The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2060-33

Advanced School on Non-linear Dynamics and Earthquake Prediction

28 September - 10 October, 2009

Dating large infrequent earthquakes by damaged cave deposits

Amotz Agnon

Institute of Earth Sciences Hebrew University
Jerusalem
Israel

Dating large infrequent earthquakes by damaged cave deposits

Elisa J. Kagan* Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel, and Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel
Amotz Agnon Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel
Miryam Bar-Matthews, Avner Ayalon — Geological Survey of Israel, 30 Malkhe Israel Street, Jerusalem 95501, Israel

ABSTRACT

The long-term recurrence patterns of past earthquakes are of considerable consequence for hazard assessments, and have implications for earthquake physics. We introduce a rigorously dated record of earthquakes from an extensive number of well-preserved preseismic and postseismic precipitates from caves located off the Dead Sea transform. We dated events directly at the paleoseismic contact by means of a novel correlation method with the oxygen isotope record of the speleothems recovered in one of the caves. Within the 185 k.y. covered, we dated 38 seismite samples. These stem from 13–18 earthquakes with a mean recurrence interval of ~10–14 k.y. We show that the deformational events dated in the study caves complement independent near-fault paleoseismic records by temporal correlation with the earthquakes recorded therein. This opens up a significant new avenue of earthquake research that will provide precise dating and observational constraints on large infrequent earthquakes.

Keywords: earthquakes, U-Th dating, speleothems, wiggle matching, paleoseismicity, Dead Sea transform.

INTRODUCTION

Records derived from instruments, historical documents, and soft sediments are inherently limited in temporal and spatial span. Regional paleoseismic histories are often incomplete because of lack of surface faulting, scarcity of Quaternary strata, and difficulties in recognizing and locating reliable and dateable earthquake markers (seismites). Cave deposits (speleothems) can undergo various types of damage during earthquakes and offer significant advantages for recovering long histories of earthquakes (Forti, 1998; Gilli, 1999; Gilli et al., 1999; Delaby, 2001) (Fig. 1). A modern-day example is provided by a 1996 M 5.2 earthquake in France that caused the collapse of thin stalactites in a cave 10 km from the epicenter (Gilli et al., 1999). The cave environment is ideal for paleoseismological investigation because earthquake damage is often fossilized by postearthquake calcification and preserved from erosion. The seismic response at different depths below ground varies greatly and may produce amplification or attenuation of as much as a factor of six (Kanai et al., 1966; Bard and Tucker, 1985). Therefore direct magnitude assessment is difficult, although this caveat can ultimately be alleviated by careful comparison with independent paleoseismic records.

The Soreq and Har-Tuv Caves, Israel, are located 40 km due west of the Dead Sea transform, one of the major strike-slip fault systems in the world, active since the Neogene (Garfunkel et al., 1981). The dominant seismogenic element in the area (Fig. 2) is the Dead Sea transform, yet secondary intraplate structures generate microseismicity (Salamon et al., 2003). The location of the source of off-fault paleoseismic evidence is never precisely known, yet the most likely source in our study area is the nearby segment of Dead Sea transform. Although the Jerusalem area, close to the study sites, is not directly on any of the seismic features, it has been affected by many earthquakes. Because this area has been continuously populated and has been a major religious and political center throughout historical times, the record of these earthquakes has been studied in detail (Ambraseys et al., 1994; Amiran et al., 1994; Guidoboni et al., 1994). Paleoseismic studies have provided geological evidence of earthquakes in the Dead Sea transform region (e.g., Marco et al., 1996; Ken-Tor et al., 2001; Amit et al., 2002; Migowski et al., 2004; Begin et al., 2005).

SEISMITES IN THE CAVE SPELEOTHEM RECORD

The Soreq and Har-Tuv carbonate caves are small (<5000 m^2), shallow (12–50 m below the surface), developed in well-bedded to massive upper Cenomanian dolomite, and of phreatic origin (Frumkin et al., 1999). During the past several hundred thousand years abundant speleothems have been growing in the study caves, providing a climate record of late Pleistocene–Holocene time (Bar-Matthews et al., 1997, 2000, 2003; Ayalon et al., 2002). The calendar chronology of the speleothems in the caves was established by U-series methods (Bar-Matthews et al., 1997; Kaufman et al., 1998). The sequence of deposition in the caves is at times disturbed by unconformities, which are expressed by collapsed stalagmites, stalactites, speleothem pillars, and cave ceilings (Fig. 1B), overlain by regrowth. There are standing stalagmites with severed tops (Fig. 1A), none in close proximity to fallen ceilings. Cores drilled into calcite flowstone deposits on floors of the caves (Fig. 1C) revealed distinct laminae encasing collapsed objects (e.g., soda-straw stalactites, ceiling pieces, detritus). Predominantly horizontal fissures in speleothems and walls of caves are widespread and range from completely closed to open a few centimeters.

Mapping of the caves revealed preferential orientation of collapsed long-axis speleothems; we measured orientations of 65 long axes of fallen speleothems calcified to a subhorizontal floor with frequent east-west and north-south directions (inset, Fig. 2). Dating revealed simultaneity of collapses in diverse areas of a cave or in more than one cave (documented here). These observations are interpreted as reflecting seismic origin for the damage. In addition, nonseismic sources of damage are negated: whereas in higher latitude caves, underground ice movement and permafrost may have caused speleothem damage (Forti, 1998; Gilli, 1999; Delaby, 2001), in this part of the Levant cave temperatures were significantly above freezing during the investigated period (Frumkin et al., 1999; Bar-Matthews et al., 2000; Ayalon et al., 2002). Human and animal activity is ruled out as source of damage because the caves were closed to the surface until artificial opening in the twentieth century. Sediment fill is scarce and there is no evidence of water flow, sediment creep, or subsidence. These lines of evidence are consistent with the criteria set by Forti (1998) and Gilli (1999) for establishing a seismic source of damage in caves. Thus, our working hypothesis is that the damage and unconformities in the speleothems represent seismically induced features (here termed seismites).

CHRONOLOGY OF THE SEISMITES

For this study, more than 90 speleothem seismite samples were collected in the Soreq and Har-Tuv Caves by hammer and by core driller (5–10 cm diameter) while striving for spatial randomness. We avoided unnecessary

*E-mail: elisak@huji.ac.il.

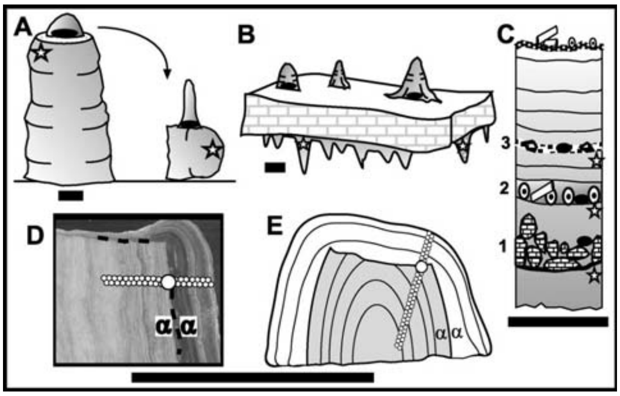

Figure 1. Speleothem seismites in study caves. Open stars and solid ellipses mark pre-earthquake and postearthquake deposits, respectively. A: Stalagmite with severed top and postseismic regrowth. B: Collapsed ceiling with preseismic stalactites (below) and postseismic stalagmites (above). C: Core in flowstone exposing fallen ceiling pieces (1), thin stalactites (2), and detrital layers (3). D: Section of severed stalagmite with postearthquake unconformable regrowth; dashed line is paleoseismic contact. E: Schematic cross section of severed stalagmite with regrowth. U-Th-dated laminae indicated by α. Small circles are schematic representations of stable isotope drilling points. Age of event is defined by datum intersecting contact (largest circle). Scale bars = 10 cm.

damage to the natural splendor of the caves. Drilling positions were chosen to incorporate, where possible, both the preseismic and postseismic material. The unconformity between preseismic and postseismic speleothem laminae is termed the paleoseismic contact. Figures 1D and 1E depict broken speleothems with regrowth exposing the angular unconformity at the paleoseismic contact. For dating we chose 38 seismites with well-defined paleoseismic contacts and adequate material. The laminae adjacent to the paleoseismic contact were separated into subsamples with a 0.4 mm diamond saw for U-Th dating by α-counting. Seven grams of calcite were taken for each subsample for α-dating. To avoid contamination by collapse debris at the contact, it was necessary to saw material at a distance of a few millimeters from the contact (a concern that is overcome by the wiggle-matching stable isotope measurements, which delicately reach the contact). Sample purification and U and Th separation before the $^{234}U/^{230}Th$ α-counting followed Bar-Matthews et al. (1997) and Kaufman et al. (1998).

The dating of damaged speleothems for detailed paleoseismic interpretation requires sampling speleothem growth from both preseismic and postseismic material as close as possible to their mutual contact. One of the foremost uncertainties encountered in dating paleoearthquakes is the accuracy of the age of the paleoearthquake horizon beyond analytical precision, such as the error resulting from a wide bracket between the pre-event and post-event dates (Atakan et al., 2000). The relatively large amount of material taken for U-Th α-dating, which increases the distance required from the contact, causes the U-Th date to represent an average of as much as thousands of years of growth and to be older or younger (for preseismic or postseismic material, respectively) than the actual age of the contact (degree of age offset depends on rate of sedimentation). To overcome this obstacle, and to improve the precision of paleoseismic ages, a novel approach was devised and applied for the first time: after $^{234}U/^{230}Th$ dating, a high-resolution $\delta^{18}O$ profile was prepared for each seismite, for which the size of an aliquot was 0.2–0.5 mg and therefore can come very close to the contact. The profile for each seismite sample was compared (wiggle matched) to the Soreq Cave comprehensive profile (SCCP) (GSA Data Repository Fig. DR1[1]), a continuous, detailed, and rigorously dated (by U-Th thermal ionization mass spectrometry [TIMS]) composite of profiles from 24 fast-growing speleothems and based on 90 TIMS dates resulting in 30–100 yr resolution (Bar-Matthews et al., 1997, 2000, 2003; Kaufman et al., 1998; Ayalon et al., 2002; Kolodny et al., 2003). (Stable isotope and wiggle-matching techniques are expanded upon in the Data Repository; see footnote 1.)

All seismite $\delta^{18}O$ profiles were straightforwardly wiggle matched with the Soreq Cave comprehensive profile (Fig. DR1; see footnote 1). The propagated errors for wiggle-matching ages (Table DR1; see footnote 1) take into account the uncertainty in the rigorously duplicated U-Th TIMS dates from the Soreq Cave and the fit of the oxygen profiles of damaged speleothems with the continuous oxygen profile of the Soreq Cave. In most cases the fit of the wiggle matching is very good. Thus, our estimate of the maximum propagated error for a wiggle-matching seismite age is taken as the maximum error in the TIMS dating, 2σ ~2%, while some samples have somewhat larger errors. The ages of the seismic events are determined by considering the ages at, beneath, and above the paleoseismic contact, or in some cases, only the dates above the contact (Data Repository; see footnote 1).

Ages of 38 collapses resolve as many as 18 seismic events sufficiently large to have caused damage. Earthquakes were dated to earlier than 5.1–6.3, earlier than 12.5–14.5, 35.5–40.5, 46.5–46.7, 51.0–52.0, 70.2–72.8, earlier than 76.2–79.8, 95.3–98.7, 100.3–104.7, 103.3–108.7, earlier than 109.0–113.0, earlier than 116.6–121.4, 125.5–130.5, earlier

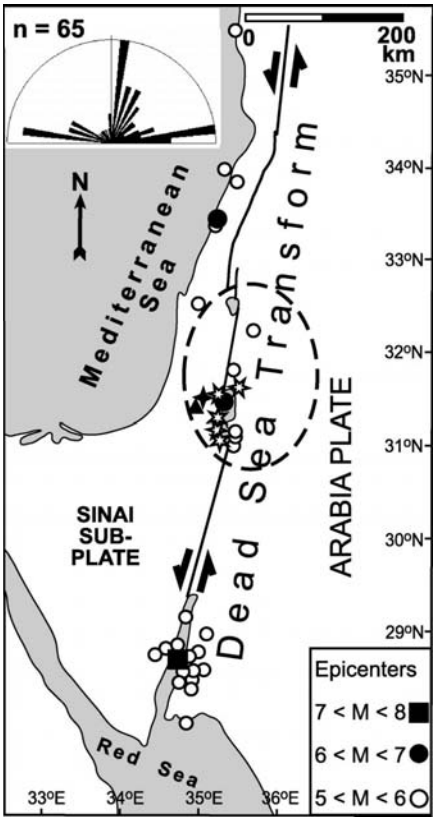

Figure 2. Tectonic setting of Soreq and Har-Tuv Caves, located 40 km due west of Dead Sea transform. Triangle—study cave sites; four-pointed star—city of Jerusalem; open six-pointed stars—sites of dated lacustrine paleo-Dead Sea seismites. Holocene—cores at Dead Sea shore (Migowski et al., 2004); Lisan Pleistocene—PZ1 section (Marco et al., 1996; Hasse-Schramm et al., 2004); pre-Lisan—MR section (Waldmann, 2002) and earthquake-damaged archaeological sites (Karcz et al., 1977); circles—epicenters of instrumentally recorded earthquakes (1900–2000) according to Geophysical Institute of Israel (http://www.gii.co.il). Dashed ellipse encompasses isoseismal zone VII for 1927 M6.2 earthquake north of Dead Sea (Avni, 1999). Rose diagram (inset, upper left) shows orientations of long axes of 65 fallen stalactites and stalagmites cemented on subhorizontal surfaces in Soreq Cave.

[1]GSA Data Repository item 2005046, U-Th and stable isotope wiggle matching procedures, Table DR1, ages of 38 seismites from the Soreq and Har-Tuv Caves, and Figure DR1, wiggle matching of $\delta^{18}O$ profile of seismite sample with that of Soreq Cave comprehensive profile, is available online at www.geosociety.org/pubs/2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

than 132.3–137.7, 144.3–151.7, 150.5–157.5, earlier than 159.5–166.5, and 170.0–184.0 ka (Table DR1; see footnote 1). The mean recurrence interval for 18 cataclysmic earthquakes during 185 k.y. is 10 k.y. Three events were dated in both study caves (events iii, iv, xviii), one of the criteria for establishing seismic origin. Of the 18 events, 13 are well constrained by either 2 boundaries (both preseismic and postseismic ages) or by more than 1 seismite, whereas the other 5 events are constrained by a single boundary and a single seismite (these 5 less constrained events [ii, v, vii, viii, xii] are older than 76 ka and are not implicated in the correlation with other records that we present here). As in most paleoseismic studies, the age uncertainties may have caused two separate but contiguous earthquakes to be grouped into one event; yet such events may be considered seismotectonic events, perhaps with causative interaction (King and Cocco, 2001).

Conceivably not all events were sampled as a result of the enormous number of seismites and the fact that younger ones may cover older ones. Yet the fact that more than two-thirds of the dates of seismites concur with other seismites in our study (within the small dating uncertainties) indicates that our record approximates the actual distribution of destructive earthquakes. We stress that although sampling was widespread and random, 13 is the absolute least number of earthquakes.

CORRELATION WITH INDEPENDENT PALEOSEISMIC RECORDS

It is desirable to compare the cave seismite record to other dated independent paleoseismic records from the region. Such records are available for the past ~75 k.y. from the sedimentary archives of the Dead Sea and its late Pleistocene precursor, Lake Lisan (e.g., Marco et al., 1996; Ken-Tor et al., 2001). Migowski et al. (2004) found excellent correlation between disturbed sedimentary layers (seismites) in the Holocene Dead Sea section and the historical paleoearthquake record, confirming the validity of the Lisan–Dead Sea seismite record and suggesting that it can be used as a solid reference for paleoseismic activity in the region.

Six paleoseismic events that occurred during the past ~75 k.y. are identified and dated by 20 damaged speleothems (Fig. 3). An event at 5.1–6.3 ka correlates with a 5.3–5.4 ka event recorded in the Dead Sea cores (Migowski et al., 2004) and with damage at an archaeological site, Tellelat Ghassul (Karcz et al., 1977). Two events (at 51.0–52.0 and 35.5–40.5 ka) correlate with seismites in the Lisan record (at 52 and 39 ka) recorded in the PZ1 section (Marco et al., 1996; Hasse-Schramm et al., 2004). Two other events (at 46.5–46.7 and 12.5–14.5 ka) coincide with 2 hiatuses in the lacustrine sections: the hiatus from 49 to 44 ka (Machlus et al., 2000; Haase-Schramm et al., 2004) and from ca. 14 to 12.8 ka (Stein, 2002). An event at 70.2–72.8 ka correlates with a cluster of seismites in the pre-Lisan section, observed in the Masasda and Mor sections (Waldmann, 2002).

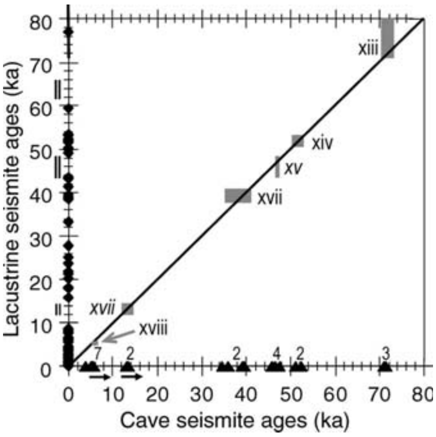

Figure 3. Correlation of cave seismite ages (triangles, *x*-axis) with lacustrine seismite ages (diamonds, y-axis). Diagonal line represents 1:1 correlation. Gray rectangles indicate intersection of ages of seismites from independent records; Roman numerals indicate event title (Table DR1; see footnote 1). Note that correlation line goes through all 6 rectangles: 4 corresponding to cave-lacustrine simultaneous events, 2 additional rectangles corresponding to correlation of cave events with lacustrine hiatuses (italics). Width of rectangles derives from age of cave event, which is acquired from amalgamation of seismite ages in each event group, discussed in Data Repository (see footnote 1), while numbers above triangles indicate number of dated collapses per cave event. Gray arrows below *x*-axis indicate that 2 youngest events, xvii and xviii, are constrained only by postseismic dates, albeit closely clustered in time (in these cases, rectangle width derives from uncertainty of oldest seismite). Height of rectangles derives from error of lacustrine seismite ages or age of lacustrine hiatus. Errors in lacustrine seismite ages are ~ ±0.8 k.y. for Lisan and yet smaller for Holocene, while one pre-Lisan seismite cluster has a ±6.2 k.y. error (error bar, top of y-axis). Double lines near the *y*-axis indicate intervals of hiatuses in lacustrine record (Machlus et al., 2000; Stein, 2002; Hasse-Schramm et al., 2004).

DISCUSSION AND CONCLUSIONS

Extreme events are required for noticeable damage in the research caves. Modern examples have shown that the threshold shaking intensity for speleothem damage is likely to exceed VII on the European Medvedev-Sponheuer-Karnik scale, and the magnitude, even for a very close epicenter, exceeds 5 (Gilli et al., 1999). The last strong earthquake in the Dead Sea area was on 11 July 1927, M 6.2, and generated shaking intensities between VI and VII around the research caves (Fig. 2), leaving no evidence in the cave seismites dated thus far. Numerous earthquakes of this magnitude and larger have occurred in the area throughout history (Amiran et al., 1994). No historical earthquakes show in our record, where the youngest event we have found occurred at ca. 5.1–6.3 ka, correlating with archaeological and sedimentary evidence (Fig. 3).

Threshold ground acceleration for breaking speleothems and the attenuation relations provide constraints on earthquake size. A preliminary calculation shows that for flawless, perfectly cylindrical speleothems, the ground acceleration needed to break by flexion is proportional to the diameter divided by the square length, giving a minimum value of 2 m s^{-2} for some speleothems in a Belgian cave (Cadorin et al., 2001). The geometry of the speleothems studied here would require higher accelerations in excess of 1 g. Such accelerations would result from an M 7.5–8 event at the Dead Sea transform (using a minimum distance of 60 km to incorporate Arava faulting, attenuation relation of Ambraseys et al. [1996], and amplification factor 6 [Bard and Tucker, 1985]).

Extrapolating the Gutenberg Richter relation from the instrumental window of 100 yr (Salamon et al., 2003) to the recurrence interval on the scale of 10 k.y., apparent from the present study, gives a maximum magnitude of 8.2. Since our record may be at present incomplete, we can consider a shorter mean recurrence interval such as 6 k.y., with a maximum magnitude 7.6 (Klinger et al., 2000). A significantly shorter recurrence would require a less complete (more sparsely sampled) record, which is unlikely since we would then expect to find more than 18 ages in 38 dated collapses. Further dating of collapses in the research caves will test this agreement between the independent considerations of recurrence intervals and ground acceleration.

While the limited number of dated events precludes a rigorous statistical approach, an indication of the sense of the distribution can be derived by the standard deviation of 6 k.y., and a coefficient of variation (standard deviation divided by the mean) of 0.6, which suggests periodic behavior (Kagan and Jackson, 1991; Ben-Zion and Rice, 1995). Even if we grouped two distinct earthquakes to a single event as a result of dating uncertainty, the long-term quiescence between events still seems to show periodicity. Large earthquakes along a single fault have been suggested to show a roughly cyclic behavior (Wesnousky, 1994). When these events are more frequent than expected from Gutenberg Richter relationships, they are coined ''characteristic earthquakes.'' Infrequent events, whether characteristic or not, may accommodate some of the sizable slip deficits previously noted (Salamon et al., 2003).

Previously, researchers recognized the potential for using cave deposits to reconstruct important paleoseismic events; however, until now, the capability to take advantage of this special medium by precise dating has not been established. We show that dating damage to caves and deposits in them is a practicable paleoseismic method. Cave records from outside the plate-boundary zone can provide very long-term archives of regional earthquakes that are essential for the understanding of the earthquake-generating process. The research caves, rich with datable, damaged speleothems, will permit us to test our interpretation by additional sampling and dating, a project that is currently under way. This method is especially valuable in karstic and tectonically active regions, particularly regions where speleothem growth has been continuous, such as at mid- to low latitudes.

ACKNOWLEDGMENTS

We thank A. Kaufman for helpful advice regarding the U-Th dating. We also thank E. Ram and S. Ashkenazi for valuable help in the field, and I. Segal, A. Vaks, D. Asael, and L. Laor for assistance in the laboratory. The manuscript benefited from the constructive reviews of editor B. van der Pluijm, H. Ron, and an anonymous referee. We thank M. Stein for assistance with the ages of the Lisan seismites and for fruitful discussions, and S. Marco and R. Bookman for beneficial suggestions. This work was funded by a grant from the Ministry of National Infrastructure of Israel (20-17-02).

REFERENCES CITED

Ambraseys, N.N., Melville, C.P., and Adams, R.D., 1994, Macroseismic information: The seismicity of Egypt, Arabia, and the Red Sea—A historical review: Cambridge, Massachusetts, Cambridge University Press, p. 19–110.

Ambraseys, N.N., Simpson, K.A., and Bommer, J.J., 1996, Prediction of horizontal response spectra in Europe: Earthquake Engineering and Structural Dynamics, v. 25, p. 371.

Amiran, D.H.K., Arieh, E., and Turcotte, T., 1994, Earthquakes in Israel and adjacent areas: Macro seismic observations since 100 B.C.E.: Israel Exploration Journal, v. 44, p. 260–305.

Amit, R., Zilberman, E., Enzel, Y., and Porat, N., 2002, Paleoseismic evidence for time dependency of seismic response on a fault system in the southern Arava valley, Dead Sea rift, Israel: Geological Society of America Bulletin, v. 114, p. 192–206.

Atakan, K., Midzi, V., Moreno Toiran, B., Vanneste, K., Camelbeeck, T., and Meghraoui, M., 2000, Seismic hazard in regions of present day low seismic activity: Uncertainties in the paleoseismic investigations along the Bree fault scarp (Roer Graben, Belgium): Soil Dynamics and Earthquake Engineering, v. 20, p. 415–427.

Avni, R., 1999, The 1927 Jericho earthquake, comprehensive macroseismic analysis based on contemporary sources [Ph.D. thesis]: Be'er Sheva, Ben-Gurion University of the Negev (in Hebrew with English abstract).

Ayalon, A., Bar-Matthews, M., and Kaufman, A., 2002, Climatic conditions during marine isotopic stage 6 in the eastern Mediterranean region as evident from the isotopic composition of speleothems: Soreq Cave, Israel: Geology, v. 30, p. 303–306.

Bard, P., and Tucker, B.E., 1985, Underground and ridge site effects: A comparison of observation and theory: Seismological Society of America Bulletin, v. 75, p. 905–922.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 1997, Late Quaternary paleoclimate in the Eastern Mediterranean region from stable isotope analysis of speleothems at Soreq Cave (Israel): Quaternary Research, v. 47, p. 155–168.

Bar-Matthews, M., Ayalon, A., and Kaufman, A., 2000, Timing and hydrological conditions of sapropel events in the Eastern Mediterranean, as evident from speleothems, Soreq Cave, Israel: Chemical Geology, v. 169, p. 145–156.

Bar-Matthews, M., Ayalon, A., Gilmour, M., Matthews, A., and Hawkesworth, C., 2003, Sea-land oxygen isotopic relationships from planktonic foraminifera and speleothems in the eastern Mediterranean region and their implication for paleorainfall during interglacial intervals: Geochimica et Cosmochimica Acta, v. 67, p. 3181–3199.

Begin, Z.B., Steinberg, D.M., Ichinose, G.A., and Marco, S., 2005, A 40,000 yr unchanging seismic regime in the Dead Sea rift: Geology, v. 33, p. 257–260.

Ben-Zion, Y., and Rice, J.R., 1995, Slip patterns and earthquake populations along different classes of faults in elastic solids: Journal of Geophysical Research, v. 100, p. 12,959–12,983.

Cadorin, J.F., Jongmans, D., Plumier, A., Camelbeeck, T., Delaby, S., and Qunif, Y., 2001, Modeling of speleothem failure in the Hotton cave (Belgium): Is the failure earthquake induced?: Geologie en Mijnbouw, v. 80, p. 315–321.

Delaby, S., 2001, Palaeoseismic investigations in Belgian caves: Netherlands Journal Geoscience: Geology en Mijnbouw, v. 80, p. 323–332.

Forti, P., 1998, Seismotectonic and paleoseismic studies from speleothems: The state of the art: Han 98-Tectonique: Karst et Seismes, p. 79–81.

Frumkin, A., Ford, D.C., and Schwarcz, H.P., 1999, Continental oxygen isotope record of the last 170,000 years in Jerusalem: Quaternary Research, v. 51, p. 317–327.

Garfunkel, Z., Zak, I., and Freund, R., 1981, Active faulting in the Dead Sea Rift: Tectonophysics, v. 80, p. 1–26.

Gilli, E., 1999, Evidence of paleoseismicity in a flowstone of the Observatoire cave (Monaco): Geodinamica Acta, v. 12, p. 159–168.

Gilli, E., Levret, A., Sollogoub, P., and Delange, P., 1999, Research on the February 18, 1996, earthquake in the caves of the Saint-Paul-de-Fenouillet area (eastern Pyrenees, France): Geodinamica Acta, v. 12, p. 143–158.

Guidoboni, E., Comastri, A., and Traina, G., 1994, Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century: Rome, Instituto Nazionale di Geofisica, 504 p.

Haase-Schramm, A., Goldstein, S.L., and Stein, M., 2004, U-Th dating of Lake Lisan (late Pleistocene Dead Sea) aragonite and implications for glacial East Mediterranean climate change: Geochimica et Cosmochimica Acta, v. 68, p. 985–1005.

Kagan, Y.Y., and Jackson, D.D., 1991, Long-term earthquake clustering: Geophysical Journal International, v. 104, p. 117–133.

Kanai, K., Tanaka, T., Yoshizawa, S., Morishita, T., Osada, K., and Suzuki, T., 1966, Comparative studies of earthquake motions on the ground and underground: II: Tokyo, Earthquake Research Institute Bulletin, v. 44, p. 609–643.

Karcz, I., Kafri, U., and Meshel, Z., 1977, Archaeological evidence for subrecent seismic activity along the Dead Sea–Jordan rift: Nature, v. 269, p. 234–235.

Kaufman, A., Wasserburg, G.J., Porcelli, D., Bar-Matthews, M., Ayalon, A., and Halicz, L., 1998, U-Th isotope systematics from the Soreq Cave, Israel and climatic correlations: Earth and Planetary Science Letters, v. 156, p. 141–155.

Ken-Tor, R., Agnon, A., Enzel, Y., Stein, M., Marco, S., and Negendank, J.F.W., 2001, High-resolution geological record of historic earthquakes in the Dead Sea basin: Journal of Geophysical Research, v. 106, p. 2221–2234.

King, G.C.P., and Cocco, M., 2001, Fault interaction by elastic stress changes: New clues from earthquake sequences: Advances in Geophysics, v. 44, p. 1–38.

Klinger, Y., Avouac, J.P., Dorbath, L., Abou Karaki, N., and Tisnerat, N., 2000, Seismic behaviour of the Dead Sea fault along Araba valley, Jordan: Geophysical Journal International, v. 142, p. 769–782.

Kolodny, Y., Bar-Matthews, M., Ayalon, A., and McKeegan, K.D., 2003, A high spatial resolution $\delta^{18}O$ profile of a speleothem using an ion-microprobe: Chemical Geology, v. 197, p. 21–28.

Machlus, M., Enzel, Y., Goldstein, S.L., Marco, S., and Stein, M., 2000, Reconstruction of Lake Lisan levels by correlating fan-delta and lacustrine deposits: Quaternary International, v. 73–74, p. 137–144.

Marco, S., Stein, M., Agnon, A., and Ron, H., 1996, Long-term earthquake clustering: A 50,000 year paleoseismic record in the Dead Sea Graben: Journal of Geophysical Research, v. 101, p. 6179–6191.

Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., and Stein, M., 2004, Recurrence pattern of Holocene earthquakes along the Dead Sea transform revealed by varve-counting and radiocarbon dating of lacustrine sediments: Earth and Planetary Science Letters, v. 222, p. 301–314.

Salamon, A., Hofstetter, A., Garfunkel, Z., and Ron, H., 2003, Seismotectonics of the Sinai subplate—The eastern Mediterranean region: Geophysical Journal International, v. 155, p. 149–173.

Stein, M., 2002, The fall and rise of the Dead Sea during the post-Glacial and the Younger Dryas event, *in* Abstracts, 12th annual V.M. Goldschmidt Conference, Davos: Geochimica et Cosmochimica Acta, v. 66, special supplement, p. 738.

Waldmann, N., 2002, The geology of the Samra Formation in the Dead Sea Basin [M.S. thesis]: Hebrew University of Jerusalem, 175 p.

Wesnousky, S.G., 1994, The Gutenberg-Richter or characteristic earthquake distribution—Which is it?: Seismological Society of America Bulletin, v. 84, p. 1940–1959.

Manuscript received 14 September 2004
Revised manuscript received 22 December 2004
Manuscript accepted 23 December 2004

Printed in USA