The Kinematics of the 1033 A.D. Earthquake Revealed by the Damage at Hisham Palace (Jordan Valley, Dead Sea Transform Zone)

by L. Alfonsi, F. R. Cinti, and G. Ventura

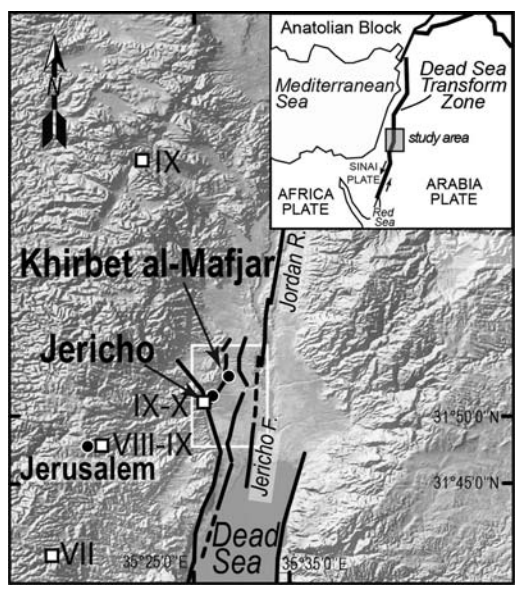
INTRODUCTION

The reconstruction of the seismic history of an archaeological site is generally based on historical sources and/or archaeoseismological data. However, these data alone give, in most of the cases, only qualitative information and cannot be used to unequivocally recognize the kinematics of past earthquakes and causative fault. A multidisciplinary approach merging archaeological information and geological data is useful to better constrain the age of past earthquakes, identify the fault movement(s), and clarify the seismotectonic picture of a region. The Hisham palace (724–743 A.D. to about 1400 A.D.; Baramki, 1936, 1938; Whitcomb, 1988), which is the main building of the Khirbet al-Mafjar archaeological site (Jordan Valley), records damages related to past seismic shaking. The site is located within the tectonically active Dead Sea Transform zone in the western Jordan Valley, and it is one of the most famous so-called desert castles of the early Islamic period (Fig. 1). The 749 A.D. earthquake, for which the macroseismic epicenter is unknown, is identified as responsible for the severe damage at Hisham palace (Amiran *et al.*, 1994). However, a relatively low (VII degree) macroseismic intensity is assigned at Hisham palace for this event, and surface-faulting evidence has been found about 100 km north of Khirbet al-Mafjar (Marco *et al.*, 2003). Another earthquake that occurred in the area could also have left traces on the palace architecture, that is, the 1033 A.D. event (Table 1, Fig. 1).

Here, we bring together and analyze new coseismic data from field survey and historical pictures, critically revise the deformation pattern from literature, and review the seismological insights from archaeological excavations. Khirbet al-Mafjar also preserves evidence of surface faulting, a rare and exceptional feature in archaeological sites. The collected data and results allow us to (1) identify the earthquake responsible for the damage at Hisham palace, (2) recognize the possible seismogenic structure and its kinematics, (3) contribute to the reconstruction of the past historical seismicity affecting the area during the palace occupation, and (4) improve the knowledge of the seismotectonic setting of the Jordan Valley.

GEOLOGICAL SETTING

The Dead Sea Transform zone (Fig. 1) is about 1100 km long, a north–south striking, left-lateral fault system representing the active boundary between the Arabian and African plates (Garfunkel *et al.*, 1981). The north–south striking Jericho fault belongs to this system and runs along about half the length of the Dead Sea Basin in its middle part. On land, the fault affects the central sector of the Jordan Valley (Gardosh *et al.*, 1990). The Jericho fault, which cuts Holocene terrains, is characterized by prevailing strike-slip movements with minor extensional and compressive components (Reches and Hoexter, 1981). In the Jordan Valley, Global Positioning



▲ **Figure 1.** Geodynamic setting (inset) and schematic map of the Dead Sea fault system in the Jericho Valley. Macroseismic intensity of the 1033 A.D. earthquake occurred in the Khirbet area (data from Guidoboni and Comastri, 2005). Location of the archaeological site and of main fault traces is reported. The white square delimits the area shown in Figure 6.

doi: 10.1785/0220130060

Table 1
Macroseismic Evidences of the 749 A.D. and 1033 A.D. Earthquakes in Palestine

Date	Location	Description	References
18 January 746–749	Palestine	Destruction of Tiberias, Damascus, and Beit-Shean, the spring of water which was by Jericho moved six miles. The destruction of Khirbet al-Mafjar has been correlated with this event (1). This destruction has been dated from ceramics found at the site (2). The whole set of damage is not resulting of a single earthquake as commonly acquainted, but from at least three sizeable events during 746–757 A.D. (3). First event in Palestine on 18 January 746 affected Jordan and Syria (Tiberias, Kinnereth faulting extending north and south for about 100 km). Second event on 749 A.D. or early 750 affecting Syria and Mesopotamia. Of the third on 9 March 757 little is known, described as one of some size affecting Palestine and Syria and effects on Jerusalem.	(1) Russell, 1985 (2) Baramki, 1942 (3) Ambraseys, 2009
18 January 749	Palestine	Damage field from Damascus, Baalbek, to Mt Tabor, Jerusalem, spring near Jericho moved six miles out of its place (4).	(4) Guidoboni *et al.*, 1994
5 December 1033–4 January 1034	Ramla	Much of the damages were sustained in Ramla, Nablus, Baniyas, and Jericho. Jericho sustained equally heavy damage, with loss of life. What was left damaged was demolished by the inhabitants. Tiberias mountains moved as sheep. In Nablus half of the buildings collapsed killing about 300 people. Source reports the collapse of Jericho. Probable source location at sea (1).	(1) Ambraseys, 2009
5 December 1033	Israel Palestine	Jericho (IX–X), Ramla (IX), Nablus (IX), Jerusalem (VIII–IX), Hebron (VIII), Acre (VIII–IX), Tiberias (VII–VIII), Baniyas (VII–VIII), Ascalon (VII–VIII), and Gaza (VI–VII). Eight days of shocks at Ramla, city abandoned, one third of Ramla razed to the ground. Jericho and its inhabitants were swallowed up, same for Nablus and near villages. The epicenter located in the Judaea mountains, between Ramla, Jericho, and Nablus. M_e 6.0, Io = IX (2).	(2) Guidoboni and Comastri, 2005

Descriptions of effects and damages of the 749 and 1033 A.D. earthquakes from the cited references and reported to have produced effects at the Khirbet al-Mafjar site and surroundings.

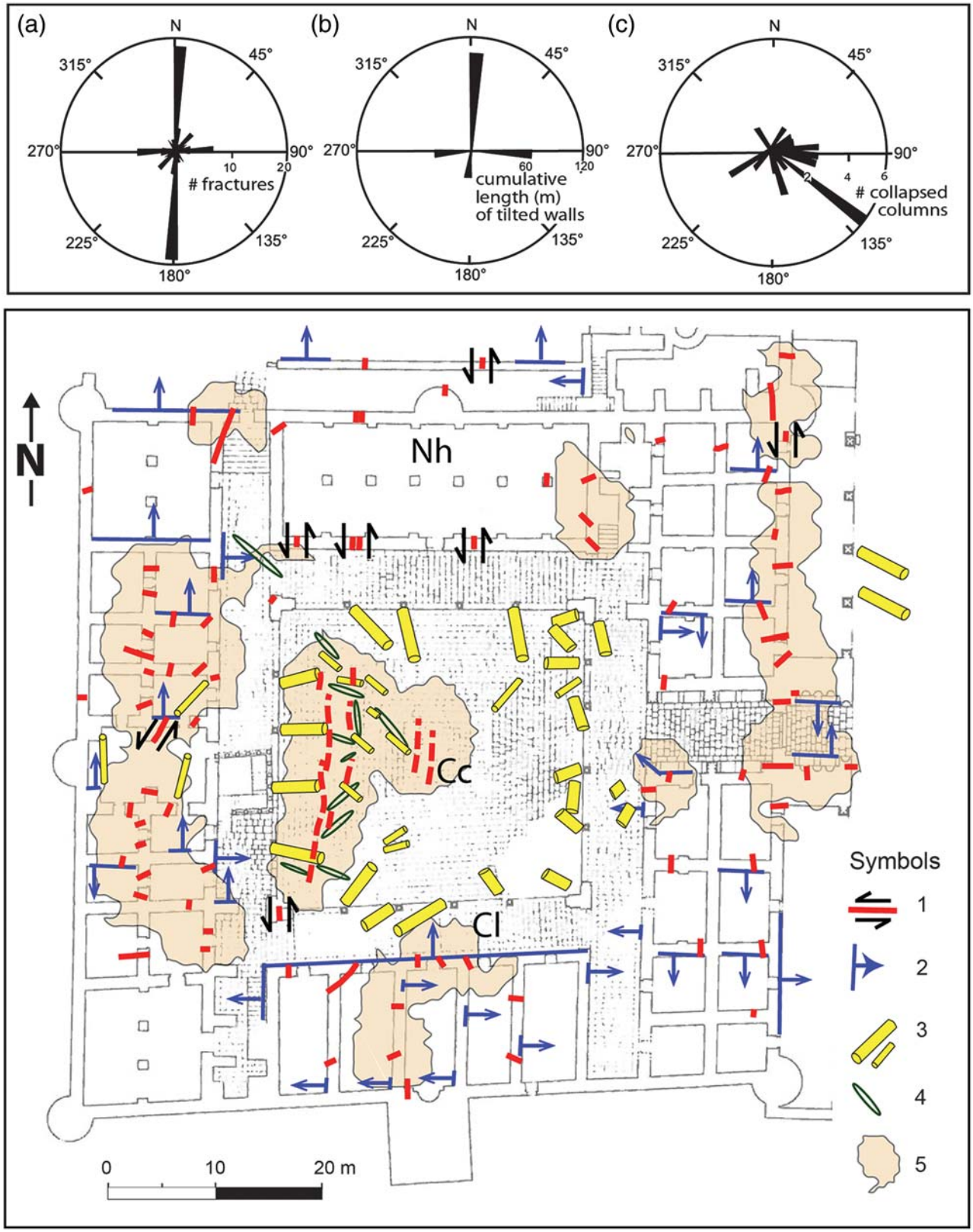
System (GPS) data by Wdowinski *et al.* (2004) show present-day left-lateral slip rates of 3.7 ± 0.4 mm/yr.

Available focal mechanisms of earthquakes occurring in this area are consistent with a strike-slip stress regime with sub-horizontal $\sigma 1$ and $\sigma 3$ striking northwest–southeast and northeast–southwest, respectively (Hofstetter *et al.*, 2007). The 1927 M_L 6.2 earthquake is the most recent event that caused damage and casualties in the Jericho settlement (Avni *et al.*, 2002), and large-magnitude seismic events are documented in historical times (Guidoboni *et al.*, 1994; Ambraseys, 2009).

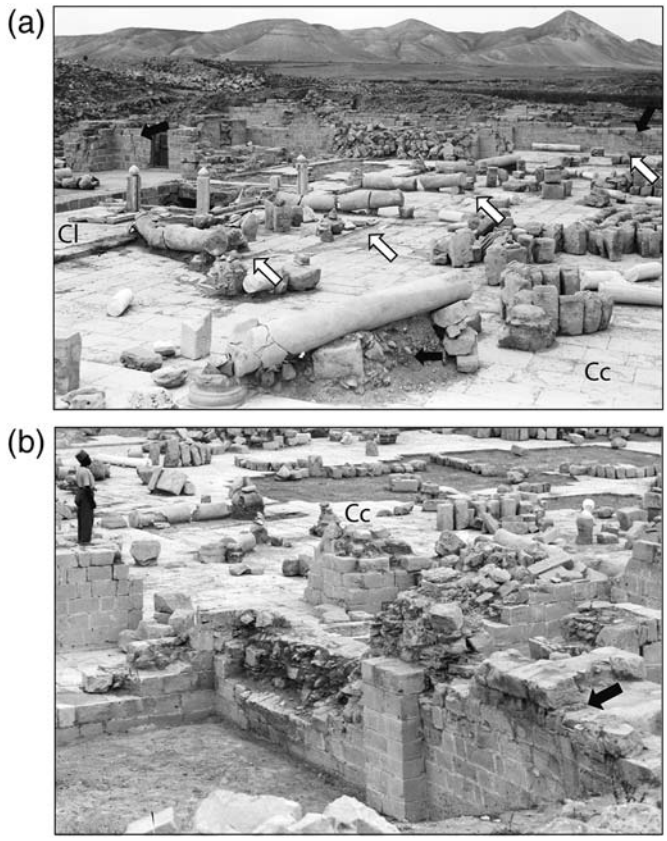
Field data and available seismic lines show north–south to north-northeast–south-southwest-striking subvertical faults bounding the eastern edge of the uplifted Jericho block (Fig. 1; Lazar *et al.*, 2006). The Khirbet al-Mafjar archaeological site is located 3 km north of Jericho in a relatively flat area of the Jordan syntectonic sedimentary wedge.

DAMAGE AND FAULTING AT KHIRBET AL-MAFJAR

The Hisham palace is an Umayyad two-storey building with an almost regular squared plan and a court (Fig. 2d; Hamilton, 1959). The whole structure is built of two facing walls of calcarenite and limestone ashlar masonry with rubble filling. The first floor, collapsed and nowadays removed, was a replica of the ground floor. We executed a field survey and new damage recognition at the palace, also positioning images of the thirties (Fig. 3a,b; Matson and Matson, 1934–1939; Baramki, 1936, 1937, 1938, 1942). Coseismic elements such as tilted structures, displaced walls and pavements, and colonnade failure are summarized in Figure 2d, in which about 70% of the data points are original from this study, and 30% are merged from previous analyses (Karcz and Kafri, 1981; Reches and



▲ **Figure 2.** Rose diagrams of (a) strike of fractures, (b) direction of tilting versus cumulative length of titled walls, and (c) direction of column collapse. (d) Map of the surveyed coseismic effects at Hisham palace (Khirbet al-Mafjar site). Original plan of the palace is modified from Hamilton (1959). Nh, North hall; Cc, Central court; Cl, Cloister; 1, crack and fault; black arrow, direction of movement; 2, tilting and warping of wall (arrow toward the direction of movement); 3, column of the ground floor (larger symbol) and of the first floor (smaller symbol); circle, column top; 4, deformation of floor (sunk and pop-up); 5, fracture density (>1/8 m^2).



▲ **Figure 3.** Pictures from Matson and Matson (1934–1939) showing the ruins of the palace as appeared during Baramki excavation. (a) View of the central court from the south: white arrows, fracture alignments along the pavement structure; black arrows, debris lying under the collapsed columns. Widespread tumbles and column failures are exposed. (b) Tilted bearing wall a meter wide, the black arrow indicates the direction of inertial wall movement (view from northwest).

Hoexter, 1981). The observed damage defines a severe earthquake scenario. Most of the brittle structures affect the supporting and divisor walls (Figs. 2 and 4a,b). These structures are faults and open cracks with dip generally > 50° and width up to 20 cm. The faults offset archaeological structures with left-lateral slips up to 10 cm. Some structures with mixed shear (sinistral)-opening mode have also been recognized (Fig. 4b). In the western portion of the pavement of the central court, roughly north–south striking cracks and vertical deformations occur (Fig. 3). The flagstones are deformed in a pop-up-like array. These deformations have a linear continuity of about 30 m and align to the faults and shear-opening structures affecting the walls of the north and south cloister (Fig. 2). The fractures at Hisham palace have a preferred north–south strike and a second-order east–west strike (Rose diagram in Fig. 2a). Fracture density (shaded pale orange areas in Fig. 2d) evidences two roughly north–south elongated subparallel areas located on the western side of Hisham palace, and one, also north–south elongated, on the eastern side. Fifty meters north of the north hall area, we observed a 6 m wide shear zone consisting of high-angle fractures and faults exposed on the northern wall of an archaeological trench (Fig. 4c). The vertical displacement across this zone is of the order of tens of centimeters. No data are available to strictly constraint the age of faulting. The plaster and the drainage channel close to the trench wall are affected by fracturing aligned with the deformed zone (Fig. 5).

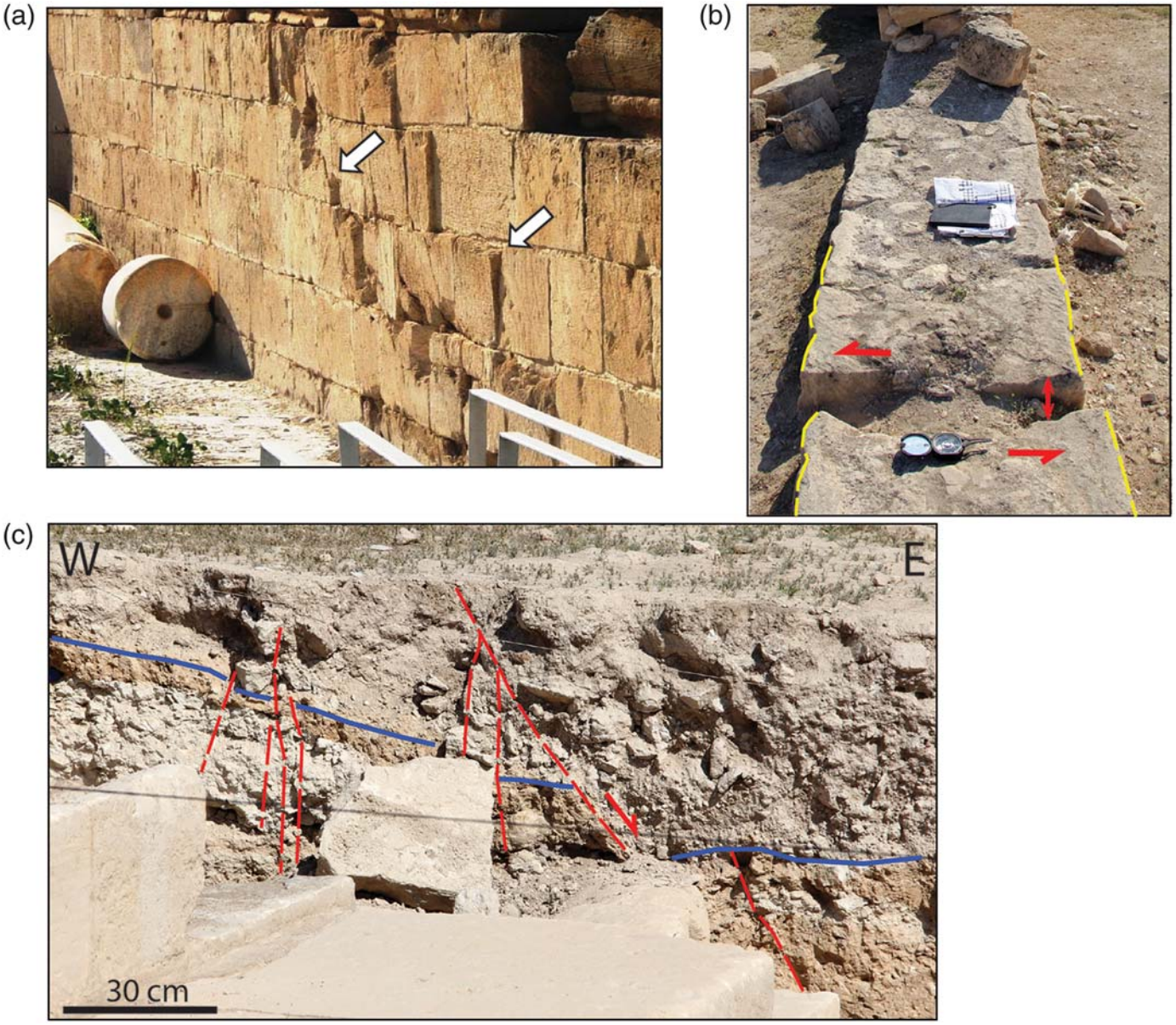
Several walls are tilted and/or warped up to 15° (Figs. 2 and 3b). Rose diagram in Figure 2b shows the cumulative length of tilting, for which the preferred sense is north. The occurrence of this preferred sense of tilting confirms the seismic nature of the observed damage (Paz, 1997). A human skeleton found in a room facing the east cloister under debris of an arch that collapsed in 1000–1400 A.D. could be also indicative of seismic shaking (Baramki, 1938).

The overall position of the failed columns has been reconstructed from original reports and pictures and it is reported in Figure 2. Most colonnade collapses cluster mainly toward the southeastern quadrant (Rose diagram in Fig. 2c). The direction of column failure is due to the traction effect of the first-floor collapse.

EARTHQUAKE TIMING

The archaeological data testify to an uninterrupted occupancy from eighth century until 1000 A.D. of the Hisham palace (Whitcomb, 1988). Therefore, if earthquakes occurred in this time period, the effects should not have implied a total destruction with consequent occupancy contraction or abandonment. Toppled walls and columns in the central court cover debris containing 750–850 A.D. old ceramic shards (Whitcomb, 1988). Recently unearthed collapses north of the court confirm a widespread destruction after the eighth century (Jericho Mafjar Project, The Oriental Institute at the University of Chicago http://www.jerichomafjarproject.org, last accessed January 2013). These elements support the action of a destructive shaking event at the site later than the 749 A.D. earthquake. The two well-constrained, major historical earthquakes recognized in the southern Jordan Valley are the 749 and 1033 A.D. (Table 1; Marco *et al.*, 2003; Guidoboni and Comastri, 2005). We assign an IX–X intensity degree to the here-recorded Hisham damage, whereas a VII degree has been attributed to the 749 A.D. earthquake at the site (Marco *et al.*, 2003). Furthermore, Whitcomb (1988) defines an increment of occupation of the palace between 900 and 1000 A.D. followed by a successive occupation in the 1200–1400 A.D. time span. On the basis of the above, and because no pottery remains are instead associated with the 1000–1200 A.D. period at Hisham palace (Whitcomb, 1988), we suggest a temporary, significant contraction or abandonment of the site as consequence of a severe destruction in the eleventh century.

We propose the 1033 A.D. earthquake as the causative event for the Hisham destruction, also according with the known macroseismic pattern (Fig. 1; Guidoboni and Comastri, 2005). This event provoked heavy damage with loss of life and

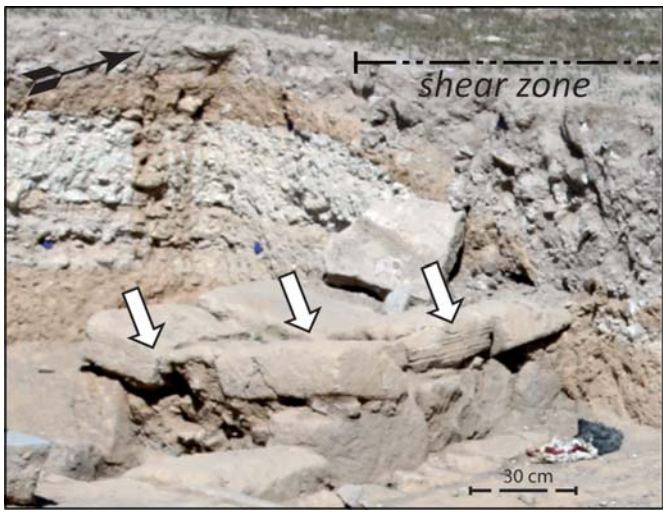


▲ **Figure 4.** (a) Closely spaced faults with 10 cm left-lateral slips crossing the east–west-oriented bearing wall of the North hall (view from southeast). (b) Mixed Mode I–II (open-shear) fracture of an east–west-striking bearing wall (view from west). (c) Part of a 6 m wide shear zone consisting of >50° dipping north–south-striking fractures and faults (in red) outcropping on the north wall of an archaeological trench. Blue lines allow the eye to identify the displaced flood-related deposits. View from south.

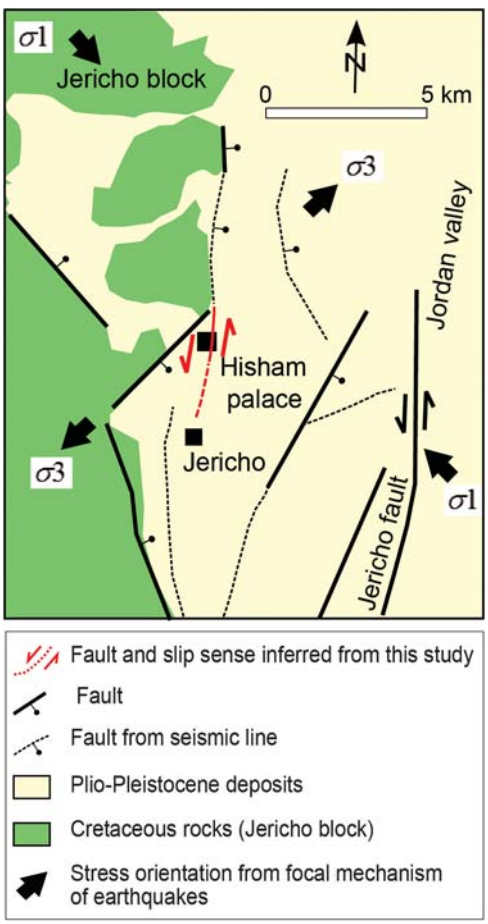
collapses at Jericho (Ambraseys, 2009), which is only 3 km from Hisham. The scenario related to this earthquake is fully consistent with the one we reconstructed at Hisham palace.

SEISMOTECTONIC CONSIDERATIONS

The preferred sense of tilting of the Hisham walls and the colonnade-collapse direction indicate, according to structural dynamic models by Paz (1997) and Hinzen (2009) on inelastic inertial structures, a ground shaking by seismic waves coming from the northern quadrant. Although the cause of most of the earthquake-induced damage at Hisham palace is ground shaking, some of the mapped features have a clear tectonic origin. These features include the occurrence of (a) left-lateral faults, (b) north–south- to north-northeast–south-southwest-striking fractures and cracks, (c) aligned fractures up to 30 m long crossing the whole palace formed during the 1033 A.D. earthquake, and (d) a 6 m wide north–south- to north-northeast–south-southwest-striking shear zone affecting the ground. All these data define a syn- and post-1033 A.D. brittle deformation zone. This zone may represent the southern prolongation of the north–south-striking, subvertical fault recognized by field and seismic data (Fig. 6). This fault accommodates the deepening of the Jericho syntectonic sedimentary basin. The



▲ **Figure 5.** Drainage channel in the northern section of the site affected by fracturing closely aligned with the shear zone outcropping along the northern trench edge (view from southeast).



▲ **Figure 6.** Structural sketch map and stress-field configuration in the Hisham palace surroundings (data from Hofstetter *et al.*, 2007, and Lazar *et al.*, 2006). Red line and arrows represent the coseismic rupture and slip related to the 1033 A.D. event inferred from this study.

prevailing left-lateral slips we recognize at Hisham palace along north–south- to north-northeast–south-southwest-striking structures are fully compatible with the strike-slip stress regime of the Jordan area of the Dead Sea fault system, which is characterized by a northwest–southeast subhorizontal $\sigma 1$ (Fig. 6; Hofstetter *et al.*, 2007). As a result, we conclude that the 1033 A.D. earthquake originated within this stress field.

CONCLUSIONS

Khirbet al-Mafjar provides the rare opportunity to study the combined effects of seismic shaking and tectonics on an archaeological site, and to interpret these effects within a coherent seismotectonic setting. The damage scenario at Hisham palace is mostly produced by a single, strong earthquake as derived from the archaeological and field data. The damage at Hisham indicates a minimum IX–X intensity degree for the destructive event. This, when combined with the archaeological stratigraphy, converge to the 1033 A.D. event as the cause of the severe and widespread damage at Hisham palace. The event occurred in an area located north of Jericho and Khirbet al-Mafjar and the probable causative fault is north–south- to north-northeast–south-southwest-striking, with left-lateral strike-slip kinematics, extending north of Hisham. The fault kinematics at Hisham is fully consistent with the strike-slip stress regime acting at regional scale in the southern Jordan Valley.

ACKNOWLEDGMENTS

We are grateful to the Italian archaeological mission to Jericho (University La Sapienza, Rome) for onsite logistics and discussions. The manuscript also benefited from discussions with L. Cucci and A. Tertulliani (Istituto Nazionale di Geofisica e Vulcanologia, [INGV]) and A. Pizza (Civil Protection Department, Italy). G. V. is supported by the International Year of Planet Earth, United Nations Educational, Scientific and Cultural Organization (IYPE-UNESCO) project Creep.

REFERENCES

Ambraseys, N. N. (2009). *Earthquake in the Mediterranean and in the Middle East: A Multidisciplinary Study of Seismicity up to 1900*, Cambridge University Press, New York, 968 pp.

Amiran, D. H. K., E. Arieh, and T. Turcotte (1994). Earthquakes in Israel and adjacent areas: Macroseismic observations since 100 B.C.E., *Isr. Explor. J.* **44,** 260–305.

Avni, R., D. Bowman, A. Shapira, and A. Nur (2002). Erroneous interpretation of historical documents related to the epicenter of the 1927 Jericho earthquake in the Holy Land, *J. Seismol.* **6,** no. 4, 469–476.

Baramki, C. C. (1936). Excavation at Khirbet el Mefjer, *Q. Dep. Archaeol. Palest.* **5,** 132–138.

Baramki, C. C. (1937). Excavation at Khirbet el Mefjer, *Q. Dep. Archaeol. Palest.* **6,** 157–168.

Baramki, C. C. (1938). Excavation at Khirbet el Mefjer, *Q. Dep. Archaeol. Palest.* **8,** 51–53.

Baramki, C. C. (1942). Excavation at Khirbet el Mefjer, *Q. Dep. Archaeol. Palest.* **8,** 153–159.

Gardosh, M., Z. Reches, and Z. Garfunkel (1990). Holocene tectonic deformation along the western margin of the Dead Sea, *Tectonophysics* **180,** 123–137.

Garfunkel, Z., I. Zak, and R. Freund (1981). Active faulting in the Dead Sea rift, *Tectonophysics* **80,** 1–26.

Guidoboni, E., and A. Comastri (2005). *Catalogue of Earthquakes and Tsunamis in the Mediterranean Area from the 11th to the 15th Century*, Istituto Nazionale di Geofisica e Vulcanologia, Storia Geofisica Ambiente (INGV-SGA), Bologna, Italy, 1037 pp.

Guidoboni, E., A. Comastri, and G. Traina (1994). *Catalogue of Ancient Earthquakes in the Mediterranean Area up to the 10th Century*, Storia Geofisica Ambiente (SGA) editorial production.

Hamilton, R. W. (1959). *Khirbat al-Mafjar: An Arabian Mansion in the Jordan Valley*, Oxford Clarendon, Oxford, 352 pp.

Hinzen, K. G. (2009). Sensitivity of earthquake-toppled columns to small changes in ground motion and geometry, *Isr. J. Earth Sci.* **58,** nos. 3–4, 309–326, doi: 10.1560/IJES.58.3-4.309.

Hofstetter, R., Y. Klinger, A. Q. Amrat, L. Rivera, and L. Dorbath (2007). Stress tensor and focal mechanisms along the Dead Sea fault and related structural elements based on seismological data, *Tectonophysics* **429,** 165–181, doi: 10.1016/j.tecto.2006.03.010.

Karcz, I., and U. Kafri (1981). Studies in archeoseismicity of Israel: Hisham's palace, Jericho, *Isr. J. Earth Sci.* **30,** 12–23.

Lazar, M., Z. Ben-Avraham, and U. Schattner (2006). Formation of sequential basins along a strike–slip fault—Geophysical observations from the Dead Sea basin, *Tectonophysics* **421,** 53–69.

Marco, S., M. Harta, N. Hazan, L. Lev, and M. Stein (2003). Archaeology, history, and geology of the A.D. 749 earthquake, Dead Sea transform, *Geology* **31,** 665–668.

Matson, G. E., and E. Matson (1934–1939). Photograph Collection, Library of Congress, Prints and Photograph Division, http://www.loc.gov/pictures/collection/matpc/ (last accessed December 2012).

Paz, M. (1997). *Structural Dynamics: Theory and Computation*, Chapman and Hall, London, United Kingdom, 650 pp. ISBN-13: 9780412074615.

Reches, Z., and D. F. Hoexter (1981). Holocene seismic and tectonic activity in the Dead Sea, *Tectonophysics* **80,** 235–254.

Russell, K. E. (1985). The earthquake chronology of Palestine and northwest Arabia from the 2nd through the mid-8th century A.D., *Bull. Am. School Oriental Res. Jerusalem* **260,** 37–60.

Wdowinski, S., Y. Bock, G. Baer, L. Prawirodirdjo, N. Bechor, S. Naaman, R. Knafo, Y. Forrai, and Y. Melzer (2004). GPS measurements of current crustal movement along the Dead Sea fault, *J. Geophys. Res.* **109,** B05403, doi: 10.1029/2003JB002640.

Whitcomb, D. (1988). Khirbet al-Mafjar reconsidered: The ceramic evidence, *Bull. Am. School Oriental Res. Jerusalem* **271,** 51–67.

L. Alfonsi
F. R. Cinti
G. Ventura
Istituto Nazionale di Geofisica e Vulcanologia
Via di Vigna Murata 605
00143 Roma, Italy
francesca.cinti@ingv.it