Full-Vector Paleomagnetic Secular Variation Records from Latest Quaternary Sediments of Lake Malawi (10.0°S, 34.3°E)

Steve Lund¹, Ellen Platzman¹, and Tom Johnson²

- 1) Department of Earth Sciences, University of Southern California, Los Angeles
2) Large Lakes Observatory, University of Minnesota-Duluth

Abstract

We have conducted a paleomagnetic study of Late Quaternary sediments from Lake Malawi, East Africa, in order to develop a high-resolution record of paleomagnetic secular variation (PSV). This study has recovered PSV records from two cores (3P, 6P) in northern Lake Malawi (10.0°S, 34.3°E). The PSV appears to be recorded in fine-grained detrital magnetite/titanomagnetite grains. Detailed af demagnetization of the natural remanence (NRM) shows that a distinctive characteristic remanence (ChRM) is demagnetized from ~20-80 mT, which decreases simply toward the origin. The resulting directional PSV records for 3P and 6P are easily correlatable with 29 distinct inclination features and 29 declination features. The statistical character of the PSV in both cores is consistent with Holocene PSV noted at other Holocene equatorial sites. Radiocarbon dating of the cores is based on 18 independent radiocarbon dates and four dated stratigraphic horizons that can be correlated into each core. The final directional PSV time series cover the last 24,000 years with an average sediment accumulation rate of ~30 cm/kyr. We have also developed a relative paleointensity estimate for these PSV records based on normalizing the NRM (after 20 mT af demagnetization) by the SIRM (after 20 mT af demagnetization). Changing sedimentation patterns complicate any attempt to develop a single paleointensity record for the entire core lengths. We have developed a relative paleointensity record for the last 6000 years that has 14 correlatable features including 5 notable peaks in intensity. Three of these peaks are synchronous with paleointensity highs farther north in SE Europe/SW Asia/Egypt but two of the peaks are at times of low paleointensity farther north. We interpret this to indicate that Lake Malawi (10°S) is at least partly under the influence of a different flux-regeneration region of the outer-core dynamo. A relative paleointensity record was also developed for ~11,000-24,000 YBP; the general pattern appears to be consistent with other published records, but our confidence in the correlations is more limited.

Introduction

Our understanding of the prehistoric secular variation of the geomagnetic field requires a global distribution of high-resolution, well-dated paleomagnetic records. The Holocene (~0-12,000 ybp) is perhaps the only time interval with

sufficient time control wherein we can hope to develop a global, high-resolution space/time pattern of geomagnetic field variability. To date, there are several regions where relatively little is known about Holocene field variability; the African continent is one of those regions. This study is the first in a series of new studies to carry out detailed paleomagnetic studies of lake sediments from the East African Rift Valley. The primary goal is to recover full-vector records (both field directions and intensity) of paleomagnetic secular variation (PSV) for Holocene time to help improve our understanding of the space/time pattern of PSV. The secondary goal is to develop a paleomagnetic chronostratigraphy in the lake sediments that can permit independent correlation and dating among the lakes on a regional scale both as an aid to improved PSV age dating and as an aid for regional paleoclimate studies.

Lake Malawi Setting

Lake Malawi (Figure 1) is a fault-bounded tectonic lake, the southernmost lake of the East African Rift Valley, which contains up to 4 km of Quaternary sediment (Scholz and Rosendahl, 1988). The lake is ~570 km long, an average of ~40 km wide, and up to 700 m deep; it is the second largest of the East African Rift lakes by volume.

Lake Malawi receives significant clastic flux from a number of rivers along its margin; the highest clastic flux occurs in the north. This is because the northern part of the lake receives ~2500 mm/yr rainfall, associated with the African Monsoon, while the southern part of the lake receives only ~600 mm/yr rainfall (Eccles, 1974). The lake today drains to the south through the Shire River outfall (Figure 1). Variable long-term rainfall, however, has intermittently lowered the lake level, stopped outfall, and made Malawi a closed-basin lake (Finney et al., 1996; Barry, 2001; Barry et al., 2002; Johnson et al., 2002).

The deep lake sediments are currently laminated due to seasonal variations between relatively high clastic flux versus high diatomaceous particle flux (Barry, 2001; Barry et al., 2002). The laminated sediments are currently being preserved due to almost permanent anoxia in lake water column below ~220 m (Eccles, 1974) preventing significant bottom sediment bioturbation. The clastic sediments in the deep basin average 3-4 microns in mean grain size (Barry, 2001). Previously, the deep sediments have intermittently been more homogenous suggesting more constant and higher proportion clastic flux, more oxygenated bottom water, and/or sediment bioturbation due to regular whole-lake overturn.

T. Johnson and colleagues (Barry, 2001; Barry et al., 2002) collected a series of cores from the north part of the lake in 1997/1998 for paleoclimate studies. This study uses two piston cores recovered from their Lake Malawi coring in 1998, MAL98-3 and MAL98-6. The two cores were collected within about 100 m of one another in ~390 m water depth (Figure 1). MAL98-3P is 881 cm long; MAL98-6P is 901 cm long.

Magnetic Measurements

Cores MAL98-3P (called 3P for simplicity hereafter) and MAL98-6P (called 6P hereafter) were u-channelled for our paleomagnetic and rock magnetic studies. The initial NRM of the u-channels were measured and then the u-channels were step-wise demagnetized in alternating magnetic fields (af) at 10 mT, 20 mT, 30 mT and 40 mT and measured. Selected u-channels were then stepwise af demagnetized in 10 mT steps from 50-100 mT. The u-channels were then given an artificial anhysteretic remanence (ARM, 100 mT af, 0.05 mT steady field), which was measured and then stepwise af demagnetized at 10 mT, 20 mT, and 40 mT and measured. Finally, all u-channels were given a saturation isothermal remanence (SIRM, 1 T steady field), which was measured and then stepwise demagnetized at 10 mT, 20 mT, and 40 mT and measured. Selected u-channels also had their ARMs and SIRMs stepwise af demagnetized at 20 mT steps from 60-100 mT.

Figure 2 shows the directional variation of selected samples under af demagnetization. It is clear that almost all samples have a single paleomagnetic direction that is demagnetized between 10-80 mT, which demagnetizes toward the origin. The ChRM of all samples was calculated in the 10-40 mT interval normally and in the 10-80 mT interval in u-channels that had been further demagnetized. The characteristic remanence (ChRM) typically has maximum angles of deviation (MAD) of less than 3° for samples in the 10-40 mT interval (most samples) and MAD angles of less than 4° in the 10-80 mT interval (selected u-channels). We see no evidence for significant directional differences depending on whether we used the 10-40 mT or 10-80 mT ChRMs. There is commonly a 'viscous' magnetic overprint, which is demagnetized by 10 mT, but on occasion, the overprint may extend to 20 mT. The simple characteristic remanence is associated normally with more than 70% of the total NRM.

Figure 3 shows the normal pattern of NRM, ARM, and SIRM intensity loss under increasing af demagnetization. The NRM intensity loss under af demagnetization is strongly coherent over the entire core length. Most samples have median destructive fields (MDFs) of 30-40 mT. Samples from the uppermost 1 m of both cores had lower MDFs indicative of a coarser magnetic grain-size distribution; these samples are all less than 1000 years old and may indicate when runoff patterns and clastic flux changed due to human activities. ARM and SIRM coercivities have MDFs of 20-40 mT. The NRM, ARM, and SIRM coercivities are consistent with a magnetic remanence that resides in magnetite/titanomagnetite as opposed to ferric phases (e.g., hematite).

Figure 4 shows the NRM, ARM, and SIRM intensity variations in core 3P after 20-mT af demagnetization. NRM values are stable in intensity throughout the core. However, intensity values for ARM and SIRM increase significantly below 6 m. ARM and SIRM coercivity increases in this same range and we interpret this to be the result of a deeper lake and finer-grained magnetic minerals below 6 m. The rock magnetic intensity variations (NRM, ARM, SIRM) notable in Figure 4 can be correlated in detail between the two cores (Figure 5, closed circles) over their entire lengths.

Previously, Barry and colleagues (Barry, 2001; Barry et al., 2002) measured magnetic susceptibility on all of the 1997/1998 Lake Malawi cores. All of the

magnetic susceptibility records are available in Barry (2001). We have correlated cores 3P and 6P to several of the 1998 cores (98-1P, 98-2P, 98-4P) that were collected near to our studied cores (Figure 1), using the magnetic susceptibility records in Barry (2001). Selected, correlatable magnetic susceptibility features from all 5 cores are tabulated in Appendix 1: Supplementary Information. Appendix 1 also tabulates key rock magnetic (ARM, SIRM) correlations between cores 3P and 6P. All of the correlations appear to be consistent with one another. We plot the magnetic susceptibility and rock magnetic correlations of Appendix 1 in Figure 5.

Our rock magnetic measurements suggest that the magnetic mineral carrying the NRM is magnetite or a titanomagnetite. This conclusion was also reached by several other previous paleomagnetic studies of East African Lake sediments (Thouveny and Williamson, 1988; Williamson et al., 1991; Mothersill, 1996) and environmental magnetic studies (Ngobi et al., 1998; Wetter et al., 2007). Several paleomagnetic studies of exposed Quaternary East Africa Rift sediments and lavas also document that magnetite/titanomagnetite minerals are always the dominant magnetic phases in the rocks (Gromme et al., 1970; Reilly et al., 1976; Tamrat et al., 1995).

Directional Paleomagnetic Secular Variation

Figure 6 shows the characteristic remanences for cores 3P and 6P as a function of depth in each core. There is a clear pattern of paleomagnetic secular variation described by the inclination and declination variability with strong serial correlation among directions located near to one another stratigraphically in each core and a similar strong correlation between directions at isochronous horizons in the two cores. We have labeled 29 inclination features and 29 declination features that are correlatable between the two cores. We have also plotted the PSV feature correlations in Figure 5 (solid circles). These correlations are not significantly different (± 5 cm) from the rock magnetic correlations and indicate that we have a good, reproducible method of correlating the magnetic results from the two cores.

The inclinations and declinations have a notable oscillatory pattern with typically $\pm 20^\circ$ variability in both inclination and declination. The vector mean direction for core 3P is $I = -21.3^\circ$ and $D = -3.3^\circ$ ($\alpha_{95} = 1.0^\circ$) with a directional dispersion of 15.5° . The vector mean direction for core 6P is $I = -22.4^\circ$ and $D = 0.1^\circ$ ($\alpha_{95} = 0.8^\circ$) with a directional dispersion of 12.2° . Core 3P has a ΔI anomaly (Lund, 2001) of -1.9° and 6P has a ΔI anomaly of -3.0° given a site axial dipole inclination of -19.4° . All of these statistical values are consistent with previous Holocene PSV estimates for equatorial sites in Indonesia (Lund et al., 2007).

Radiocarbon Dating and PSV Time Series

We used the radiocarbon dates determined by Barry (2001; Barry et al., 2002) from 5 of the 1998 Malawi cores (Figure 1; Table 1) to estimate time/depth

relationships for cores 3P and 6P. We have transferred the radiocarbon date depths in core 98-1P, 98-2P, and 98-4P to cores 3P and 6P using the magnetic susceptibility correlations listed in Appendix 1 and shown in Figure 5. Barry (2001) calibrated the radiocarbon dates using CALIB 3.0 (Stuiver and Reimer, 1993) after subtracting 450 y from each date as an average correction for old, reworked carbon mixed in with the bulk organic matter. We have recalibrated the radiocarbon dates (Table 1) in the same manner but using CALIB7.1 (Stuiver and Reimer, 1993). We ignored radiocarbon dates from core 98-13P because it was recovered from the lake's central basin, and we could see no clear way to correlate them to the other cores. We have also used estimated radiocarbon ages or varve ages for four distinct horizons (A1-A3 (tephras), C1 (distinctly colored lamination)) from Barry (2001), which could be identified or correlated into cores 3P and 6P. Table 1 shows the estimated depth in 3P and 6P for radiocarbon dates and event horizons from other cores.

Our internal correlations between the two cores (Appendix 1; Figure 5) also estimate isochrons between the two cores. We have compared the depth estimates for each dating horizon versus our internal correlation between the two cores and determined whether and to what extent they differ (delta cm in Table 1). Half the dates are in agreement as to placement in the two cores; the other half have differences of 2-12 cm in relative placement. We cannot see a method of reconciling those differences, so we have used the depth estimates from the magnetic susceptibility correlations. (Also, the small depth differences (~6 cm ave) are typically only ~200 years in duration and largely fall within our radiocarbon age uncertainties.)

In the end, we found the radiocarbon dates from cores 1P, 2P, and 4P to be internally consistent with the exception of one date in 2P (9550 C14 ybp, 537.5 cm), which is internally consistent and in sequence with other dates in 2P, but its placement in cores 3P and 6P is not consistent with other correlated dates. We think this is due to a problem in correlating this date to the other cores and we have ignored it in this analysis. We have also not used any of the dates from 3P and 6P themselves for the dates are not internally consistent and are not consistent with the correlated dates.

Our final time/depth curves for cores 3P and 6P are shown in Figure 6. They have a very similar pattern of time/depth variation as one might expect for their close spatial location in the lake. The final PSV time series cover the last 24,000 years with an average sediment accumulation rate of ~30 cm/kyr. Sediment accumulation is higher in the Holocene (~40 cm/kyr) and lower in the Late Pleistocene (~20 cm/kyr).

We have used these chronologies to plot the directional PSV versus time in Figures 8 and 9. The ages of the directional features shown in Figures 6, 8, and 9 are listed in Table 2. Six of the correlative PSV features (underlined in Table 2) have significantly different ages in the two cores for the same features. We attribute this to one or more of the following potential errors: 1) inaccurate PSV waveform morphology in one or both records, 2) inaccurate placement of radiocarbon dates in one or both records, 3) dating inaccuracies related to linear interpolation of feature ages between successive dated horizons in one or both cores.

Relative Paleointensity

The paleointensity of the local paleomagnetic field was estimated by normalizing the NRM intensity to some rock magnetic indicator of magnetic mineral concentration. We evaluated both ARM and SIRM for this purpose. Figure 10 shows ratios of NRM/ARM and NRM/SIRM at three different levels of af demagnetization, 10 mT, 20 mT, and 40 mT. Each of the ratios was renormalized to unit mean for our comparison. All six normalizers in each core give results that are not significantly different, although normalizers at 10 mT are a bit more noisy. ARM variability strongly co-varies with SIRM variability (correlation coefficient = 0.96), but it shows larger amplitude variability than does SIRM (or the NRM) (Figure 4). This is probably due to the fact that ARM is more sensitive to the finest grain sizes of magnetic minerals, over-emphasizing intervals with higher fine-grained magnetic concentration and under-emphasizing intervals with relatively less fine-grained magnetic concentration. We thus used SIRM at 20 mT as the preferred normalizer to estimate relative paleointensity, NRM20/SIRM20.

The highest apparent paleointensity values occur between 3.5-5.5 m depth (6,000-11,000 YBP) in both cores attaining values almost 2 times the values above this interval and 3 times the values below this interval. This interval (indicated the grey zone in Figure 10) is associated with the lowest ARM and SIRM values of the cores (indicated by the grey zone in Figure 4). We think these high apparent intensity values are a rock magnetic artifact of the low ARM and SIRM intensities and are associated with changing sedimentary and environmental conditions across the Pleistocene/Holocene boundary. We have thus chosen to evaluate the relative paleointensities in two separate intervals: 0-3.5 m (0-6,000 YBP) and 5.5-9 m (11-24,000 YBP).

Relative paleointensity estimates for the Holocene interval in cores 3P and 6P are shown in Figure 11. There is a strong coherence in the variability in the two cores. We have identified 14 correlatable features in the two cores; these features are dated in Table 2. These correlations are synchronous with PSV directional correlations noted in Figure 6. These two aspects of field variability (directions and intensity) must strictly and synchronously covary at Lake Malawi. Relative paleointensity estimates for the latest Pleistocene interval in cores 3P and 6P are shown in Figure 12. There is a reproducible pattern of paleointensity in the two cores, but we have not chosen to label any specific intensity features other than to note a general slow rise in paleointensity with decreasing age for most of the interval.

Discussion

We have developed a directional PSV record for Lake Malawi (10°S) for the last 24,000 years, based on 18 radiocarbon dates (Figure 7). We have identified 29 reproducible inclination features and 29 reproducible declination features (Figures

8, 9) in two cores (3P and 6P). We can compare these results with four other previous paleomagnetic studies of African Lakes. Barton and Torgersen (1988) studied two ~5-m cores from Lake Turkana (3°N) that covered the last ~1000 years, based on extrapolation from Pb210 age dating of the near-surface sediments. They identified a pattern of inclination and declination variability that is consistent with that estimated from historical measurements (GUFM1, Jackson et al., 2000; see Figure 8). We interpret our features I1 and I2 (Figure 8) to correspond to this pattern, but we date feature I2 to be ~800 YBP rather than ~350 YBP, as estimated from historical measurements. This may indicate a higher abundance of old, reworked carbon than Barry (2001) accounted for (450 y) in some of our dates, but we have not made any further correction for that at this time. The inclination value of feature I2 is about -10° or -15°, but the historical estimate for the field at ~450 YBP is ~0°. Our overall inclination average is within ~2° of axial dipole expectation, so we are not certain whether our data are wrong or whether GUFM1 is wrong in this region. Our declinations in the uppermost ~50 cm of both cores were twisted during the coring process, so we have no record of declination variability in Lake Malawi for the last ~800 years.

Thouveny and Williamson (1988) studied two sediment cores from Lake Barombi Mbo (4.5°N) and recovered a composite PSV record for the last 25,000 years based on 8 radiocarbon dates. The PSV records of the two cores are correlatable in their 5-m interval of overlap. Some age inversions and large age uncertainties make the detailed chronology somewhat uncertain. We were not able to develop any unique correlation with this sequence because of the dating uncertainties and a lack of any distinctive correlative PSV features.

Williamson et al. (1991) studied two sediment cores from southern Lake Tanganyika (8.5°S) and recovered PSV records for the last ~25,000 years based on 6 radiocarbon dates (all older than ~12,000 YBP). The two records are correlatable in a ~9-m interval of overlap. They correlated selected PSV features from Lake Tanganyika to Lake Barombi Mbo; however, we consider those correlations possible but uncertain given the relatively poor age control in both lakes. We do not see any distinctive PSV features in these records that we can confidently correlate with our Lake Malawi PSV records.

Finally, Mothersill (1996) carried out paleomagnetic studies of 9 sediment cores from Lake Victoria (0°) and 4 sediment cores from Lake Albert (2°N). Ten radiocarbon dates on the Lake Victoria cores and one radiocarbon date on the Lake Albert cores indicate the PSV records are all less than ~5000 YBP. The inclination and declination variability in the Lake Victoria cores is not easily correlatable among the cores and relatively uncertain chronology in each core complicates any possible correlation. The inclination and declination variability in the Lake Albert cores seems to be more correlatable among the cores, but only one radiocarbon date makes dating the sequence very uncertain. There is clearly PSV variability in these cores that is comparable to what we see at Lake Malawi, but differences in PSV records among the cores and poor age control make any PSV correlations to our Lake Malawi PSV records very uncertain.

We have also developed a relative paleointensity record for Lake Malawi for the last 6000 years with 14 correlative paleointensity features. We can compare that

record with a number of paleointensity studies from farther to the North. The closest four paleointensity studies are Egypt (EGY-26°N; Aitken et al., 1984; Hussain, 1983, 1987; Odah et al., 1995; Odah, 1999), Central Asia (CAS-38°N; Nachasova and Burakov, 2000), Greece (GRE-37°N; Aitken et al., 1989), and Georgia (GEO-42°N; Nachasova and Burakov, 1987, 1996, 1997). All of these are paleointensity records developed from archeological/archeomagnetic studies and can be considered absolute records in their intensity estimates and high-resolution in their age control. The paleointensity estimates from these four sites are summarized in Figure 11.

Our relative paleointensity results indicate 4 intervals of high intensity: features 2-3, 5, 7-11, and 13 (grey zones in Figure 11, top). Three of the intervals have correlative intensity highs in the more northerly sites (Figure 11, bottom): features 2-3 (~500-1400 YBP), 5 (~2500-2900 YBP), and 7-11 (~3100-3800 YBP). However, Lake Malawi also has an intensity high where the more northerly sites have relatively low intensity: 13 (~4800-5600 YBP). If our chronologies are correct, this suggests that the magnetic field at Lake Malawi is being influenced part (or all) of the time by different flux-regenerating regions in the outer-core dynamo than the more northerly sites. One model of flux regeneration in the outer-core dynamo would argue that convection rolls, related to observable high-latitude flux lobes (Bloxham and Gubbins, 1985; Gubbins and Bloxham, 1987), control field variability and that longitudinal bands of flux variability associated with individual convection rolls should strongly co-vary in both the Northern and Southern Hemisphere. Our results suggest that Northern-Hemisphere and Southern-Hemisphere regions of flux regeneration in the same ('European') longitude band (~30°W-60°E) do not strongly co-vary; they may intermittently co-vary and then vary out-of phase, or they may simply be independent with random intervals of apparent correlation.

Finally, we have developed a relative paleointensity record from our Lake Malawi cores for the interval 11-24,000 YBP. Our results are reproducible between the records and show a broad trend to higher paleointensity for most of the time interval. There are a number of millennial-scale paleointensity highs on top of that trend. Two other relative paleointensity records show similar features: the PISO-1500 relative paleointensity record of Channell et al. (2009) is a stack of 53 global records, the relative paleointensity record from deep sea core JPC14 (29°N, Atlantic Ocean) of Schwartz et al. (1998) (Figure 12, bottom). Both show the same trend in paleointensity and group of millennial-scale paleointensity highs as our Lake Malawi records. However, we are not certain about the correlation of the paleointensity highs at this time.

Conclusions

We have conducted a paleomagnetic study of Late Quaternary sediments from Lake Malawi in order to develop a high-resolution record of paleomagnetic secular variation (PSV). This study has recovered PSV records from two cores (3P, 6P) in northern Lake Malawi (10°S). The PSV is recorded in fine-grained detrital magnetite/titanomagnetite grains. Detailed af demagnetization of the natural remanence (NRM) shows that a distinctive characteristic remanence (ChRM) is

demagnetized from ~20-80 mT, which decreases simply toward the origin. The resulting directional PSV records for 3P and 6P are easily correlatable with 29 distinct inclination features and 29 declination features. The statistical character of the PSV in both cores is consistent with that noted in other equatorial sites in Indonesia (Lund et al., 2007).

Radiocarbon dating of the cores is based on 18 independent radiocarbon dates and four dated stratigraphic horizons that can be correlated into each core. The final PSV time series cover the last 24,000 years with an average sediment accumulation rate of ~30 cm/kyr. Sediment accumulation is higher in the Holocene (~40 cm/kyr) and lower in the Late Pleistocene (~20 cm/kyr).

We have also developed relative paleointensity estimates for this PSV record for the last 6000 years and for 11-24,000 YBP based on normalizing the NRM (after 20 mT of demagnetization) by the SIRM (after 20 mT of demagnetization). The relative paleointensity in the last 6000 years has 14 correlatable features including 5 peaks in intensity. Three of these peaks are synchronous with paleointensity variability farther north in SE Europe/SW Asia/Egypt but two of the peaks are at times of low paleointensity farther north. We interpret this to indicate that Lake Malawi (10°S) is at least partly under the influence of a different flux-regeneration region of the outer-core dynamo. The older paleointensity records have a pattern that is consistent with some other published records, but we are not sure of specific millennial-scale correlations.

Acknowledgements: The sediment cores used in this study were collected under the auspices of IDEAL (International Decade of East Africa Lakes). The USA National Science Foundation funded the paleomagnetic studies under grant EAR-1316507.

References

- Aitken, M., A. Allsop, G. Russell, and M. Winter, Geomagnetic intensity in Egypt and West Asia during the second millennium BC, *Nature*, 310, 305-308, 1984.
- Aitkin, M., A. Allsop, G. Bussell, and M. Winter, Geomagnetic intensity variation during the last 4000 years, *Phys. Earth Planet. Int.*, 56, 49-58, 1989.
- Barry, S., 2001, Stratigraphic correlation and Geochronology of varved sediments from Lake Malawi, East Africa, MS Thesis, University of Minnesota, 135 pp.
- Barry, S., M. Filippi, M. Talbot, and T. Johnson, 2002, Sedimentology and geochronology of late Pleistocene and Holocene sediments from northern Lake Malawi, in E. Odada and D. Olego (eds.) *The East African Great Lakes: Limnology, Paleolimnology, and Biodiversity*, 369-391.
- Barton, C. and T. Torgersen, 1988, Paleomagnetic and ^{210}Pb estimates of sedimentation in Lake Turkana, East Africa, *Paleogeog., Paleoclim., Paleoecol.*, 68, 53-60.
- Bloxham, J. and D. Gubbins, 1985, The secular variation of the Earth's magnetic field, *Nature*, 317, 777-781.
- Channell, J., C. Xuan, and D. Hodell, 2009, Stacking paleointensity and oxygen isotope data for the last 1.5 Myr (PISO-1500), *Earth Planet. Sci. Lett.*, 283, 14-23.
- Eccles, D., 1974, An outline of the physical limnology of Lake Malawi, *Limn. And Ocean.*, 19, 730-742.
- Finney, B. P., Scholz, C. A., Johnson, T. C., Trumbore, S., and Southon, J., 1996, Late Quaternary lakelevel changes of Lake Malawi, in Johnson, T. C., and Odada, E. O., eds., *The Limnology, Climatology, and Palaeoclimatology of the East African Lakes*: Toronto, Gordon and Breach, p. 495-508.
- Gubbins, D. and J. Bloxham, 1987, Morphology of the geomagnetic field and implications for the geodynamo, *Nature*, 325, 509-511.
- Hussain, A., Archeomagnetic investigations in Egypt: inclination and field intensity determinations, *J. Geophys.*, 53, 131-140, 1983.
- Hussain, A., The secular variation of the geomagnetic field in Egypt in the last 5000 years, *Pageoph.*, 125, 67-90, 1987.
- Jackson, A., A. Jonkers, and M. Walker, 2000, Four centuries of geomagnetic secular variation from historical records, *Phil. Trans. Roy. Soc. A*, 358, 957-990.

- Johnson, T., E. Brown, J. McManus, S. Barry, P. Barker, and F. Gasse, 2002, A high-resolution paleoclimate records spanning the last 25,000 years in southern East Africa, *Science*, 296, 113-115.
- Mothersill, J., 1996, Paleomagnetic results from Lakes Victoria and Albert, Uganda, *Stud. Geophys. Geod.*, 40, 25-35.
- Nachasova, I. and K. Burakov, Change in the intensity of the geomagnetic field in the second millennium BC in the territory of Georgia, *Geomag. And Aeron.* , 27, 766-768, 1987.
- Nachasova, I., and K. Burakov, Geomagnetic field variations in Central Asia for the last two milleniums: World data analysis, *Geomag. And Aerson.*, 35, 844-850, 1996.
- Nachasova, I., and K. Burakov, 8000-year geomagnetic intensity variaition, *Geomag. And Aerson.*, 37, 115-118, 1997.
- Nachasova, I., and K. Burakov, Archeointensity of the geomagnetic field in the fifth millennium BC in northern Mesopotamia *Geomag. And Aeron.*, 35, 398-402, 1995.
- Nachasova, I., and K. Burakov, The geomagnetic field intensity in Central Asia from 6000 to 3000 BC, *Izvestiya, Phys. Solid Earth*, 36, 358-363, 2000.
- Ngobi, G., T. Johnson, and P. Solheid, 1998, Environmental magnetism of late Pleistocene/Holocene sequences from Lake Victoria, East Africa, in J. T. Lehman (ed.), *Environmental Change and Response in East African Lakes*, 59-73.
- Odah, H., Improvement of t he secular variation curve of the geomagnetic field in Egypt for the last 6000 years, *Earth Planets Space*, 51, 1325-1329, 1999.
- Odah, H., F. Heider, A. Hussain, H. Soffel, and M. ElGamili, Paleointensity of the geomagnetic field from 4000 BCDto 150 AD using the Thellier method, *J. Geomag. Geoelect.*, 47, 41-58, 1995.
- Scholz, C., and B. Rosendahl, 1988, Low lake stands in Lakes Malawi and Tanganyika, East Africa, delineated with multifold seismic data, *Science* 240, 1645-1648
- Schwartz, M., S. P. Lund, and T. C. Johnson, 1998, Geomagnetic field intensity from 12,000-71,000 years BP as recorded in deep sea sediments of the Blake Outer Ridge, North Atlantic Ocean, *J. Geophys. Res.*, 103, 30,407-30,416.
- Stuiver, M., and Reimer, P.J., 1993, Extended 14C data-base and revised CALIB 3.0 14C calibration program 1993: *Radiocarbon*, v. 35, p. 215-230.

- Sturm, M., Siegenthaler, c., and Pickrill, R.A., 1995, Turbidites and 'homogenites' A conceptual model of flood and slide deposits: Publ. IAS-16th Regional Meeting Sedimentology, Paris, v. 22.
- Thouveny, N. and D. Williamson, 1988, Paleomagnetic study of Holocene and Upper Pleistocene sediments from Lake Barombi Mbo, Cameroun: first results, Phys. Earth Planet. Int., 52, 193-206.
- Wetter, L., K Verosub, and J. Russell, 2007, Geophys. Res. Lett., 34, L12707, doi:10.1029/2007GL029984.
- Williamson, D., N. Thouveny, C. Hillaire-Marcel, A. Mondeguer, M., Taieb, J. Tiercelin, and A. Vincens, 1991, Chronological potential of paleomagnetic oscillations recorded in late Quaternary sediments from Lake Tanganyika, Quat. Sci. Rev., 10, 351-361.

Figure Captions

Figure 1: Map of Lake Malawi showing the locations of cores M98-1P, M98-2P, M98-3P, M98-4P, and M98-6P. (Modified from Barry et al., 2002.)

Figure 2: AF demagnetization diagram for four horizons from cores 3P and 6P. The numbers after 3P and 6P indicate the sediment depth (cm) of each sample in the cores. The dots represent the tip of a paleomagnetic vector after a specific level of af demagnetization and measurement. The solid (open) dots represent a projection of the vector on the X-Z (X-Y) axis. The numbers indicate level of af demagnetization from 0-80 mT. The dots closest to the origin represent the vector left after 100 mT af demagnetization.

Figure 3: Pattern of NRM, ARM, and SIRM remanence loss under sequential af demagnetization from 0-100 mT. The numbers after 3P and 6P indicate the sediment depth (cm) of each sample in the cores.

Figure 4: NRM, ARM, and SIRM intensity variation in core M98-3P after 20-mT af demagnetization. The grey zone indicates a particular interval of rock magnetic variability that is considered in our relative paleointensity estimates.

Figure 5: Stratigraphic correlation of paleomagnetic features (inclination, declination, paleointensity) between cores 3P and 6P (open circles) and similar correlation of rock magnetic variability (NRM, ARM, SIRM) between cores 3P and 6P (closed circles). Magnetic susceptibility correlations between 3P and 1P, 2P, 4P, and 6P (Appendix 1) are also shown for comparison.

Figure 6: Paleomagnetic inclinations and declinations (ChRMs) of cores 3P (top) and 6P (Bottom). 29 correlatable inclination features and 29 correlatable declination features are noted.

Figure 7: Radiocarbon chronology of cores 3P and 6P. 18 radiocarbon dates and four dated horizons (Table 1) could be correlated into cores 3P and 6P. The resulting composite curves were used to develop a chronostratigraphy for each core. The dashed lines indicate the preferred chronostratigraphy used when individual dates were a bit out of line from the general trends.

Figure 8: Paleomagnetic inclinations and declinations (ChRMs) of cores 3P (top) and 6P (Bottom) for the last 10,000 years. At left, the historical estimate of inclination and declination variability (GUFM1) for the last 400 years is indicated by 'x's. 29 correlatable inclination features and 29 correlatable declination features are noted.

Figure 9: Paleomagnetic inclinations and declinations (ChRMs) of cores 3P (top) and 6P (Bottom) for 10-24,000 YBP. 29 correlatable inclination features and 29 correlatable declination features are noted.

Figure 10: Relative paleointensity records for cores 3P and 6P. The grey interval identifies a specific interval with distinctive rock magnetic properties that preclude using this interval for paleointensity studies versus intervals above and below it.

Figure 11: (top) Relative paleointensity records for cores 3P and 6P for the last 6000 years. 14 correlatable features are noted. (bottom) Paleointensity records from four sites farther to the north that we compare with our relative paleointensity records. The records come from Egypt (EGY), Central Asia (CAS), Georgia (GEO), and Greece GRE).

Figure 12: (top) Relative paleointensity records for cores 3P and 6P for 11-24,000 YBP. (bottom) Paleointensity records from two other published records that we compare with our relative paleointensity records.

TABLE 1: Lake Malawi Radiocarbon Dates

Core/ event	depth (cm)	C14-age (YBP)	±2s	CAL-max (YBP)	CAL-min (YBP)	CAL-ave (YBP)	3P-dep (cm)	6P-dep (cm)	delta (cm)
M98-1P									
	55.5	1880	55	1416	1265	1336	92	70	0
	167	4015	60	3992	3692	3861	225	198	0
	307	6270	65	6757	6469	6623	378	337	0
	460.5	9010	85	9765	9404	9541	481	458	10
	627.5	13330	100	15703	15106	15391	680	670	2
	765.5	19010	270	23046	21802	22421	815	795	10
M98-2P									
	139.5	2510	50	2147	1918	2029	138	98	0
	239.5	4020	65	4001	3692	3868	227	199	12
	379.5	6260	65	6749	6450	6610	367	328	0
	500.5	8820	110	9538	9089	9353	450	430	8
	537.5	9550	120	10581	9903	10277	481	458	10
	648	11450	85	13044	12723	12876	602	595	3
	744	14450	100	17355	16623	16999	721	710	3
	744	15150	130	18225	17561	17886	721	710	3
M98-3P									
	85.5	5950	50	6401	6259	6302	85.5		
	221	modern							
	366	6890	50	7430	7271	7361	366		
M98-4P									
	2.5	1500	90	1180	767	970	5	3	0
	134.5	2550	65	2185	1923	2079	130	91	0
	257.5	4420	80	4643	4220	4431	239	215	11
	257.5	3650	40	3495	3353	3422	239	215	11
M98-6P									
	387	7550	60	8019	7817	7928		387	
	517.5	9020	530	10879	8371	9616		517.5	
	670.5	6690	50	7264	7139	7168		670.5	
A1						276	12	1.5	0
C1						505	36	14.5	0
A2						651	56.5	30	0
A3						4307	253	224	0

Table 2: Age estimates (Cal. YBP) of PSV directional and relative paleointensity features

PSV Feat.	Age 3P	Age 6P	PSV Feat.	Age 3P	Age 6P	PSV Feat.	Age 3P	Age 6P
INC-1	500±150	600±150	INC-23	16600±150	16700±150	DEC-18	11200±200	11200±200
INC-2	1150±150	1150±100	INC-24	18250±150	18400±150	DEC-19	<u>11500±100</u>	<u>11700±200</u>
INC-3	1500±100	1500±100	INC-25	18850±200	18800±100	DEC-20	<u>11850±150</u>	<u>12050±150</u>
INC-4	1750±75	1725±50	INC-26	19500±200	19500±200	DEC-21	12500±150	12600±150
INC-5	2100±125	2000±100	INC-27	22800±200	23000±200	DEC-22	12950±100	12850±50
INC-6	2400±150	2400±175	INC-28	24100±200	24100±200	DEC-23	13550±150	13550±50
INC-7	2750±100	2800±100	DEC-1	700±300	700±300	DEC-24	14250±100	14250±200
INC-8	3400±150	3200±100	DEC-2	1700±50	1650±100	DEC-25	15150±200	15100±200
INC-9	4100±150	3950±200	DEC-3	2000±100	2000±100	DEC-26	18700±100	18700±100
INC-10	4700±200	4700±250	DEC-4	2300±150	2300±150	DEC-27	<u>20400±200</u>	<u>20700±200</u>
INC-11	5300±150	5200±150	DEC-5	2600±150	2650±100	DEC-28	21900±200	22000±200
INC-12	5750±100	5750±150	DEC-6	2900±50	2900±50	DEC-29	23750±150	23800±150
INC-13	6800±300	6900±300	DEC-7	3150±100	3050±100	INT-1	<u>250±200</u>	<u>600±200</u>
INC-14	8100±200	8100±100	DEC-8	<u>3400±100</u>	<u>3200±100</u>	INT-2	<u>800±100</u>	<u>1100±100</u>
INC-15	8700±75	8700±75	DEC-9	4000±100	3950±200	INT-3	1450±150	1600±150
INC-16	9150±150	9025±50	DEC-10	4700±100	4800±100	INT-4	2000±150	2000±150
INC-17	9700±200	9750±200	DEC-11	5200±150	5300±150	INT-5	2400±150	2400±150
INC-18	11200±100	11250±200	DEC-12	5900±100	5900±150	INT-6	<u>2750±150</u>	<u>2950±150</u>
INC-18a	<u>11900±150</u>	<u>12150±150</u>	DEC-13	<u>6850±200</u>	<u>7100±200</u>	INT-7	3200±150	3250±100
INC-19	13000±100	13100±50	DEC-14	7400±150	7500±150	INT-8	3400±100	3350±100
INC-20	13850±150	13750±150	DEC-15	8200±100	8300±150	INT-9	3550±100	3500±100
INC-21	14550±150	14500±150	DEC-16	8600±100	8800±150	INT-10	3350±100	3200±100
INC-22	15300±200	15300±200	DEC-17	9100±75	9100±50	INT-11	4000±100	4000±100
INT-12	4350±100	4500±100	INT-13	5350±100	5350±100	INT-14	5750±100	5750±100

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12