

High-resolution paleoecological records from Lake Malawi show no significant cooling associated with the Mount Toba supereruption at ca. 75 ka

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ABSTRACT

The impact of the ca. 75 ka Mount Toba (Indonesia) supereruption on regional and global climate has been controversial. East Africa is pivotal for qualifying this impact, specifically in addressing a hypothesis that this eruption caused a volcanic winter leading to a genetic bottleneck in anatomically modern human populations. If the Toba eruption caused a volcanic winter in East Africa, effects should be recorded in sediments from climatologically sensitive ecosystems. In deep tropical lakes, cooler temperatures would have reduced the density contrast between the epilimnion and hypolimnion, causing increased mixing, hypolimnion oxygenation, and enhanced nutrient advection. Such environmental changes produce noticeable and predictable responses in lake fossil assemblages and sediment loading. Here we present the first paleoecological evidence from East Africa of environmental conditions surrounding the eruption in a high-resolution (~8–9 yr) analysis of two cores collected by the Lake Malawi Drilling Project. These cores contain an undisturbed record of sedimentation before, during, and after deposition of the youngest Toba Tuff. Concentrations of climate-sensitive ecological indicators such as phantom midges, diatoms, and other algae through a >270 yr interval bracketing the Toba cryptotephra show no unusual or sustained deviations from background variability within Lake Malawi associated with the hypothesized post-Toba cooling. We find no evidence for significantly enhanced mixing or ecosystem disturbance that would be anticipated following a volcanic winter.

INTRODUCTION

Impact from the Mount Toba (Indonesia) supereruption at ca. 75 ka on global and regional climate has been extensively debated (Ambrose, 1998; Williams et al., 2009; Lane et al., 2013a, 2013b; Roberts et al., 2013). Estimates of the duration of this eruption also vary (Rampino and Self, 1992, 1993; Zielinski et al., 1996; Timmreck et al., 2012), and it is argued that the eruption led to a rapid decline in early anatomically modern human populations in East Africa (Rampino and Self, 1992, 1993; Ambrose, 1998, 2003). Recent identification of the youngest Toba Tuff (YTT) as a cryptotephra layer in Lake Malawi (LM) sediment cores marks the first African record of the Toba supereruption. Because of relatively high sedimentation rates, it is possible to sample and analyze the LM cores at subdecadal levels. Furthermore, prior studies (Stone et al., 2011) show that this record is sensitive to ecological disturbances in East Africa, the region where anatomically modern humans first appear in the fossil record (Day, 1969). Here we present a high-resolution ecological analysis of two LM cores across the interval containing the YTT. Our sampling resolution records an average of ~8–9 yr per interval; the entire sampled interval in both cores extends ~50 yr before and ~220 yr after deposition of the YTT, allowing us to directly compare lake ecology pre-YTT and post-YTT.

The Toba supereruption is estimated to have released 40× more debris into the atmosphere than the largest historical volcanic eruption of Tambora (Indonesia) in A.D. 1815 (Oppenheimer, 2002). Ash from the Toba supereruption has been identified in India, the Indian Ocean, the South China Sea, and recently as a cryptotephra layer in LM cores (Oppenheimer, 2002; Lane et al., 2013a), ~7300 km west of Mount Toba (Fig. 1).

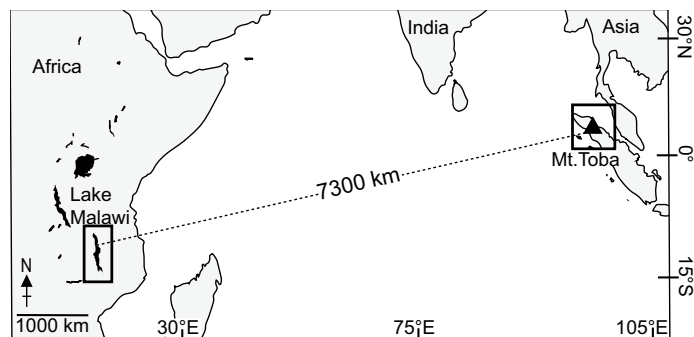


Figure 1. Generalized map showing the location of Lake Malawi in East Africa relative to Mount Toba, Indonesia.

An early hypothesis argued that the Toba eruption would have forced global cooling of ~3–5 °C (Rampino and Self, 1992) and could have initiated 200 yr of cooling, as recorded in the Greenland Ice Sheet Project II ice core at the beginning of stadial 20 (Zielinski et al., 1996). More recent modeling, however, has been unable to reproduce this magnitude of cooling. Robock et al. (2009) suggested that a decade-long volcanic winter could be produced by a Toba-like eruption, explicitly noting that plant and animal life would be seriously affected. Timmreck et al. (2012) proposed that 5 °C cooling for only 5 yr would have occurred in eastern and southern Africa. Oppenheimer (2002) presented arguments for less significant global cooling, ~1 °C.

Debate thus far on the impact of the Toba supereruption on continental ecosystems has been hampered by the paucity of undisturbed stratified paleoecologic records containing the YTT ash (as discussed in Williams et al., 2009). Advancing this debate in relation to modern human evolution requires that such records be obtained in proximity to the regions of Africa where evidence exists for anatomically modern *Homo sapiens* at the time of the Toba eruption, and that they include ecological indicators that are sensitive to climate fluctuations. With the discovery of the YTT in exquisitely preserved sediment of the LM drill cores, we are now in a position to address this issue directly.

Lake Malawi occupies a large (29,500 km², 706 m deep), long-lived (older than 7 Ma) rift basin (Scholz et al., 2006) in the southern African tropics. The lake is meromictic and stratification is maintained by temperature (Patterson and Kachinjika, 1995). The long sedimentary record and well-studied and diverse ecosystems of LM make it an ideal repository for records of long- and short-term climatic fluctuations.

The cores were retrieved in 2005 by the Lake Malawi Drilling Project (Scholz et al., 2006). Core 2A was retrieved from the northern basin in a region subject to upwelling variability. Core 1C was retrieved from the central basin near the deepest part of the lake (Scholz et al., 2006). In our study, we focus on paleoecologic records that have proven highly informative in prior studies of LM cores (Cohen et al., 2007; Stone et al., 2011). Specifically, we examined the core for evidence of lake water-column mixing, which in deep, meromictic tropical lakes is enhanced by cooling surface water (epilimnetic) temperatures and suppressed by warmer

surface waters. It is well documented that surface warming suppresses mixing on seasonal to centennial time scales in the deep tropical lakes of Africa (e.g., Tierney et al., 2010).

Diatoms are a key indicator of water-column mixing in LM (Kilham, 1990; Stone et al., 2011). Planktonic diatoms such as *Aulacoseira*, *Stephanodiscus*, and *Cyclotella* are sensitive to changes in lake mixing and common in the LM sediment record. When the lake is strongly stratified, limiting nutrients for diatoms (primarily P and Si) are sequestered in the hypolimnion, allowing the epilimnion to be dominated by low-nutrient specialist plankton such as *Cyclotella*. In contrast, colder conditions promote mixing and nutrient upwelling, which creates conditions more favorable for *Aulacoseira* (high P and Si) and *Stephanodiscus* (high P, low Si) growth (Kilham, 1990). Thus, a simple diatom mixing index (DMI) using these three genera [$(Aulacoseira + Stephanodiscus)/Cyclotella$] is a useful indicator of the degree of lake stratification (low) or mixing (high).

The green algae *Botryococcus* and *Pediastrum* are indicators of primary productivity. *Botryococcus* is an easily adaptable and successful colonizer that occurs over a wide variety of conditions (Guy-Ohlson, 1992). *Pediastrum* is common in mesotrophic and eutrophic lakes (Jankovská and Komárek, 2000). In late Pleistocene sediments from the Lake Malawi drill cores, *Pediastrum* abundance is strongly negatively correlated with lake surface-water temperatures (A. Cohen, unpublished data; Woltering et al., 2011). *Botryococcus* show a similar pattern of increasing during cooling events, albeit more muted than for *Pediastrum*.

Larvae of the phantom midge (*Chaoborus edulis*) are extremely abundant zooplankton in the LM ecosystem (Irvine, 1995). Their concentration in LM in both the modern lake, and as fossils in sediments, is related to limnologic conditions and indirectly to water temperature variability. Warm conditions enhance lake stratification, promoting bottom-water anoxia, offering the larvae a diurnal refuge from fish predation. Cold conditions reduce the density contrast between the epilimnion and hypolimnion, weakening stratification, increasing the depth of oxygenation, and increasing predation on *Chaoborus*, largely eliminating them from oxygenated bottom waters.

Spicules from benthic sponges that require oxygenated waters for growth are commonly washed into offshore, anoxic bottom sediments and recovered from cores in low concentrations. Deepening of the oxicle and enhanced ventilation of LM bottom waters results in a substantial increase in the flux of sponge spicules and other benthic invertebrates (Cohen et al., 2007).

If ash and aerosol discharge from the Toba supereruption caused a volcanic winter in East Africa of even a few degrees celsius, LM would undergo significant epilimnetic cooling, resulting in instability and mixing of the water column, a deepening of the oxicle, and partial to complete oxygenation of the hypolimnion. With these changes a pronounced decrease in *Chaoborus* is expected, as is a peak in the DMI, the appearance of benthic invertebrates, and an impact on the surrounding watershed sediment discharge. These changes should be abrupt and associated with YTT deposition. A simplified illustration of LM dynamics under warm and highly stratified conditions, and under significantly cooler conditions, is presented in Figure 2.

METHODS

LM cores 2A-10H-2 and 1C-8H-1 were continuously sampled in ~3–4 mm intervals, each representing ~8–9 yr, with no stratigraphic breaks between adjacent samples. Samples were collected from 15 intervals below, and from 30 intervals above, the YTT in each core. Petrographic smear slides (see the GSA Data Repository¹) were prepared for all samples us-

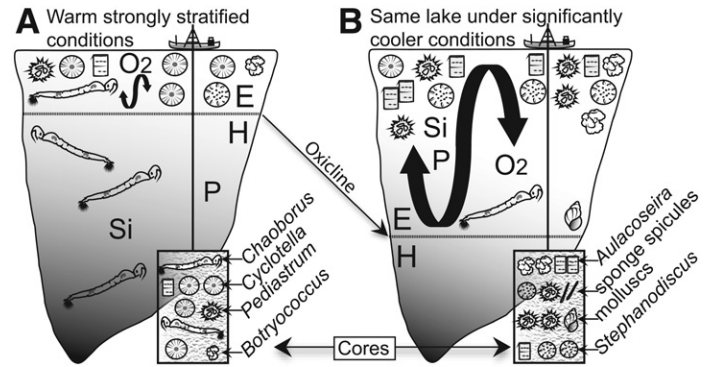


Figure 2. Conceptual illustration showing Lake Malawi dynamics under warm and cooler climatic conditions. A: Under warm conditions, the lake is strongly stratified, *Chaoborus* finds refuge in anoxic hypolimnion, and the diatom *Cyclotella* dominates. H—hypolimnion; E—epilimnion. B: Under colder conditions, the lake is better mixed, oxygen penetrates deeper into the metalimnion, fish predation of *Chaoborus* increases, benthic invertebrate populations expand, and nutrient upwelling allows the diatoms *Aulacoseira* and *Stephanodiscus* to bloom.

ing standard methods (Tool for Microscopic Identification; <https://tmi.lacore.umn.edu/>) to identify mineralogical and paleoecological trends for all size fractions prior to sample preparation. A small aliquot from each sample was taken for diatom analysis. A second aliquot from each sample was weighed prior to and after oven drying at 40 °C to determine water content. The non-diatom fractions of the samples were disaggregated in distilled water, screen-washed using 45 µm stainless steel sieves, and then counted at 180× magnification. Samples for diatom analysis were treated with 10% HCl and 35% H₂O₂. Diatom concentrates were spiked with microspheres and mounted in a high-refractive index medium. We identified a minimum of 300 diatom valves with a transmitted light microscope at 1000× magnification.

We use a floating chronology based on the stratigraphic position of the YTT cryptotephra in the cores identified by Lane et al. (2013a, 2013b), dated to 75 ± 0.9 ka (1σ error) (Mark et al., 2014). We assume linear sedimentation rates in the study interval derived from the radiocarbon-dated portion of the cores (see Scholz et al., 2007), with the exception of one turbidite in core 2A that is assumed to have been deposited in <1 yr.

RESULTS

In core 2A, the YTT was identified at 26.752–26.772 m below lake floor (mblf) (C. Lane and T. Johnson, 2015, personal commun.) within a prominent light colored horizon with small-scale ripple lamination, ~1 cm above a small turbidite (Fig. 3). The light layer and darker sediments immediately below and above it are sedimentologically very similar, consisting of mostly diatom frustules, with color differences probably resulting from slight differences in organic matter concentration. Low-amplitude fluctuations and changes in all of the key ecological indicators are below the level of background variability in the study interval. Large peaks in *Chaoborus*, sponge spicules, and DMI co-occur at ~26.798 mblf in the core, coincident with an increase in sedimentation associated with the turbidite. There are no benthic molluscs or ostracodes in any core samples, indicating that at no time were bottom waters oxygenated in association with the YTT event. Overall, there is little variability in the concentrations of any key ecological indicators including the DMI in sediments deposited before and after the YTT. In the 1C core (Fig. 4), the YTT was identified at 28.08–28.10 mblf (Lane et al., 2013a). Unlike site 2A, the sediments are laminated throughout the YTT interval. Ecological indicators present before, during, and after the YTT show low-amplitude fluctuations, within the range of intrasample variability typically observed in LM cores, with no changes in their concentrations above background levels. Sponge spic-

¹GSA Data Repository item 2015278, detailed smear slide and diatom data, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

Site 2 GLAD7-MAL05-2A-10H-2

lat. 10°01.06'S
long. 34°11.16'E
361 m water depth

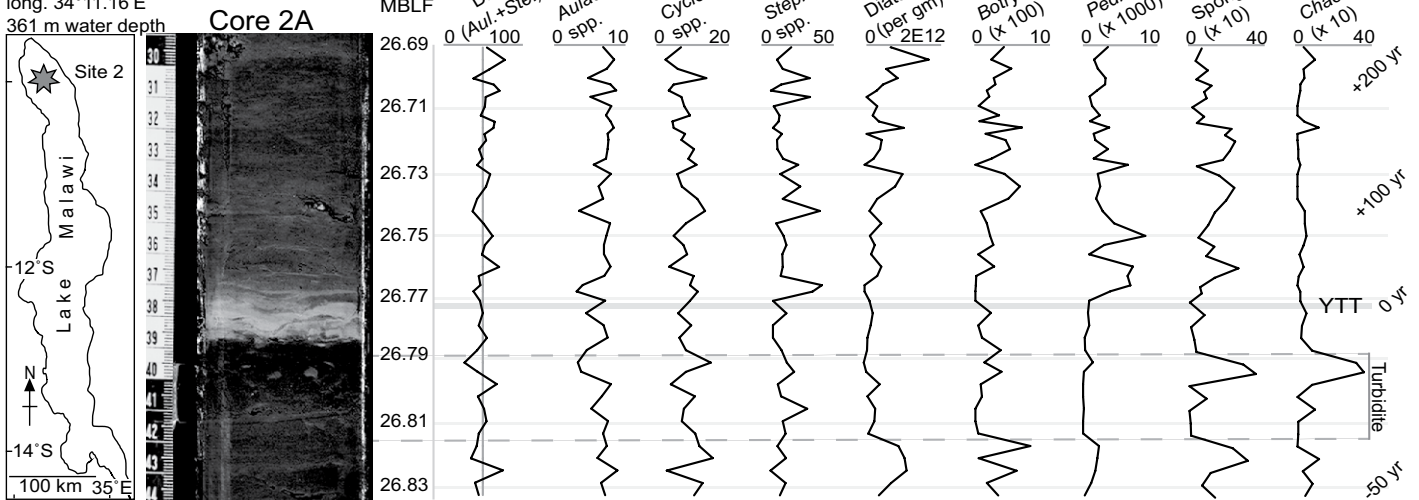


Figure 3. Drill core 2A-10H-2, showing the location of core recovery site 2 in Lake Malawi, East Africa. Plotted data are the diatom mixing index (DMI) [(*Aulacoseira* + *Stephanodiscus*)/*Cyclotella*], and counts per dry gram of *Aulacoseira* (*Aul.*), *Cyclotella*, and *Stephanodiscus* (*Ste.*), the green algae *Botryococcus* and *Pediastrum*, sponge spicules, and *Chaoborus*. The range over which the youngest Toba Tuff (YTT) was identified is highlighted. MBLF—meters below lake floor.

Site 1 GLAD7-MAL05-1C-8H-1

lat. 11°17.66'S
long. 34°26.15'E
592 m water depth

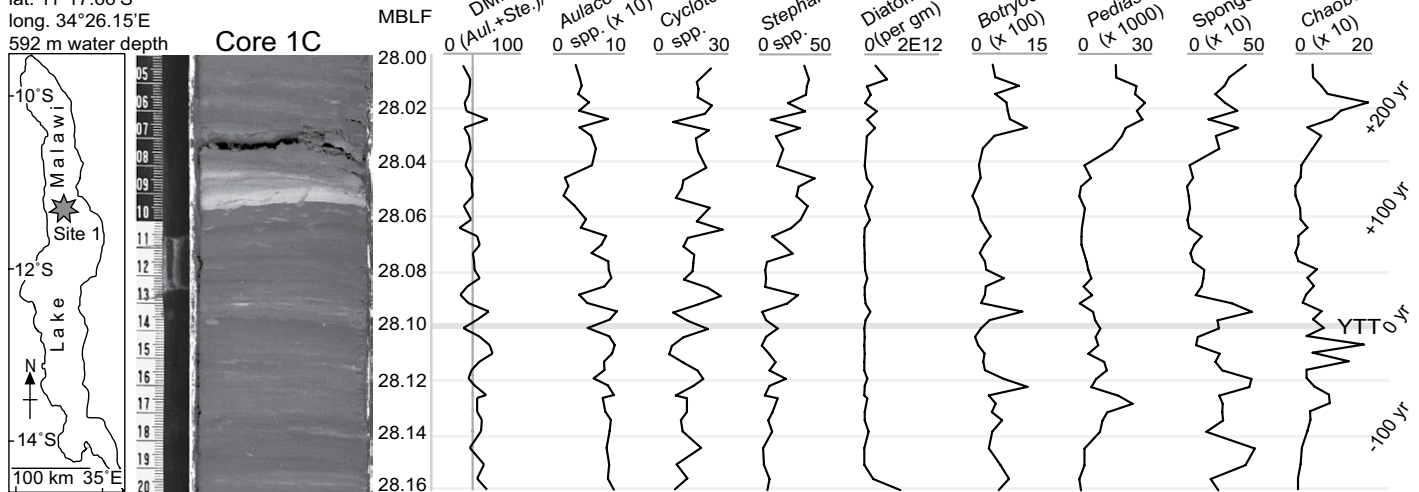


Figure 4. Drill core 1C-8H-1 showing the location of core recovery site 1 in Lake Malawi (East Africa). Plotted data and abbreviations as in Figure 3.

ule abundances decline above the YTT and no ostracodes or molluscs occur at any point in the core, again indicating that at no time were bottom waters at the core site oxygenated immediately before, during, or after the YTT episode. A slight overall decrease in the DMI occurs over the entire sampled interval, although second-order fluctuations occur.

DISCUSSION

The key finding of this study is the lack of significant change to lake ecology following deposition of the YTT at the resolution of our analysis, a change that would be expected from a major cooling-related disruption to the LM ecosystem. The absence of any consistent directional change at two widely separated (>100 km apart) and limnologically distinct sites supports the conclusion that at the temporal scale of sample resolution and time averaging available from this record, the ecological variability observed immediately before and after the occurrence of the YTT is not unusual.

Simultaneous spikes in the DMI, concentrations of *Chaoborus*, sponge spicules, and detrital sediments at 26.798 mblf in core 2A are attributed to the turbidite at 26.812 mblf (i.e., prior to the YTT, and thus unrelated to it), based on our smear slide counts. The YTT cryptotephra layer is above the turbidite and is not disturbed by it, as shown by the discrete stratigraphic separation of YTT cryptotephra from earlier locally derived and probably reworked Rungwe volcanic cryptotephra reported by Lane et al. (2013a). Comparison of sediments immediately before and after both the turbidite and the YTT-containing intervals in core 2A, and immediately before and after the YTT in core 1C, shows no directional variation in concentrations of any ecological indicators present, including DMI, sponge spicules, algae, and *Chaoborus*, therefore indicating ecosystem stability over the entire sampled interval. Our findings are consistent with those of Lane et al. (2013a, 2013b) using both high-resolution scanning X-ray fluorescence data and, over longer time scales and at lower time resolution, using

TEX₈₆ paleotemperature measurements, which detected no evidence for lake overturn driven by temperature fluctuations. It could be argued that evidence of cooling is not observed in our record because the duration of the Toba cooling was shorter than the subdecadal resolution of our core sampling. We reject that argument for two reasons. First, the individual samples are not instantaneous snapshots but rather time-averaged representations of environmental conditions over each sampling interval, and those intervals are continuous. A major environmental perturbation would thus be sampled within the time-averaged sample in which it occurred, and should be recorded, even if briefly. Second, a cooling perturbation that is too brief or of a magnitude too small to affect the LM ecosystem is equally unlikely to have had a profound cooling effect on the surrounding terrestrial ecosystem, given that today even seasonal climatic variability is strongly registered in the annual limnologic and mixing cycle of LM (Patterson and Kachinjika, 1995).

CONCLUSION

In our investigation of subdecadal paleolimnological variability at LM from two widely separated core sites immediately before, during, and after the YTT horizon, we find no evidence of a profound environmental perturbation of the lake ecosystem. Minor variability certainly exists throughout our record, but its magnitude is well within ranges observed elsewhere in the LM drill cores and is far exceeded by other documented early late Pleistocene climatically driven limnologic events (Cohen et al., 2007; Scholz et al., 2007; Stone et al., 2011). Conditions in LM appear stable across the entire duration of our several hundred-year-long records, with no evidence of enhanced lake mixing from a cooling event. When viewed from a longer term time perspective, the YTT interval marks the onset of prolonged (10⁴ yr time scale) relative stability in the LM ecosystem (Stone et al., 2011). The excellent preservation of the LM cores and the high resolution of our sampling intervals allow us to compare both short-term and longer term changes in the lake and surrounding watershed before and after the YTT deposition. Thus, in the record covering at least 50 yr prior to the eruption and ~220 yr after the eruption, we find no evidence to support the hypothesis that a volcanic winter caused by the Mount Toba supereruption resulted in substantial cooling in East Africa.

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