Ash from the Toba supereruption in Lake Malawi shows no volcanic winter in East Africa at 75 ka

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Author contributions: T.C.J. conceived the project; C.S.L. and T.C.J. designed the analytical procedure; C.S.L. and B.T.C. performed research; and C.S.L., B.T.C., and T.C.J. wrote the paper.

The injection of ash and aerosols into the stratosphere by explosive volcanic eruptions can trigger complex climatic feedbacks, often promoting surface cooling (1−3). Voluminous ash fall deposits blanket landscapes, at least locally, smothering vegetation, blocking sunlight, and contaminating water supplies. The Youngest Toba Tuff (YTT) has been identified in sediments from the South China Sea (3) and across the Indian Ocean, 7,000 km west of the source volcano in Sumatra. Lake Malawi is 600 km long, 35 km wide, and has a maximum depth of 700 m; it is the second largest and the southernmost great lake in East Africa and was not the cause of a human genetic bottleneck at that time.

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Results

Tephra layers in Lake Malawi sediments are derived primarily from the Rungwe Volcanic Province (RVP) to the northwest of Lake Malawi. A cryptotephra layer was found at 28.08−28.10 Ma B.P. in sediments from Lake Malawi >7,000 km west of the source volcano in Sumatra. The YTT isochron provides an accurate and precise age estimate for the Lake Malawi paleoclimate record, which revises the interpretation of past climatic events in East Africa. The YTT in Lake Malawi is not accompanied by a major change in sediment composition or evidence for substantial temperature change, implying that the eruption did not significantly impact the climate of East Africa and was not the cause of a human genetic bottleneck at that time.
metals and distinctly different from the RVP tephra, which are predominantly trachydacitic in composition (26), or from any other known contemporary East African rhyolitic tephra sources (27, 28) (Fig. 3). Instead, the cryptotephra composition correlates to that of the 75 ka YTT (29) (Table 1 and Table S1). We subsequently found the YTT at 26.77–26.79 MBLF in drill site MAL05-2A, which confirms the existing stratigraphic correlation between the central and northern basin cores.

**Discussion**

Our discovery of ash from the 75 ka eruption of Toba (YTT) in Lake Malawi, ∼7,300 km from the caldera in Sumatra, increases the previously known dispersal distance of ash from this super-eruption by nearly 3,000 km (Fig. 1), extending the areal coverage of this deposit to at least 2 × 10^7 km^2. A recent model suggests that transportation of the Toba ash westward over Africa was most likely by coignimbrite processes (30). YTT dispersal may have further exceeded the current estimates, and we predict that further cryptotephra investigations will recover YTT from other sites in Africa.

Recent dating of the YTT by high precision ^40^Ar/^39^Ar dating of near-vent sanidine phenocrysts has generated two partially overlapping age estimates: 75.0 ± 0.9 ka (4) and 73.88 ± 0.32 ka (17). The difference between these ages is attributed to the standards and optimization models used in the ^40^Ar/^39^Ar age calibration process (4). Here we take the age of 75.0 ± 0.9 ka B.P., which was calculated using the currently best constrained ^40^Ar/^39^Ar optimization model (4, 31) as the most robust age for the YTT, and import it into a revised Bayesian age model for the Lake Malawi central basin core, MAL05-1C (Fig. 4). The resulting model differs from the previously published age–depth model (24) by ∼10 ka at a depth of 28.10 MBLF (Materials and Methods). The revised age–depth model reveals that the published age estimates based on some previously identified paleomagnetic events and optically stimulated luminescence dates from MAL05-1C are inaccurate for sediment older than ∼50 ka. Between 20 and 30 MBLF, the revised age–depth model yields a higher average sedimentation rate of ∼0.03 cm/year, consistent with the upper part of the core, which was dated extensively by radiocarbon (24). The stratigraphic position of key climatic “events” within the Lake Malawi sediments can now be more accurately pinpointed; for example, the hypothesized 75 ka human bottleneck (10) moves from ∼37 MBLF to ∼28 MBLF in MAL05-1C. Other features of the record are also redated, such as the East African megadroughts (24), which must have terminated at least 10 ka earlier than the previous estimate of 75 ka B.P. Clearly, existing comparisons of the Lake Malawi paleoclimate data to other regional and global records (24, 25, 32) will need to be revised in the light of these findings. If YTT can be located in other African paleoclimate archives, this valuable isochron will facilitate more precise comparisons between records that currently have poor age control beyond the limits of radiocarbon dating (>50 ka B.P.).

The sediments of Lake Malawi contain YTT cryptotephra within an undisturbed, thin-bedded interval. The first deposition of the YTT is well constrained to within 1 cm (Fig. 2), equivalent to ∼30 y (Materials and Methods). The sharp base of the tephra profile in Fig. 2A indicates deposition from an airfall event. In-washed ash from the lake catchment may also have reached the core location; however, ash concentrations drop dramatically after 2 cm (∼60 y). With less than 3,500 glass shards per gram of sediment found within 1 cm depth of core, we estimate that the ash would not have formed a visible layer over the Malawi catchment. The direct impact of such a low concentration of fine-
grained ash on the local ecosystem during half a century would have been negligible. We microscopically examined smear slides of sediment at a 2-mm interval from below, within, and above the YTT horizon in Malawi core MAL05-1C. The sediments are Aulacoseira-dominated diatomaceous silty clay and display no obvious change in composition throughout the 4-cm interval (28.07–28.11 MBLF). An X-ray fluorescence (XRF) scan of the interval displays a slight rise in the ratio of Si/Ti, an indication of slightly elevated diatom productivity (33), but no change in other parameters, such as sulfur content, in the ratio of Fe/Ti (suggesting no major shift in redox conditions in the lake), or in the ratio of incoherent to coherent signal strength, which reflects the abundance of organic matter in Lake Malawi sediment (33) (Fig. 2). Lake Malawi is presently anoxic below 200 m depth, and it was likely in this state at the time of the eruption of Toba. Had regional temperature cooled by ∼4 °C, as has been estimated from climate models of the eruption’s impact (14), the lake would likely have experienced massive overturn of the water column, a major iron oxidation event, and extermination of much of the biota in the upper water column. The sediments in core 1C display no clear evidence for such a catastrophic event.

Paleotemperature reconstructions using the TEX86 organic biomarker display no unusual response to the Toba eruption. A previously published paleotemperature record of core MAL05-2A was carried out at a resolution of ∼1,000 y (32). We analyzed the Toba horizon and four additional depths in MAL05-2A for TEX86 and found the Toba interval records a temperature drop of ∼1.5 °C relative to sediment above and below this horizon (Fig. S1). This cooling is less severe than what is observed in other parts of the MAL05-2A record. We conclude that the hypothesized “volcanic winter” that followed the Toba eruption did not have a significant impact on the climate of East Africa and was not the cause of a human bottleneck in Africa around 75 ka B.P.

Materials and Methods
Cryptotephra layers were detected using standard physical separation methods (34). Contiguous and continuous 10-cm samples were treated with 1 mol/L HCl, sieved (>25 μm) and density separated (1.95–2.55 g·cm⁻³) to isolate volcanic glass shards, which were counted under high-power microscopy. Intervals of >20 shards per gram were resampled and reprocessed to locate the cryptotephra layer to within 1-cm depth. Tephra shards were mounted on a 25-mm epoxy resin stub and polished to expose internal surfaces for analysis by electron microprobe.

Single-grain major and minor element compositions were measured using electron microprobe wavelength dispersive spectrometry at the University of Oxford Research Laboratory for Archaeology and the History of Art, using a Jeol JXA8600 electron microprobe, in wavelength dispersive mode, with...
15-keV accelerating voltage, 6-nA beam current, and 10-μm defocused beam. On-peak count times were 10 s for Na; 30 s for Si, Al, Ca, Fe, Mg, Ti, and Mn; and 60 s for P. The electron probe was calibrated using a suite of characterized minerals and oxides standards; accuracy and precision was monitored by intermittent analysis of fused volcanic glass standards ATHO-G and StHS6/80-G, from the Max-Planck-Institut für Chemie–Dingwell (MPI-DING) collection (35, 36) (Table S1).

The revised age model for the top 30 m of MAL05-1C (Fig. 4) was generated using 15 radiocarbon ages (7) and the latest high-precision YTT age estimate of 75.0 ± 0.9 ka (4) in a Bayesian P-Sequence depositional model (37), run in OxCal version 4.1 (38) with outlier analysis (39) and interpolation at 0.5 m intervals. Radiocarbon dates were calibrated using the IntCal09 curve (40). The approximate sedimentation rate of 0.03 cm·year⁻¹ stated in the text for the time interval around the YTT deposition was calculated directly from our age model, using the interval 20–30 m. Across this interval, the model has a 2-sigma uncertainty of between 2% and 10%.

The analytical methods used to determine TEX86 were identical to those described elsewhere (32).

Table 1. Chemical composition of YTT glass shards in Lake Malawi, compared with proximal samples from the Toba caldera in Sumatra, Indonesia and YTT ash from the Indian archaeological site of Jwalapuram (29)

<table>
<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>TiO₂</th>
<th>Al₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Total*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryptotephra layer, MAL05-1C 28.10 MBLF Average (n = 18)</td>
<td>77.24</td>
<td>0.05</td>
<td>12.41</td>
<td>0.84</td>
<td>0.07</td>
<td>0.77</td>
<td>2.95</td>
<td>5.61</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2 SD</td>
<td>1.79</td>
<td>0.04</td>
<td>0.31</td>
<td>0.14</td>
<td>0.08</td>
<td>0.06</td>
<td>0.19</td>
<td>0.37</td>
<td>0.45</td>
<td></td>
</tr>
<tr>
<td>Cryptotephra layer, MAL05-2a 26.78 MBLF Average (n = 9)</td>
<td>77.22</td>
<td>0.04</td>
<td>12.32</td>
<td>0.84</td>
<td>0.07</td>
<td>0.78</td>
<td>3.2</td>
<td>5.47</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>2 SD</td>
<td>0.47</td>
<td>0.05</td>
<td>0.27</td>
<td>0.11</td>
<td>0.05</td>
<td>0.03</td>
<td>0.21</td>
<td>0.26</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>YTT, Toba caldera Average (n = 118)</td>
<td>77.24</td>
<td>0.06</td>
<td>12.54</td>
<td>0.85</td>
<td>0.07</td>
<td>0.05</td>
<td>0.78</td>
<td>3.10</td>
<td>5.20</td>
<td></td>
</tr>
<tr>
<td>2 SD</td>
<td>0.7</td>
<td>0.06</td>
<td>0.39</td>
<td>0.24</td>
<td>0.09</td>
<td>0.04</td>
<td>0.21</td>
<td>0.34</td>
<td>0.29</td>
<td></td>
</tr>
<tr>
<td>YTT, Jwalapuram, India Average (n = 113)</td>
<td>77.36</td>
<td>0.06</td>
<td>12.49</td>
<td>0.87</td>
<td>0.07</td>
<td>0.07</td>
<td>0.75</td>
<td>3.25</td>
<td>4.93</td>
<td></td>
</tr>
<tr>
<td>2 SD</td>
<td>0.28</td>
<td>0.02</td>
<td>0.2</td>
<td>0.09</td>
<td>0.04</td>
<td>0.1</td>
<td>0.78</td>
<td>0.16</td>
<td>0.16</td>
<td></td>
</tr>
</tbody>
</table>

*All data normalized to water free compositions. Table S1 contains the full dataset and associated secondary standard analyses. For details of analytical conditions, see Materials and Methods.
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