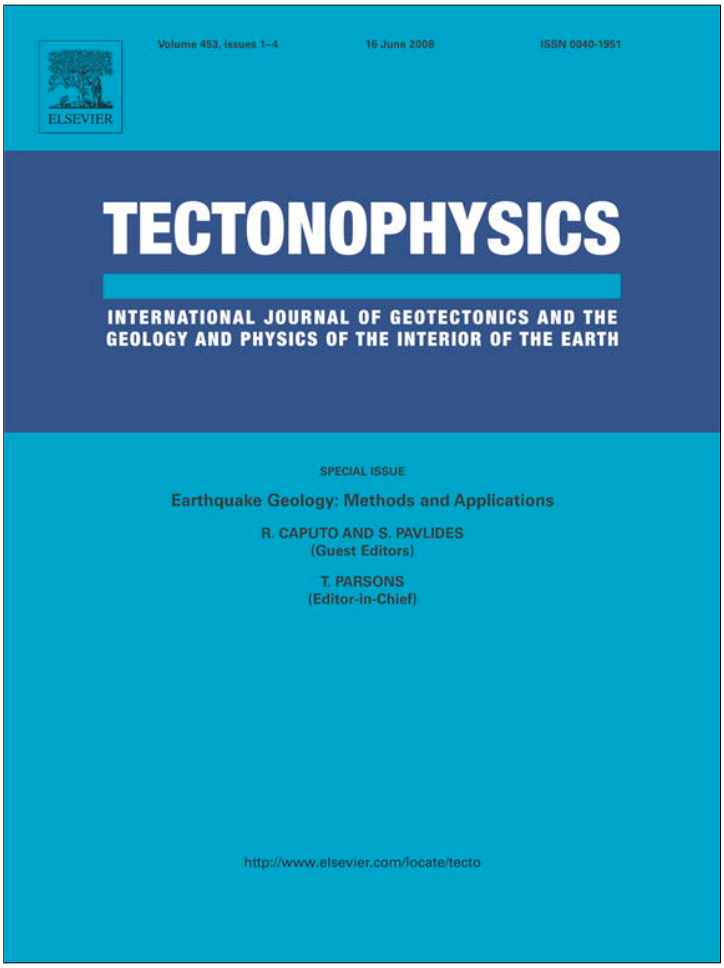

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Recognition of earthquake-related damage in archaeological sites: Examples from the Dead Sea fault zone

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Abstract

Archaeological structures that exhibit seismogenic damage expand our knowledge of temporal and spatial distribution of earthquakes, afford independent examination of historical accounts, provide information on local earthquake intensities and enable the delineation of macroseismic zones. They also illustrate what might happen in future earthquakes. In order to recover this information, we should be able to distinguish earthquake damage from anthropogenic damage and from other natural processes of wear and tear. The present paper reviews several types of damage that can be attributed with high certainty to earthquakes and discusses associated caveats. In the rare cases, where faults intersect with archaeological sites, offset structures enable precise determination of sense and size of slip, and constrain its time. Among the characteristic off-fault damage types, I consider horizontal shifting of large building blocks, downward sliding of one or several blocks from masonry arches, collapse of heavy, stably-built walls, chipping of corners of building blocks, and aligned falling of walls and columns. Other damage features are less conclusive and require additional evidence, e.g., fractures that cut across several structures, leaning walls and columns, warps and bulges in walls. Circumstantial evidence for catastrophic earthquake-related destruction includes contemporaneous damage in many sites in the same area, absence of weapons or other anthropogenic damage, stratigraphic data on collapse of walls and ceilings onto floors and other living horizons and burial of valuable artifacts, as well as associated geological palaeoseismic phenomena such as liquefaction, land- and rock-slides, and fault ruptures. Additional support may be found in reliable historical accounts. Special care must be taken in order to avoid circular reasoning by maintaining the independence of data acquisition methods.

Keywords: Earthquakes; Archaeoseismology; Active faults; Earthquake damage; Dead Sea fault

1. Introduction

Earthquake research requires the reconstruction of longest possible records. The extension of instrumental record into the past is commonly done by studying faults that record the history of linear morphogenic earthquakes (Caputo, 2005) and by documenting off-fault earthquake-triggered deformation usually referred to as seismites (Agnon et al., 2006). However, deformed man-made structures of known age and original shape can provide additional information on past earthquakes (see Caputo and Helly, 2008-this volume). Archaeoseismology is the study of earthquake-related damage in archaeological sites. Ambraseys (1973), Karcz et al. (1977), and Karcz and Kafri (1978) pointed out the potential and importance of combining archaeological and geological data for obtaining valuable data about ancient earthquakes. A film on the subject by A. Nur (The Walls Came Tumbling Down) as well as a book edited by Stiros and Jones (1996) promoted and boosted archaeoseismological research. Archaeological records of past earthquakes can (i) constrain the time, local intensities, spatial distribution of strong ground motions, (ii) be used to develop isoseismal maps, (iii) define epicentral locations and (iv) possibly estimate magnitudes. A methodology and criteria for identification of earthquakes from archaeological data were suggested by Stiros and Jones (1996), who used mostly Greek, Italian, and Turkish examples. Subsequently, archaeoseismological research was used to recover information on past earthquakes in many old world regions, e.g., Italy (Galadini and Galli, 2001; Guidoboni et al., 2002; Guidoboni, 2003), Greece (Koukouvelas et al., 2001; Monaco and Tortorici, 2004; Caputo and Helly, 2005), Turkey

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(Hancock and Altunel, 1997), Spain (Silva et al., 2005), China (Yang et al., 2003), Middle East (Nur and Cline, 2000; Meghraoui et al., 2003; Haynes et al., 2006) and also in Arkansas, United States (Tuttle and Schweig, 1995).

Data from archaeological excavations should be evaluated critically in order to ensure their reliability and usefulness. In addition to earthquakes, several different processes can damage archaeological sites, potentially bringing about similar results, often hard or even impossible to distinguish. The reliability of the interpretation relies on the ability to determine the cause as well as rule out alternative non-seismic causes. Uncertainty levels should be associated with the interpretations.

This work presents and discusses examples from the Dead Sea fault zone, a plate boundary that accommodates sinistral motion of the Arabia and Sinai tectonic plates (Fig. 1). Archaeoseismic research in this region benefits from several advantages. Humans inhabited or passed through the Middle East since about two million years ago (Braun et al., 1991). People who lived there since the invention of writing as well as pilgrims make it an ideal region for studying historical earthquakes and abundant archaeological remains, many of which are precisely dated, make the use of archaeoseismological methods very appealing and rewarding. An important advantage is the relatively long recurrence intervals, longer than the uncertainty in most dating methods. The fault system is relatively simple, making the identification of the source also simple. The Middle East historical earthquake catalogues are probably complete for the last two millennia. This is demonstrated by the full representation of the reported earthquakes in the seismite record in the Dead Sea sediments and the absence of seismites not correlated to reported earthquakes (Ken-Tor et al., 2001; Migowski et al., 2004).

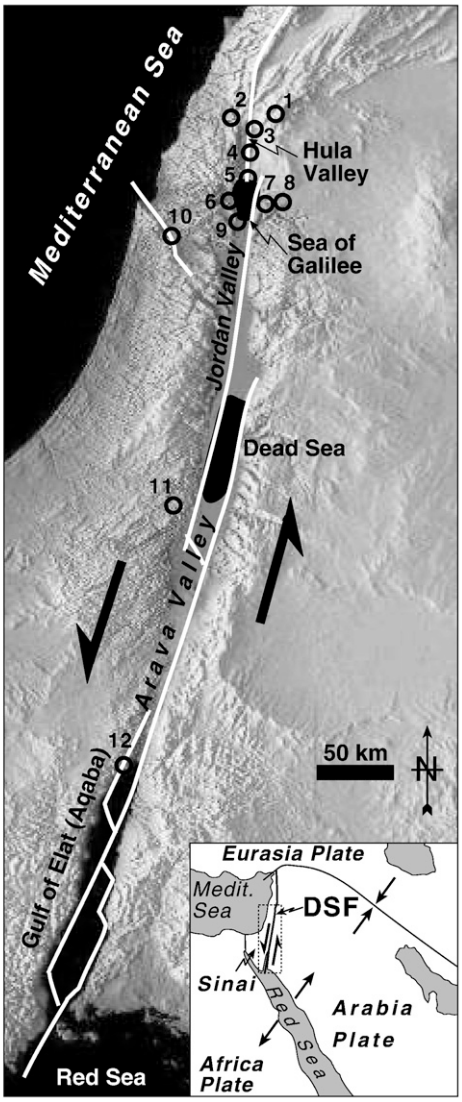

Fig. 1. Location map of sites mentioned in the text. 1—Kal'at Nimrod, 2—Kadesh, 3—Omarit 4—Ateret (Vadum Iacob), 5—Bet Zayda trench study, 6—Tiberias, 7—Sussita, 8—Um el Kanatir, 9—Ohalo, 10—Megiddo (Armageddon), 11—Mampsis, 12—Elat underwater site. Inset: tectonic plates in the Middle East.

Damaged archaeological structures in other seismogenic regions are beyond the scope of this paper but similar principles apply there too.

2. Types of damage

2.1. Fault rupture

The most obvious earthquake damage is the rare cases of faults that intersect archaeological sites and displace the structures. A unique case of two earthquakes that offset a Crusader fortress (2.1 m, Fig. 2A), and an Ottoman mosque that was built on top of the fortress (0.5 m, Fig. 2B), is reported by Ellenblum et al. (1998). Examples of other sites that are offset by faults are reported from Israel (Belitzky and Garfinkel, 2005), Jordan (Klinger et al., 2000; Niemi et al., 2001; Haynes et al., 2006), Iran (Ambraseys and Jackson, 1998), Syria (Meghraoui et al., 2003), Greece (Monaco and Tortorici, 2004), and Turkey (Hancock and Altunel, 1997). The Great Wall of China was offset by the $M \sim 8$, 1739 earthquake and possibly in previous earthquakes as well (Zhang et al., 1986).

A rupture in a structure that is not directly related to faulting is found in Um el Kanatir (Fig. 2C), where a water trough is offset about 1 m by a seismogenetic landslide (Wechsler et al., 2006a). This special case should serve as a cautionary note, meaning that we have to verify a fault before declaring a faulted site. Care should also be taken in the assessment of the long-term slip in cases where the offset structures span only part of the fault zone. In these cases, the observed slip is a minimum, as additional slip may have occurred on other fault strands outside the archaeological site.

Given the precise important information gleaned from offset structures it would be very useful to launch focused archaeological surveys along active faults. Ancient roads, aqueducts, walls, fences etc. potentially record the fault activity, whether they are faulted or unfaulted.

2.2. Sliding of arch blocks

Masonry arches are common in ancient structures, typically used in construction of gates, large windows, bridges, domes and vaults. Arches are made of wedge-shaped blocks, commonly without cement. Keystones that slid downward are common in earthquake-stricken regions. Models of arch failure were developed with large-scale field tests (Boothby et al., 1998), analytical solutions (Blasi and Foraboschi, 1994; Sinopoli et al., 1997), and numerical modeling of dynamic behavior under basal motions or vertical loads (Bicanic et al., 2003; De Luca et al., 2004). The only model that faithfully reconstructs the sliding of blocks of masonry arches is based on dynamic finite element analyses on real cases (Kamai and Hatzor, in press). These authors conclude that only strong earthquakes can induce the sliding of blocks from arches (Fig. 2D). They also discovered that blocks could slide down only if the vertical load on the arch is small. Blocks of arches that originally supported heavy walls above them could slide only after these walls fell. Arches enclosed by different walls on both sides deform asymmetrically, i.e., one or more of the side blocks slides down (Fig. 2E). Otherwise, where similar walls enclose the arch, the keystone slides down (Fig. 2D). Kamai and Hatzor's (in press) dynamic analyses show that this type of damage is an unequivocal result of an earthquake.

2.3. Horizontal shifting of large blocks

Gravity is a trivial factor that is always accounted for in any construction. In contrast, horizontal forces are not common, their action is episodic, and their magnitudes are usually uncertain. If the building was never buried, we can exclude the action of roots and soil flow due to wetting and drying. Hence, only earthquakes can exert forces large enough to overcome friction and displace large heavy blocks by horizontal sliding (Fig. 2F). The shifting is made possible by the vertical component of the earthquake vibrations, which relieves the overburden and reduces the effective friction. It is therefore incorrect to estimate the acceleration required to slide the blocks by measuring the static friction between them.

2.4. Aligned falling of columns

Columns that supported high structures were built either by carving the entire column in a single block or by placing drum-like blocks one on top of the other. In certain cases the drums were reinforced by inserting or casting metal dowels (usually iron with melt lead) in cavities between the drums. In several places we find groups of monolithic columns that fell aligned, all in the same direction (Fig. 2G), or the drum columns that fell with the drums imbricated (Fig. 2H). In the case of Sussita (2G), some of the columns are misaligned with their bases, suggesting two stages of falling. Either they first fell and then rolled, or they first "jumped" in one direction and then fell in another direction. The direction of collapse is not indicative of the direction from which the seismic waves came. This erroneous notion, first made by Mallet (1862) is still used by some modern authors to calculate the position of an epicenter, a practice which has no scientific basis (Ambraseys, 2006). Also, the belief that the direction of fall is parallel with the direction of the near-field ground motion due to strike-slip surface faulting in an earthquake is not necessarily correct (Ambraseys, 2006). The

Fig. 2. Examples of damage in archaeological sites. Locations indicated on Fig. 1. A. An offset wall of the Crusader fortress of Vadum Iacob (in recent time called "Ateret"). Dashed line shows original geometry. The 2.1-m-offset is the sum of 1.6 m and 0.5 m displacement caused by the earthquakes of May 20, 1202 and October 30, 1759 respectively (Ellenblum et al., 1998). Site 4 in Fig. 1. B. An offset wall of the Ottoman Mosque that is built on top of the Crusader fortress of Vadum Iacob. The associated earthquake occurred on October 30, 1759 (Ellenblum et al., 1998). Site 4 in Fig. 1. C. A water trough in Um el Kanatir left-laterally offset about 1 m on the margin of a landslide triggered by the earthquake of January 18, 749 (Wechsler et al., 2004). Site 8 in Fig. 1. D. A keystone slid down in an arch enclosed symmetrically by a wall. Photographed in Mampsis (Kamai and Hatzor, in press). Site 11 in Fig. 1. E. Blocks on the sides of arches on the left slid down in the earthquake of 1759 in Kal'at Nimrod. Throughout the site, arches in walls that trend E–W are deformed whereas similar arches in N–S trending walls have remained intact. Site 1 in Fig. 1. F. Horizontal shift of large ashlars in the Hellenistic temple of Kadesh. Site 2 in Fig. 1. G. Aligned fallen columns of a Late Byzantine church in Sussita (originally called Hippos). An inscription that bears a date of 591 AD in one of the four excavated churches of Sussita it is concluded that the destruction of the site occurred in the 749 earthquake (Segal, 2007). Site 7 in Fig. 1. H. Drums of a column that collapsed in the Roman temple of Omarit. Site 3 in Fig. 1. I. Chipped corners of ashlars in the 13th century Arabic fortress Kal'at Subeiba (now called Kal'at Nimrod), which was hit by the earthquake of 1759. The original joints and fractures in the stones have different orientations. Site 1 in Fig. 1. J. Imbricated arrangement of the western wall of the Um el Kanatir synagogue, which fell westward (right side in the photo). Two earthquakes hit the site in 551 and 749 AD (Wechsler et al., 2006b). This arrangement cannot form where walls collapse by slow protracted deterioration. Site 8 in Fig. 1. K. Collapsed wall of the northern watchtowers of Kal'at Nimrod lay in disarray at the bottom of a steep slope. The large ashlars fell in 1759. L. A deformed, wall in Megiddo, part of a Late Iron Age, 8th century BC building (Marco et al., 2006). Site 10 in Fig. 1. M. Leaning Iron Age II (9th century BC) columns in Megiddo (Marco et al., 2006). The supports at the bottom are modern. Site 10 in Fig. 1. N. An episode of tilting is exhibited by an angle between tilted stone floor and an overlying horizontal plaster floor in Megiddo. The stratigraphy shows that the tilting postdates the lower and predates the upper floor, but the precise time of construction is archaeologically indistinguishable. Both were built in the Iron Age II (9th century BC). Since the upper floor remained perfectly horizontal in the last 3 millennia we assume that the tilting of its precedent was rapid and exceptional, probably associated with an earthquake (Marco et al., 2006). Site 10 in Fig. 1. O. Fractures cross a sector of a Roman (Herodian) theatre and overlaying Byzantine walls together with the underlying bedrock in the Galei Kinneret site, Tiberias. The damage occurred in the earthquake of 749 (Marco et al., 2003). Site 6 in Fig. 1. P. Faulted sediments in the Galei Kinneret site, Tiberias. The time of faulting is constrained by the ages of the walls. The pebbly-sandy sediments abut the wall on the right, which is from the late 7th–early 8th century (Byzantine period). The layers are faulted, and continuous unfaulted beds (above the dashed white line) overlay the fault (white arrow). The foundation of the wall on the left, dated to the late 8th century (early Arabic period), is 1.5 m higher than the foundations of the Byzantine wall foundations. It was excavated (dashed black line) into the post-fault beds (Marco et al., 2003). Site 6 in Fig. 1. Q. An archaeological site in the Gulf of Elat (Aqaba) that includes a circular coral-like wall is submerged 4–5 m below sea level. The fringing coral reef that separates it from the shore is seen in the back (dark). Similar structures are abundant on shore since the domestication of animals some 10 kyrs ago. Because a slow rise of the sea level would result in scattering of the stones by wave action, Shaked et al. (2004) conclude that the site was subsided rapidly to a level below the wave action, most probably in an earthquake. Site 12 in Fig. 1. R. A sequence of lake sediments in the Palaeolithic site of Ohalo, on the southern shore of the Sea of Galilee encloses a 20 ka old living surface (arrow), where delicate artifacts were found in articulation (Nadel et al., 2001). We maintain that the rise of water occurred rapidly, most likely during an earthquake, because slow rise would result in scattering of the delicate materials by wave action. Site 9 in Fig. 1. S. Two earthquakes in one structure: Remains of a single room farmer's house (surrounded by a dashed line) are seen on the floor of an early 6th century synagogue in Um el Kanatir. This peculiar location and the use of stones from the synagogue walls indicate that the farmer built the house after the synagogue collapsed (see picture J). A second destruction event is evident in the farmer's house, where tools and ceramics were found on the floor, buried by the collapsed walls. Site 8 in Fig. 1.

direction of falling depends on the whole structure, in particular the foundations or stylobates and the overlying cornice. Additional factors are imperfections or deliberate damage (i.e., for stealing the dowels).

2.5. Chipping of block corners

Chipped corners (Fig. 2I) may be attributed to protracted wear along pre-existing fractures or joints. Slow penetration of water along the contacts between blocks may facilitate weathering and formation of clay may result in alternating expansion and contraction during wetting and drying respectively. During earthquakes, the warping of walls relives the burden on the outer side of a bend and increases it on the inside. The large pressure, which may be applied on the corners of the blocks, can chip off the block corners. Where the chipping crosses bedding planes, joints, and fractures, and is common to many blocks, it can be considered an earthquake-related deformation.

2.6. Collapsed walls

High quality masoned walls, usually made of large heavy stones that fit tightly to each other with or without cement, characterize many ancient monumental buildings and defense walls. Like in the case of horizontal sliding of blocks, the toppling of such walls requires horizontal forces. The difference is in the final position of the sliding blocks, which in the case of fallen walls moved beyond the stable configuration.

The fallen blocks of walls that were toppled by earthquakes are mutually supported and are in contact with each other. Fine material e.g., eolian or alluvial sand or dust often fills voids and gaps between the blocks. In the case of slow deterioration, some fine material accumulates in the periods between episodes of block falling, limiting or even preventing block contacts. Collapse during earthquakes often results in imbricate arrangements (Fig. 2J) of the blocks whereas slow deterioration forms a disordered, un-oriented arrangement. However, high walls that fall downhill are also disordered (Fig. 2K).

2.7. Deformed walls and floors

Walls, which were built straight and erect, are observed warped in many sites (Fig. 2L). In some places, the walls are inclined toward both sides.

Thick walls, about several tens of centimeters wide, show open vertical fractures between the two outer facets, which bulge outward. This is typical of vertical pressure on the wall. Earthquakes might tilt structures (Fig. 2M), but the possibility of slow deformation should be carefully examined and excluded before accepting the earthquake hypothesis. An angle between

Fig. 2 (*continued*).

tilted floor and an overlying horizontal floor of archaeologically indistinguishable age (Fig. 2N) exhibits an episode of tilting in Megiddo, the site of Armageddon. The tight time interval and the very close bedrock lead Marco et al. (2006) to suggest seismic cause for the tilt. In many places these kinds of deformation cannot be uniquely attributed to earthquakes because differential settling of the ground is likely to produce a similar effect. It is therefore crucial to examine the foundations and rule out non-seismic tilt. Deformation of walls that lay on solid bedrock is most likely seismogenetic.

2.8. Through-cutting fractures

Earthquake-related fractures may be difficult to distinguish from other processes such as differential settlement of building sections and sagging of the ground. Fractures that crosscut structures and extend into solid bedrock on which they are built seem likely to be seismogenic (Fig. 2O). Fractures that cross several blocks and are different with pre-existing fractures in the individual blocks are also likely to have been caused by earthquakes. Interpretation is easier where the buildings are built on solid bedrock because rigid structures that are built on plastic soil are likely to yield by fracturing after several cycles of wetting and drying.

3. Supportive evidence

In addition to structural damage, we should also consider circumstantial and other indirect evidence, which either support or dismiss the seismogenic damage hypothesis.

3.1. Complete destruction of settlements

Historical texts attribute total destruction of ancient cities or villages to several earthquakes. Widespread complete destruction is observed in a few sites, which were left in ruins and never rehabilitated, such as Shivta and Rehovot in the Negev (southern Israel). However, it is difficult to discern earthquake destruction from normal deterioration especially where the quality of construction is poor. Characteristic earthquake damage to individual buildings should be identified and other processes should be excluded before we determine that earthquake was the cause of the destruction. Several settlements in southern Israel, in particular the Nabatean towns, were built of local chalk or soft limestone, which weathers easily. Weathering of the lower building stones cause the collapse of the walls in a manner that might look very similar to earthquake damage.

3.2. Abandonment of affected settlements

Abandonment is expected if the settlement, as well as its environment, were devastated by an earthquake. However, other possible causes should be excluded before an earthquake is assumed. Widespread rebuilding and fixing of damaged structures in a settlement clearly indicates destruction and subsequent return of the citizens and rehabilitation. If the dating is reliable and shows a gap between the destruction and the restoration, we can assume that the place was abandoned for a while.

Preliminary analyses of pollen records from varved Dead Sea deposits show signs of a disaster. Samples from single seasonal laminae above both the 31 BC and the 363 AD earthquake seismites indicate a short-term (a few years) intense impact. The pollen samples are interpreted to show that after both earthquakes cereal fields and olive groves were abandoned (Leroy and Marco, 2006).

3.3. Historical records

Texts and drawings are valuable sources of information on historical events in general and earthquakes in particular. Several catalogues have been compiled for Middle East earthquakes (Ambraseys et al., 1994; Guidoboni et al., 1994; Amiran et al., 1994; Guidoboni and Comastri, 2005; Sbeinati et al., 2005). Problems associated with historical accounts are discussed by several authors (Ambraseys, 1971; Guidoboni et al., 1994; Karcz, 2004). Uncertainties result, for example, from fragmentary accounts, limited to positive reporting and no reports on places where nothing was damaged or felt, amalgamation of two or even more events into a single report, deliberate exaggeration, different calendars and use of relative dating, mis-identification of geographical names, errors in translations and misunderstanding of old languages and terminology. Despite these difficulties, the historical information is extremely useful for independently corroborating archaeological observations. We should make efforts and use primarily credible information from multiple primary sources, which is crosschecked and examined in the light of contemporary context.

3.4. Geological evidence

Palaeoseismic evidence in the form of fault rupture is an easily interpretable form of supporting evidence. For example, the palaeoseismic trench study at the southern end of the Jordan Gorge Fault (Marco et al., 2005) confirms earlier archaeoseismic observations of displaced walls at the northern end of the fault segment (Marco et al., 1997; Ellenblum et al., 1998). Seismites, sediments that were deformed by earthquake shaking, is another form of supportive evidence for the location and local intensity of historical earthquakes (Ken-Tor et al., 2001), provided they can be dated precisely. Other forms of geological seismic indicators include landslides, rockfalls, and liquefaction associated with archaeological artifacts (Guccione, 2005). Tsunami deposits that are associated with archaeological sites along the coast as well as artificial reservoirs that were filled by sediments, which were deformed by earthquakes. The age of sediments that accumulate in multi-layered archaeological sites can be constrained tightly by applying archaeological and historical knowledge (Fig. 2P).

In special cases tree rings record earthquake-triggered disturbance to the roots or breakage of branches (Jacoby, 1997; Lin and Lin, 1998; Wells et al., 2001).

3.5. Absence of weapons

Destruction because of a violent conflict may appear very similar to earthquake-triggered collapse. The walls collapse upon living surfaces, people flee from their homes leaving their valuables behind, and even aligned falling of columns may result from deliberate destruction. Probably the main difference is the conspicuous presence of arrowheads, spears, etc.

Fire may be associated with earthquakes where thatched roofs, fabrics, and wooden beams were common. Ovens and fireplaces are active continuously even in dwellings of nomadic peoples of our time.

3.6. Burial of living surfaces

Bodies of humans and domesticated animals and valuable artifacts, which are found beneath collapsed ceilings, indicate a sudden unexpected destruction, typical of earthquakes. Burial of dead people or killing of people might mislead the interpretation. Therefore, a careful search for signs of deliberate execution or ceremonial burial is required. Crushed skeletons that were found in numerous sites in the Mediterranean region under fallen walls illustrate how people were caught by surprise (Nur and Cline, 2000).

3.7. Subsidence of living surfaces

Archaeological sites that are submerged in water bodies (lakes or sea) exhibiting only minor or no damage may indicate rapid subsidence, the kind observed in many modern earthquakes. The alternative interpretation of submergence by rise of water level should be examined considering the slow rate of this process. Wave action would destroy or damage delicate structures during slow rise of lake or sea levels. In contrast, rapid subsidence of the shore to levels below the destructive power of waves would preserve the site. Subsequent sedimentation might bury the structures. Fig. 2Q and R shows two examples.

3.8. Multiple events and temporal correlation

In archaeological sites that are rich in indicative coins, ceramics and other artifacts it is possible to determine the age very precisely. Temporal correlation with reported historical earthquakes can provide time series of events. An example is found in Um el Kanatir, where an early 6th century synagogue walls collapsed westward (Fig. 2J) along with aligned columns (Fig. 2S). This type of collapse may be attributed to earthquakes. After the collapse, a farmer used the stones from the walls to build a small house on the synagogue floor. The farmer's house also collapsed, but toward the east. Typical farming tools were found on its floor as well as in the synagogue's archive below the floor. Abundant indicative ceramics in the farmer's house is dated up to the middle of the 8th century AD, which according to the historical earthquake catalogues constrains the latter of the two earthquakes to that of 749 AD. The earlier event is constrained to pre-749 and post-early 6th century. The most likely earthquake is that of 551 AD (Wechsler et al., 2006b).

4. Implications to earthquake record

How the archaeoseismic data improve the quality of the earthquake record in the Levant is clearly documented by the following examples.

Verification of historical accounts is provided by the findings in Um el Kanatir (Site 8 on Fig. 1) and Tiberias (Site 6) and in Vadum Iacob (Site 4). Damage associated with the 551 AD and the 749 AD earthquakes was identified in Um el Kanatir, and rupture of the 749 earthquake was identified in Tiberias (Marco et al., 2003; Wechsler et al., 2006a). In Vadum Iacob, several structures that were faulted during the 1202 and 1759 earthquakes have been unearthed (Marco et al., 1997; Ellenblum et al., 1998). The archaeoseismic findings in Tiberias together with palaeoseismic observations north of the Dead Sea (Reches and Hoexter, 1981) constrain the 749 AD rupture length to about 100 km. The historical data show that the rupture is located approximately at the centre of the maximum damage zone (Marco et al., 2003).

Because of the uncertain reliability of historical records, the crosscheck provided by archaeological data is essential. An example of careful treatment of the historical accounts of the earthquakes of 20 May 1202 and 30 October 1759 is provided by isoseismal maps compiled for these events (Sieberg, 1932; Ambraseys and Melville, 1988; Ambraseys and Barazangi, 1989). Later archaeoseismic work on offset walls (Marco et al., 1997; Ellenblum et al., 1998) confirms the history-based locations and magnitudes and additional corroboration comes from subsequent palaeoseismic trench studies (Daëron et al., 2005; Marco et al., 2005). These examples justify the use of historical macroseismic data for constraining the ruptures of the associated earthquakes.

Evidence of subsidence in Ohalo by the Sea of Galilee (Nadel et al., 2001) and at the Gulf of Elat (Aqaba) (Shaked et al., 2004) prove the recent persistence of the long-term style of deformation. The sites, which are located within two basins, show earthquake-related subsidence, in accordance with the tectonic setting.

Hence, a multi-disciplinary research based on historical-, archaeo- and palaeoseismological data on past earthquakes will ultimately facilitate the development of a reliable picture of the spatial-temporal distribution of earthquakes in the Levant.

5. Conclusions

The combination of active seismicity and long architectural history of the Levant offers a wealth of earthquake-related damage in archaeological sites. The identification of the causes for damage depends on our ability to recognize features that are uniquely associated with earthquakes as well as features that preclude other processes of slow deterioration or human-caused damage to structures. Comparing models of static versus dynamic cyclic loading is a robust tool. It should be developed further and applied for analysis of various types of observed damage. Archaeological and historical information together are often more accurate then radiometric dating. Geological information, mostly on- and off-fault palaeoseismic data, should be considered for mutual testing of the archaeological information. In places where faults intersect with archaeological sites, offset structures enable precise determination of time, sense and amount of slip. Characteristic off-fault damage types include horizontal shifting of large building blocks, downward sliding of one or several blocks from masoned arches, collapse of heavy, stably-built walls, chipping of corners of building blocks, and aligned falling of walls and columns. Other damage features are less conclusive and require additional supportive evidence, e.g., fractures that cut across several structures, leaning walls and columns, warps and bulges in walls. Hence, the synergetic use of archaeology, history, engineering, and geology is the key to successful reliable interpretations.

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