Measurement of $^{10}$Be from Lake Malawi (Africa) drill core sediments and implications for geochronology

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A B S T R A C T
The cosmogenic radionuclide $^{10}$Be was measured from drill core sediments from Lake Malawi in order to help construct a chronology for the study of the tropical paleoclimate in East Africa. Sediment samples were taken every 10 m from the core MAL05-1C to 80 m in depth and then from that depth in core MAL05-1B to 382 m. Sediment samples were then taken at a higher resolution of every 2 m from MAL05-1C. They were then leached to remove the authigenic fraction, the leachate was processed to separate out the beryllium isotopes, and $^{10}$Be was measured at the TAMS Facility at the University of Arizona. The $^{10}$Be/$^{9}$Be profile from Lake Malawi sediments is similar to those derived from marine sediment cores for the late Pleistocene, and is consistent with the few radiocarbon and OSL IR measurements made from the same core. Nevertheless, a strong correlation between the stable isotope $^{9}$Be and the cosmogenic isotope $^{10}$Be suggests that both isotopes have been well mixed before deposition unlike in some marine sediment cores. In addition, the correlation of beryllium isotopes to a proxy of lake level TOC (Total Organic Matter) from Lake Malawi indicates that the concentrations of $^{10}$Be in the lake sediments result from the combined effects of global and local climates on lake level, local hydrology, and sediment transport in the Lake Malawi basin rather than as a direct response to its production in the atmosphere modulated by the intensity of the Earth’s dipole. Therefore, a direct correlation of the $^{10}$Be/$^{9}$Be to a chronology derived from the paleomagnetic variations measured from marine sediments was not possible. Nevertheless, a comparison of the $^{10}$Be/$^{9}$Be chronology, allowing for decay, at Lake Malawi to that of the global marine paleomagnetic record suggests that the bottom of core MAL05-1B is no more than 750 ka in age.

1. Introduction

We investigated using the cosmogenic radionuclide $^{10}$Be to date sediments from Lake Malawi because its half life duration is appropriate for the time frame in which the lake sediments were deposited, as well as the possibility of tying this record to that of marine sediments. More than 600 m of the core have been obtained from Lake Malawi (Scholz et al., 2006, and Scholz et al., 2011—this issue), located in the southern part of the East African Rift Valley. Sediments from Lake Malawi contain an important record for the study of the tropical paleoclimate. However, most of the sediments of the core from Lake Malawi are well beyond the approximate 50 kyr range of radiocarbon dating. In addition, paleomagnetic data are difficult to interpret because of the low latitude of the drill site coupled with the fact that the core is unoriented. Lake Malawi lies in the western branch of the African rift valley and is the second largest ($22,490 \text{ km}^2$) and second deepest (~700 m) of the African rift lakes (Johnson and Ng’ang’a, 1990). The lake’s long, narrow and deep morphology, as well the positions of bathymetric deep areas and sediment depocenters are all controlled by its origin as a series of linked half-graben basins (Rosendahl, 1987; Scholz and Rosendahl, 1990). Multiple reflection seismic surveys of the lake have shown a very thick accumulation of rift sediments within the basin, in places exceeding several kilometers (Scholz, 1989). The lake itself is probably at least early Pliocene in age, based on both the sediment thickness inferred from seismic data and outcrop exposures of lacustrine deposits along the lake’s margin (Betzler and Ring, 1995).

Although Lake Malawi today is deep and freshwater, with an outlet to the Shire River, many lines of evidence show that this has not always been the case. Early studies of seismic stratigraphic data from Lake Malawi indicated that extraordinary lake level fluctuations had occurred in the lake’s past (Scholz and Rosendahl, 1988), although from that data alone the timing of such events could not be constrained. Detailed studies of some of these lake level drops of up to 550 to 600 m below modern lake level, documented by the Lake Malawi drill cores attest to extraordinary climate variability in terms of moisture balance (Scholz et al., 2007; Cohen et al., 2007; Brown et al., 2007). This history is crucial in addressing questions about the
climate and environmental change of eastern Africa. For example, how have climate variables such as moisture and wind direction changed over the glacial/interglacial and orbital cycles, how are these changes tied to global climate, and how has the response of Lake Malawi to these changes influenced local and regional flora and fauna? And lastly, how has this extraordinary climate variability influenced human evolution and expansion?

Geochronology is central to addressing these questions. The cosmogenic radionuclide $^{10}$Be has advantages that may be applicable to dating the sediments of Lake Malawi. $^{10}$Be is always being produced in the atmosphere and removed within a year by dry and wet precipitations. Thus, there is a constant supply of $^{10}$Be to the waters of Lake Malawi, within which the $^{10}$Be is removed to the sediments below. Hence, $^{10}$Be can be measured from all the sediments throughout the length of the core. The presumed age of the oldest sediments at the bottom of the core is less than the half life of $^{10}$Be ($1.34 \times 10^6$ yrs, Nishiizumi et al., 2007). In addition, the production of $^{10}$Be with time varies significantly. This variance in production is random in time due to the randomness in the intensity of the dipole field that modulates it. Thus, a $^{10}$Be record possibly could be correlated to the paleomagnetic record and would be unique. The record of the intensity of the dipole field has been progressively pushed back to approximately 2 Ma from stacked marine sediment core records over the last decade (Valet et al., 2005) which would cover the entire duration of sedimentation expected for the Lake Malawi drill cores. However, variations in $^{10}$Be concentrations due to the impact of climate on lake levels, sedimentation rate, and sediment composition need to be addressed and may make the method inapplicable.

In 2005 the Lake Malawi Drilling Project (LMDP) recovered approximately 600 m of high quality drill core from two sites in Lake Malawi, the southernmost of the African Rift Valley great lakes (Scholz et al., 2006) (Fig. 1 map). Lake Malawi was drilled in order to obtain a high quality and continuous record of paleoclimate variability in the African continental tropics. Sedimentological indicators such as

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Fig. 1. Locations of the two sites in Lake Malawi and bathymetry. Site 2, in the northern Lake Malawi is at a water depth of 361 m, and site 1 (cores B & C) is at a water depth of 593 m.
a dominance of sublittoral to deep water mud (in large part laminated) and limited evidence of paleosols or other evidence of prolonged exposure show that deposition in the core record was very continuous and, compared to similar duration marine drill core records, very rapid. Recent measurements of $^{10}$Be were made from test samples from the recently acquired drill core from Lake Malawi, East Africa (Scholz et al., 2006).

The longest of the Lake Malawi cores, MAL05–1B extended to 382 m below the lake floor and a water depth of 593 m, with an average core recovery of 92% (Fig. 1 core stratigraphy). Based on initial geochronometric information (paleomagnetic reversal and excursion data) this core was initially estimated to extend back to 1.5 Ma from estimated reversal picks, which would have made it by far the longest continuous core record yet obtained from the continent of Africa. However, a firm chronology based on these methods alone is uncertain and other unpublished data now suggest a much younger age for the base on the 1B core. Uncertainties about the interpretation of the paleomagnetic record, the temporal range limitations of both the OSL and $^{14}$C methods, and the uncertainty of success in applying other dating methods because of limited amounts of appropriate materials (e.g. Ar/Ar, and U-series dating) led us to explore how $^{10}$Be might be used for dating the older parts of the Malawi core record.

The variations in the concentration of the cosmogenic radionuclide $^{10}$Be in marine (Robinson et al., 1995; Frank et al., 1997; Carcaillet et al., 2004) and lake sediments (Horiiuchi et al., 1999; Ljung et al., 2007; Belmaker et al., 2008) can serve as a proxy for the cosmic-ray flux. Since the intensity of the cosmic-ray flux is inversely related to the intensity of the geomagnetic field the history of the latter can be derived. The geochemical cycle of $^{10}$Be on the Earth begins as high energy cosmic-rays, primarily in the upper atmosphere, break oxygen and nitrogen apart (small amounts of $^{10}$Be are also produced in situ in materials on the surface of the earth and are of interest in geomorphology). Consequently, the production of $^{10}$Be is proportional to the cosmic-ray flux incident upon the Earth which, in turn, is a function of the intensity of the primary galactic and solar cosmic-rays, and their modulation by the solar and geomagnetic fields. After $^{10}$Be is produced it is quickly scavenged by particulate matter, and within a year is precipitated onto the surface of the earth. After deposition onto the surface of the earth $^{10}$Be is transported by water, wind, or currents within the sea. Most $^{10}$Be (that which has not decayed during transport) is eventually sequestered in ice, soils, and lake and marine sediments, though it may be recycled later (McHargue and Damon, 1991).

Initial studies of $^{10}$Be in Antarctic ice, (Raisbeck et al., 1987) showed that the concentration varied with depth and was found to be anomalously high at 35 and 60 ka. These wide variations in the concentration of $^{10}$Be in time were shown to be global in extent by later work in marine sediments (McHargue et al., 1995). This was shown, for example, at DSDP Leg 64, site 480, a drill site lying on a slope of the Guaymas Basin in the Gulf of California (660 m in depth) that was chosen because of its high sedimentation rate (100 cm/kyr) and varied sediments. At this site there was evidence for two geomagnetic excursions, the Mono Lake and the Laschamp, in which the inclination of the dipole field deviated far from normal (Levi and Karlin, 1989). $^{10}$Be concentrations in sediments from the sections of the core near these excursions were unusually high. In general, the variations in the $^{10}$Be concentrations, except for the $^{10}$Be anomaly associated with the Mono Lake, seemed consistent with what would be expected for modulation of the dipole field as shown by the research on the magnetization of marine and lake sediments (Tric et al., 1992; Meynadier et al., 1992; Thouveny et al., 1993; Carcaillet et al., 2004; Knudsen et al., 2008).

From sediments from the Blake Outer Ridge (site CH88–10P) $^{10}$Be production was shown to vary inversely related to the geomagnetic field (McHargue et al., 2000). $^{10}$Be data from this site was directly compared to the paleointensity data that were measured from the same sediment samples (Schwartz et al., 1998). A direct comparison of variances best showed the relationship between $^{10}$Be and the paleointensity data. This was done by converting the $^{10}$Be data to variances, and the NRM/ARM paleointensity data (Natural Remanent Magnetization/Anhysteretic Remanent Magnetization) to inverse variances about linear regressions.

Previous work on sediments from the Gulf of California and the Blake Outer Ridge showed that it was possible to obtain reliable cosmic-ray records from $^{10}$Be from marine sediments. Nevertheless, reliable isotopic and paleointensity measurements from sediments, corals, or ice, are typically difficult to obtain. Many environmental complications affect the deposition of $^{10}$Be (Kok, 1999; Frank, 2000). Lake systems are even more sensitive to short-term environmental influences than the ocean due to the sensitivity of their lake levels, sediment supply, and water chemistry to regional climate. With these problems in mind the earlier work on two marine sediment cores from the Atlantic and the Pacific will be compared to the $^{10}$Be results from Lake Malawi to provide context.

2. Methodology

The two cores obtained by the Lake Malawi Drilling Project in this initial study were initially sampled at intervals of 10 m throughout the 80 m of core MAL05–1C, and in core MAL05–1B from 80 to 382 m. Sediment samples were then later taken every 2 m in core MAL05–1C. The sediment samples from Lake Malawi were cut in 1-cm thick blocks, estimated to represent about an average of about 20 yrs of sedimentation. A 1–2 g split of the each sample was processed keeping the rest of the sample in reserve. Each split was leached in a solution of 25% acetic acid and 0.04 M hydroxylamine-HCl to separate the authigenic mineral fraction of the sediment from the terrigenous fraction (Bourles et al., 1989). The composition of the authigenic fraction of the sediment more closely reflects the composition of seawater than the whole sediment (McHargue et al., 2000) and is composed of exchangeable ions, carbonates, and iron–manganese hydroxides. An aliquot of the leachate was diluted with 5% HNO3 and set aside for Inductively-Coupled Plasma Atomic Emission Spectrometer (ICP AES) analysis of elemental composition (Fe, Al, Ca, Mn, and Mg). The residue was washed, dried, and weighed. The difference, the mass loss, between the initial mass and the residue is the presumed authigenic fraction of the sediment. A 2-ng beryllium carrier was added to the remaining solution. The beryllium was separated and purified by solvent extraction, precipitation of Be(OH)$_2$, and then combusted to BeO.

Beryllium-10 was measured on the Tandem Accelerator Mass Spectrometer at the University of Arizona. In past measurements the blank ($^{10}$Be/$^{9}$Be) for the beryllium carrier averaged less than $2 \times 10^{-14}$. Repetitive measurements of the NIST standard (SRM 4325) have determined that the typical error for a $^{10}$Be measurement with the tandem accelerator to be less than 2%.

3. Results and discussion

The sediment mass loss after leaching varied from less than 5% to almost 30%. A plot of the summed cation concentration for the major elements of the aliquot against the measured mass loss shows that, within the error of analytical and physical measurement of the samples, the relationship is close to linear. Most of the weight loss is attributable to the leaching of iron and manganese, and to a lesser extent, calcium and magnesium species. Aluminum is slightly negatively correlated to the mass loss from leaching. The concentrations of beryllium in the leachate, particularly $^{10}$Be, are independent of the amount of sediment loss. This may be due to the restriction of beryllium in the pore water and exchangeable phases of the sediment during accumulation of the iron/manganese hydroxide phases.
We compared the data from Lake Malawi cores 1B and 1C to data from the Gulf of California (DSDP site 64, core 480) in order to define the differences between the depositional regimes of marine and lake sediments. The sediments deposited in the Gulf of California are varved and are composed of alternating variations in the concentrations of clay from terrestrial sources and seasonally induced diatom blooms. Iron versus the aluminum obtained from the leachate from sediment samples of the Gulf of California in Fig. 2b are plotted, along with that of the totally digested residue after leaching. The aluminum to iron ratio of the leachate is significantly different from that of the clays and the diatoms in the residue of the varved sediments. (The silicates are not attacked by the mild leaching during removal of the iron-enriched authigenic fraction of the sediments.)

A plot of beryllium and beryllium-10 measured from the same samples shows that the $^{10}$Be content in the authigenic fraction of the sediment is closer to its probable oceanic content than that in the residue (Fig. 2b). The concentration of the terrigenous beryllium ($^{9}$Be) is higher in the clay-rich residue than in the more diatomaceous residue. In the diatomaceous residue the beryllium isotopes are more similar to that of the authigenic fraction than the terrigenous residue as would be expected. Nevertheless, both the clay-rich and diatomaceous residues are on the same trend line indicating riverine source dependence between $^{9}$Be and $^{10}$Be. On the other hand, in the authigenic fraction, the concentrations of beryllium and $^{10}$Be are largely independent at site 480 due to the different origins of $^{10}$Be and beryllium in the open sea.

The residue, that is the sediment remaining after leaching, was not processed for the Lake Malawi sediments for the initial study. Nevertheless, comparisons can be made between the marine sediments from the Gulf of California and those from Lake Malawi. There are significant differences in the composition of those sediments deposited in an open ocean environment to those deposited in a restricted lake basin. The aluminum and iron concentrations in the residue for the ocean sediments (Fig. 2) are similar to that of the terrigenous material, such as clays within the sediments and diatoms. The aluminum to iron ratio of the authigenic fraction of marine sediments from the Gulf of California is positively correlated and is slightly under 0.2 similar to that of sea water of 0.25 (Martin and Whitfield, 1983). On the other hand, the aluminum to iron ratio of the authigenic fraction of Lake Malawi sediments are not correlated to one another (Fig. 3). The ratio of aluminum to iron ranges from 0.01 to 0.1 probably reflecting significant variations in lake and pore water chemistry with time affecting iron removal and accumulation in the sediments.

![Fig. 2. Measurements of aluminum, iron, and beryllium isotopes from two phases of the marine sediments, the leached and the residue, from the Gulf of California (DSDP Leg 64, site 480) are plotted as a comparison to the lake sediments from Lake Malawi in Fig. 4.](image)

(a) Aluminum as a function of iron from two phases of Gulf of California sediments, the leachate (authigenic fraction) and the residue (terrigenous and diatomaceous fraction). (b) $^{10}$Be as a function of total beryllium from the leachate and residue of marine sediments from the Gulf of California.
There is a significant difference between the concentrations of the beryllium isotopes between the authigenic fraction of the marine and lake sediments. The concentration of $^{10}$Be to beryllium is 50 to 80 times higher in the marine sediments of the Gulf of California than in the lake sediments due to increased scavenging from vigorous upwelling. The residence time of $^{10}$Be in the open sea is nearly 1000 yrs (McHargue and Damon, 1991), whereas that in the lake may be in the order of a few yrs to a few decades depending on the river input, lake levels, and sediment deposition.

More importantly the distribution of $^{10}$Be in the authigenic fraction with respect to $^9$Be is significantly different. At DSDP site 480 $^{10}$Be is not correlated to beryllium ($r=0$). This is as a result of $^{10}$Be and beryllium ultimately having different sources and not having mixed before their removal to the sediments. Almost all $^{10}$Be originates in the atmosphere (Lal, 1988). Only a small amount of $^{10}$Be ($<$1%) is produced in situ, that is, within the surface materials of the earth. Beryllium ($^9$Be), the stable form of the isotope, instead is largely derived from terrigenous materials. The two isotopes mix during transport in the hydrological cycle. At site 480 the complete independence of $^{10}$Be from $^9$Be indicates little to no mixing of the two isotopes before deposition. Thus the deposition of $^{10}$Be at site DSDP 480 directly related to its production in the atmosphere. On the other hand, $^{10}$Be and $^9$Be in the sediments at Lake Malawi are more strongly correlated ($R=0.80$) than the marine sediments from the Gulf of California. A significant amount of the $^{10}$Be deposited in the sediments at Lake Malawi has been recycled and mixed with $^9$Be. The variations in the iron and aluminum data and the dependence of $^{10}$Be on $^9$Be indicate that the interpretation of the $^{10}$Be data from Lake Malawi as a representative primarily of cosmogenic deposition may be problematical. The extent to which $^{10}$Be that is produced in the atmosphere just prior to precipitation to Lake Malawi can be distinguished from that recycled through aeolian and hydrological processes is therefore uncertain.

Fig. 4 shows the two isotopes of beryllium plotted separately for both core C and B from the Lake Malawi sediments. The strong correlation in Fig. 3b indicates there are similarities between the two plots of beryllium (Fig. 4a) and $^{10}$Be (Fig. 4b). Most notably at a depth of 150 m there is a sharp increase in both beryllium and $^{10}$Be probably due to a sharp decrease in the sedimentation rate. In addition, both show a trend to lesser concentrations at depth in the core, beryllium weakly ($r=-0.39$) and $^{10}$Be more strongly ($r=-0.62$), perhaps due to decay. Mixing of both isotopes in the watershed of the lake during
soil formation, riverine and aeolian transportation of sediments, and deep water deposition would be expected.

A higher resolution look of the trends for $^{10}$Be and beryllium for core 1C is shown in Fig. 5a and b, respectively. Also shown in Fig. 5c are the TOC (Total Organic Carbon) data for the same section for comparison (Lyons et al., 2011-this issue). The TOC is a proxy for the past lake depth of Lake Malawi (Lyons et al., 2011-this issue). During lowstands of the lake the TOC is low when arid conditions (Cohen et al., 2007) limit runoff and sediment to coarser grained inputs. During highstands, along with the increased sediment supply in more finely laminated intervals, there is an increase in the terrestrial organic matter (Cohen et al., 2007). The depth intervals for transgressions and regressions of the lake level in Fig. 5c are highlighted by the dotted lines and correlated to the beryllium isotope data in Fig. 5a and b. The concentration of the beryllium isotopes do not directly correlate with the concentration of the organic matter in the sediments. However, the regressions and transgressions of Lake Malawi as reflected by the TOC data is also, in part, reflected in the beryllium isotope data. For example, the lowering of the lake level between 45 and 70 m is associated with a decrease in the concentration of the beryllium isotopes of the same section. In addition, a rise in the lake level interpreted from the sediments between 85 and 70 m corresponds to an increase in the concentration of the beryllium isotopes. Similarly, a rise in the lake level from 30 to 10 m, followed by a lowering for sediments less than 10 m of core depth, correspond to an increase and then a decrease in beryllium isotopes, respectively. On the other hand, a significant transgression between 38 m and 30 m is not associated with an increase in beryllium isotopes but a decrease.

For comparison to the Lake Malawi data the global production of $^{10}$Be as a function of the averaged paleomagnetic field intensities from several marine sediment cores is shown in Fig. 6b (Valet et al., 2005). In Fig. 6a the concentration of $^{10}$Be/$^{9}$Be in the core C at site 1 at Lake Malawi core is plotted with depth. From the organic matter from the upper most part of the core numerous radiocarbon dates are available and the depth and time boundaries are plotted (Scholz et al., 2007, Supporting Information). These depths of the youngest and oldest radiocarbon-dated samples in Fig. 6a are correlated with their dates in Fig. 6b. In addition, the oldest obtained OSL IR (Optically-stimulated luminescence dating) result is correlated in the same manner thus bracketing the sediments measured in time. Also shown for comparison in Fig. 6b are the MIS (Marine Isotopic Stages) associated with this time period. The increases in the $^{10}$Be/$^{9}$Be ratio are roughly consistent with the $^{10}$Be production rates as derived from the paleomagnetic intensity record. The $^{10}$Be/$^{9}$Be ratio is low in the Holocene due to the more intense dipole fields. The maximum $^{10}$Be/$^{9}$Be in MIS 3 may be associated with the Laschamp geomagnetic excursion. A secondary peak of $^{10}$Be in MIS 4 is consistent with similar increases in $^{10}$Be concentrations seen in marine sediment cores and ice cores in Antarctica. A significant $^{10}$Be/$^{9}$Be increase, and associated perhaps with the Blake Event, is more sharply defined in the sediments than would be expected from the $^{10}$Be production curve but is consistent with the $^{10}$Be data from the Blake Outer Ridge (not shown). The above interpretation assumes the excesses of $^{10}$Be to $^{9}$Be in the $^{10}$Be/$^{9}$Be ratio are due to increases in the production rate of $^{10}$Be in the atmosphere. However, the excess of $^{10}$Be to $^{9}$Be may result from an increased collection for $^{10}$Be precipitating from the atmosphere due to a greatly expanded surface area of Lake Malawi during highstands...
with respect to recycled $^{10}$Be and $^9$Be. Therefore, the above correlations are problematical.

The history of the dipole field has been extended to 2 million yrs by stacking together the data from sediment cores from different areas of the world (Valet et al., 2005). In Fig. 7 the averaged intensity of the geomagnetic field by Valet et al (2005) (Fig. 7b) is compared to the $^{10}$Be/$^9$Be ratio for the entire core 1B from Lake Malawi (Fig. 7a). The mean paleomagnetic dipole field intensities (Valet et al., 2005) have been converted to the production of $^{10}$Be by the method of Lal (1988). In order to make comparisons of the $^{10}$Be data as measured from the sediments in terms of concentration (atoms/g), or by the ratio of $^{10}$Be to beryllium ($^{10}$Be/$^9$Be), it is necessary to take in account the decay of $^{10}$Be (half life of 1.34 million yrs). The concentrations of $^{10}$Be have not been corrected to their “original” concentrations because the time scale has not been established. Therefore, the production of $^{10}$Be has been modified to reflect the decay since earlier periods of time — the production of $^{10}$Be has not increased with time as might be inferred from Fig. 6. The sediments below 80 m were taken every 10 m so all the results down to 380 m have been compressed for comparison against the plot of the geomagnetic field. The dotted lines show possible correlations to broad features both in the $^{10}$Be/$^9$Be data and the geomagnetic data. There does seem to be a rough similarity between the two data sets. For example, a significant decrease in $^{10}$Be/$^9$Be at depths in the core deeper than 300 m and an increase from 200 to 300 m is reflected in the $^{10}$Be production curve for the time interval older than 400 kyr. Also, the rate of the decrease in $^{10}$Be/$^9$Be is consistent with the decay of $^{10}$Be. The implication from Fig. 7 is that the bottom of the core may be between 650 to 750 thousand yrs in age.

However, as was discussed earlier, it is not likely that the $^{10}$Be concentrations in the Lake Malawi sediments are directly tied to its production in the atmosphere but is mostly recycled from several sources. In addition, the changes in lake level affect the transport of the beryllium isotopes to the lake, and the changing surface area of the lake effects the collection of atmospheric $^{10}$Be. The correlation between the two data sets may be either coincidence, or a secondary correlation between climate and the geomagnetic field and then between climate, lake level, and sediment deposition.
4. Conclusion

Measurements of $^{10}$Be were made on the Lake Malawi drill core MAL05-1C at intervals of every 2 m to a depth of 80 m and then every 10 m from core 1B to near the bottom at 380 m. $^{10}$Be and $^{9}$Be, in addition to several major elements, indicate that a record of past lake water chemistry can be obtained from the authigenic fraction of the sediments. Comparisons between the results for $^{10}$Be/$^{9}$Be and those from a marine sediment core from the Gulf of California highlighted some differences between the oceanic and lacustrine sedimentary regimes. A profile for the $^{10}$Be/$^{9}$Be ratio from Lake Malawi does show correspondence, with some differences, with the global $^{10}$Be production for the late Quaternary. The bottom of the core is no older in age than 750,000 yrs (perhaps as young as 650,000 yrs) rather than the 1.5 million yrs of original estimates. However, the correlation between $^{10}$Be and $^{9}$Be in Lake Malawi sediments unlike that of the Gulf of California suggests a significant recycled component of $^{10}$Be. Perhaps more importantly, the wide variations in the lake level affect the flux of the beryllium isotopes to the lake sediments significantly. When the lake level is high there is an increased flux of beryllium isotopes to the lake from the surrounding drainage basin. In addition, the increased surface area of the lake enhances the collection of $^{10}$Be from the atmosphere with respect to that of the recycled beryllium isotopes. When the lake level is low during times of aridity transport of the beryllium isotopes to the lake from the local drainage basin is restricted and direct precipitation of $^{10}$Be from the atmosphere is less due to a much smaller lake surface area. Thus, any correspondence between the $^{10}$Be/$^{9}$Be profile and the known $^{10}$Be production profile may reflect an indirect relationship between the dipole field and climate. The effects of climate on lake levels, sedimentation rate, and water chemistry will affect the concentration of $^{10}$Be within the sediments, and climate, in part, may be influenced by the dipole field. Unfortunately, the effects on the local climate on sedimentation and lake levels may obscure even the effects of the secondary correlation,
and a potential chronology as well. Nevertheless, these interdependent effects may be better understood by further work on the lacustrine $^{10}$Be geochemical cycle.

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References


