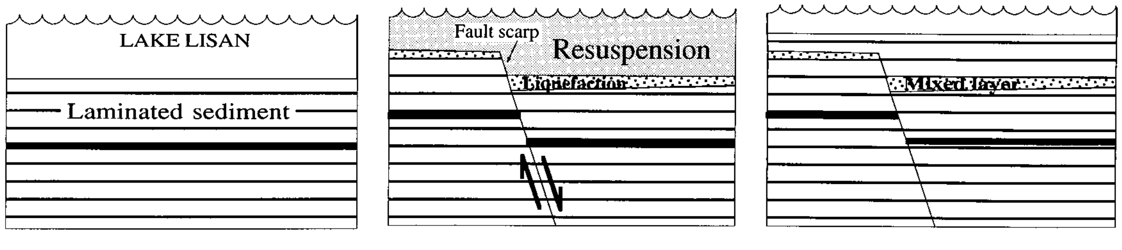

Figure 4. Interpretation of observed fault–mixed layer association shown in Figure 2. A: Laminated sediments are deposited at bottom of Lake Lisan. B: Fault offsets surface, creating subaqueous scarp. Top of sediment is deformed, liquefied, and resuspended during coseismic movements. Mixed layer forms on both sides of fault scarp when suspended sediments resettle. Mixed layer in downthrown block is slightly thicker. C: Sedimentation continues; thicker sequence accumulates on downthrown block.

may occur at a magnitude as low as 5 (Audemard and de Santis, 1991) or 4.6 (Sims and Garvin, 1995), but a quantitative analysis (J. R. L. Allen, 1986) based on observations (Kuribayashi and Tatsuoka, 1975; Youd, 1977) indicates that sand liquefaction is more characteristic of greater magnitudes. The clay content in the Lisan (20%–35%) and the grain sizes of a few micrometres (Begin et al., 1974; Arkin and Michaeli, 1986) make it less prone than sand to liquefaction (Allen, 1982). Surface faults are rarely reported from earthquakes of less than magnitude 5.5 (Bonilla et al., 1984; Wells and Coppersmith, 1994), and their existence in the Masada area also indicates the magnitude. The data are insufficient to show whether the faults are throughgoing, the uppermost part of a "flower-structure," or the surface manifestations of lateral spreading due to deeper seismogenic slip events. However, the repetitive faulting and its congruence with active faulting in the Dead Sea area (Fig. 1) support a tectonic origin.

The studied faults do not displace the top of the Lisan Formation. The uppermost ~5 m of the Lisan Formation were deposited after faulting migrated, and the current active fault lies ~3 km east of the Dead Sea shore (Garfunkel et al., 1981). Seismic profiles in the Dead Sea reveal thinning of recent sediments toward fault segments (Ben-Avraham et al., 1993), showing a similar pattern of active syndepositional fault scarps.

The faults near Masada provide high spatial and temporal resolution of a faulting stage, showing repetitive slip events on the order of several tens of centimetres on the same planes within periods on the order of 10^3–10^4 yr. The events are typically separated by several hundred years of quiescence.

Mixed layers are found throughout the Lisan Formation and subsequent Dead Sea sediments away from observed faults (Marco et al.). We postulate that they formed by similar seismogenic shaking, and the population of mixed layers in each locality represents the group of strongest events ($M \geq 5.5$) within the time of the Lisan and the Dead Sea. Hence, these lake sediments contain the longest paleoseismic record along the Dead Sea transform (>70 kyr), and possibly the longest in the world.

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