Late Pleistocene paleomagnetic secular variation from the Sea of Galilee, Israel

Shmuel Marco
Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv, Israel

Received 6 September 2001; revised 23 April 2002; accepted 23 April 2002; published 5 November 2002.

[1] Stable magnetization of laminated lacustrine Lisan Formation show typical paleomagnetic secular variation and a possible geomagnetic field excursion. ^{14}C ages from the top and assumed 0.9 mm/yr deposition rate constrain the recorded section between 29–28 ka and 22–23 ka. Samples were recovered from two trenches at the southwestern shore of the Sea of Galilee, a graben within the Dead Sea Transform system. The angle between the two site mean directions is 21°, but retilting the beds to horizontal reduces it to 7°, indicating pre-folding, probably depositional magnetization. Aberrations of field directions at one locality, where VGPs deviate >40° from the geographic north, and low NRM intensities between 29–28 ka and 25–24 ka, are contemporaneous with the Mono Lake Excursion. If the correlation is correct, the new data support the hypothesis that the excursion was global, justifying its utilization as a chronological datum. *INDEX TERMS:* 1513 Geomagnetism and Paleomagnetism: Geomagnetic excursions; 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy; 1522 Geomagnetism and Paleomagnetism: Paleomagnetic secular variation; 1560 Geomagnetism and Paleomagnetism: Time variations—secular and long term; 1540 Geomagnetism and Paleomagnetism: Rock and mineral magnetism. **Citation:** Marco, S., Late Pleistocene paleomagnetic secular variation from the Sea of Galilee, Israel, *Geophys. Res. Lett.*, *29*(21), 2015, doi:10.1029/2001GL014038, 2002.

1. Introduction

[2] Extremely low level of the Sea of Galilee ("Kinneret" in Hebrew) in the last couple of years exposed a new area, which provides an opportunity to investigate stratigraphic sections that were under water.

[3] The purpose of the study is to recover the paleomagnetic record from pre-Kinneret sediments. In particular, I searched for secular variation of the geomagnetic field and distinct features, possibly field excursions, which can serve for magnetostratigraphy. Geomagnetic excursions are defined as deviations of the virtual geomagnetic poles (VGP) by more than 40° from geographic north that return to the pre-existing polarity [*Barbetti and McElhinny*, 1976; *Merrill and McFadden*, 1994]. During periods of constant polarity geomagnetic excursions can serve as magnetostratigraphic markers, provided their precise ages are determined and their regional or global manifestation is ascertained. The present paleomagnetic analysis is based on a total of 126 samples from two 4.5-m-deep trenches (47 + 79). The trenches were excavated 30 m apart in the Ohalo Paleolithic site, the southwestern shore of the Kinneret (Figure 1), Trench OH1 in 1999 and Trench OH2 in 2000. The lake water that flooded the trenches limited the working time to 5–6 hours. The sediments exposed in the trenches are damp, soft, 0.5–1 mm thick laminas of alternating fine detritus and aragonite. The excellent preservation and the high sedimentation rate are important where fine details of paleomagnetic secular variation are sought. A northward ~16° dip was measured at OH1, whereas in OH2 the beds are horizontal.

[4] The age of the section is constrained by the archeological site at its top. Over 30 ^{14}C dates determined by several different laboratories fall between 19 and 20 thousands carbon years [*Nadel et al.*, 2001; 1995]. *Schramm et al.* [2000] show that between 18 and 25 ka the U series ages are consistently 3 kyrs older than ^{14}C ages. Assuming that U series reflect calendar ages, Ohalo site is 22–23 kyrs old. Based on the age and the laminated lacustrine nature of the sediment, the section is attributed to the Lisan Formation, deposited from 70 ka to 15 ka [*Kaufman et al.*, 1992; *Schramm et al.*, 2000]. I further assume a deposition rate of about 0.9 mm/yr, like the Lisan Formation near the Dead Sea and the Holocene deposits in the Kinneret [*Thompson et al.*, 1985]. The bottom of the studied section is therefore about 28–29 ka.

[5] Sampling for paleomagnetic analyses was done with standard 8 cm^3 plastic boxes. The magnetization was measured with a "2G Enterprise" cryogenic magnetometer at the Geophysical Institute of Israel.

[6] Following the measurement of the natural remanent magnetism (NRM) the samples were subjected to stepwise demagnetization by an alternating field (AF), starting with 5 milliTesla (mT) and going up to 80 mT in 5 or 10 mT increments until the remaining intensity of the sample dropped to about 5%–20% of the initial NRM value. Characteristic directions were defined by a principal component analysis [*Kirschvink*, 1980]. The characteristic direction is that of the longest segment of several demagnetization levels with the largest R that passes a 1° linearity test. R is the length of the resultant vector normalized to the absolute sum of individual vectors.

2. Results and Discussion

[7] All but five samples show stable directions often with a soft overprint that is removed by AF of 5 mT. The unstable samples were omitted from the analyses.

2.1. Deformation

[8] Young deformation in the Sea of Galilee basin is evident at the surface as open folds in the Lisan Formation in the Ohalo site, and earthquake ruptures along the Dead

0094-8276/02/2001GL014038$05.00

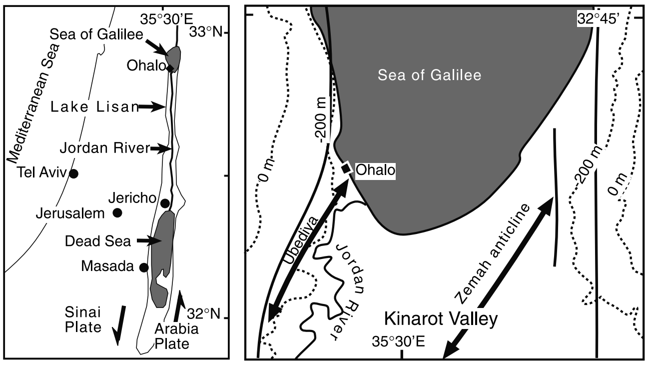

Figure 1. Location maps. The faults (solid lines) are part of the Dead Sea Transform system. An anticline (double arrow) that is exposed in Ubediya as well as seismic reflections across the Kinarot Valley [*Rotstein et al.*, 1992] appears to affect the Ohalo area.

Sea Transform [*Ellenblum et al.*, 1998; *Marco et al.*, 2000]. Seismic images and geological observations also reveal recent deformation [*Ben-Avraham et al.*, 1986; *Heimann and Ron*, 1993; *Rotstein et al.*, 1992]. An anticline that is exposed nearby in Ubediya and is evident in seismic reflections across the Kinarot Valley appears to affect the Ohalo area as well (Figure 1).

[9] Since the two exposures are only 30 m apart, identical in age and lithology, the different paleomagnetic directions are attributed to the open folds that are apparent in the Ohalo site. The 5-kyr-long studied section is too short to average out the secular variation, therefore only the relative movement of the two exposures can be demonstrated as a 21° difference of the mean paleomagnetic directions. Rotating the tilted OH1 beds 16° about their strike back to horizontal reduces the difference to 7°. This reduction indicates a pre-folding, depositional magnetization. Locking-in of magnetization may postdate deposition by up to several centuries [*Marco et al.*, 1999].

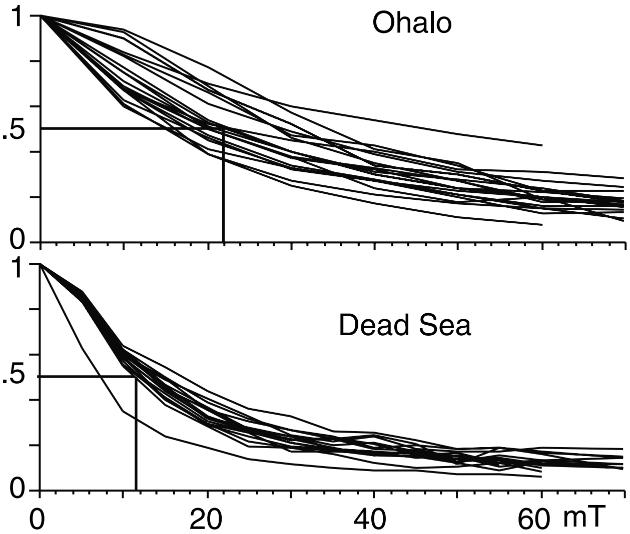

Figure 2. Demagnetization curves of all Ohalo samples compared with those of Lisan Formation from Dead Sea area. Median destructive field in Ohalo ranges between 15 and 35 mT with average of 21 mT. Mean MDF value in Dead Sea samples is 12 mT.

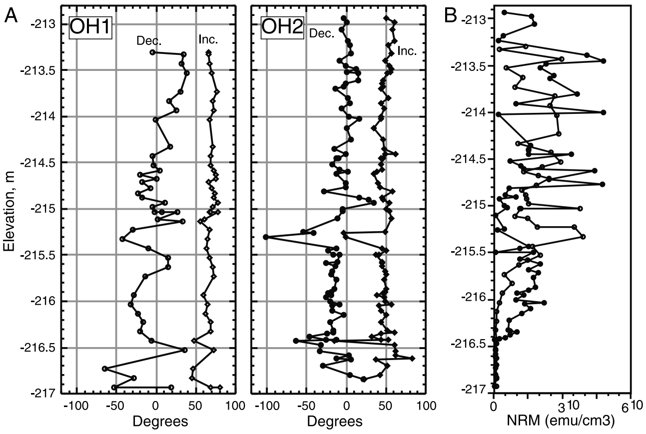

Figure 3. A. Characteristic declinations (circles) and inclinations (diamonds) in the Ohalo sections. Prominent aberrations appear between −215 m and −215.5 m and between −216.4 and −217 m (relative to mean sea level). B. Lower NRMs at the bottom coincide with the aberations.

2.2. Magnetic Properties

[10] Between 80% and 95% of the NRM is typically removed by applying an alternating field of 35 mT to 70 mT. This portion of the NRM is carried by low- to medium-coercivity minerals. High-coercivity grains, possibly hematite and/or goethite or other single-domain grains, carry the remaining 5%–20%. The direction is commonly very stable even at high levels of AF. The median destructive field (MDF) is between 15 and 35 mT with average of 21 mT (Figure 2). NRM intensities are typically an order of magnitude higher than in the Lisan Formation near the Dead Sea [*Marco et al.*, 1998], and the typical coercivity is somewhat higher too. This might be due to either a higher content of magnetic minerals or higher content of single-domain ferromagnetic grains. Detritus from Tertiary flood basalts around the Sea of Galilee probably cause these differences.

2.3. Secular Variations

[11] The current declination in the study area is 3° and the inclination is 48°. The characteristic field directions (Figure 3) show typical secular variation with larger variation in the declinations. Similar pattern of secular variation in the two sections indicates reliable magnetic signals. Another indication for the signal reliability is the lack of correlation between the magnetic directions and changes in the lithology, a problem that was noted in other sections and discussed

Table 1. Mean Directions and Fisher Statistics

Group	Dec./ Inc.	α_{95}	κ	R	VGP Lat.	VGP Lon.	dp	dm	VGP-GAD
OH1-NRM	351/71	5.1	16	0.94	66	23	5.0	8.9	24
OH1-Ch	354/70	3.4	44	0.98	68	26	3.5	5.9	22
OH2-NRM	348/45	5.8	6	0.84	78	278	9.9	7.3	12
OH2-Ch	349/49	3.9	18	0.94	80	292	6.3	5.2	10

All angles are in degrees. For each trench the NRM and the characteristic (Ch) mean directions are presented.

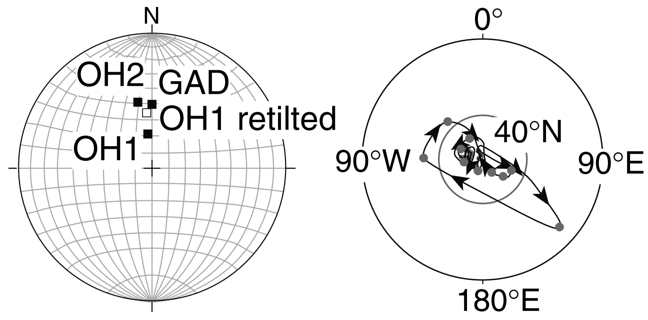

Figure 4. Left: The mean directions are compared to the GAD (0°/52°) and to retilted OH1 (open symbol). Right: The Mono Lake Excursion may be detected where the VGPs deviate by more than 40° from GAD. Equal angle projection shows the OH2 poles from −216 to −214 m.

by *Jacobs* [1994]. The scatter of the NRMs (R = 0.94, κ = 15.8, and α_{95} = 5.4°) is significantly larger than that of the characteristic directions, where R = 0.98, κ = 44, and α_{95} = 3° (Table 1), indicating the presence of an overprint. The mean VGPs of OH1 and OH2 deviate from the geographic north 22° and 10° respectively. The deviation is probably caused by both inadequate averaging of the secular variation and by local deformation, mostly folding, that cause the difference between the two sites.

2.4. Mono Lake Excursion?

[12] Conspicuous aberrations of the field directions are observed in section OH2 and less clearly in OH1 between −215 and −215.5 m and between −216.4 and −217 m. The VGPs in few samples deviate by over 40° from GAD (Figure 4). NRM intensities are significantly lower than in the samples above. NRM does not necessarily reflect paleo field intensity, but considering the uniform nature of the sediments the coincidence is worth noting. The anomalous direction and intensity are contemporaneous with the Mono Lake Excursion (MLE), originally noted by *Denham and Cox* [1971] and later by others (Table 2). If the identification of the MLE is correct, the Ohalo record shows that the MLE may be comprised of two 600–700 yr long sub-events separated by nearly a millennium of relatively normal secular variation. The excursion occurs within maximum range of 29–24 ka and minimum range of 28–25 ka. The problems concerning the nature and age of the Mono Lake excursion have been discussed elsewhere [e.g., *Jacobs*, 1994 and references therein]. The present study possibly adds another location to the list of the excursion. It certainly requires repetition in more samples before the MLE can be declared here. If at the end the MLE proves to be absent from the Middle East records, the hypothesis that the MLE is regional instead of global nature is strengthened. The results of this study will be compared to the contemporaneous records of the Lisan Formation near the Dead Sea [*Freed et al.*, 2001; *Marco et al.*, 1998]. The accrual of these kinds of data from around the world is needed to resolve this issue.

3. Conclusions

[13] The sediments from two trenches in the Lisan Formation show stable depositional magnetization, which record typical secular variation. The inclinations from one trench are consistently steeper than the other set due to folding, but the 21° difference is reduced from to 7° after tilt correction, indicating pre-folding magnetization. The folds reflect the last 20 kyr internal deformation of the basin.

[14] Comparison to other studies show that the magnetic properties of the Lisan Formation vary according to locally exposed rocks.

[15] Conspicuous aberrations of the field directions occur within maximum age range of 29–24 ka, similar to the age of the MLE in other places. The possible detection of the MLE here supports the hypothesis of the global nature of the excursion, justifying its utilization as a worldwide chronological datum. Repetition of denser sampling and more precise dating is needed in order to portray the detailed behavior of the field.

[16] **Acknowledgments.** I thank Dani Nadel who discovered the Paleolithic site at Ohalo and heads the archeological excavations, introduced me to the site and provided the trenches and assistance in fieldwork. Hagai Ron is acknowledged for fruitful discussions. Joseph C. Liddicoat

Table 2. Records of the Mono Lake Excursion

Location	Rock type	Dating methods	Age, ka	Reference
Mono Lake, California	Lacustrine	^{14}C and tephra stratigraphy	26	*Denham and Cox* [1971]
Mono Lake, California	Lacustrine	^{14}C and tephra stratigraphy		*Liddicoat and Coe* [1979]
Mono Basin, California, Carson Sink and Pyramid Lake, Nevada	Lacustrine	^{14}C and tephra stratigraphy	28	*Liddicoat* [1992]
Mono Lake, California	Lacustrine	^{14}C and tephra stratigraphy		*Coe and Liddicoat* [1994]
Lake Lahontan, Nevada	Lacustrine	^{14}C and tephra stratigraphy	28–26	*Liddicoat* [1996]; *Liddicoat et al.* [1982]
Summer Lake, Oregon	Lacustrine	Tephra stratigraphy	28–25	*Negrini et al.* [1984]
Gulf of California	Marine	^{14}C and Biostratigraphy	29–26	*Levi and Karlin* [1989]
Tule Lake, California	Lacustrine	Tephra stratigraphy	28–27	*Rieck et al.* [1992]
Santa Maria Volcano, Guatemala	Magmatic	Magma flux	28–25	*Conway et al.* [1994]
Yermak Plateau	Marine	^{14}C and ^{18}O, ^{10}Be, ^{230}Th stratigraphy	29–24	*Nowaczyk et al.* [1994]
Greenland Sea	Marine	^{14}C, ^{13}C, ^{18}O, and Biostratigraphy	28–27	*Nowaczyk and Antonow* [1997]
Iceland Sea	Marine	^{14}C and Biostratigraphy	34.5–33.5	*Voelker-Antje et al.*, [2000]
Kumaun, North India	Fluvio-lacustrine	^{14}C	26–25	*Kotlia et al.* [1997]
Uttar Pradesh, India	Fluvio-lacustrine	^{14}C	25–24	*Bhalla et al.* [1998]
Sea of Galilee, Israel	Lacustrine	^{14}C	29–24	This study

and an anonymous reviewer are thanked for constructive reviews. Financial support was received from Israel Science Foundation grant #690/99.

References

Barbetti, M. F., and M. W. McElhinny, The Lake Mungo geomagnetic excursion, *Philos. Trans. R. Soc. London*, *281*, 515–542, 1976.

Ben-Avraham, Z., G. Shaliv, and A. Nur, Acoustic reflectivity and shallow sedimentary structure in the Sea of Galilee, Jordan Valley, *Marine Geology*, *70*, 175–189, 1986.

Bhalla, M. S., B. S. Kotlia, and K. Subrahmanyam, Magnetostratigraphy of fluviolacustrine sediments from Pithoragarh area, Uttar Pradesh, *Journal of the Geological Society of India*, *51*(2), 167–170, 1998.

Coe, R. S., and J. C. Liddicoat, Overprinting of natural magnetic remanence in lake sediments by a subsequent high-intensity field, *Nature*, *367*, 57–59, 1994.

Conway, F. M., J. F. Diehl, W. I. Rose, and O. Matias, Age and magma flux of Santa Maria Volcano, Guatemala; correlation of paleomagnetic waveforms with the 28,000 to 25,000 yr. B.P. Mono Lake excursion, *Journal of Geology*, *102*(1), 11–24, 1994.

Denham, C. R., and A. Cox, Evidence that the Laschamp polarity event did not occur 13,300–30,400 years ago, *Earth Planet. Sci. Lett.*, *13*, 181–190, 1971.

Ellenblum, R., S. Marco, A. Agnon, T. Rockwell, and A. Boas, Crusader castle torn apart by earthquake at dawn, 20 May 1202, *Geology*, *26*(4), 303–306, 1998.

Freed, M., M. Stein, A. Starinsky, S. Marco, H. Ron, and J. Beer, Secular variations in the geomagnetic field and distribution of cosmogenic nuclides: Evidence from the Lisan Formation, in *Isr. Geol. Soc. Ann. Meeting*, edited by Z. Gvirtzman and R. Amit, 35 pp., Elat, 2001.

Heimann, A., and H. Ron, Geometric changes of plate boundaries along part of the northern Dead Sea Transform: Geochronologic and paleomagnetic evidence, *Tectonics*, *12*(2), 477–491, 1993.

Jacobs, J. A., *Reversals of the Earth Magnetic Field*, 346 pp., Cambridge University Press, 1994.

Kaufman, A., Y. Yechieli, and M. Gardosh, Reevaluation of the lake-sediment chronology in the Dead Sea Basin, Israel, based on new $^{230}Th/^{234}U$ dates, *Quat. Res.*, *38*, 292–304, 1992.

Kirschvink, J. L., The least-squares line and plane analysis of paleomagnetic data, *Geophys. J. R. Astron. Soc.*, *62*, 699–718, 1980.

Kotlia, B. S., M. S. Bhalla, C. Sharma, G. Rajagopalan, R. Ramesh, M. S. Chauhan, P. D. Mathur, S. Bhandari, and T. Chacko, Palaeoclimatic conditions in the upper Pleistocene and Holocene Bhimtal-Naukuchiatal lake basin in south-central Kumaun, North India, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *130*(1–4), 307–322, 1997.

Levi, S., and R. Karlin, A sixty thousand year paleomagnetic record from Gulf of California sediments: Secular variation, late Quaternary excursions and geomagnetic implications, *Earth Planet. Sci. Lett.*, *92*, 219–233, 1989.

Liddicoat, J. C., Mono Lake excursion in Mono basin, California, and at Carson Sink and Pyramid Lake, *Geophys. J. Int.*, *108*, 442–452, 1992.

Liddicoat, J. C., Mono Lake Excursion in the Lahontan Basin, Nevada, *Geophys. J. Int.*, *125*(2), 630–635, 1996.

Liddicoat, J. C., and R. S. Coe, Mono Lake geomagnetic excursion, *J. Geophys. Res.*, *84*(B1), 261–271, 1979.

Liddicoat, J. C., K. R. Lajoie, and A. M. Sarna-Wojcicki, Detection and dating of the Mono Lake Excursion in the Lake Lahontan Sehoo Formation, Carson Sink, Nevada, in *Eos, Transactions, American Geophysical Union*, pp. 920, American Geophysical Union, 1982.

Marco, S., H. Ron, M. O. McWilliams, and M. Stein, High-Resolution Record of Geomagnetic Secular Variation from Late Pleistocene Lake Lisan Sediments (Paleo Dead Sea), *Earth Planet. Sci. Lett.*, *161*, 145–160, 1998.

Marco, S., H. Ron, M. O. McWilliams, and M. Stein, The locking in of remanence in Late Pleistocene sediments of Lake Lisan (palaeo Dead Sea), in *Palaeomagnetism and Diagenesis in Sediments*, edited by D. H. Tarling and P. Turner, pp. 47–52, Geological Society, London, Special Publications, London, 1999.

Marco, S., T. Rockwell, A. Heimann, A. Agnon, and R. Ellenblum, Historical earthquake deformations revealed by 3D trenching on Dead Sea Transform, in *Hokudan International Symposium and School on Active Faulting*, edited by K. Okumura, K. Takada, and H. Goto, pp. 261–263, Hokudan, Japan, 2000.

Merrill, R. T., and P. L. McFadden, Geomagnetic field stability: Reversal events and excursions, *Earth Planet. Sci. Lett.*, *121*, 57–69, 1994.

Nadel, D., I. Carmi, and D. Segal, Radiocarbon dating of Ohalo II: Archaeological and methodological implications, *Journal of Archaeological Science*, *22*(6), 811–822, 1995.

Nadel, D., S. Belitzky, E. Boaretto, I. Carmi, J. Heinemeier, E. Werker, and S. Marco, New dates from submerged Late Pleistocene sediments in the southern Sea of Galilee, Israel, *Radiocarbon*, *43*(2), 1167–1178, 2001.

Negrini, R. M., J. O. Davis, and K. L. Verosub, Mono Lake geomagnetic excursion found at Summer Lake, Oregon, *Geology*, *12*(11), 643–646, 1984.

Nowaczyk, N. R., and M. Antonow, High-resolution magnetostratigraphy of four sediment cores from the Greenland Sea; I, Identification of the Mono Lake excursion, Laschamp and Biwa I/Jamaica geomagnetic polarity events, *Geophys. J. Int.*, *131*(2), 310–324, 1997.

Nowaczyk, N. R., T. W. Frederichs, A. Eisenhauer, and G. Gard, Magnetostratigraphic data from late Quaternary sediments from the Yermak Plateau, Arctic Ocean: Evidence for four geomagnetic polarity events within the last 170 Ka of the Brunhes Chron, *Geophys. J. Int.*, *117*, 453–471, 1994.

Rieck, H. J., A. M. Sarna-Wojcicki, C. E. Meyer, and D. P. Adam, Magnetostratigraphy and tephrochronology of an upper Pliocene to Holocene record in lake sediments at Tulelake, Northern California, *Geological Society of America Bulletin*, *104*(4), 409–428, 1992.

Rotstein, Y., Y. Bartov, and U. Frieslander, Evidence for local shifting of the main fault and changes in the structural setting, Kinarot basin, Dead Sea transform, *Geology*, *20*, 251–254, 1992.

Schramm, A., M. Stein, and S. L. Goldstein, Calibration of the ^{14}C time scale to 50 kyr by ^{234}U-^{230}Th dating of sediments from Lake Lisan (the paleo-Dead Sea), *Earth Planet. Sci. Lett.*, *175*, 27–40, 2000.

Thompson, R., G. M. Turner, M. Stiller, and A. Kaufman, Near East paleomagnetic secular variation recorded in sediments from the Sea of Galilee (Lake Kinneret), *Quaternary Res.*, 1985.

Voelker-Antje, H. L., P. M. Grootes, M. J. Nadeau, and M. Sarnthein, Radiocarbon levels in the Iceland Sea from 25–53 kyr and their link to the Earth's magnetic field intensity, *Radiocarbon*, *42*(3), 437–452, 2000.

S. Marco, Department of Geophysics and Planetary Sciences, Tel Aviv University, Tel Aviv, 69978, Israel. (shmulik@terra.tau.ac.il)