Archaeoseismic Evidence of Two Neolithic (7,500–6,000 B.C.) Earthquakes at Tell es-Sultan, Ancient Jericho, Dead Sea Fault

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INTRODUCTION

Information on past earthquakes in the Dead Sea basin and the adjacent region was recovered from seismites and faults in lake sediments. Seismites are found in the 70- to 15-ka Lisan formation (Marco *et al.*, 1996) and in the subsequent Dead Sea deposits (Ken-Tor *et al.*, 2001; Migowski *et al.*, 2004; Kagan *et al.*, 2011). Other sources for palaeoseismic data came from damaged speleothems in caves some 40 km west of the Dead Sea Transform (DST) (Kagan *et al.*, 2005; Braun *et al.*, 2009). The present work aims at recovering the earthquake record from the ancient settlement of Jericho (Palestine), renowned as the archaeological site of Tell es-Sultan, inhabited in a period in which we have no local geological information. Tell es-Sultan is suitable for archaeoseismic investigations because (1) it is located in a seismically active area (Fig. 1); (2) it was inhabited continuously during the last 11,000 yr; and (3) the history of the site was repeatedly studied by archaeologists, providing abundant documentation.

Starting from the early nineteenth century to the modern expeditions, archaeologists have associated peculiar damaging, fracturing, and human remains discovered at the ancient Jericho site to repeated seismic shaking events during the whole Neolithic history of the site, that is, from approximately 11,000 B.C. up to 6,000 B.C. (Tables 1 and 2). Prof. J. Garstang and Dame K. Kenyon led the two main archaeological teams that considered earthquake effects in this period (Garstang *et al.*, 1935; Garstang and Garstang, 1948; Kenyon, 1957, 1981). Both renowned for their precious work on the Levant sites, in particular, Dame K. Kenyon was the first to apply the concept of archaeological stratigraphy and to define the still-used chronology for the Levantine Neolithic culture. The analysis in this work descends from their observations. Kenyon (1981) recognized damages as the result of strong ground shaking, based on findings that the layers referred to the interval 8,500–6,000 B.C., archaeologically belonging to the Pre-Pottery Neolithic A and B (PPNA and PPNB) levels. An earlier archaeological expedition led by Prof. J. Garstang (Garstang *et al.*, 1935; Garstang and Garstang, 1948) revealed the presence of surface fracturing affecting the PPNB (7,500–6,000 B.C.). In particular, this latter interval bears distinct traces of seismic effects, and the analysis and the review of the archaeological elements of the PPNB, the one investigated in this work, offer the opportunity to discriminate on the occurrence and on the characteristics of one or more seismic events.

The map in Figure 2 shows the distribution of the PPNB damages in the site. This map locates elements of different age, not connected in time and space to date, within the same frame. Earthquake effects are inferred from the position, orientation, and analysis of the original pictures and the archaeological stratigraphic sections within the Tell.

A critical issue is the age of the evidence found at different parts of the site. At present, it is impossible to perform new sampling for absolute dating, because the Neolithic layers are a few meters below the surface and the access to the Tell for excavation is restricted (Figs. 2 and 3e, today views). We calibrated the radiocarbon ages reported by Kenyon (1981) using Calib Rev 6.0.0 (Stuiver and Reimer, 1993; Reimer *et al.*, 2009). The calibrated ages were inconsistent with the archaeological stratigraphy, being affected by large uncertainties in values and by doubtful sampling context. We therefore used the archaeological stratigraphy and relative periodization for correlation between damaged strata (Kenyon, 1981; Nigro and Taha, 2006).

Our main goals are (1) to isolate the seismic effects at the Tell within the PPNB and attribute them to specific events; (2) to constrain their temporal sequence through the convergence and analysis of the documented observations; (3) to provide a rough estimate of the shaking recurrence at the site; (4) to impose some constraint on the fault responsible for the local deformation at the Tell by combining field data; (5) to contribute to the understanding of the behavior of the earthquake source in the area of Jericho and of the associated vulnerability menacing the population and sites with high cultural heritage value as Jericho and the nearby Qasr Hisham, Herod's Palace, and Saint George Monastery in Wadi Quilt; and (6) to

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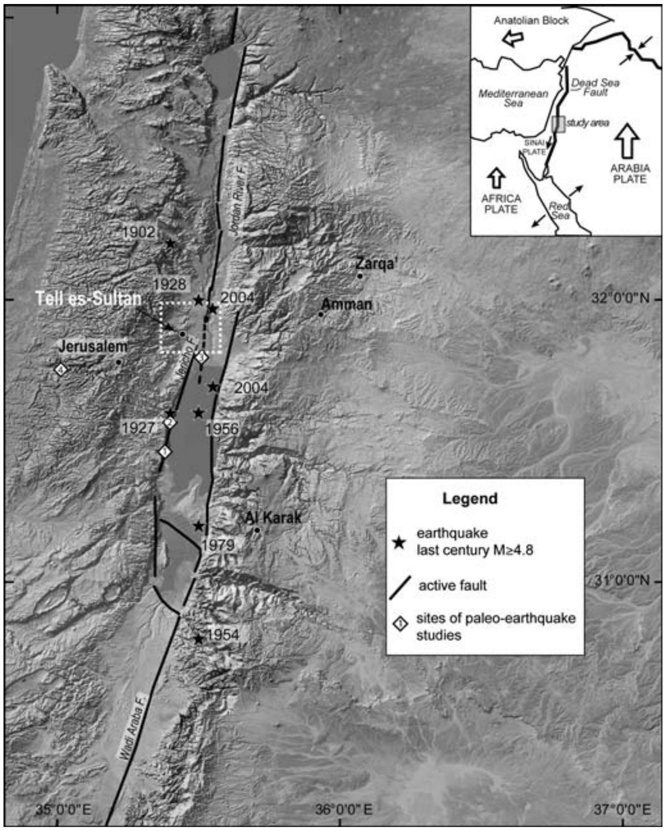


▲ **Figure 1.** Schematic tectonic map of the Dead Sea area showing the location of Tell es-Sultan, the main fault traces of the Dead Sea fault system (black line), and the instrumental earthquakes in the last 100 yr (black star). The white diamond refers to the site of paleoearthquake analysis from (1) lacustrine cores (Migowski *et al.*, 2004), (2) fan—delta sequence (Enzel *et al.*, 2000), (3) trenching (Reches and Hoexter, 1981; Lazar *et al.*, 2010), and (4) speleothems (Braun *et al.*, 2009). The white dashed box includes the area of Figure 5. The inset shows the Dead Sea fault system and the relative plate motion.

search for independent earthquake signatures to be compared and merged with other datasets of earthquake records (e.g., seismites, speleoseismites).

THE TELL ES-SULTAN: TECTONIC AND ARCHAEOLOGICAL SETTING

The ancient town of Jericho is located within the DST fault zone (Fig. 1). The DST is approximately a 1,000-km-long, north–south-striking, left lateral fault system of the active boundary between the Arabian and African plates (e.g., Garfunkel *et al.*, 1981). The DST shows relatively low level of activity in modern time, but larger-magnitude seismic events were documented in the historical reports (Guidoboni *et al.*, 1994; Ambraseys, 2009). One of the main fault strands of the transform zone system is the Jericho fault bounding the Dead Sea basin on the west side (Reches and Hoexter, 1981; Gardosh *et al.*, 1990). A linear escarpment at approximately 6 km southeast of modern Jericho is thought to be the surface expression of the Jericho fault on land (Begin, 1974; Lazar *et al.*, 2010). The 1927 earthquake with an M 6.2 (Ben-Menahem *et al.*, 1976; Shapira *et al.*, 1993) is the most recent event that caused widespread damage and casualties in the modern Jericho settlement. The revised 1927 epicenter is approximately 30 km south of the Jericho site (Avni *et al.*, 2002; Fig. 1). Direct evidence of this event at the historical site of Jericho has not been reported by the postearthquake expeditions in the archaeological stratigraphy. Instead, archaeological traces suggest earthquake devastation back in time (Table 1).

The separation of earthquake-related damages in the archaeological layers of Jericho was made possible by the intrinsic characters of the site resulting in the classical Tell structure, where subsequent archaeological levels firmly seal the preceding occupation soils. When the village experienced destruction, there was no possibility, or need, to remove the debris completely, and the inhabitants continued to build on top of the ruins. The superposed archaeological layers in the last 11,000 yr

Table 1
Periods with Earthquake-Induced Damaging as Inferred from Archaeological Data at Tell es-Sultan

Time Interval (Archaeological Period)	References
10,500–8,500 B.C. (Natufian)	Kenyon (1981)
8,500/8,300–7,500 B.C. (Pre–Pottery Neolithic A)	Kenyon (1981), Ambraseys (2006, 2009)
7,500–6,000 B.C. (Pre–Pottery Neolithic B)	Garstang and Garstang (1948), Kenyon (1981), Ambraseys (2009)
6,000–5,000 B.C. (Pottery Neolithic A)	Kenyon (1981)
3,400–3,100 B.C. (Early Bronze IA)	Kenyon (1957, 1978), Ben-Menahem (1991), Ambraseys (2009)
2,700 B.C. (Early Bronze IIB)	Avi-Yonah and Stern (1978), Karcz *et al.* (1977), Kenyon (1981), Ben-Menahem (1991), Nigro (2009)
2,300–1,950 B.C. (Early Bronze IVA–B; Middle Bronze I)	Garstang and Garstang (1948), Kenyon (1957, 1981), Ambraseys (2006, 2009), Nigro (2009)
2,100–1,560 B.C. (Early Bronze IVB; Middle Bronze I)	Ben-Menahem (1991)
2,100–1,560 B.C. (Middle Bronze III)	Kenyon (1957, 1981), Ben-Menahem (1991)

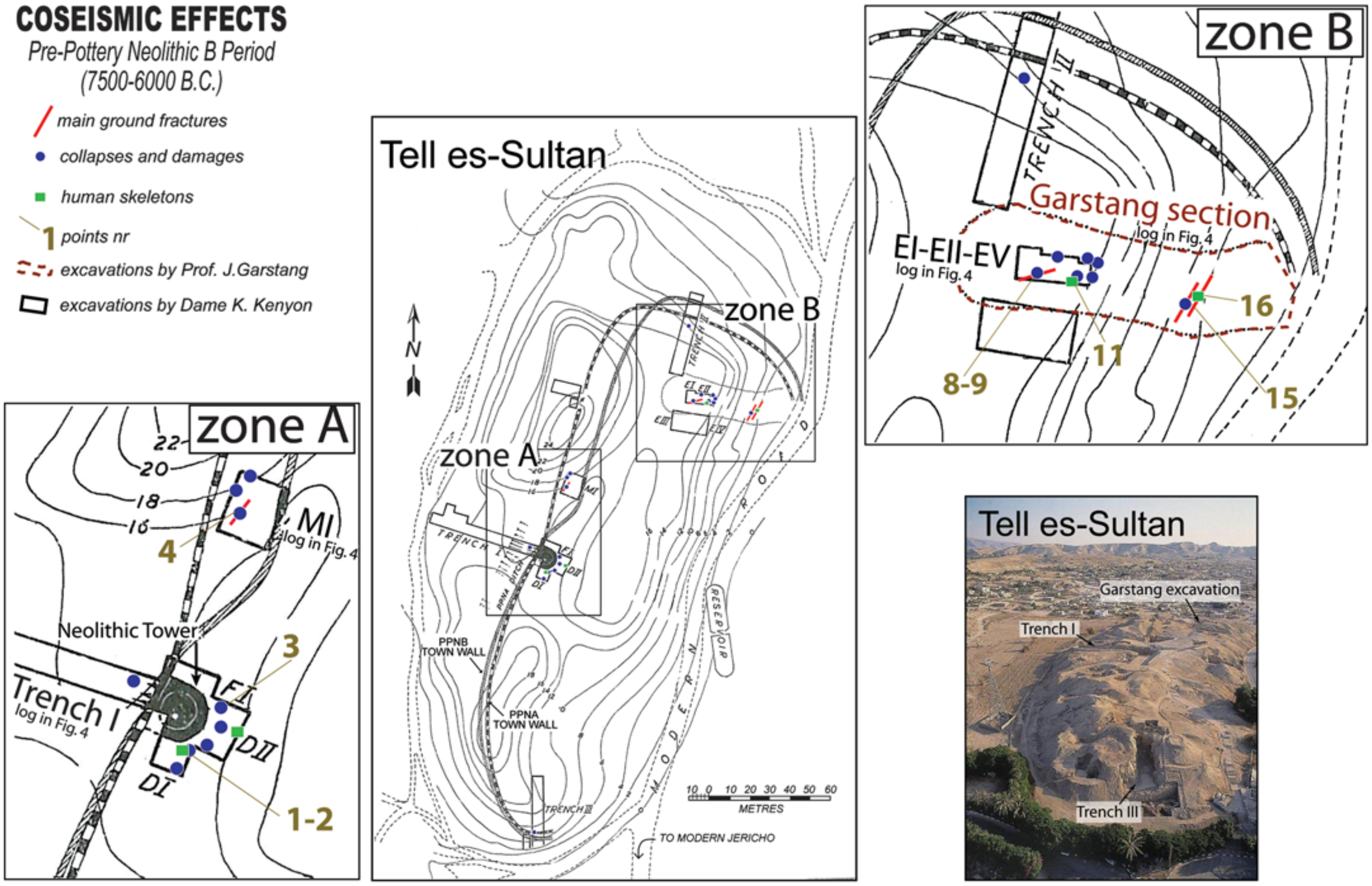
Table 2
Earthquake-Induced Damages at Tell es-Sultan as Reported by the Archaeological Reports for the Pre-Pottery Neolithic B Period (7,500–6,000 B.C.)

Point no.	Original Archaeological Description (source)	Seismically Induced Effects	Archaeological Stage, Location, Phase
1	"At the end of stage XVI there was a considerable collapse. The wall stumps of the buildings in square FI were buried beneath a filling of fallen bricks, and the western end of the walls were denuded to floor levels. It is clear that the terrace wall along the western edge of the building must have collapsed…;.There was however a complete rebuilding." (Kenyon, 1981, p. 75)	Considerable collapses, destruction, decay, rebuilding	Stage XVII, F I xxx, xxxa, Tr. I xxi–xxii, DI xliiii
2	"Overlying the surface of stage XVII is a further bricky fill. Since this is succeed by new building in the whole excavated area, it presumably indicates a major stage of destruction and decay…;.In this part of DI and over the whole FI there was a bricky fill…;the filling represents a destruction and decay level…;it contained a remarkable number of bodies, at least thirty…the bodies were for the most part found simply in the mass of the fill, with no observable evidence of any graves…;the complete body lies on the plastered floor position prone as if in the position in which the individual collapse…;.The examination of skeletal remains, provide no evidence of wounds…;.A more probable explanation is that a large number of the inhabitants were killed as a result of an earthquake…;." (Kenyon, 1981, pp. 77–78)	Earthquake casualties	Stage DI, XVII A FI xxxi, DI xlii, DII xxx–xxxi
3	"The buildings of this stage were seriously damaged by an earthquake. The clearest evidence of this came from the north end of square FI. Here wall 102 collapsed outwards (northwards) in one piece, sheering off at the level of the central room to the south." (Kenyon, 1981, pp. 87–88)	Collapsed wall, collapsed artifacts	FI, Stage XXIII–XXIV, FI xxxvii–xxxviii, DI xlvi–xlvii, DII xxxiv–xxxv
4	"A substantial crack in section J—K…;may indicate that the rebuilding was necessary because of an earthquake." (Kenyon, 1981, p. 243)	Surface fracturing	Square M, stage XI, phases lxiv–lxvia
5	"The destruction of the phase xxxiv buildings is marked by a thick brick fill, up to 0.75 m thick. All the wall north of point 21 m. were destroyed." (Kenyon, 1981, p. 132)	Collapses, subsequent rebuilding,	Trench II, stage IX, phase xxxiv–xxxvi
6	"Phase xxxviii was preceded by a considerable collapse in the eastern half of the area. The new wall and floors were founded on a fill of about 0.35 of broken bricks and debris, and all the walls east of, and including the west wall of the old courtyard are new." (Kenyon, 1981, p. 291)	Collapses, brick debris, rebuilding	Squares E's stage X, phase xxxviii
7	"Phase xlvi involved the complete rebuilding of the western range, and the almost complete rebuilding of the eastern range. In the western range the debris of the collapse of the phase xlv buildings produced a fill as much as 0.70 m .thick…;." (Kenyon, 1981, p. 294)	Destruction, debris fill	Squares E's, stage XI, phase xlv—stage XII, phase xlvi
8	"…;In the courtyard was observed for the first time a remarkable cracks. Examination of the section, however, showed that it originated in phase liii…;." (Kenyon, 1981, p. 295)	Surface fracturing	Squares E's stage XII, phase xlvii
9	"This phase would seem to have followed a major collapse of the preceding building in the western range, resulting in the accumulation of a thick layer of debris, which was traced back within the house. The crack in the floor levels, which was clearly visible in the phase xlvii at courtyard level, could be traced in the stratification key to this level, and is probably associated to the collapse. It is tempting to regard it as an earthquake crack (fault), but Professor Zeuner did not consider this probable, as the base of the crack did not continue downwards." (Kenyon, 1981, p. 298)	Surface fracturing, major collapse	Square E's, stage XIII, phase liii
10	"On the section line there had been a crack in the preceding fill, into which some surface are sagged." (Kenyon, 1981, p. 300)	Surface fracturing	Squares E's stage XIII, phase liv

(Continued next page.)

Table 2 (continued)
Earthquake-Induced Damages at Tell es-Sultan as Reported by the Archaeological Reports for the Pre-Pottery Neolithic B Period (7,500–6,000 B.C.)

Point no.	Original Archaeological Description (source)	Seismically Induced Effects	Archaeological Stage, Location, Phase
11	"The changes in plans between phase lv and lvi were not great, but the fill between the floors of the two phases nevertheless indicated a fairy considerable destruction, and possibly a major disaster. The fill was full of burnt material—A number of lines could be traced which probably represented fallen roof-beams. These were not actually burnt…;presumably they fell before they were thoroughly set on fire…;.Numerous burnt clay fragments from the roof surface were also in the fill. Within the rooms of the eastern range is a hard bricky fill, presumably derived from the collapsed walls…;.Still more interesting is the fact that buried beneath the fill were a number of bodies…;.The skeletons are curiously mutilated and incomplete…;.The group naturally suggests comparison with the similar but larger group in square FI." (Kenyon, 1981, pp. 302–303)	Crushed bodies, considerable destruction, collapse	Square E's stage XIII, phase lv–lvi
12	"Between phase lvi and phase lviii there seems to intervene a decay level, in which at least the eastern range was in ruins…;." (Kenyon, 1981, p. 303)	Decay level	Square E's XIII, phase lvii
13	"Phase lxi represents the most complete rebuilding for a very long time. From phase liii onwards, though there is evidence of considerable destruction at the various stages…;Now, thick brick debris filled the whole range…;every wall is rebuilt in a slightly different position…;.In the bricky fill beneath the new western range were some skeletal remains…;it is possible that they represent a foundation sacrifice." (Kenyon, 1981, pp. 305–306)	Considerable destruction, subsequent rebuilding	Square E's stage XIV. Phase lxi
14	"Phase lxiv was separated from phase lxv by another major destruction, of which the thick brick fill in the western range, and the alteration of the position of wall are evidence. Phase lxv represents the lowest level reached by Professor Garstang, his level XI." (Kenyon, 1981, p. 308)	Major destruction, brick debris	Square E's stage XV, phase lxv
15	"To these common cause of decay there should be added the effects of earthquakes, visible traceable at certain of these levels where great fissures appear through walls and floors. These were, however, exceptional, and their trace are generally quite marked." (Garstang and Garstang, 1948, p. 46)	Surface fracturing	Garstang's excavation level X–XIm
16	"In the other case a man's head was found that have been completely severed from his body, as may be seen in our photograph on Plate IXb; but as the excavation continued we noticed a continuous fissure across the floor of the room and running up the walls, telling of an earthquake which by a remarkable coincidence has subsequently produced this curious illusion of decapitation." (Garstang and Garstang, 1948, p. 51)	Skeletons remains, surface fracturing	Great Garstang's level XI
17	"It was therefore between phases xix and xx that there was a considerable erosion, which have been due to a serious collapse of the town wall…;.At the end of phase xxi there was a major destruction or collapse, and very little of the earlier plan survives into the next stage." (Kenyon, 1981, pp. 186–187)	Collapse, skeletons	Trench III, stage IX, phase xxi–xxii
18	"In square FI, were a number of hearths, hollows, and surfaces that break into the ruins of the last Pre–Pottery B house. They must represent a squatting or camping stage after the disappearance of the Pre Pottery Neolithic B town. No pottery is associated with them." (Kenyon, 1981, p. 92)	Squatting stage	FI, stage XXVI, phase xliii, DI I



▲ **Figure 2.** Map of coseismic effects at Tell es-Sultan between 7,500 and 6,000 B.C. (Pre–Pottery Neolithic B). The locations of the effects are marked by numbers (descriptions as in Table 2). Original plan of the Tell modified from Kenyon (1981).

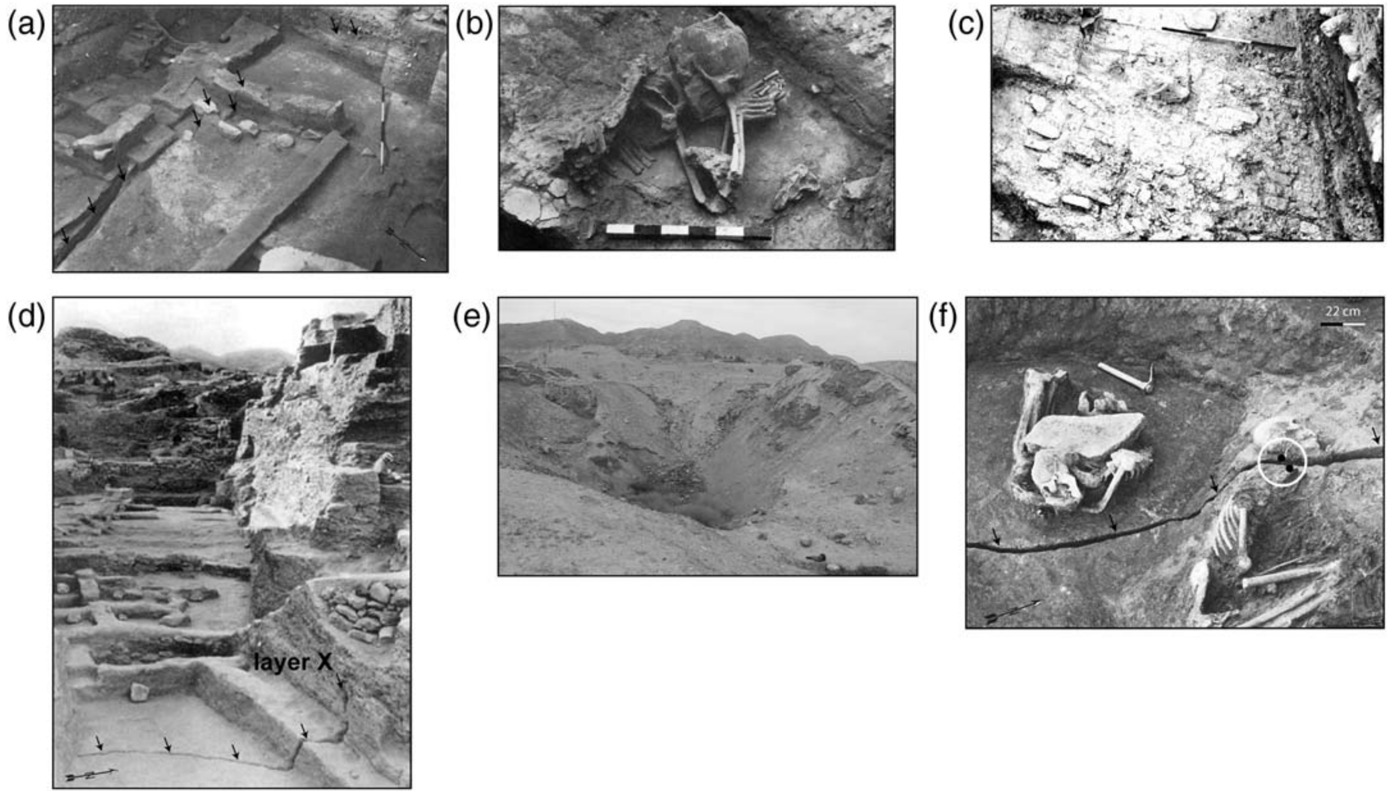
constitute the artificial hill of the ancient Jericho up to about 10 m above the surrounding ground level (Fig. 2). This setting prevents buried and older archaeological levels from severe damaging associated to the younger shaking events.

Town wall encircling the inhabited quarters and the monumental public structures, such as the Neolithic tower (Fig. 2), appeared since the PPNA (8,500–7,500 B.C.), testifying to the presence of an organized social community. The favorable geographical position of the Oasis of Jericho and the environmental conditions are the cause of the continuous occupation of the area. Indeed, the presence of perennial water springs and the climate favored the persistent occupation of Tell es-Sultan from the Natufian (ca. 11,000 B.C.) up to the Iron Age (ca. 1,200 B.C.), with a flourishing occupation during the Neolithic stages. The artifacts of the Neolithic masonry and buildings are made on massive mudstone boulders and on sun-dried brick constructions. These constructions are vulnerable, and local collapses may occur even without earthquakes. Hence, it is critical that the archaeoseismic analysis of the deformation identifies a specific cause to the observed damage, that is, earthquake, fire, flash flood, or deliberate destruction (Marco, 2008).

ARCHAEOSEISMIC OBSERVATIONS IN THE PPNB STRATA

Figure 2 and Table 2 present a set of features recognized as seismically induced effects at Tell es-Sultan in the archaeological PPNB period (7,500–6,000 B.C.). Both the map and the table were based on our review of the archaeological documents, including the analysis of the stratigraphy, that enhance seismic shaking activities undefined in number and timing. We excluded in the map damage caused by human invasions, structural collapses, fires, or natural hazards other than earthquake. Although the distribution in the map does not reflect the complete damaged field of the Tell, it gives significant information on the nature and extension of the damage itself. Furthermore, when this picture is framed in a chronological context, it allows inferring the time–space occurrence of the individual elements (see the section Time Constraints on the PPNB Earthquakes Occurrence).

In the following paragraphs, we describe the significant damage elements, although more than one effect coexist at several points, that is, a set of fractures associated to major collapse and human skeletons trapped under the fallen structures. In general, the observed fractures appeared to the excavators as

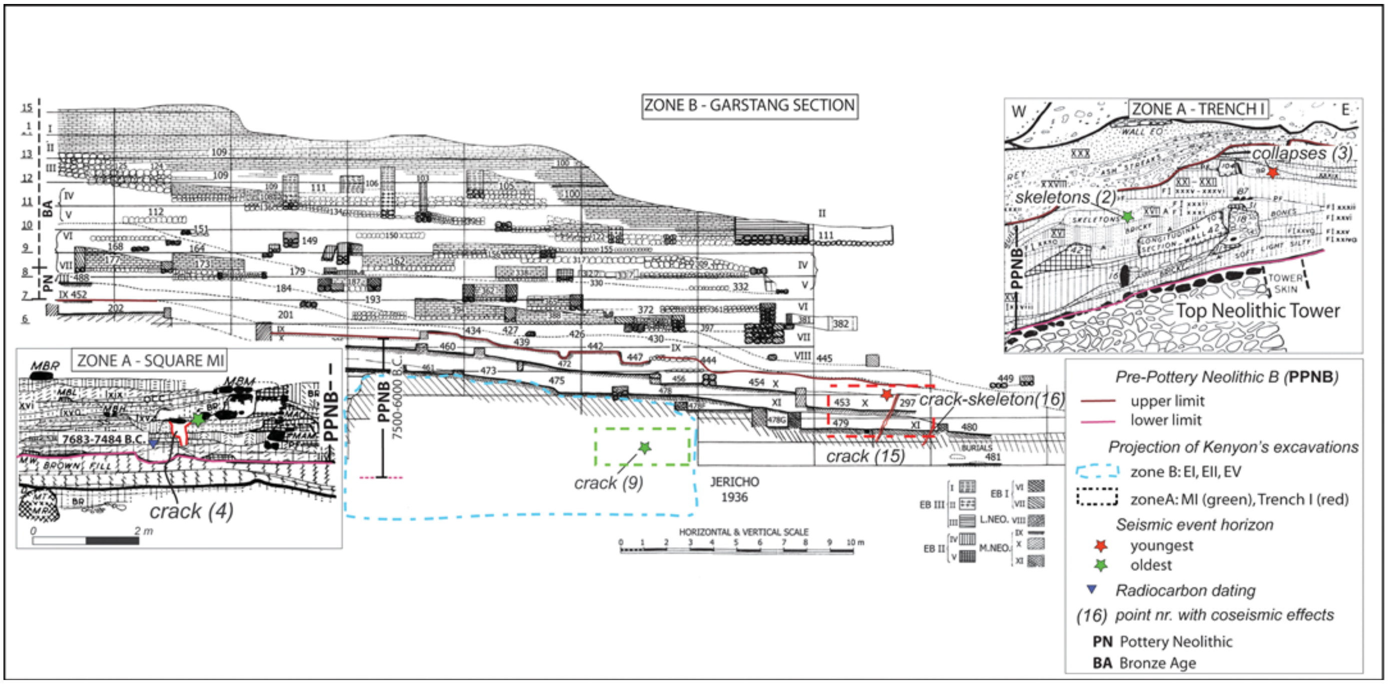


▲ **Figure 3.** Photos illustrating some of the effects caused by seismic shaking at Tell es-Sultan (numbered as in Figure 2 and Table 2). Original pictures from Kenyon (1981). (a) Black arrows point to fractures crossing the floor and the perimeter wall of Pre-Pottery Neolithic B houses. (b) Human skeleton found under a collapsed wall. (c) View from the top of a complete northward collapse of a wall, giving the illusion of a pavement. Original pictures from Garstang and Garstang (1948). (d) East view of the Garstang excavation. Visible in the foreground is a fracture crossing the floor and the adjacent wall affecting layer X, dated as the latest stage of Pre–Pottery Neolithic B. (e) The Garstang excavation as appears today (same shot position). (f) Black arrows point to a fracture crossing a pavement and a skeleton. An apparent displacement of skull versus body is observable. The white circle inscribes the possible correspondence between the cervical and neck bones (black dots).

well-preserved open elements while removing the fillings. No calcification of the fracture was observed to be prevented by the climate of the Jericho area. The fractures did not result from lateral spreading because (1) the weight loading the fractured layers is not so high, (2) the observed fractures are always accompanied with other features in an extended deformed area, and (3) most of them occur in the flat central sector of the Tell.

Widespread devastation of original structures was observed in the west side of the Tell (Fig. 2, zone A). Here, human skeletons were found underneath collapsed building walls (Fig. 2, points 1 and 2; Fig. 3b). The houses were completely dismembered in the collapse, and strengthening and rebuilding followed on the same plans. Figure 3c shows the complete collapse of a wall that fell in one piece northward (Fig. 2, point 3; Table 2). The occurrence of a pervasive fracture was also documented, and based on our reconstruction, its strike was northeast—southwest (point 4). The houses were rebuilt, and Kenyon (1981) suggested that the rebuilding was necessary because of an earthquake destruction (see also Table 2).

The layers of PPNB appear intensively damaged also at the northeastern side of the Tell (Fig. 2, zone B). Also, here, coseismic open fractures are clearly documented (points 9, 15, and 8). We used the original pictures and sections to define the position and orientation of these fractures and then to determine the relative movement along their trace. Figure 3a is a top view of a set of open fractures crossing the floor and the walls of a courtyard of a house. The set is composed of at least three segments reaching a minimum visible extent of 3 m, with a mean direction of 085° and an opening of approximately 20 cm. Figure 3d shows one of the major fractures at the Neolithic Tell. The marked fractures displace artifacts of different materials and shapes (walls and floors) and maintain a constant direction (040°), suggesting a tectonic origin, for at least 5 m (the original plans are in the Archives of the Garstang Museum of Archaeology, University of Liverpool, UK). The upper termination of the fractures in the wall, according to the archaeoseismic stratigraphic section in Figure 4, is within layer X, that is, the upper terminus of the PPNB period. Another interesting feature concerning the studied earthquakes is shown in Figure 3f, where both a profound fracture and human remains are found. Garstang and Garstang (1948) noted that the head of the skeleton to the right is severed from the body,



▲ **Figure 4.** Archaeoseismic stratigraphic sections modified from Garstang and Garstang (1948) and Kenyon (1981). Dashed squares in Garstang's section are the approximate projections of Kenyon's excavations both from zone A (logs in the inset) and zone B. The time—space relations between the layers and the observed coseismic effects (point numbers as in Figure 2 and Table 2) are illustrated. Horizons of the seismic shaking events recognized within the Pre-Pottery Neolithic B period are marked by stars.

giving the illusion of decapitation. However, in fact, the cause for the head displacement was a fracture. The excavation further downward revealed a continuous few-centimeter open fracture across the floor, indicating an earthquake that gave this illusion. Nur and Burgess (2008) suggested a right lateral offset between the ribs and skull position of the skeleton. We measured a relative lateral movement of a few centimeters. Based on different marker points, such as the cervical bone versus the spinal column (Fig. 3f, circled part), the offset could be also interpreted as left lateral. A small step is apparent on the right side of the photo, suggesting minor vertical offset with east side down. Placing the two images and then the fractures of Figure 3d and 3f within the log of Figure 4, we noted two parallel fractures about 3 m apart. The main fracture affects the lower part of layer X, belonging to the younger stage of the PPNB period. The deformation observed within layer X extends for about 30 m along the section, affecting floors, house walls, and human remains (Fig. 4). A group of human skeletons was also found not in burial position, whose deaths may be attributed to sudden events such as collapse and destruction (Fig. 4, point 11).

TIME CONSTRAINTS ON THE PPNB EARTHQUAKES OCCURRENCE

In Figure 4, we project the stratigraphic position of the seismically induced deformation observed at zones A and B (Fig. 4, dashed boxes and referred points). Once placed in archaeological correlation, the highly deformed layers at different sites of excavations allow a definition of the temporal sequence of the events.

The fracturing at point 9 (zone A) was interpreted as a shaking effect acting in the first half of the PPNB period. The effects observed at points 4 and 2 (zone B) occurred within layers of the same time interval. Hence, we assumed that all these shaking effects resulted from the same seismic event (Fig. 4, green stars). The position of the event horizon relative to the archaeological periodization suggests the occurrence of the event at about 7,000 B.C., well after the beginning of the PPNB period. The only radiocarbon age from the deformed layer at the early stage of PPNB, consistent with the archaeological periodization and of good quality, is 7,683–7,484 B.C. (calibrated age, 2σ range; sample BM-1320, $8,540\pm 65$ B.P.; Kenyon, 1981); this age would predate the event (Fig. 4, zone A, square MI).

A younger event was recognized through the analysis of points 3, 15, and 16 from zones A and B of the map (Fig. 4, red stars). The effects were observed within layers dated to the end of the PPNB. In particular, the fracture of point 15 partially crosses the layers of the latest PPNB period, marked with Roman number X (Fig. 4), and it is sealed by the undisturbed portion of the same layer and successive layer IX (beginning of PPA, i.e., well after 6,000 B.C.). These observations constrain the occurrence of the second seismic shaking of the studied period approximately 6,000 B.C., and not later.

In summary, we isolated two deformation events related to seismic shaking. We identified their event horizons: The older event is set within the first half of the PPNB period, that is, 7,500–7,000 B.C., and the younger one, close to the upper time limit of the PPNB, that is, approximately 6,000 B.C. The two events were separated by undisturbed archaeological strata, including rebuilding phases, that were marked as stage XIV in zone B by Kenyon (1981) and corresponded to layers XII–XIII of Garstang and Garstang (1948), matching the first half of the PPNB period.

EARTHQUAKES FINDINGS

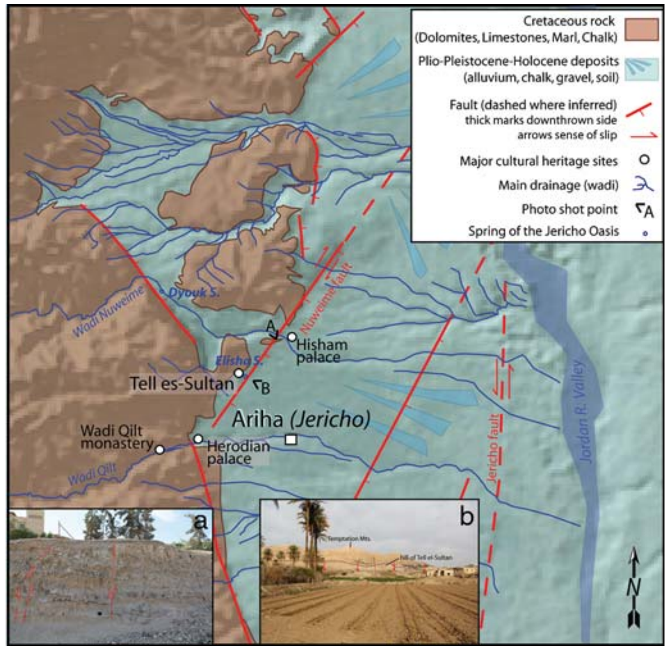
Events Recognition

Our interpretation of the archaeological observations provides the isolation of two deformation events striking the Tell es-Sultan in the 7,500–6,000 B.C. interval (PPNB), the younger event approximately 6,000 B.C. and the previous one likely at approximately 7,000 B.C. We attribute the deformation to earthquakes. We further interpret the absence of other damages within the PPNB as evidence that no other major earthquakes affected the Tell during this interval of time. The two PPNB events are not cited in the archaeological literature of the region. Historical earthquakes were evidenced from trenching by Lazar *et al.* (2010) and Reches and Hoexter (1981) and from lake seismites analysis by Kagan *et al.* (2011) (see Fig. 1 for location). More than 30 km south of the Jericho site, evidence for earthquake occurrence within our time interval was reported by Enzel *et al.* (2000), who described faulting and liquefaction features on fan-delta sequence associated with the activity of the Jericho fault between 9,500 and 7,000 yr B.P. Migowski *et al.* (2004) inferred that the older seismites (~5, 000–7, 000 B.C.) in their laminated sedimentary cores (see Fig. 1 for location) can be correlated with the disturbances of Enzel *et al.* (2000). The authors cannot correlate their older records to any earthquake, because the current dataset of archaeoseismological and paleoseismological literature lack of clear earthquake determination back to ~6, 000 B.P. At least two deformed layers in the Migowski's sequence between 5,600 and 6,800 B.C. possibly correlate with our seismic events. Further evidence for seismic events in the time interval analyzed in this work comes also from damaged speleothems at the Soreq and Har-Tuv caves, nearly 40 km west of Tell es-Sultan (Fig. 1), where earthquake evidence at ~8.6 ka has been found (Braun *et al.*, 2009).

In this context, the earthquakes' timings defined in this work, that is, the two Neolithic events at ~7, 000 and 6,000 B.C., represent an independent check for the earthquake occurrences reconstructed with different approaches and for correlation among different records.

Earthquake Shaking Recurrence at Tell es-Sultan

Our results show that Tell es-Sultan was seismically shaken twice in 1,000–1,500 yr, most probably 1,000 yr, by damaging earthquakes. Moreover, at Jericho, evidence of a major shaking effect was documented at the end of PPNA (i.e., at approximately 7,500 B.C.) at different sections of the site. A widespread collapse of the encircling town wall was associated to a sudden major disaster directly attributed to an earthquake



▲ **Figure 5.** Geological sketch of the Tell es-Sultan surrounding area. Fault traces (Roth, 1970; Begin, 1974; Shamir *et al.*, 2005; Shamir, 2006) and the location of Tell and other major sites of great cultural interest are reported. Photos: (a) fault zone in a Cretaceous deposit northeast of the Tell; (b) view from the southeast of a northeast—southwest-trending scarp (red arrows point the crest) along the Nuweime fault trace. Tell es-Sultan is in the background.

(Kenyon, 1957, 1981; Bar-Yosef, 1986). Assuming this interpretation credible and placing it as the immediate antecedent earthquake of the two events recognized in this work, we infer a rough average recurrence interval for earthquake shaking at the site of 750 yr (two interevents in 1,500 yr, 7,500–6,000 B.C.). Although this estimate refers to seismic shaking in a limited period at Tell es-Sultan, in which the seismic sources are unknown, it falls in the range of previously published recurrence values in a comparable time window for the Dead Sea area. Migowski *et al.* (2004) defined an earthquake recurrence interval of 500 yr for the period 8,000–5,500 B.C. from paleoseismites within the Dead Sea. Also accounting for a larger time window, the average repeat time for strong earthquakes ($M \geq 6.5$) based on paleoseismological, archaeological, and seismological studies in the fault system of the Dead Sea basin, converges to ~500 yr during the past 60,000 yr (Hamiel *et al.*, 2009 and references therein).

Implications for the Earthquakes Source

Solely on the basis of our data, we cannot determine the faults responsible for the prehistorical recognized earthquakes. However, a reconstruction of the active fault system of the DST in the area of Tell es-Sultan (Shamir *et al.*, 2005) and the observed young scarps indicate that the system includes the main approximately north–south-trending left lateral Jericho fault to the east and the broad zone of distributed faults west of it (Fig. 5). One of these latter, the northeast–southwest-trending

Nuweime fault bounds the area of Tell es-Sultan (Begin, 1974; Shamir *et al.*, 2005). The right lateral normal motion is attributed to this fault based on current seismicity (Shamir, 2006).

A morphological step is observed along the southeastern margin of the Tell (Fig. 5, picture), and its southern and northern extension traces the position of the Nuweime fault. Paleoseismic investigation could impose tighter constraints on the activity of the Nuweime fault. In a seismic context, the activity of the Nuweime fault would contribute to the vulnerability of the Tell area, being one of the possible faults responsible for the seismic shaking damages at the Tell and surrounding region.

CONCLUSIONS

The merging of archeological and geological data in the area of Tell es-Sultan leads us to the following conclusions:

- Two events damaged parts of Tell es-Sultan in the PPNB. The youngest event occurred approximately 6,000 B.C. and the previous one at approximately 7,000 B.C., separated by an $\sim 1,000$-yr interval.
- Considering an older event documented at the end of the PPNA (approximately 7,500 B.C.), we infer a rough average recurrence interval for damaging earthquakes at Tell es-Sultan of 750 yr. This value is comparable with other estimates from analysis of different records of seismic features in the area.
- The Nuweime active fault that bounds the Tell is a plausible source for local seismic shaking, contributing to the vulnerability of the area.
- This case study highlights the possibility to cover lack of information on the prehistory of a seismically prone area through the analysis of archaeological documentations of past expeditions as precious source for archaeoseismic investigators.

Finally, the more extended is the reconstruction of the seismic history at a site, the more reliable is the seismic hazard estimation affecting the population and the cultural heritage. This is particularly crucial in the case of Jericho, often called "the oldest city in the world," where past archaeological records are one of the possibilities to investigate such prehistorical events, especially when original data vanish with time.

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