LOAD STRUCTURE SEISMITES IN THE DEAD SEA AREA, ISRAEL: CHRONOLOGICAL BENCHMARKING WITH ^{14}C DATING

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ABSTRACT. The Dead Sea is a terminal lake located in the seismically active zone of the Syro–African Rift Valley. The water level of the Dead Sea has been receding dramatically during the last decades, resulting in significant entrenchment of wadis towards its shores. Exposed sections in fan deltas reveal abruptly changing facies of alluvial fan, beach, and shallow lacustrine environments. Our study focuses on soft sediment deformations of the load–structure type. Though of limited lateral extent, their field characteristics concur with the widely accepted criteria that define seismites. This paper demonstrates the potential of load–structures as seismic–chronological benchmarks through radiocarbon dating. We present the first evidence of ^{14}C correlation between two types of seismites in different locations: load structure and mixed layer.

INTRODUCTION

The Dead Sea and its Late Pleistocene precursor, Lake Lisan, have experienced large fluctuations during the Late Quaternary in response to climatic variations (Klein 1982; Begin et al. 1985; Bowman 1971, 1988; Frumkin et al. 1991; Kaufman et al. 1992; Bruins 1994). Since 1930 the level of the Dead Sea has dropped by 21 meters.

The plain between the Dead Sea and the western fault escarpment of the Rift Valley is narrow. Wadis (ephemeral streams) are entrenched here in lacustrine deposits and in telescopic sequences of alluvial fans that radiate from exits of canyons at the fault escarpment (Sneh 1979; Bowman 1988). The continuing decline and retreat of the lake level of the Dead Sea exposed coastal areas previously covered by water. The lowered base level triggered entrenchment by wadis through the fan deltas in the coastal zone. Hence, many new exposures were formed in recent years. Seventeen of such exposures in various alluvial fan deltas (Figure 1) were studied in detail by Bowman et al. (2000). The studied sections show interbedding of facies that indicate abrupt environmental changes between shallow lacustrine, beach, fan deltas, and alluvial conditions.

Unique sedimentary features in the Dead Sea Basin are soft sediment deformation structures (Marco and Agnon 1995; Marco et al. 1996; Enzel et al. 2000; Ken-Tor et al. 2000; Bowman et al. 2000). We investigated a particular type, called *load structures*, that we observed in most fan deltas of the Dead Sea region, including those of the Kidron, Hazezon, and Mor wadis on the western side, and in the fan delta of Wadi Mujib in Jordan on the eastern side of the Rift Valley (Figure 1). The soft sediment load structures concur with the widely accepted criteria for defining a "seismite" on the basis of the following field characteristics: 1) location in a tectonically active area, 2) low cohesion of loosely consolidated, metastable sands, and silts, 3) similarity to structures formed experimentally under conditions of earthquake–induced liquefaction, 4) relation to areas where gravity control can be precluded, 5) a stratigraphically sandwiched position of the deformed layers between undeformed strata, 6) a spatially wide stratigraphic occurrence of the deformed units, and 7) cyclic repetitions of the load structures.

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Near East Chronology: Archaeology and Environment. RADIOCARBON, Vol 43, Nr 3, 2001, p 1383–1390
Proceedings of the 17th International ^{14}C Conference, edited by Hendrik J Bruins, I Carmi, and E Boaretto

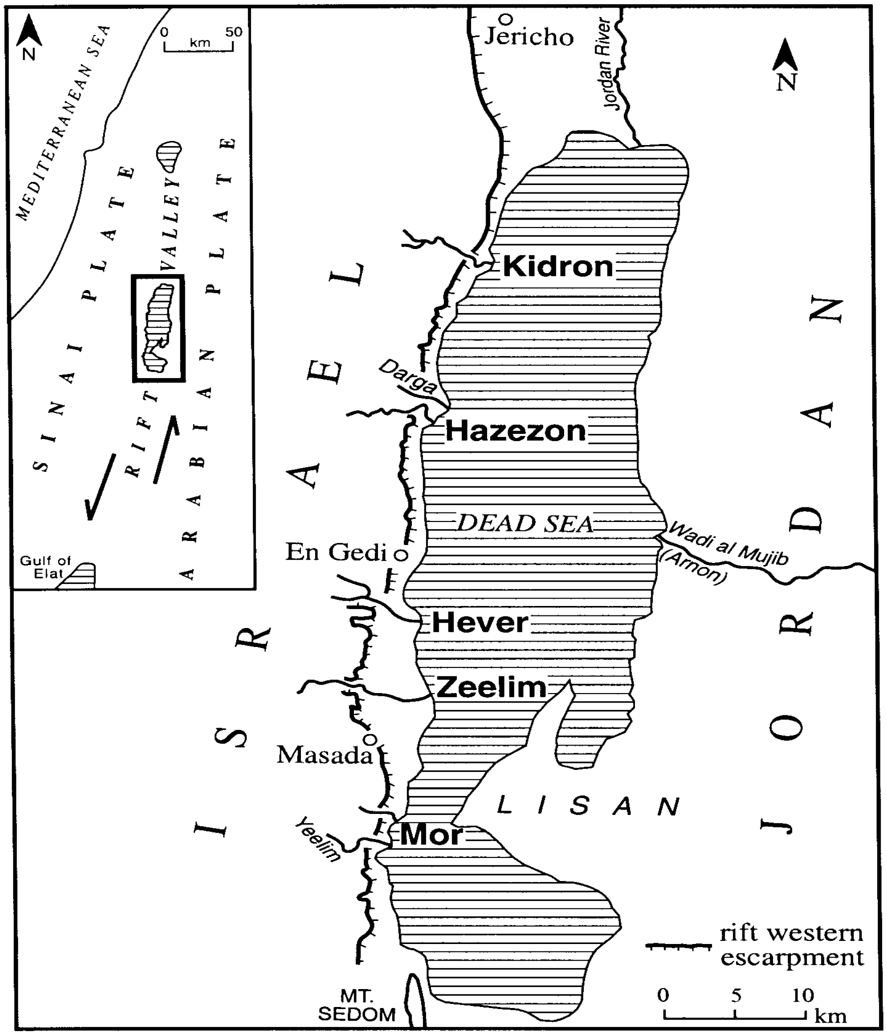

Figure 1 Location map showing the investigated alluvial fans (Bowman et al. 2000) in bold. Radiocarbon studies were conducted in the Ze'elim fan delta by the coast.

The assembled field data provide compelling evidence for a seismic origin of these deformations (Bowman et al 2000) and the term seismite seems, therefore, appropriate. Earthquake shocks probably caused these load structure deformations in soft sediments on the lakebed of suited textural composition, sufficiently loose and saturated with water. More consolidated deeper layers were probably not deformed. Later in time younger sediments covered the deformed layers. The lateral stratigraphic continuity of the load structure seismites is usually limited at each site to only a few tens of meters due to rapid textural changes in the fan delta environment. However, the appearance of seismites in all but one (Hever) of the studied fan deltas underlines their widespread occurrence.

Of seismic origin are also deformations of the mixed layers type (Marco and Agnon 1995; Marco et al. 1996; Ken-Tor et al. 2000, 2001), which provide an important record of earthquakes in the region. Mixed layer deformations have a wide spatial extent and represent the deeper lacustrine facies.

Major geological events, such as earthquakes and volcanic eruptions, can function as chronological benchmarks on a regional scale across disciplinary boundaries (Dever 1992; Bruins and van der Plicht 1996; Manning 1999). Radiocarbon dating of seismites in various geographic locations and landscape settings is important for interdisciplinary geological, geographical and archaeological research (Bruins and Mook 1989).

We examine 1) the potential to synchronize through ^{14}C dating seismites of the load structure and mixed layers types from different exposures in the Dead Sea area, and 2) whether load structure seismites may be correlated with historic earthquakes.

METHODS

In the exposed fan delta of Wadi Ze'elim by the coast, where fluviatile, beach, and lacustrine sediments clearly interfinger, a section exhibiting soft sediment deformation load structures was selected for ^{14}C dating. The section overlies Lisan lacustrine sediments and is, therefore, of Holocene age. The exposure is located at a distance of about 300 m southwest from another section with deformations of the mixed layers type investigated in detail by Ken-Tor et al. (2000, 2001).

Six organic samples, mostly small twigs or tiny stems embedded in sedimentary layers, were extracted for ^{14}C dating in the section of wadi Ze'elim. The organic samples were dated at the Radiocarbon Laboratory of the University of Groningen (van der Plicht 1996). All samples were first treated by the acid/alkali/acid (AAA) method (Mook and Waterbolk 1985), combusted to CO_2 and (for AMS samples only) transferred into graphite (Aerts-Bijma et al. 2001). Most samples contained too little carbon for conventional ^{14}C method and were dated by accelerator mass spectrometry (AMS).

^{14}C Dates of the Multifacies Ze'elim Section

The observed load structures in the studied Ze'elim section are of various magnitudes: small isolated ball-and-pillow structures as well as big and very big balls. The balls are composed of silt to coarse sand with some clay and marl laminae. The host sediment is sand, muddy sand or sandy mud.

The patchy seismite horizons in the sampled exposure are classified as A, B, C, D, E, F, and G (Figure 2, Table 2). Seismites A, B and C appear to be the lowest, i.e. the oldest deformed load structures in the section, while seismite G is the uppermost, i.e. the youngest, in the stratigraphic sequence. Note, that seismites E and F seem to merge laterally westwards into one deformed unit. Stratigraphic merging between A, B, and C may also not be excluded. The sequence of load structure seismites in our section shows no stratigraphic continuity to the mixed layers seismites of Ken-Tor et al. (2000; 2001) in her section situated 300 m to the northeast of ours.

The upper surface plain at the sampled section in the Ze'elim fan delta above seismite G consists of massive gravel (Figure 2). Organic samples Ze'elim 1 and 2 were collected from a depth of 270 cm below that surface from just below a single gravel layer embedded in medium to coarse sand and rich in fine organic remains. The ^{14}C dates are relatively close: 860 ± 40 (GrA–14265) and 970 ± 50 (GrA–14464). The calibrated 1σ ages of these dates are in the range of 1060–1250 cal AD and 1010–1160 cal AD, respectively (for detailed calibration results see Table 1). The dated single gravel layer lies about 15 cm below seismite layer D (Figure 2), which is characterized by sandy balls with truncated tops.

Organic samples Ze'elim 3 and 4 were collected from another layer at a depth of 340 cm below the surface 70 cm below the distinct single gravel layer that marks the position of the previous samples.

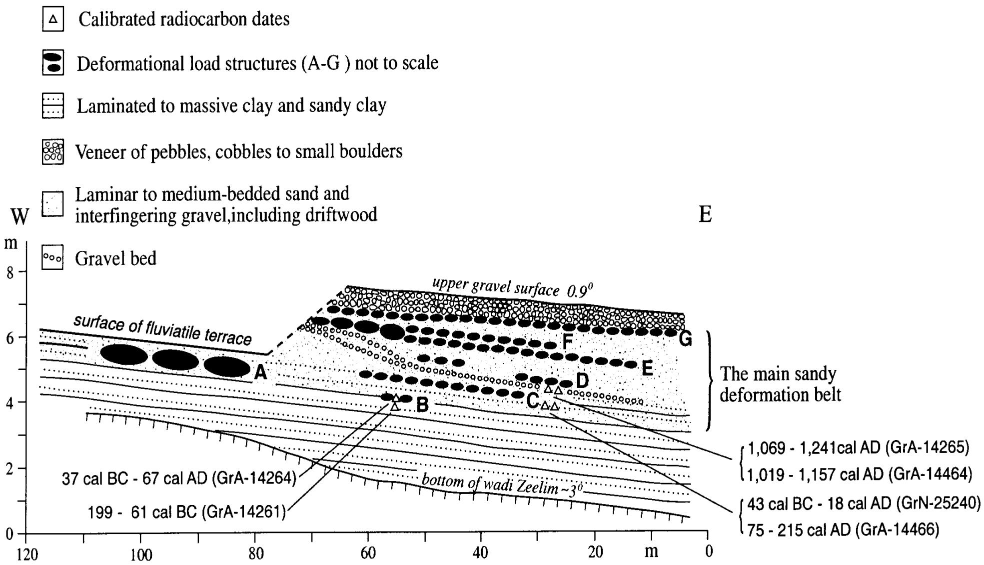

Figure 2 The northern bank exposure of wadi Ze'elim by the Dead Sea shore. Note the lower onlapping sandy clay unit that is almost free of deformation structures. The sandy unit contains the main cycles of load structures (A-G) and a one-clast-thick gravel bed that dies out lakewards. The exposure illustrates an interfingering pattern between the off-lapping, capping gravel, the shallow nearshore sands and the deeper lake sediments.

The lateral distance between samples Ze'elim 3 and 4, within the same layer, was 2 m. The ^{14}C dates differ somewhat: 2020 ± 20 (GrN–25240) and 1880 ± 50 (GrA–14466). Sample 3 was the largest sample and the only one in the series measured by proportional gas counting (the conventional ^{14}C method). Its ^{14}C age seems too old within the studied stratigraphic sequence in comparison with the other dates, indicating a non–uniform age of the organic material that became incorporated in the same sampled layer. Unlike the older date, the younger 1880 ± 50 (GrA–14466) fits very well, stratigraphically, in the ^{14}C sequence. The 1σ calibrated age of the younger date ranges from 70–220 cal AD. This dated layer lies stratigraphically 34 cm below seismite C and 9 cm above seismite B (Figure 2).

Organic sample Ze'elim 5 could be extracted from within a load structure seismite layer (seismite B), 355 cm below the surface and 85 cm below the prominent single gravel layer (Figure 2). This seismite layer, 10 cm thick, exhibits ball structures and is composed of loose sand and distorted marl–clay laminae. The ^{14}C date is 1980 ± 40 BP (GrA–14264) and the calibrated 1σ age ranges from 40 cal BC to 70 cal AD.

The last organic sample in this exposure, Ze'elim 6, consisted of a tiny twig embedded within a thin sandy layer, 3 cm thick. The sample was collected at a depth of 374 cm below the surface, 103 cm below the prominent single gravel layer, and 13 cm below seismite B, dated above. The ^{14}C date is 2120 ± 40 BP (GrA–14261) and the 1σ calibrated age has a range of 200–60 cal BC, fitting well with the stratigraphy and other ^{14}C dates.

Table 1 ^{14}C dates and calibrated ages in the multifacies Ze'elim outcrop

Field sample	Depth (cm)	^{14}C sample number	^{14}C date (BP)	Calibrated date Cal25	Calibrated date OxCal	$\delta^{13}C$ (‰)
Ze'elim 1	270	GrA–14265	860 ± 40	1069–1081, 1125–1135, 1157–1223, 1231–1241 cal AD	1060–1090 (6.2%) 1120–1140 (5.7%) 1150–1250 (56.3%) cal AD	–24.17
Ze'elim 2	270	GrA–14464	970 ± 50	1019–1065, 1083–1123, 1137–1157 cal AD	1010–1070 (29.5%) 1080–1160 (38.7%) cal AD	–25.84
Ze'elim 3	340	GrN–25240	2020 ± 20	43–16, 15–8, 3 cal BC – 2 cal AD, 15–18 cal AD	45 cal BC–5 cal AD (63.1%) 10–20 cal AD (5.1%)	–11.96
Ze'elim 4	340	GrA–14466	1880 ± 50	75–137, 143–179, 191–215 cal AD	70–220 (68.2%) cal AD	–24.46
Ze'elim 5	355	GrA–14264	1980 ± 40	37–31, 21–11 cal BC, 1–67 cal AD	40–10 cal BC (11.5%) 0–70 cal AD (56.7%)	–11.22
Ze'elim 6	374	GrA–14261	2120 ± 40	199–187, 179–91, 73–61 cal BC	200–90 (62.0%) 80–60 (6.2%) cal BC	–10.93

DISCUSSION AND INTERPRETATION

As in all research involving ^{14}C dating, the relationship between the age of the organic matter used for dating and the event to be dated has to be assessed. A certain time lag exists between sedimentary deposition and earthquake deformation, as is also noted by Ken-Tor et al. (2001). The difference may range from near zero to the maximum time the accumulating sedimentary layer can remain in loosely metastable condition susceptible for liquefaction by earthquakes. This mainly depends on the rate of deposition and lake level changes.

Another uncertainty is the residence time of the organic matter in the landscape system, before its final deposition, as it is washed down the wadis and alluvial fans with occasional floods. The organic debris may also float some time in the Dead Sea waters before deposition. Yechieli et al. (1993) established a residence time of less than 100 years for the organic material to reach the Dead Sea. The size and type of organic matter, i.e. pieces of wood, tiny branches, stems, seeds, may have influence on individual residence times.

The difference in age of samples from the same layer, such as GrA–14265 (860 ± 40 BP) and GrA–14464 (970 ± 50 BP), as well as GrN–25240 (2020 ± 20) and GrA–14466 (1880 ± 50 BP), is 110 and 140 ^{14}C years, respectively. This may well be explained by variations in the residence time of the organic matter involved. GrA–14265 and GrA–14464 are within 2σ from each other, thus statistically acceptable as "similar date." It may seem logical to calculate the average of different ^{14}C dates derived from the same layer. However, in these circumstances the younger date may be closest to the age of earthquake deformation.

Organic samples Ze'elim 1 and 2 are from a single–clast bed (Figure 2 between seismites C and D; Tables 1, 2) that represents an intense alluvial flood event, by which the clast bed was transported farthermost towards the lake. The youngest date of the two, 860 ± 40 BP (GrA–14265) that may be closest to the time of deformation, yields a 1σ calibrated ^{14}C age of 1060–1250 cal AD.

The lower boundary of seismite D is only 7 cm above the dated gravel layer. Therefore, seismite D is somewhat younger than the latter date, but the wide calibrated age range may allow overlap. Historically known earthquakes reported as strong or causing damage in Jerusalem or in the Rift Valley occurred in 1063, 1068, 1117, 1202, 1212, 1312, 1456/1457 (Amiran et al. 1994). Thus, there are

Table 2 Stratigraphy of load–structure seismites and ^{14}C dates in the sampled Ze'elim outcrop

Stratigraphy	Depth below surface (cm)	^{14}C sample	^{14}C date (BP)	Calibrated age range	Historical earthquakes (provisional correlation)
Surface layer	0–75				
Seismite G	80				
Seismite F	125				
Seismite E	160				
Seismite D	250				1063, 1068, 1117, 1202, 1212, 1312, 1456/1457 AD
Single gravel layer in sand	270	GrA–14265 GrA–14464	860 ± 40 970 ± 50	1060–1250 cal AD	
Seismite C	300				
Sandy layer with laminae	340	GrN–25240 GrA–14466	2020 ± 20 1880 ± 50	70–220 cal AD	
Seismite B	355	GrA–14264	1980 ± 40	40 cal BC–70 cal AD	31 BC 30, 33, 48 AD
Sandy layer	374	GrA–14261	2120 ± 40	200–60 cal BC	

Explanatory notes: Column 3: GrN is the Groningen laboratory code for conventional ^{14}C dates and GrA for AMS dates. Calibration columns: the calibration of the dates from conventional radiocarbon years BP into astronomical years has been carried out according to two methods: Cal 25 (van der Plicht 1998) and OxCal (Bronk Ramsey 1999), which give similar results. Both programs use the latest internationally recommended calibration data (Stuiver and van der Plicht 1998). Last column: the $^{13}C/^{12}C$ stable isotope abundance ratio of carbon $\delta^{13}C$ is expressed in permil (‰) deviation relative to a standard. This number is also used to correct conventional ^{14}C dates (expressed in BP) for isotopic fractionation.

various events possible for correlation with seismite D. If organic matter could be found in or close to seismites D, E, F, G, correlation with historical earthquakes would become more precise.

Seismite unit B (Ze'elim 5, Figure 2; Table 2) has a 1σ calibrated ^{14}C date of 40–10 cal BC (11.5%), 1–70 cal AD (56.7%). Thus it may be correlated in time with a number of historic earthquakes that occurred during 31 BC, 30 AD, 33 AD, and 48 AD (Arvanitakis 1903; Willis 1928; Sieberg 1932; Turcotte et al. 1988; Amiran et al. 1994). On September 2 in 31 BC an earthquake caused great destruction and numerous casualties in Judea, Qumran, Massada, and Jericho. Eyewitness accounts testify to the damage: *"many animals and 30,000 persons perished"* (Josephus, Antiquities) *"Jason's tomb in Jerusalem was destroyed"* (Rahmani 64); *"in the Galilee the earthquake was severe… Chammath (Tiberias) was destroyed"* (Sieberg 1932). At 30 AD a slight earthquake was felt in Jerusalem (Sieberg 1932). At 33 AD another earthquake was reported *"which caused slight damage to the Temple"* (Arvanitakis 1903; Willis 1928). The earthquake at 48 AD was described (Willis 1928) as *"light in Palestine and Jerusalem,"* though some *"houses in Jerusalem suffered damages"* (Sieberg 1932).

One of these events must have been the earthquake that triggered seismite B. The earthquake of 31 BC was clearly the most severe and may be regarded as a likely candidate. This is consistent with the results of Ken-Tor et al. (2000, 2001). They investigated in detail a lacustrine section some 300 meter north–east of our exposure. Their ^{14}C date of 1950 ± 60 BP (KIA–3223) for their seismite unit B is virtually the same as our date 1980 ± 40 BP (GrA–14264). These close results from different sections, different types of seismites and different ^{14}C labs is very promising indeed for chronological benchmarking. It provides, to the best of our knowledge, the first chronological correlation based on ^{14}C dating between two different sorts of seismites; load structures and mixed layers at different exposures. We conclude that the same seismic event triggered a deformation of the mixed layers type in the aragonitic-detritic laminated lacustrine environment and formed load structures in sandy deposits under shallow water/beach conditions. Moreover, the remarkable age equivalence strengthens our claims (Bowman et al. 2000), so far mainly based on field relations, that the load structures are seismites.

Our oldest ^{14}C age (sample 6, Table 1), 2120 ± 40 BP (GrA–14261) in the presented series is from an undisturbed layer 13 cm below seismite B. This date is exactly the same as the ^{14}C date of seismite unit A of Ken-Tor et al. (2000, 2001). The time coincidence may indicate unfit textural conditions for liquefiable deformation at our exposure site as compared to the lacustrine conditions at the section situated at a lower topographic level investigated by Ken-Tor et al. (2001).

Considering stratigraphic relationships within our section, the large deformed load structure A may be correlated with seismites B and C (Figure 2), also in view of the rather close time correlation between Ze'elim 4 (GrA–14466, 1880 ± 50 BP) and Ze'elim 5 (GrA–14264, 1980 ± 40 BP). Likewise, the convergence of load structures E and F into one bigger deformation may support the hypothesis that a number of temporally close seismic events may mold one seismite (Marco et al. 1996).

In conclusion, *load structure* seismites in interfingering alluvial, beach and shallow lacustrine facies were shown to correlate through ^{14}C dating with mixed layers seismites for chronological benchmarking. Successful correlation with known historical earthquakes depends upon the time width of the calibrated ^{14}C date and the number of known earthquakes within that time range.

REFERENCES

Aerts-Bijma AT, van der Plicht J, Meijer HAJ. 2001. Automatic AMS Sample combustion and CO_2 collection. *Radiocarbon*. This issue.

Amiran DHK, Arieh E, Turcotte T. 1994. Earthquakes in Israel and adjacent areas: macroseismic observations since 100 B.C.E. *The Israel Exploration Journal* 44: 261–305.

Arvanitakis GL. 1903. Essai sur le climat de Jerusalem. *Bulletin de l'Institut d'Egypte* 4:178–89.

Begin ZB, Broecker W, Buchbinder B, Druckman Y, Kaufman A, Magaritz M, Neev D. 1985. Dead Sea and Lake Lisan levels in the last 30,000 years. *Geological Survey of Israel, Report* 29/85. 18 p.

Bowman D. 1971. Geomorphology of the shore terraces of the late Pleistocene Lisan lake (Israel). *Palaeogeography, Palaeoclimatology, Palaeoecology* 9:183–209.

Bowman D. 1988. The declining but non–rejuvenating base level-the Lisan Lake, the dead Sea area, Israel. *Earth Surface Processes and Landforms* 13:239–49.

Bowman D, Banet–Davidovich D, Bruins HJ, van der Plicht J. 2000. Dead Sea shoreline facies with seismically–induced soft–sediment deformation structures, *Israel Journal of Earth Sciences* 49:197–214.

Bronk Ramsey C. 1999. OxCal Program version 3.3. University of Oxford, Radiocarbon Accelerator Unit.

Bruins HJ. 1994. Comparative chronology of climatic and human history in the southern Levant from the late Chalcolithic to the Early Arab Period. In: Bar-Yosef O, Kra R, editors. *Late Quaternary chronology and paleoclimates of the Eastern Mediterranean*. Tucson. Radiocarbon, University of Arizona. p 301–14.

Bruins HJ, Mook WG. 1989. The need for a calibrated radiocarbon chronology of Near Eastern archaeology. *Radiocarbon* 31(3):1019–29.

Bruins HJ, van der Plicht J. 1996. The Exodus enigma. *Nature* 382:213–14.

Dever WG. 1992. A case–study in biblical archaeology: the earthquake of ca. 760 BCE. *Eretz–Israel* 23:27–35.

Enzel Y, Kadan G, Eyal Y. 2000. Holocene earthquakes inferred from a fan–delta sequence in the Dead Sea graben. *Quaternary Research* 53:34–48.

Frumkin A, Magaritz M, Carmi I, Zak I. 1991. The Holocene climatic record of the salt caves of Mount Sedom, Israel. *Holocene* 1:191–200.

Josephus. Antiquities XV, V, 121–147. War, I , XIX, 370–80.

Kaufman A, Yechieli Y, Gardosh M. 1992. Reevaluation of the lake sediments chronology in the Dead Sea basin, Israel, based on new 230Th/U dates. *Quaternary Research* 38:292–304.

Ken-Tor R, Agnon A, Enzel Y, Marco S, Negendank J, Stein M. 2000. High–resolution geological record of historic earthquakes in the Dead Sea basin. 17th International radiocarbon conference, Israel, p 55. Submitted to *Journal of Geophysical Research*.

Ken-Tor R. 2001. Precision of calibrated radiocarbon ages of historic earthquakes in the Dead Sea basin. *Radiocarbon*. This issue.

Klein C. 1982. Morphological evidence of lake level changes, western shore of the Dead Sea. *Israel Journal of Earth Sciences* 31:67–94.

Manning SW. 1999. *A test of time–the volcano of Thera and the chronology and history of the Aegean and east Mediterranean in the mid second millennium BC*. Oxford: Oxbow Books.

Marco S, Agnon A. 1995. Prehistoric earthquake deformations near Masada, Dead Sea graben. *Geology* 23(8):695–8.

Marco S, Stein M, Agnon A, Ron H. 1996. Long–term earthquake clustering, a 50,000 year paleoseismic record in the Dead Sea graben. *Journal of Geophysical Res*earch 101:6179–91.

Mook WG, Waterbolk HT. 1985. Handbook for Archaeologists. Nr 3. *Radiocarbon dating.* Strasbourg: European Science Foundation.

Rahmani LY. 1964. Jason's Tomb. Atiqot 4 (Hebrew Series). p 30.

Sieberg A. 1932. Untersuchungen uber Erdbeben und Bruchschollenbau im ostlichen Mittelmeergebiet. Denkschriften der medizinisch–naturwissenschaftlichen Gesellschaft zu Jena 18. p 159–273.

Sneh A. 1979. Late Pleistocene fan deltas along the Dead Sea Rift. *Journal of Sedimentary Petrology* 49:541–52.

Stuiver M, van der Plicht J, editors. 1998. Intcal 98: calibration issue. *Radiocarbon* 40(3).

Turcotte T, Arie E. 1988. Catalog of earthquakes in and around Israel. Preliminary safety analysis report, Israel Electric Corporation Ltd. Appendix 2.5A.

van der Plicht J. 1996. Radiocarbon dating in Groningen: advances in gas counting and AMS, University of Groningen.

Willis B. 1928. Earthquakes in the Holy Land. *Bulletin of Seismological Society of America* 18:73–103.

Yechieli Y, Magaritz M, Levy Y, Weber U, Kafri U, Woelfli W, Bonani G. 1993. Late Quaternary geological history of the Dead Sea area, Israel. *Quaternary Research* 39:59–67.