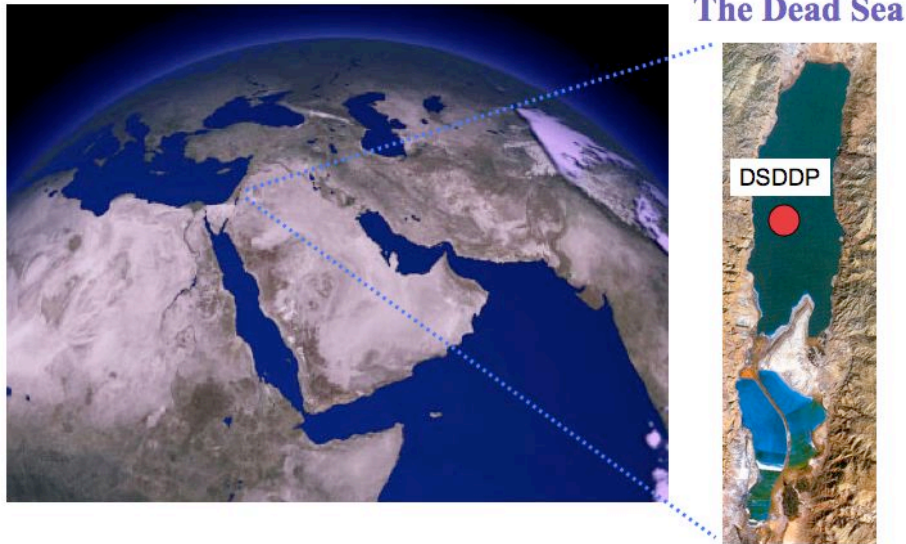


The Dead Sea Deep Drilling Project (DSDDP)

The Dead Sea as a Global Paleo-Environmental, Tectonic, and Seismological Archive

by Steven L Goldstein, LDEO/Columbia U, and Emi Ito, U Minnesota



**Partially Funded by the International Continental Scientific Drilling
Program (ICDP)**

ICDP Proposal Principal Investigators:

Israel: Zvi Ben Avraham, Tel Aviv University, Tel Aviv
Mordechai Stein, Geological Survey of Israel, Jerusalem
Amotz Agnon, Hebrew University, Jerusalem

USA: Steven L. Goldstein, Lamont-Doherty Earth Obs., Columbia University, New York

Germany: Achim Brauer, GeoForschungsZentrum, Potsdam

Switzerland: Gerald Haug, ETH, Zurich

Japan: Yoshinori Yasuda, International Research Center for Japanese Studies, Kyoto

The Dead Sea Deep Drilling Project

Scientific Value: The Dead Sea, located in the Dead Sea Basin (*DSB*) at the lowest continental elevation on Earth (422 mbsl), has alternately expanded during ice ages and contracted during interglacials. At its maximum extent during the last ice age as glacial Lake Lisan, it filled the DSB from its present location northward to the Sea of Galilee (*Fig. 1*). Its changing size and composition through time reflect the climatic-hydrologic history and the tectonic architecture of its location, in the mid-latitudes, on the continent, and on the boundary between the Saharan desert and Mediterranean climate zones^{e.g. 1, 2-4}. These changes are recorded and preserved in the lake sediments, giving them unique potential for investigating the expansion and contraction of these climatic zones, as well as the linkages between high latitude and tropical climate. Moreover, because the DSB formed by the Dead Sea Transform Fault, it is an active tectonic region where sediments preserve the history of earthquakes. The DSB is also the locus of humankind's migration out of Africa, and the home of peoples from Paleolithic to modern times. Studies of the sedimentary sections exposed on the Dead Sea margins have been applied to issues with global and regional implications associated with *paleoclimate, tectonics, paleoseismology, paleomagnetism and human history*.

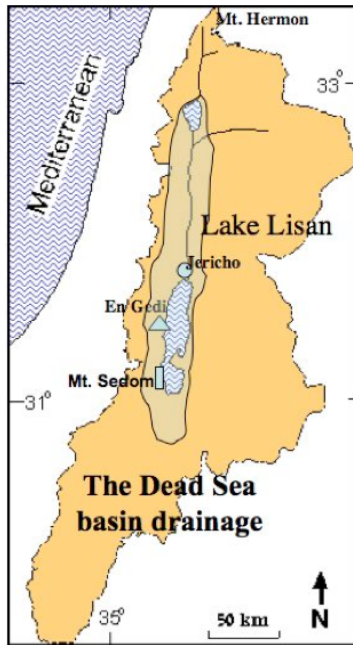


Fig. 1. Dead Sea drainage basin, including the Sea of Galilee and the present-day Dead Sea, and its maximum extent during the last ice age as Lake Lisan.

The exceptional value of the DSB lake sediments as a historical archive is shown by the sediments deposited along the Dead Sea margins by last glacial Lake Lisan. The Lisan Formation (*Fig. 2*) is comprised of up to ~40 meters of sediment deposited over nearly 60,000 years (~70 to ~11 ka)⁵⁻⁹, and records ice age conditions with seasonal time-resolution^{e.g. 3}, due to regular deposition of thin (~1 mm thick) layers of precipitated inorganic carbonate during dry seasons (from lake evaporation) and detritus during wet seasons (from erosion of the marginal highlands). It also includes clastic-rich layers associated with storms or near-littoral conditions, gypsum layers associated with extreme dry periods and lake level drops, and jumbled “mixed layers” caused by earthquakes^{e.g. 10, 11-14}. The carbonate layers can be dated by U-series and ¹⁴C, and the combination of radiometric dating and layer counting affords the opportunity to unravel the Near East climatic-hydrologic and tectonic history at up to seasonal time resolution^{e.g. 15}. The Lisan Formation overlies deposits from Lakes Amora and Samra, representing previous ice age high-stands extending back to at least 780 ka¹⁴. Investigations of the subaerial deposits have addressed changes in regional and global paleomagnetism and cosmogenic isotope production^{e.g. 3, 8, 16, 17}, and have led to development of new approaches to dating lake sediments and using them to reconstruct past climate and lake level variations^{1, 7, 10, 11}, as well as to studying paleoseismicity^{e.g. 12, 15, 18, 19, 20}.

The subaerial lake deposits, however, show critical limitations:

- Even in the best-preserved subaerial sections of the Lisan Formation along the Dead Sea margin, *time intervals are missing due to lake level fluctuations and erosion*. The deposits from these time missing intervals, however, should lie at the bottom of the Dead Sea.
- *Subaerial deposits from older ice ages are in less pristine form than the Lisan Formation, and have even less complete stratigraphies*. It is expected that these deposits survive in more pristine form in the interior of the lake.

- *There are no subaerial deposits from interglacials, due to low lake levels.* The deposits representing the history of warm climate intervals are only accessible at the bottom of the Dead Sea.

Funding Considerations: In order to overcome these critical limitations, a group of PIs from Israel, USA, and Germany have sought support for more than a decade from the *International Continental Scientific Drilling Program (ICDP)* for a deep drill core in the Dead Sea. By the time the final proposal was submitted in February 2009, we had a strong international team from several institutions in ICDP member countries (Israel, US, Germany, Switzerland, and Japan). The purpose of the drilling is to recover a *long, continuous, high resolution* paleo-seismic and climatic archive, going back several glacial-interglacial cycles. The seismic information will be integrated with the basin development and rift tectonics, and the paleo-hydrologic and climatic information will be integrated and evaluated in framework of global climate modeling. Major research goals are listed in the Appendix.

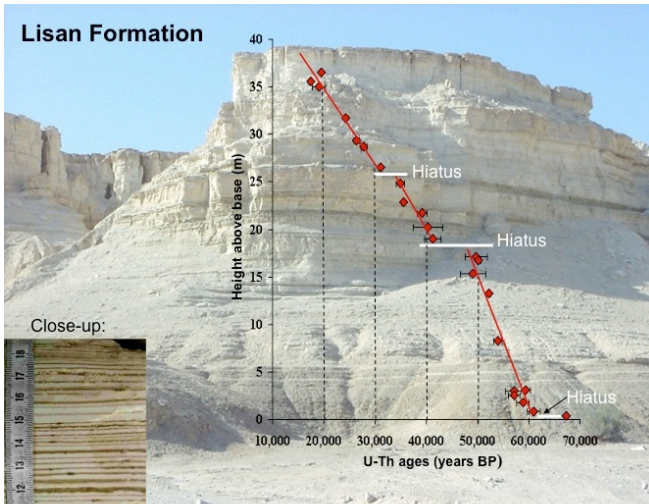


Fig. 2. Lisan Formation near the southern Dead Sea. Photo shows the section deposited between ~70K and ~15K years ago. Graph shows ages and locations of hiatuses (Haase-Schramm et al. 2004). The inset (bottom left) shows aragonite and dark detritus layering representing dry and wet

ICDP agreed in Fall 2009 to fund the drilling, and the DSDDP is expected to recover a lacustrine section of the past 600-800 ka. ICDP provides \$800,000, ~40% of the drilling cost of \$2.1M. ICDP has requested that the PIs seek matching funds from their respective countries.

Consultations with NSF at Fall 2009 AGU and by telephone in early 2010 suggested P2C2 as the most appropriate program to apply for funding. The proposal deadline for this program is in October 2010, and special conditions have developed that affect the schedule. ICDP has scheduled a drilling operation to core Lake Van, Turkey, during summer and fall 2010. *DOSSEC*, the drilling organization, and *ICDP* have requested that the Dead Sea drilling be scheduled following it in order to avoid the expense of transporting the drill rig back to the US and then again to the Middle East.

US Participation: Over the past 15 years, there has been ongoing US participation in Dead Sea studies with external funding from the US-Israel Binational Science Foundation, led by Steven Goldstein in the US and Mordechai Stein in Israel. The grants that have funded US efforts are listed in the appendix. In 2010, Emi Ito has joined the group as a US-based PI, adding additional US presence and strength to the project.

Considering the extensive interdisciplinary track record from studies of the subaerial deposits, and the potential for excellent science from these cores, we propose that the drilling deserves participation by US funding agencies. A Dead Sea deep drill core that covers several glacial-interglacial periods represents both a major step forward and a great opportunity for US investigators. We propose that NSF contribute a share of the drilling costs on the order of \$150,000, which would be about 7% of the cost. Possibilities might include contributing through an EGER or a RAPID grant. We can be sure that this unique set of cores will have a great influence on diverse fields of the geosciences.

Steven Goldstein 11/23/10 7:27 PM

Formatted: Not Highlight

Steven Goldstein 11/23/10 7:27 PM

Formatted: Not Highlight

References Cited:

1. Bartov, Y., S.L. Goldstein, M. Stein, and Y. Enzel, *Geology*, 31, p. 439-442, 2003.
2. Kolodny, Y., M. Stein, and M. Machlus, *Geochimica Et Cosmochimica Acta*, 69, p. 4045-4060, 2005.
3. Prasad, S., J.F.W. Negendank, and M. Stein, *Journal of Quaternary Science*, 24, p. 690-696, 2009.
4. Stein, M., *Journal of Paleolimnology*, 26, p. 271-282, 2001.
5. Kaufman, A., *Geochimica Et Cosmochimica Acta*, 35, p. 1269-&, 1971.
6. Kaufman, A., Y. Yechieli, and M. Gardosh, *Quaternary Research*, 38, p. 292-304, 1992.
7. Haase-Schramm, A., S.L. Goldstein, and M. Stein, *Geochimica Et Cosmochimica Acta*, 68, p. 985-1005, 2004.
8. Schramm, A., M. Stein, and S.L. Goldstein, *Earth and Planetary Science Letters*, 175, p. 27-40, 2000.
9. Stein, M. and S.L. Goldstein, *Geol. Soc. Am. Spec Paper*, 401, p. 141-154, 2006.
10. Bartov, Y., M. Stein, Y. Enzel, A. Agnon, et al., *Quaternary Research*, 57, p. 9-21, 2002.
11. Bartov, Y., Y. Enzel, N. Porat, and M. Stein, *Journal of Sedimentary Research*, 77, p. 680-692, 2007.
12. Marco, S., M. Stein, A. Agnon, and H. Ron, *Journal of Geophysical Research-Solid Earth*, 101, p. 6179-6191, 1996.
13. Stein, M., A. Starinsky, A. Katz, S.L. Goldstein, et al., *Geochimica Et Cosmochimica Acta*, 61, p. 3975-3992, 1997.
14. Torfstein, A., I. Gavieli, A. Katz, Y. Kolodny, et al., *Geochimica Et Cosmochimica Acta*, 72, p. 2491-2509, 2008.
15. Migowski, C., A. Agnon, R. Bookman, J.F.W. Negendank, et al., *Earth and Planetary Science Letters*, 222, p. 301-314, 2004.
16. Marco, S., H. Ron, M.O. McWilliams, and M. Stein, *Earth and Planetary Science Letters*, 161, p. 145-160, 1998.
17. Stein, M., S.L. Goldstein, and A. Schramm, *Radiocarbon*, 42, p. 415-422, 2000.
18. Niemi, T.M. and Z. Benavraham, *Geology*, 22, p. 395-398, 1994.
19. Ken-Tor, R., A. Agnon, Y. Enzel, M. Stein, et al., *Journal of Geophysical Research-Solid Earth*, 106, p. 2221-2234, 2001.
20. Ken-Tor, R., M. Stein, Y. Enzel, A. Agnon, et al., *Radiocarbon*, 43, p. 1371-1382, 2001.

Appendix:

Major DSDDP Research Goals:

- **Recover the sedimentary history of the DSB** during the past several hundred ka or more, covering several glacial-interglacial cycles.
- Reconstruct the **limnological history** of the lakes that occupied the basin, and establish the **climatic history of the past several glacial-interglacial climatic cycles**.
- Establish a **high-resolution chronology** by U-series dating of primary aragonite. The U-Th chronology will be completed and extended by high-resolution oxygen isotope stratigraphy.
- Establish annual chronologies of selected time intervals by lamina-counting. The data will be used to **extract paleo-climate frequencies** for several glacial-interglacial cycles
- Establish the **paleo-hydrology** of the drainage area, and explore the brine-freshwater relations during different lakes (e.g., Lisa, Amora, Samra), as well as the contributions from the major regional freshwater sources (e.g. Mt. Hermon, the main source of Jordan River water, and floods) during glacial and interglacials. This will be used to evaluate **effects of long-term climatic trends versus short-term fluctuations**.
- Compare the sedimentary record of the DSDDP cores, which reflect the deeper water lacustrine facies, with the higher elevation sedimentary records on the basin margins that are sensitive to **lake level fluctuation**, applying established approaches used in the Lisan and Holocene Dead Sea sequences. This comparison can be extended for some time periods of the earlier lakes.
- Establish the behavior of **abrupt limnological-hydrological** events (e.g. catastrophic drying or rising of the lakes).
- Compare the **limnological-hydrological history of the Dead Sea water-bodies** with regional and global climatic records from the Red and Mediterranean Seas, Atlantic deep-sea cores, ice cores and other lake records (e.g. east African lakes; Syrian and Anatolian lakes).
- Establish the **paleomagnetic history** of the Dead Sea Basin; construct secular variation curves and explore the characteristics of geomagnetic excursions (e.g. the Laschamp excursion, already recognized in the land record).
- Establish a **high-resolution paleoseismic record** by identifying and dating disturbed sediments.
- Study the composition and history of **wind-blown desert dust** to the lakes and monitor **paleo-storm tracks**.
- Investigate the geochemistry and depositional conditions of the main **salt layers**. Reconstruct the environmental-climatic conditions of these catastrophic occurrences.
- Integrate geochemical, **hydrological, limnological, and palynological information for linkage with global climatic models** for the past 500-600 ka.
- Investigate the **tectonic and subsidence history** of the Dead Sea Basin during the late Quaternary.
- Investigate the **relationships between human culture development and climatic changes and tectonic events** in the region, utilizing correlation and integration of the DSB data with the lacustrine archives in the northern Jordan Valley (e.g. the B'enot Ya'akov, Ubediya and Erq-El Ahmer Formations where prehistoric cultures were recovered).
- Integrate the drill core data with those derived from the limited previous drilling operations and land exposure studies, in order to **evaluate potential environmental risks** such as destabilization and collapse of the lake shores, regional earthquakes, catastrophic floods, aridity, groundwater-saline water interaction and the fate of the Dead Sea and its drainage system.

Previous External Funding for US-based Dead Sea Basin-related Projects:

- Goldstein, S. (USA), Katz, A. (Israel), "The geochemical history of Lake Lisan (the Paleo-Dead Sea) as a tracer of continental climate change during the last glacial period"; US-Israel Binational Science Foundation, 1997-2000; \$57,000.
- Goldstein, S. (USA), Gavrieli, I. (Israel), Stein, M. (Israel), "Limnology and Climatic History of the Dead Sea Basin during the Last Glacial Period", US-Israel Binational Science Foundation, 2002-2005, \$150,000.
- Goldstein, S.L. (USA.), Almogi-Labin, A. (Israel) and Stein, M. (Israel), "Sources and climate controls of fine-particle transport to the Gulf of Aden-Dead Sea Rift from late Quaternary deep sea cores and lacustrine sediments", US-Israel Binational Science Foundation, 2007-2011, \$180,000.
- Ben Avraham, Z. (Israel), Stein, M. (Israel), Agnon, A. (Israel), Goldstein, S.L. (USA), Brauer, A. (Germany), Haug, G. (Switzerland), Yasuda, Y. (Japan), "The Dead Sea Deep Drilling Project (DSDDP): The Dead Sea as a Global Paleo-environmental, Tectonic, and Seismological Archive", International Continental Drilling Program (ICDP), 2010-2011, \$800,000, to be matched with individual country contributions.

Impacts of ICDP PI Publications:

As of July 2010, ISI lists 118 papers published by the ICDP PIs on the Dead Sea Basin since 1990 (the search used the keywords Dead Sea or Lisan or Amora or Samra or Sedom, and was refined to include only the ICDP proposal PIs, and to exclude abstracts, corrections, and editorial material). These papers, listed below, have >2100 citations and an h-index of 26. Among these top 26, the US ICDP proposal PI S. Goldstein is a co-author of the papers ranked #2, 4, 9, 12, 23 in the citations list. Among these studies, 13 US institutions are listed. Among all the institutions represented in these studies, Columbia University is listed as #5, after Hebrew University, the Geological Survey of Israel, Tel Aviv University, and GeoForschungsZentrum Potsdam.

Papers by ICDP PIs since 1990:

(118 papers, h-index =26 as of August 3, 2010; these are in bold with ranking and # of citations)

- Achmon, M., BenAvraham, Z., 1997. The deep structure of the Carmel fault zone, northern Israel, from gravity field analysis. *Tectonics*, 16(3): 563-569.
- Al-Zoubi, A., Ben Avraham, Z., 2002. Structure of the earth's crust in Jordan from potential field data. *Tectonophysics*, 346(1-2): 45-59.
- Al-Zoubi, A., Shulman, H., Ben-Avraham, Z., 2002. Seismic reflection profiles across the southern Dead Sea basin. *Tectonophysics*, 346(1-2): 61-69.
- Aldersons, F., Ben-Avraham, Z., Hofstetter, A., Kissling, E., Al-Yazjeen, T., 2003. Lower-crustal strength under the Dead Sea basin from local earthquake data and rheological modeling. *Earth and Planetary Science Letters*, 214(1-2): 129-142. #26, 26 citations.**
- Bartov, Y., Enzel, Y., Porat, N., Stein, M., 2007. Evolution of the late pleistocene-holocene dead sea basin from sequence stratigraphy of fan deltas and lake-level reconstruction. *Journal of Sedimentary Research*, 77(9-10): 680-692.
- Bartov, Y., Goldstein, S.L., Stein, M., Enzel, Y., 2003. Catastrophic arid episodes in the Eastern Mediterranean linked with the North Atlantic Heinrich events. *Geology*, 31(5): 439-442. #9, 62 citations.**
- Bartov, Y., Stein, M., Enzel, Y., Agnon, A., Reches, Z., 2002. Lake levels and sequence stratigraphy of Lake Lisan, the late Pleistocene precursor of the Dead Sea. *Quaternary Research*, 57(1): 9-21. #5, 79 citations.**

- Begin, Z.B., Stein, M., Katz, A., Machlus, M., Rosenfeld, A., Buchbinder, B., Bartov, Y., 2004. Southward migration of rain tracks during the last glacial, revealed by salinity gradient in Lake Lisan (Dead Sea rift). *Quaternary Science Reviews*, 23(14-15): 1627-1636.
- Belmaker, R., Lazar, B., Tepelyakov, N., Stein, M., Beer, J., 2008. Be-10 in Lake Lisan sediments - A proxy for production or climate? *Earth and Planetary Science Letters*, 269(3-4): 447-456.
- Belmaker, R., Stein, M., Yechieli, Y., Lazar, B., 2007. Controls on the radiocarbon reservoir ages in the modern Dead Sea drainage system and in the last glacial Lake Lisan. *Radiocarbon*, 49(2): 969-982.
- Ben-Avraham, Z., Garfunkel, Z., Lazar, M., 2008. Geology and evolution of the southern dead sea fault with emphasis on subsurface structure. *Annual Review of Earth and Planetary Sciences*, 36: 357-387.
- Ben-Avraham, Z., Lyakhovsky, V., Schubert, G., 2010. Drop-down formation of deep basins along the Dead Sea and other strike-slip fault systems. *Geophysical Journal International*, 181(1): 185-197.
- Ben-Avraham, Z., Niemi, T.M., Heim, C., Negendank, J., Nur, A., 1999. Holocene stratigraphy of the Dead Sea: Correlation of high-resolution seismic reflection profiles to sediment cores. *Journal of Geophysical Research-Solid Earth*, 104(B8): 17617-17625.
- Ben-Avraham, Z., Schattner, U., Lazar, M., Hall, J.K., Ben-Gai, Y., Neev, D., Reshef, M., 2006. Segmentation of the Levant continental margin, eastern Mediterranean. *Tectonics*, 25(5).
- Ben-Avraham, Z., Schubert, G., 2006. Deep "drop down" basin in the southern Dead Sea. *Earth and Planetary Science Letters*, 251(3-4): 254-263.
- Benavraham, Z., 1992. DEVELOPMENT OF ASYMMETRIC BASINS ALONG CONTINENTAL TRANSFORM FAULTS. *Tectonophysics*, 215(1-2): 209-220. #22, 29 citations.**
- Benavraham, Z., Amit, G., Golan, A., Begin, Z.B., 1990a. THE BATHYMETRY OF LAKE KINNERET AND ITS STRUCTURAL SIGNIFICANCE. *Israel Journal of Earth Sciences*, 39(2-4): 77-83.
- Benavraham, Z., Grasso, M., 1991. CRUSTAL STRUCTURE VARIATIONS AND TRANSCURRENT FAULTING AT THE EASTERN AND WESTERN MARGINS OF THE EASTERN MEDITERRANEAN. *Tectonophysics*, 196(3-4): 269-277.
- Benavraham, Z., Lyakhovsky, V., 1992. FAULTING PROCESSES ALONG THE NORTHERN DEAD-SEA TRANSFORM AND THE LEVANT MARGIN. *Geology*, 20(12): 1139-1142.
- Benavraham, Z., Niemi, T.M., Neev, D., Hall, J.K., Levy, Y., 1993. DISTRIBUTION OF HOLOCENE SEDIMENTS AND NEOTECTONICS IN THE DEEP NORTH BASIN OF THE DEAD-SEA. *Marine Geology*, 113(3-4): 219-231.
- BenAvraham, Z., tenBrink, U., Bell, R., Reznikov, M., 1996. Gravity field over the Sea of Galilee: Evidence for a composite basin along a transform fault. *Journal of Geophysical Research-Solid Earth*, 101(B1): 533-544.
- Benavraham, Z., Tenbrink, U., Charrach, J., 1990b. TRANSVERSE FAULTS AT THE NORTHERN END OF THE SOUTHERN BASIN OF THE DEAD-SEA GRABEN. *Tectonophysics*, 180(1): 37-47.
- Benavraham, Z., Tibor, G., 1993. THE NORTHERN EDGE OF THE GULF OF ELAT. *Tectonophysics*, 226(1-4): 319-331.
- Benavraham, Z., Zoback, M.D., 1992. TRANSFORM-NORMAL EXTENSION AND ASYMMETRIC BASINS - AN ALTERNATIVE TO PULL-APART MODELS. *Geology*, 20(5): 423-426. #6, 75 citations.**
- Bookman, R., Enzel, Y., Agnon, A., Stein, M., 2004. Late Holocene lake levels of the Dead Sea. *Geological Society of America Bulletin*, 116(5-6): 555-571. #13, 45 citations.**
- Bookman, R., Lazar, B., Stein, M., Burr, G.S., 2007. Radiocarbon dating of primary aragonite by sequential extraction of CO₂. *Holocene*, 17(1): 131-137.

- Cloetingh, S., Ben-Avraham, Z., Sassi, W., Horvath, F., 1996. Dynamics of basin formation and strike-slip tectonics. *Tectonophysics*, 266(1-4): 1-10.
- Ehrhardt, A., Hubscher, C., Ben-Avraham, Z., Gajewski, D., 2005. Seismic study of pull-apart-induced sedimentation and deformation in the Northern Gulf of Aqaba (Elat). *Tectonophysics*, 396(1-2): 59-79.
- Ellenblum, R., Marco, S., Agnon, A., Rockwell, T., Boas, A., 1998. Crusader castle torn apart by earthquake at dawn, 20 May 1202. *Geology*, 26(4): 303-306. #11, 53 citations.**
- Enzel, Y., Bookman, R., Sharon, D., Gvirtzman, H., Dayan, U., Ziv, B., Stein, M., 2003. Late Holocene climates of the Near East deduced from Dead Sea level variations and modern regional winter rainfall. *Quaternary Research*, 60(3): 263-273. #8, 62 citations.**
- Eppelbaum, L., Ben-Avraham, Z., Katz, Y., 2004. Integrated analysis of magnetic, paleomagnetic and K-Ar data in a tectonic complex region: An example from the Sea of Galilee. *Geophysical Research Letters*, 31(19).
- Frumkin, A., Stein, M., 2004. The Sahara-East Mediterranean dust and climate connection revealed by strontium and uranium isotopes in a Jerusalem speleothem. *Earth and Planetary Science Letters*, 217(3-4): 451-464. #19, 33 citations.**
- Garfunkel, Z., Ben-Avraham, Z., 1996. The structure of the Dead Sea basin. *Tectonophysics*, 266(1-4): 155-176. #3, 90 citations.**
- Ginzburg, A., Ben-Avraham, Z., 1997. A seismic refraction study of the north basin of the Dead Sea, Israel. *Geophysical Research Letters*, 24(16): 2063-2066.
- Ginzburg, A., Ben-Avraham, Z., Makris, J., Hubral, P., Rotstein, Y., 1994. CRUSTAL STRUCTURE OF NORTHERN ISRAEL. *Marine and Petroleum Geology*, 11(4): 501-506.
- Gitterman, Y., Ben-Avraham, Z., Ginzburg, A., 1998. Spectral analysis of underwater explosions in the Dead Sea. *Geophysical Journal International*, 134(2): 460-472.
- Gottschammer, E., Wenzel, F., Wust-Bloch, H., Ben-Avraham, Z., 2002. Earthquake modeling in the Dead Sea Basin. *Geophysical Research Letters*, 29(12).
- Gradmann, S., Hubscher, C., Ben-Avraham, Z., Gajewski, D., Netzeband, G., 2005. Salt tectonics off northern Israel. *Marine and Petroleum Geology*, 22(5): 597-611.
- Haase-Schramm, A., Goldstein, S.L., 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*, 68(5): 985-1005. #12, 48 citations.**
- Haberland, C., Agnon, A., El-Kelani, R., Maercklin, N., Qabbani, I., Rumpker, G., Ryberg, T., Scherbaum, F., Weber, M., 2003. Modeling of seismic guided waves at the Dead Sea Transform. *Journal of Geophysical Research-Solid Earth*, 108(B7). #25, 26 citations.**
- Haberland, C., Maercklin, N., Kesten, D., Ryberg, T., Janssen, C., Agnon, A., Weber, M., Schulze, A., Qabbani, I., El-Kelani, R., 2007. Shallow architecture of the Wadi Araba fault (Dead Sea Transform) from high-resolution seismic investigations. *Tectonophysics*, 432(1-4): 37-50.
- Hadas, G., Segal, I., Yoffe, O., Stein, M., 2009. STUDY OF ROMAN ANCHOR FROM THE DEAD SEA SHORE*. *Archaeometry*, 51: 1008-1014.
- Halicz, L., Segal, I., Fruchter, N., Stein, M., Lazar, B., 2008. Strontium stable isotopes fractionate in the soil environments? *Earth and Planetary Science Letters*, 272(1-2): 406-411.
- Hazan, N., Stein, M., Agnon, A., Marco, S., Nadel, D., Negendank, J.F.W., Schwab, M.J., Neev, D., 2005. The late quaternary limnological history of Lake Kinneret (Sea of Galilee), Israel. *Quaternary Research*, 63(1): 60-77.
- Heidbach, O., Ben-Avraham, Z., 2007. Stress evolution and seismic hazard of the Dead Sea Fault System. *Earth and Planetary Science Letters*, 257(1-2): 299-312.

- Heifetz, E., Agnon, A., Marco, S., 2005. Soft sediment deformation by Kelvin Helmholtz Instability: A case from Dead Sea earthquakes. *Earth and Planetary Science Letters*, 236(1-2): 497-504.
- Heim, C., Nowaczyk, N.R., Negendank, J.F.W., Leroy, S.A.G., BenAvraham, Z., 1997. Near East desertification: Evidence from the Dead Sea. *Naturwissenschaften*, 84(9): 398-401. #21, 30 citations.**
- Kagan, E.J., Agnon, A., Bar-Matthews, M., Ayalon, A., 2005. Dating large infrequent earthquakes by damaged cave deposits. *Geology*, 33(4): 261-264.
- Katz, A., Agnon, A., Marco, S., 2009. Earthquake-induced barium anomalies in the Lisan Formation, Dead Sea Rift valley, Israel. *Earth and Planetary Science Letters*, 286(1-2): 219-229.
- Ken-Tor, R., Agnon, A., Enzel, Y., Stein, M., Marco, S., Negendank, J.F.W., 2001a. High-resolution geological record of historic earthquakes in the Dead Sea basin. *Journal of Geophysical Research-Solid Earth*, 106(B2): 2221-2234. #10, 54 citations.**
- Ken-Tor, R., Stein, M., Enzel, Y., Agnon, A., Marco, S., Negendank, J.F.W., 2001b. Precision of calibrated radiocarbon ages of historic earthquakes in the Dead Sea Basin. *Radiocarbon*, 43(3): 1371-1382.
- Kesten, D., Weber, M., Haberland, C., Janssen, C., Agnon, A., Bartov, Y., Rabba, I., Group, D., 2008. Combining satellite and seismic images to analyse the shallow structure of the Dead Sea Transform near the DESERT transect. *International Journal of Earth Sciences*, 97(1): 153-169.
- Kolodny, Y., Stein, M., Machlus, M., 2005. Sea-Rain-Lake relation in the Last Glacial East Mediterranean revealed by a delta O-18-delta C-13 in Lake Lisan aragonites. *Geochimica Et Cosmochimica Acta*, 69(16): 4045-4060.
- Larsen, B.D., Ben-Avraham, Z., Shulman, H., 2002. Fault and salt tectonics in the southern Dead Sea basin. *Tectonophysics*, 346(1-2): 71-90.
- Lazar, B., Enmar, R., Schossberger, M., Bar-Matthews, M., Halicz, L., Stein, M., 2004. Diagenetic effects on the distribution of uranium in live and Holocene corals from the Gulf of Aqaba. *Geochimica Et Cosmochimica Acta*, 68(22): 4583-4593.
- Lazar, M., Ben-Avraham, Z., Garfunkel, Z., Porat, N., Marco, S., 2010. Is the Jericho Escarpment a Tectonic or a Geomorphological Feature? Active Faulting and Paleoseismic Trenching. *Journal of Geology*, 118(3): 261-276.
- Lazar, M., Ben-Avraham, Z., Schattner, U., 2006. Formation of sequential basins along a strike-slip fault - Geophysical observations from the Dead Sea basin. *Tectonophysics*, 421(1-2): 53-69.
- Le Beon, M., Klinger, Y., Amrat, A.Q., Agnon, A., Dorbath, L., Baer, G., Ruegg, J.C., Charade, O., Mayyas, O., 2008. Slip rate and locking depth from GPS profiles across the southern Dead Sea Transform. *Journal of Geophysical Research-Solid Earth*, 113(B11).
- Lev, L., Boaretto, E., Heller, J., Marco, S., Stein, M., 2007. The feasibility of using Melanopsis shells as radiocarbon chronometers, Lake Kinneret, Israel. *Radiocarbon*, 49(2): 1003-1015.
- Lubberts, R.K., Ben-Avraham, Z., 2002. Tectonic evolution of the Qumran Basin from high-resolution 3.5-kHz seismic profiles and its implication for the evolution of the northern Dead Sea Basin. *Tectonophysics*, 346(1-2): 91-113.
- Lyakhovsky, V., Benavraham, Z., Achmon, M., 1994. THE ORIGIN OF THE DEAD-SEA RIFT. *Tectonophysics*, 240(1-4): 29-43.
- Machlus, M., Enzel, Y., Goldstein, S.L., Marco, S., Stein, M., 2000. Reconstructing low levels of Lake Lisan by correlating fan-delta and lacustrine deposits. *Quaternary International*, 73-4: 137-144. #23, 28 citations.**

- Makovsly, Y., Wunch, A., Ariely, R., Shaked, Y., Rivlin, A., Shemesh, A., Ben Avraham, Z., Agnon, A., 2008. Quaternary transform kinematics constrained by sequence stratigraphy and submerged coastline features: The Gulf of Aqaba. *Earth and Planetary Science Letters*, 271(1-4): 109-122.
- Marco, S., Agnon, A., 1995. PREHISTORIC EARTHQUAKE DEFORMATIONS NEAR MASADA, DEAD-SEA GRABEN. *Geology*, 23(8): 695-698. #7, 63 citations.**
- Marco, S., Agnon, A., 2005. High-resolution stratigraphy reveals repeated earthquake faulting in the Masada Fault Zone, Dead Sea Transform. *Tectonophysics*, 408(1-4): 101-112.
- Marco, S., Agnon, A., Ellenblum, R., Eidelman, A., Basson, U., Boas, A., 1997. 817-year-old walls offset sinistrally 2.1 m by the Dead Sea transform, Israel. *Journal of Geodynamics*, 24(1-4): 11-20. #20, 32 citations.**
- Marco, S., Hartal, M., Hazan, N., Lev, L., Stein, M., 2003. Archaeology, history, and geology of the A.D. 749 earthquake, Dead Sea transform. *Geology*, 31(8): 665-668.
- Marco, S., Rockwell, T.K., Heimann, A., Frieslander, U., Agnon, A., 2005. Late Holocene activity of the Dead Sea Transform revealed in 3D palaeoseismic trenches on the Jordan Gorge segment. *Earth and Planetary Science Letters*, 234(1-2): 189-205.
- Marco, S., Ron, H., McWilliams, M.O., Stein, M., 1998. High-resolution record of geomagnetic secular variation from Late Pleistocene Lake Lisan sediments (paleo Dead Sea). *Earth and Planetary Science Letters*, 161(1-4): 145-160.
- 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 Research-Solid Earth*, 101(B3): 6179-6191. #1, 110 citations.**
- Marco, S., Weinberger, R., Agnon, A., 2002. Radial clastic dykes formed by a salt diapir in the Dead Sea Rift, Israel. *Terra Nova*, 14(4): 288-294.
- Matmon, A., Shaked, Y., Porat, N., Enzel, Y., Finkel, R., Lifton, N., Boaretto, E., Agnon, A., 2005. Landscape development in an hyperarid sandstone environment along the margins of the Dead Sea fault: Implications from dated rock falls. *Earth and Planetary Science Letters*, 240(3-4): 803-817.
- Mechie, J., Abu-Ayyash, K., Ben-Avraham, Z., El-Kelani, R., Mohsen, A., Rumpker, G., Saul, J., Weber, M., 2005. Crustal shear velocity structure across the Dead Sea Transform from two-dimensional modelling of DESERT project explosion seismic data. *Geophysical Journal International*, 160(3): 910-924.
- Mechie, J., Abu-Ayyash, K., Ben-Avraham, Z., El-Kelani, R., Qabbani, I., Weber, M., Grp, D., 2009. Crustal structure of the southern Dead Sea basin derived from project DESIRE wide-angle seismic data. *Geophysical Journal International*, 178(1): 457-478.
- Meirova, T., Hofstetter, R., Ben-Avraham, Z., Steinberg, D.M., Malagnini, L., Akinci, A., 2008. Weak-motion-based attenuation relationships for Israel. *Geophysical Journal International*, 175(3): 1127-1140.
- Migowski, C., Agnon, A., Bookman, R., Negendank, J.F.W., 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*, 222(1): 301-314. #14, 44 citations.**
- Migowski, C., Stein, M., Prasad, S., Negendank, J.F.W., Agnon, A., 2006. Holocene climate variability and cultural evolution in the Near East from the Dead Sea sedimentary record. *Quaternary Research*, 66(3): 421-431. #17, 35 citations.**
- Neumann, F.H., Kagan, E.J., Schwab, M.J., Stein, M., 2007. Palynology, sedimentology and palaeoecology of the late Holocene Dead Sea. *Quaternary Science Reviews*, 26(11-12): 1476-1498.

- Neumann, F.H., Kagan, E.J., Stein, M., Agnon, A., 2009. Assessment of the effect of earthquake activity on regional vegetation - High-resolution pollen study of the Ein Feshka section, Holocene Dead Sea. *Review of Palaeobotany and Palynology*, 155(1-2): 42-51.
- Niemi, T.M., Benavraham, Z., 1994. EVIDENCE FOR JERICHO EARTHQUAKES FROM SLUMPED SEDIMENTS OF THE JORDAN RIVER DELTA IN THE DEAD-SEA. *Geology*, 22(5): 395-398.
- Oth, A., Wenzel, F., Wust-Bloch, H., Gottschaaemmer, E., Ben-Avraham, Z., 2007. Parameterization of a composite attenuation relation for the Dead Sea area based on 3-D modeling of elastic wave propagation. *Pure and Applied Geophysics*, 164(1): 23-37.
- Prasad, S., Negendank, J.F.W., Stein, M., 2009. Varve counting reveals high resolution radiocarbon reservoir age variations in palaeolake Lisan. *Journal of Quaternary Science*, 24(7): 690-696.
- Reshef, M., Ben-Avraham, Z., Tibor, G., Marco, S., 2007. The use of acoustic imaging to reveal fossil fluvial systems - a case study from the southwestern Sea of Galilee. *Geomorphology*, 83(1-2): 58-66.
- Reshef, M., Shulman, H., Ben-Avraham, Z., 2003. A case study of sub-basalt imaging in land region covered with basalt flows. *Geophysical Prospecting*, 51(3): 247-260.
- Roberts, N., Jones, M.D., Benkaddour, A., Eastwood, W.J., Filippi, M.L., Frogley, M.R., Lamb, H.F., Leng, M.J., Reed, J.M., Stein, M., Stevens, L., Valero-Garces, B., Zanchetta, G., 2008. Stable isotope records of Late Quaternary climate and hydrology from Mediterranean lakes: the ISOMED synthesis. *Quaternary Science Reviews*, 27(25-26): 2426-2441.
- Ron, H., Nowaczyk, N.R., Frank, U., Schwab, M.J., Naumann, R., Striewski, B., Agnon, A., 2007. Greigite detected as dominating remanence carrier in late pleistocene sediments, lisan formation, from Lake Kinneret (Sea of Galilee), Israel. *Geophysical Journal International*, 170(1): 117-131.
- Sagy, A., Reches, Z., Agnon, A., 2003. Hierarchic three-dimensional structure and slip partitioning in the western Dead Sea pull-apart. *Tectonics*, 22(1).
- Schattner, U., Ben-Avraham, Z., Lazar, M., Huebscher, C., 2006a. Tectonic isolation of the Levant basin offshore Galilee-Lebanon - effects of the Dead Sea fault plate boundary on the Levant continental margin, eastern Mediterranean. *Journal of Structural Geology*, 28(11): 2049-2066.
- Schattner, U., Ben-Avraham, Z., Reshef, M., Bar-Am, G., Lazar, M., 2006b. Oligocene-Miocene formation of the Haifa basin: Qishon-Sirhan rifting coeval with the Red Sea-Suez rift system. *Tectonophysics*, 419(1-4): 1-12.
- Schramm, A., Stein, M., Goldstein, S.L., 2000. Calibration of the C-14 time scale to > 40 ka by U-234-Th-230 dating of Lake Lisan sediments (last glacial Dead Sea). *Earth and Planetary Science Letters*, 175(1-2): 27-40. #2, 98 citations.**
- Segev, A., Rybakov, M., Lyakhovskiy, V., Hofstetter, A., Tibor, G., Goldshmidt, V., Ben Avraham, Z., 2006. The structure, isostasy and gravity field of the Levant continental margin and the southeast Mediterranean area. *Tectonophysics*, 425(1-4): 137-157.
- Shaked, Y., Agnon, A., Lazar, B., Marco, S., Avner, U., Stein, M., 2004. Large earthquakes kill coral reefs at the north-west Gulf of Aqaba. *Terra Nova*, 16(3): 133-138.
- Smit, J., Brun, J.P., Cloetingh, S., Ben-Avraham, Z., 2008a. Pull-apart basin formation and development in narrow transform zones with application to the Dead Sea Basin. *Tectonics*, 27(6).
- Smit, J., Brun, J.P., Cloetingh, S., Ben-Avraham, Z., 2010. The rift-like structure and asymmetry of the Dead Sea Fault. *Earth and Planetary Science Letters*, 290(1-2): 74-82.
- Smit, J., Brun, J.P., Fort, X., Cloetingh, S., Ben-Avraham, Z., 2008b. Salt tectonics in pull-apart basins with application to the Dead Sea Basin. *Tectonophysics*, 449(1-4): 1-16.
- Stein, M., 2001. The sedimentary and geochemical record of Neogene-Quaternary water bodies in the Dead Sea Basin - inferences for the regional paleoclimatic history. *Journal of Paleolimnology*, 26(3): 271-282. #16, 38 citations.**

- Stein, M., Almogi-Labin, A., Goldstein, S.L., Hemleben, C., Starinsky, A., 2007. Late Quaternary changes in desert dust inputs to the Red Sea and Gulf of Aden from Sr-87/Sr-86 ratios in deep-sea cores. *Earth and Planetary Science Letters*, 261(1-2): 104-119.
- Stein, M., Goldstein, S.L., Schramm, A., 2000a. Radiocarbon calibration beyond the dendrochronology range. *Radiocarbon*, 42(3): 415-422.
- Stein, M., Migowski, C., Bookman, R., Lazar, B., 2004. Temporal changes in radiocarbon reservoir age in the dead sealake Lisan system. *Radiocarbon*, 46(2): 649-655.
- Stein, M., Starinsky, A., Agnon, A., Katz, A., Raab, M., Spiro, B., Zak, I., 2000b. The impact of brine-rock interaction during marine evaporite formation on the isotopic Sr record in the oceans: Evidence from Mt. Sedom, Israel. *Geochimica Et Cosmochimica Acta*, 64(12): 2039-2053. #24, 28 citations.**
- Stein, M., Starinsky, A., Katz, A., Goldstein, S.L., Machlus, M., Schramm, A., 1997. Strontium isotopic, chemical, and sedimentological evidence for the evolution of Lake Lisan and the Dead Sea. *Geochimica Et Cosmochimica Acta*, 61(18): 3975-3992. #4, 85 citations.**
- Stein, M., Torfstein, A., Gavrieli, I., Yechieli, Y., 2010. Abrupt aridities and salt deposition in the post-glacial Dead Sea and their North Atlantic connection. *Quaternary Science Reviews*, 29(3-4): 567-575.
- Tenbrink, U.S., Benavraham, Z., Bell, R.E., Hassounch, M., Coleman, D.F., Andreasen, G., Tibor, G., Coakley, B., 1993. STRUCTURE OF THE DEAD-SEA PULL-APART BASIN FROM GRAVITY ANALYSES. *Journal of Geophysical Research-Solid Earth*, 98(B12): 21877-21894. #18, 34 citations.**
- Tenbrink, U.S., Schoenberg, N., Kovach, R.L., Benavraham, Z., 1990. UPLIFT AND A POSSIBLE MOHO OFFSET ACROSS THE DEAD-SEA TRANSFORM. *Tectonophysics*, 180(1): 71-85.
- Tibor, G., Benavraham, Z., 1992. LATE TERTIARY SEISMIC FACIES AND STRUCTURES OF THE LEVANT PASSIVE MARGIN OFF CENTRAL ISRAEL, EASTERN MEDITERRANEAN. *Marine Geology*, 105(1-4): 253-273.
- Tibor, G., Benavraham, Z., Steckler, M., Fligelman, H., 1992. LATE TERTIARY SUBSIDENCE HISTORY OF THE SOUTHERN LEVANT MARGIN, EASTERN MEDITERRANEAN-SEA, AND ITS IMPLICATIONS TO THE UNDERSTANDING OF THE MESSINIAN EVENT. *Journal of Geophysical Research-Solid Earth*, 97(B12): 17593-17614.
- Torfstein, A., Gavrieli, I., Katz, A., Kolodny, Y., Stein, M., 2008. Gypsum as a monitor of the paleo-limnological-hydrological conditions in Lake Lisan and the Dead Sea. *Geochimica Et Cosmochimica Acta*, 72(10): 2491-2509.
- Torfstein, A., Gavrieli, I., Stein, M., 2005. The sources and evolution of sulfur in the hypersaline Lake Lisan (paleo-Dead Sea). *Earth and Planetary Science Letters*, 236(1-2): 61-77.
- Torfstein, A., Haase-Schramm, A., Waldmann, N., Kolodny, Y., Stein, M., 2009. U-series and oxygen isotope chronology of the mid-Pleistocene Lake Amora (Dead Sea basin). *Geochimica Et Cosmochimica Acta*, 73(9): 2603-2630.
- van der Borg, K., Stein, M., de Jong, A.F.M., Waldmann, N., Goldstein, S.L., 2004. Near-zero Delta C-14 values at 32 kyr cal BP observed in the highresolution C-14 record from U-Th dated sediment of Lake Lisan. *Radiocarbon*, 46(2): 785-795.
- Waldmann, N., Starinsky, A., Stein, M., 2007. Primary carbonates and Ca-chloride brines as monitors of a paleo-hydrological regime in the Dead Sea basin. *Quaternary Science Reviews*, 26(17-18): 2219-2228.
- Waldmann, N., Stein, M., Ariztegui, D., Starinsky, A., 2009. Stratigraphy, depositional environments and level reconstruction of the last interglacial Lake Samra in the Dead Sea basin. *Quaternary Research*, 72(1): 1-15.

- Waldmann, N., Torfstein, A., Stein, M., 2010. Northward intrusions of low- and mid-latitude storms across the Saharo-Arabian belt during past interglacials. *Geology*, 38(6): 567-570.
- Weber, M., Abu-Ayyash, K., Abueladas, A., Agnon, A., et al. 2009. ANATOMY OF THE DEAD SEA TRANSFORM FROM LITHOSPHERIC TO MICROSCOPIC SCALE. *Reviews of Geophysics*, 47.
- Weber, M., Ayyash, K.A., Abueladas, A., Agnon, A., et al. (Desert Group), 2004. The crustal structure of the Dead Sea Transform. *Geophysical Journal International*, 156(3): 655-681. #15, 41 citations.**
- Weinberger, R., Agnon, A., Ron, H., 1997. Paleomagnetic reconstruction of a diapir emplacement: A case study from Sedom diapir, the Dead Sea Rift. *Journal of Geophysical Research-Solid Earth*, 102(B3): 5173-5192.
- Weinberger, R., Agnon, A., Ron, H., Garfunkel, Z., 1995. ROTATION ABOUT AN INCLINED AXIS - 3-DIMENSIONAL MATRICES FOR RECONSTRUCTING PALEOMAGNETIC AND STRUCTURAL DATA. *Journal of Structural Geology*, 17(6): 777-782.
- Weinstein, Y., Navon, O., Altherr, R., Stein, M., 2006. The role of lithospheric mantle heterogeneity in the generation of Plio-Pleistocene alkali basaltic suites from NW Harrat Ash Shaam (Israel). *Journal of Petrology*, 47(5): 1017-1050.