Pergamon

PII: S0264-3707(96)00041-5

J. Geodynamics Vol. 24, Nos 1–4, pp. 11–20, 1997

0264-3707/97 $17.00+0.00

817-YEAR-OLD WALLS OFFSET SINISTRALLY 2.1 m BY THE DEAD SEA TRANSFORM, ISRAEL

SHMUEL MARCO,[1,2] AMOTZ AGNON,[2] RONNIE ELLENBLUM,[3] AMIR EIDELMAN,[2] URI BASSON[4] and ADRIAN BOAS[5]

[1] Geological Survey of Israel, Jerusalem, Israel
[2] Institute of Earth Sciences, Hebrew University, Jerusalem, Israel
[3] Department of Geography, Hebrew University, Jerusalem, Israel
[4] Geosense Ltd, Tel Aviv, Israel
[5] Israel Antiquities Authority, Jerusalem, Israel

(Received 2 November 1995; accepted in revised form 10 October 1996)

Abstract—Archeological excavations in the Crusader Ateret Fortress near the Jordan River exposed E–W trending walls displaced sinistrally up to 2.1 m by the Dead Sea transform fault. A water duct, probably of Crusader age, is also offset sinistrally across the fault by about 1–2 m, but newer water ducts parallel to the former one show no displacement. The maximum width of the fault zone is about 10 m.

Post-Crusader structures show significantly less deformation, and together with the low seismic activity, suggest there has been negligible creep. It is therefore conceivable that in this particular fault segment, stress is occasionally relieved by strong destructive earthquakes associated with surface ruptures. Historical accounts include descriptions of post-Crusader earthquakes in the northern part of Israel in A.D. 1202, 1546, 1759, and 1837. These events caused destruction and casualties over large areas. We conclude that most of the displacement of the Ateret Fortress walls occurred during one of these strong earthquakes, probably that of 1202 A.D., and some additional offset occurred during subsequent events. The associated magnitude is estimated at 6.5–7.1.

The Ateret site is extremely valuable for paleoseismic studies in general, and assessment of seismic hazard to nearby population centers in particular, as there is an abundance of well-dated man-made structures and a small number of candidate earthquakes. © 1997 Elsevier Science Ltd

INTRODUCTION

Accounts of earthquake-induced surface ruptures along the Dead Sea transform fault zone are rare (Amiran, 1951; Ambraseys and Melville, 1988; Ben-Menahem, 1991; Amiran *et al.*, 1994), and some of them might be unreliable (Karcz and Kafri, 1978; Ambraseys and Karcz, 1992). Here we report the first evidence for a historical sinistral surface rupture. It was discovered during archeological excavations that began in 1994 in the Ateret Crusader Fortress, where E–W trending walls are displaced sinistrally 2.1 m by a N–S fault, and younger Muslim structures are displaced by about 0.2 m.

The Ateret Fortress is located on the active Jordan Gorge Fault, a straight segment of the Dead Sea transform between the Sea of Galilee and the Hula Valley. It was established by the Crusaders in 1178 A.D. on the western bank of the Jordan River, just south of the Benot Ya'akov bridge (Fig. 1A). Its construction terminated 11 months later due to an Arab conquest.

The Dead Sea transform forms a boundary between the Sinai and the Arabia plates (Fig. 1B). South of the Sea of Galilee the transform offsets 105 km sinistrally a variety of pre-Miocene to Early Miocene geological features (Quennell, 1956; Freund *et al.*, 1968). Recent activity along the transform is manifested by deformation of Pleistocene rocks, and by historical and current seismicity.

The trace of the Dead Sea transform is discontinuous and contains bends (Fig. 1B). Pull-apart grabens form between overlapping left-stepping jogs, for example, Hula Valley, and push-up swells form at right-stepping jogs (e.g., Rosh Pina saddle (Garfunkel, 1981)). Previous studies in the area (Picard, 1963; Picard and Golani, 1965; Belitzky, 1987; Heimann and Ron, 1987; Harash and Bar, 1988; Goren-Inbar and Belitzky, 1989; Rotstein and Bartov, 1989; Heimann and Ron, 1993) show that the Pleistocene sediments and basalts in the Benot Ya'akov Bridge area are strongly deformed and the geometry of the faults has changed with time. The Jordan Gorge has been proposed as a 'morphotectonic junction' and 'the epicentre area of strong earthquakes' (Harash and Bar, 1988).

Historical accounts include descriptions of post-Crusader earthquake-induced damage in the northern part of Israel in A.D. 1202, 1546, 1759, and in 1837 (Amiran *et al.*, 1994). The events caused destruction and casualties in the cities of Tiberias (Fig. 1B) and Baalbek (on the Yammouneh fault, some 100 km north from Ateret) and their vicinities (Amiran *et al.*, 1994). Current seismicity in the study area is subdued relative to adjacent areas (the Kinneret and Hula segments) of the Dead Sea transform (IPRG, 1983–1995; Shapira and Feldman, 1987). Salamon (1993) suggested that the plate boundary in this region becomes diffuse because the displacement is divided among several branching faults and partly accommodated by underthrust belts (Kashai and Crocker, 1987; Walley, 1988; Chaimov and Barazangi, 1990). Sparse microseismicity is distributed across the plate margin. The largest event in the last 15-year record is an M_L 4.3 earthquake in the Hula Valley just north of Ateret. Focal plane solutions show mainly sinistral motion with a minor normal component (van Eck and Hofstetter, 1990). A geodetic survey in the study area indicates that no detectable transform movement has taken place since the establishment of benchmarks in 1988 (I. Karcz, *pers. commun.* 1994).

THE YOUNG FAULT AT THE ATERET SITE

Bedrock

Pleistocene lake sediments, dipping 60°E, crop out in the area between the fortress and the Jordan River. They are underlain by the 0.8–0.9 Ma-old Yarda basalt flow (Heimann and Ron, 1993). A N–S-striking fault plane is exposed in the lake sediments east of the fortress and N-trending horizontal slickenside lineations in a basalt outcrop some 50 m south of the fortress, were considered to be an indication of a fault (S. Belitzky, *pers. commun.* 1994).

Crusader structures

The Ateret Fortress covers an area of about 150×50 m with the long dimension trending north–south. A 4 m-thick defense wall that surrounds Ateret Hill is composed of a pair of

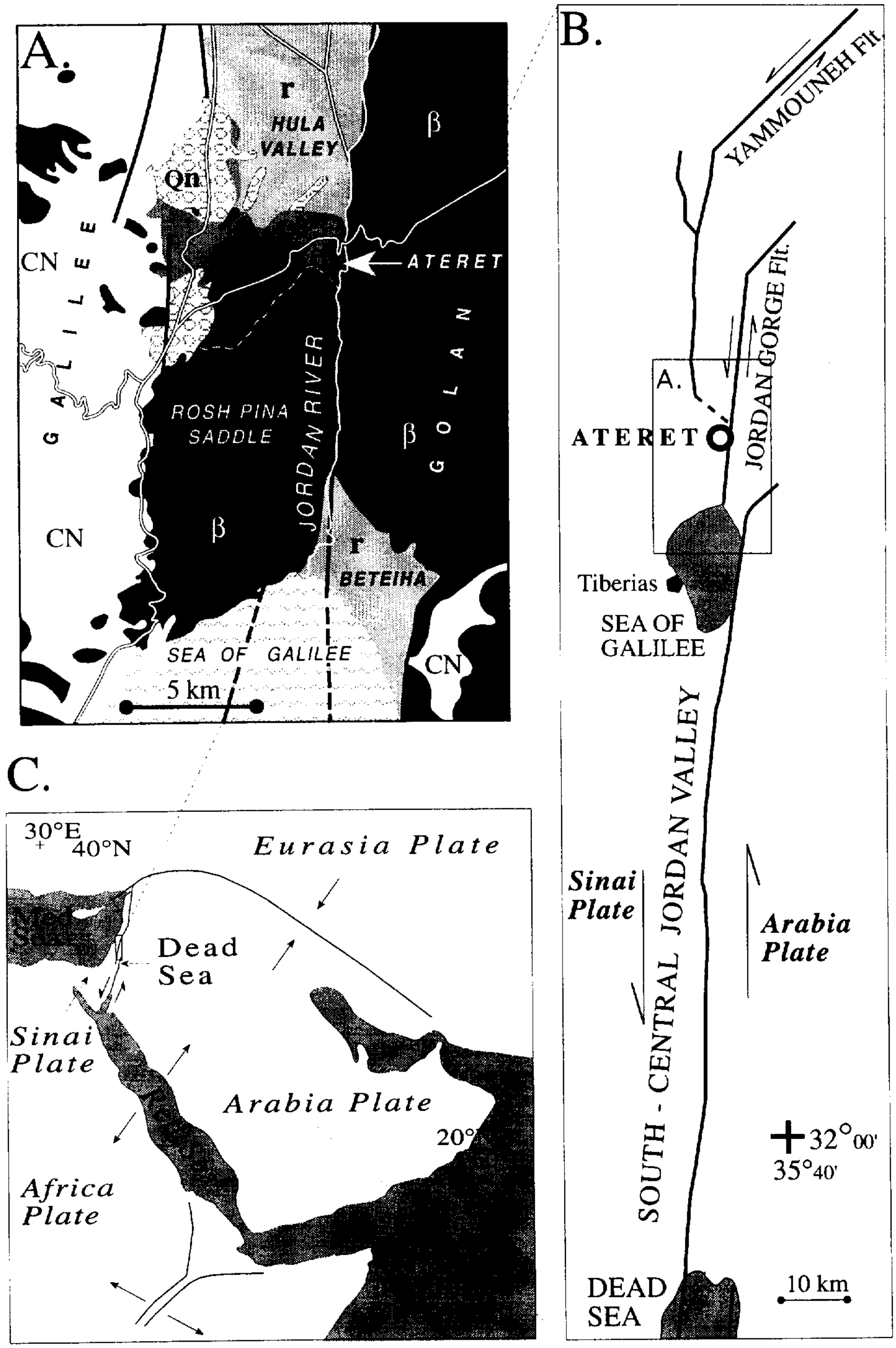

Fig. 1. Location maps: A. Geological map of the Ateret area, after Picard and Golani (1965). CN—Cretaceous to Neogene marine sediments; β—Miocene to Pleistocene basalt flows; Q1—Quaternary lacustrine sediments; Qn—Quaternary alluvium; r—recent alluvium. Solid black lines are faults. B. The Dead Sea transform and the Jordan Gorge fault segment. C. Tectonic plates of the Middle East.

parallel meticulously laid supports made with rectangular 0.5 m-thick thick limestone blocks, separated by a 2 m fill of cemented basaltic cobbles. At present, deformation is best exposed east of the excavated main gate in the southern wall (Figs 2 and 3) where left-lateral displacements amount to 2.1 m. The displacement is distributed over less than 10 m by rotations and small faults between the carved limestone blocks. All the displacements are purely horizontal (all the blocks retain their original level), and all rotations are about vertical axes. The fault lineament traverses the northern walls of the fortress where the walls are severely damaged.

Post-Crusader structures

In the northern part of the fortress, additional walls from the Arabic period show lesser left-lateral displacements of the order of 0.2–0.3 m at points which coincide with the N–S lineament. A Muslim-style room is interpreted as a mosque due to the presence of a south-facing round niche identified as a "makhreb" or a praying apse. The mosque wall is bent and offset sinistrally, and a layer of building stones, that lies imbricated directly on the floor, suggests collapse.

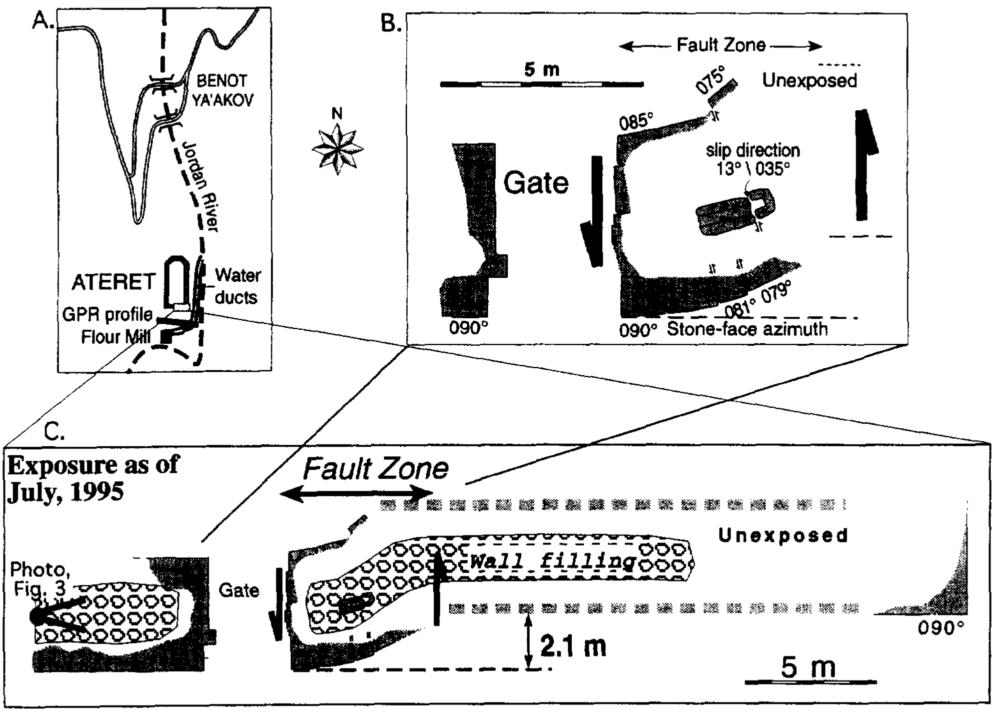

Fig. 2. Site map showing the man-made linear structures and their lateral offset. A. Location of the Ateret fortress, water-ducts, flour mill and the GPR profile. B. Detailed map of the fault zone showing displacement and rotation of masonry. C. Map of southern wall showing how the displacement was measured. The photograph in Fig. 3 was taken from the western side of the gate.

WATER DUCTS

The Ateret water-powered flour mill, with some Crusader masonry remnants, is located some 100 m south of the fortress (Fig. 2). Two water ducts link the Ateret mill with the Jordan River, one of them is displaced about 1.5 m at a point that aligns with the N–S lineament along which the fortress is displaced. The offset duct is made of Crusader-style limestone blocks, and is tentatively assigned a Crusader age. In a newer water duct that runs parallel to the old one, no

Fig. 3. Deformation of the southern wall of the Ateret Fortress looking east. Arrow points at fault zone. Location is shown in Fig. 2.

offset was observed. Local farmers remember that the newer duct operated until the 1930s. The continuous ducts suggest that the fault is currently locked. The displacement of the discontinuous duct was therefore episodic, probably during the same event that displaced the fortress.

GROUND PENETRATING RADAR (GPR) SURVEY

GPR profiles that intersect the lineament (two north and one south of the fortress) show a discontinuity of the gently inclined shallow beds at the lineament (Fig. 4). This observation adds support to our argument that the deformation of the walls occurred by surface rupture.

MAGNITUDE ESTIMATE

In order to estimate the magnitude of the earthquake that was associated with the displacement of the fortress walls, we first use the relation $M_0 = \mu A u$ (Brune, 1968) to estimate the seismic moment (M_0). We examined a range of values of average slip (u) on a fault plane whose area (A) is between 300 and 1500 km^2 assuming a shear modulus (μ) of 3.10^{11} dyne/cm^2. We then assume a moment–magnitude relation $\log M_0 = 1.5\, M_L + 16$, which was determined for earthquakes in Israel (Shapira and Hofstetter, 1993), to find the magnitude. Although Shapira and Hofstetter (1993) considered the local magnitude, M_L, other studies show that magnitudes calculated from moments approximately equal surface wave magnitudes, M_s (Wells and Coppersmith, 1994). This estimate is compared with another magnitude estimate which is based on earthquake statistics for the Middle East and considers the average slip and the length of faults (Ambraseys, 1988). The second estimate yields values that are less than 0.1 magnitude units higher in the relevant range of slip values. Figure 5 shows the range of possible magnitudes between $M = 6.0$ where the average slip is 10 cm on a 15×20 km fault, and $M = 7.4$ for an average slip of 200 cm on a 100 km-long fault (Ambraseys, 1988). If the average slip on the fault is about half the maximum surface displacement (Wells and Coppersmith, 1994), and the southern wall at Ateret exhibits the maximum offset, we may assume a 1 m average slip. This suggests that the magnitude of the earthquake associated with the slip at Ateret may be constrained between 6.6 and 7.1. If the average displacement was 2 m, the magnitude was about 7.4.

WHICH EARTHQUAKE?

We assume that the displacements at Ateret reflect the entire movement on the transform fault. The local geology and topography indicate that the fortress lies on the main N–S trending fault in the area (Fig. 1). The post-Crusader earthquakes in the northern part of Israel occurred in A.D. 1202, 1546, 1759, and 1837 (Amiran *et al.*, 1994).

Ambraseys and Melville (1988) estimated the meisoseismal zone of the 1202 A.D. (20 May) earthquake. Their estimated zone extends from 100 km south to 150 km north of Ateret. They assigned a magnitude of 7.6 to the event and calculated about 2.5 m of maximum displacement. Prior to the present findings, Ambraseys and Barazangi (1989) indicated possible surface faulting based on the "extremely elongated epicentral area" of the 1202 A.D. event. Damage from the 1546 A.D. (14 January) event extended from 150 km south to 75 km north of Ateret (Amiran *et al.*, 1994). Ambraseys and Karcz (1992) argue for a moderate magnitude ($M_S \approx 6.0$)

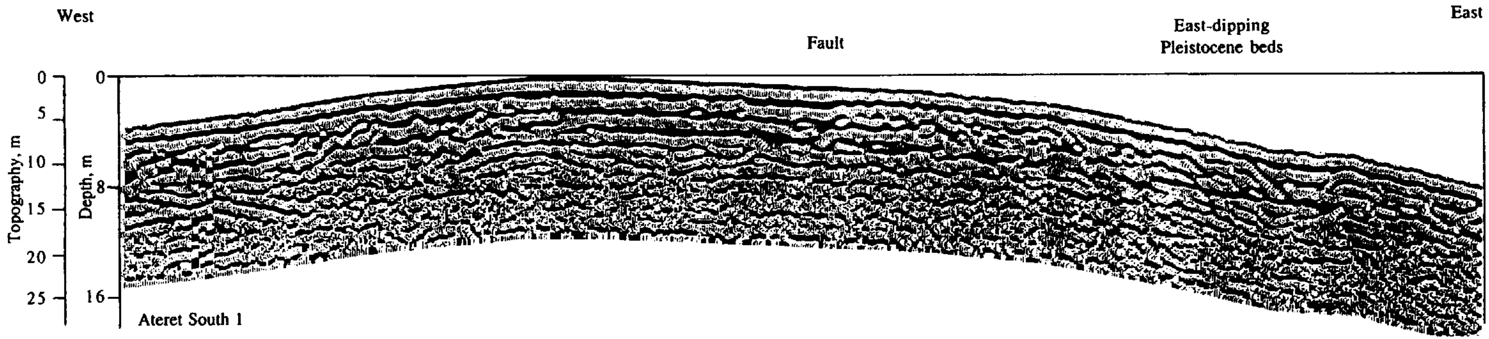

Fig. 4. A 150 m-long ground penetrating radar image south of the Ateret Fortress. The uppermost two reflections are the result of direct airwave, direct groundwave, and a possible very shallow reflector. The fault is marked where the horizontal reflectors terminate towards the east, on the fault lineament that offsets the fortress walls. The profile location is shown in Fig. 2.

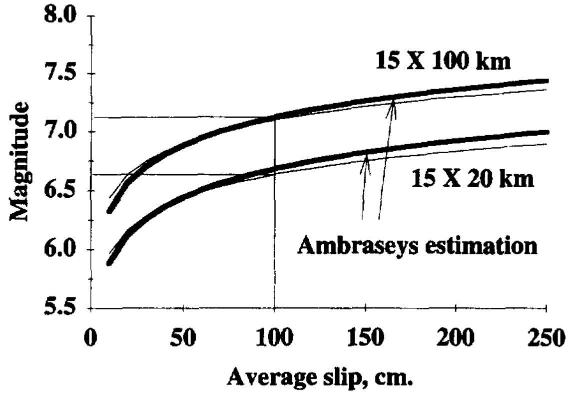

Fig. 5. Magnitude estimate. The upper pair of curves refers to a 15 × 100 km fault, the lower pair refers to a 15 × 20 km fault. Bold curves show the calculation by using Ambraseys' (1988) relation of fault length to magnitude. Faint curves show the magnitude based on the moment–magnitude relation of Shapira and Hofstetter (1993).

for this event with maximum damage in the Judean Hills. Ambraseys and Barazangi (1989) have assigned a double event for the 1759 A.D. (October 30) damage, with surface rupture in the Yammouneh segment, north of the Jordan segment of the Dead Sea transform. Their inferred southern epicentre of an $M \approx 6.6$ "foreshock" could be related to faulting at Ateret (Fig. 1). The last destructive earthquake in the study area was the $M \approx 6.3$ 1837 (January 1) Safed earthquake. The centre of the IX isoseismal of Vered and Striem (1977) coincides with the Ateret site. The last destructive earthquake that struck the Dead Sea transform was the $M \approx 6.2$ 1927 A.D. Jericho earthquake whose epicentre lies 150 km south of Ateret (Vered and Striem, 1977; Shapira *et al.*, 1992). It seems that the likely candidate for the major offset of the fortress wall is the 1202 A.D. earthquake. Later earthquakes hit the Muslim structures, perhaps adding to the offset of the Crusader structure.

Projecting the inferred extent of damage in the past to possible future earthquakes, we expect widespread damage to large population centres in Jordan, Syria, and Israel. If most of the observed slip represents a characteristic earthquake for the Jordan Gorge Fault, the region is at high risk in the near future: even at a long-term slip rate as low as 2.5 mm/y, a simple time-predictable model implies a slip deficit of ≈2 m (barring active slip on parallel strands east or west of the fortress). Precise dating of the displacement events, and documentation of possible previous events (or slip on parallel strands) are the subject of our ongoing investigation.

SUMMARY

- A strong earthquake displaced the 1178 A.D. Ateret Fortress walls by ~2 m. The magnitude is estimated at 6.5–7.1.
- Either the same earthquake or another one displaced the lower water duct of the Ateret Mill, and predates the construction of the upper water duct.
- The 1202 event is a candidate for most or all of the observed displacement. Alternatively, the 1759 and 1837 A.D. events together can account for a significant fraction of the slip if these events were limited to the Jordan Gorge Fault.
- Large population centres in Jordan, Syria, and Israel are at peril if the observed slip

represents a characteristic earthquake for the Jordan Gorge Fault. Even at a long-term slip rate as low as 2.5 mm/y, a simple time-predictable model implies high risk in the near future.

Acknowledgements—We are grateful to all the people who worked in the excavation in the soaring heat of the summer in the Jordan Valley, to the Jewish National Fund, to Shmuel Belitzky for illuminating the local geology, to Vered Eidelman-Shatil who helped in drafting the figures, and to Ron Bogosh who improved the style of the manuscript.

REFERENCES

Ambraseys N. N. (1988) Magnitude–fault length relationships for earthquakes in the Middle East. In: *Historical Seismograms and Earthquakes of the World* (Lee, W. K. H., Meyers, H. and Shimazaki, K. eds), pp. 309–310. Academic Press, San Diego.

Ambraseys N. N. and Barazangi M. (1989) the 1759 earthquake in the Bekaa valley: Implications for earthquake hazard assessment in the eastern Mediterranean region. *J. Geophys. Res.* **94,** 4007–4013.

Ambraseys N. N. and Karcz I. (1992) The earthquake of 1546 in the Holy Land. *Terra Nova* **4,** 253–262.

Ambraseys N. N. and Melville C. P. (1988) An analysis of the eastern Mediterranean earthquake of 20 May 1202. In: *Historical Seismograms and Earthquakes of the World* (Lee, W. K. H., Meyers, H. and Shimazaki, K. eds), pp. 181–200. Academic Press, San Diego.

Amiran D. (1951) A revised earthquake catalogue of Palestine. *Isr. Explor. J.* **1**, 223–246.

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

Belitzky S. (1987) Tectonics of the Korazim Saddle. M.Sc. Thesis. Hebrew University, Jerusalem (in Hebrew, English abstract).

Ben-Manahem A. (1991) Four thousand years of seismicity along the Dead Sea rift. *J. Geophys. Res.* **96,** 20,195–20,216.

Brune J. N. (1968) Seismic moment, seismicity, and rate of slip along major fault zones. *J. Geophys. Res.* **73,** 777–784.

Chaimov T. A. and Barazangi M. (1990) Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault system. *Tectonics* **9,** 1369–1386.

Freund R., Zak I. and Garfunkel Z. (1968) Age and rate of the sinistral movement along the Dead Sea Rift. *Nature* **220,** 253–255.

Garfunkel Z. (1981) Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. *Tectonophysics* **80,** 81–108.

Goren-Inbar N. and Belitzky S. (1989) Structural position of the Pleistocene Gesher Benot Ya'akov site in the Dead Sea Rift zone. *Quaternary Research* **31,** 371–376.

Harash A. and Bar Y. (1988) Faults, landslides and seismic hazards along the Jordan River Gorge, northern Israel. *Eng. Geol.* **25,** 1–15.

Heimann A. and Ron H. (1987) Young faults in the Hula pull-apart basin, central Dead Sea transform. *Tectonophysics* **141,** 117–124.

Heimann A. and Ron H. (1993) Geometric changes of plate boundaries along part of the northern Dead Sea Transform: Geochronologic and paleomagnetic evidence. *Tectonics* **12,** 477–491.

IPRG (1983–1995) Seismological Bulletins. Earthquakes in and around Israel. Institute for Petroleum Research and Geophysics, Israel.

Karcz I. and Kafri U. (1978) Evaluation of supposed archaeoseismic damage in Israel. *J. Archaeol. Sci.* **5,** 237–253.

Kashai E. L. and Crocker P. F. (1987) Structural geometry and evolution of the Dead Sea-Jordan rift systemas deduced from new subsurface data. *Tectonophysics* **141,** 33–60.

Picard L. (1963) The Quaternary in the Northern Jordan Valley. *Proceedings, Israel Academy of Sciences and Humanities* **1**(4), 1–34.

Picard L. Y. and Golani U. (1965) Israel Geological Map, 1:250,000 (northern sheet).

Quennell A. M. (1956) Tectonics of the Dead Sea rift. *Congreso Geologico Internacional, 20th sesion, Asociacion de Servicios Geologicos Africanos,* Mexico, 385–405.

Rotstein Y. and Bartov Y. (1989) Seismic reflection across a continental transform: an example from a convergent segment of the Dead Sea rift. *J. Geophys. Res.* **94,** 2902–2912.

Salamon A. (1993) Seismotectonic analysis of earthquakes in Israel and adjacent areas. Ph.D. Thesis. Hebrew University, Jerusalem (in Hebrew with English abstract).

Shapira A., Avni R. and Nur A. (1992) A new estimate for the epicenter of the Jericho earthquake of 11 July 1927. *Isr. J. Earth Sci.* **42,** 93–96.

Shapira A. and Feldman L. (1987) Microseismicity of three locations along the Jordan rift. *Tectonophysics* **141,** 89–94.

Shapira A. and Hofstetter A. (1993) Source parameters and scaling relationships of earthquakes in Israel. *Tectonophysics* **217,** 217–226.

van Eck T. and Hofstetter A. (1990) Fault geometry and spatial clustering of microearthquakes along the Dead Sea-Jordan rift fault zone. *Tectonophysics* **180,** 15–27.

Vered M. and Striem H. L. (1977) A macroseismic study and the implications of structural damage of two recent major earthquakes in the Jordan rift. *Bull. Seism. Soc. Am.* **67,** 1607–1613.

Walley C. D. (1988) A braided strike-slip model for the northern continuation of the Dead Sea Fault and its implications for Levantine tectonics. *Tectonophysics* **145,** 63–72.

Wells D. L. and Coppersmith K. J. (1994) New empirical relationships among magnitudes, rupture length, rupture width, rupture area, and surface displacement. *Bull. Seismol. Soc. Am.* **84,** 974–1002.