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Subdecadal phytolith and charcoal records from Lake Malawi, East Africa imply minimal effects on human evolution from the ~74 ka Toba supereruption

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A B S T R A C T

The temporal proximity of the ~74 ka Toba supereruption to a putative 100–50 ka human population bottleneck is the basis for the volcanic winter/weak Garden of Eden hypothesis, which states that the eruption caused a 6-year-long global volcanic winter and reduced the effective population of anatomically modern humans (AMH) to fewer than 10,000 individuals. To test this hypothesis, we sampled two cores collected from Lake Malawi with cryptotephra previously fingerprinted to the Toba supereruption. Phytolith and charcoal samples were continuously collected at ~3–4 mm (~8–9 yr) intervals above and below the Toba cryptotephra position, with no stratigraphic breaks. For samples synchronous or proximal to the Toba interval, we found no change in low elevation tree cover, or in cool climate C_3 and warm season C_4 xerophytic and mesophytic grass abundance that is outside of normal variability. A spike in locally derived charcoal and xerophytic C_4 grasses immediately after the Toba eruption indicates reduced precipitation and die-off of at least some afromontane vegetation, but does not signal volcanic winter conditions. A review of Toba tuff petrological and melt inclusion studies suggest a Tambora-like 50 to 100 Mt SO_2 atmospheric injection. However, most Toba climate models use SO_2 values that are one to two orders of magnitude higher, thereby significantly overestimating the amount of cooling. A review of recent genetic studies finds no support for a genetic bottleneck at or near ~74 ka. Based on these previous studies and our new paleoenvironmental data, we find no support for the Toba catastrophe hypothesis and conclude that the Toba supereruption did not 1) produce a 6-year-long volcanic winter in eastern Africa, 2) cause a genetic bottleneck among African AMH populations, or 3) bring humanity to the brink of extinction.

1. Introduction

The magnitude of the Indonesian Mount Toba supereruption at ~74 ka and its temporal proximity to a Late Pleistocene human population bottleneck and to various models of anatomically modern human (AMH) dispersal out of Africa have made this eruption the subject of much debate (Oppenheimer, 2002; Ambrose, 2003; Gathorne-Hardy and Harcourt-Smith, 2003; Haslam and Petraglia, 2010; Balter, 2010; Williams et al., 2010; Williams, 2012; Mark et al., 2013; Roberts et al., 2013; Lane et al., 2013b; Haslam, 2014). The youngest Toba eruption is the largest known volcanic eruption of at least the last 2 Ma. There are two competing $^{40}Ar/^{39}Ar$ age estimates for the eruption, 75 ± 0.9 ka from Mark et al. (2014) and 73.88 ± 0.32 ka from Storey et al. (2012). These ages differ due to alternative ages used for the Alder Creek sanidine dating standard (Roberts et al., 2013), but overlap using 2σ uncertainties. Based on ejected mass, the Toba supereruption was two orders of magnitude greater than the 1815 Tambora eruption, which has been linked with the 'Year Without a Summer' of 1816, a period of widespread cooling and anomalous rainfall in Northern Hemisphere continental regions that may have been linked to weakening of the Asian and African monsoons (Wegmann et al., 2014; Luterbacher and Pfister, 2015). Ash from the youngest Toba eruption, the youngest Toba Tuff (YTT), has been identified thousands of km from the Toba caldera in marine cores from the Indian

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Ocean, the Arabian Sea, and the South China Sea (Williams, 2012). From the southernmost lake in the East African Rift Valley, Lane et al. (2013a) chemically matched a cryptotephra layer in Lake Malawi cores MAL05-2A and MAL05-1C to the Toba supereruption, extending the range of the ash fall to 7300 km. An ash fallout thickness model estimates that between 0.1 and 0.5 cm of Toba ash was deposited in the Lake Malawi region, with modeled estimates of 2–3 cm of deposition in northern Tanzania and Kenya (Costa et al., 2014). Thus, the Toba supereruption isochron is likely to become an important marker in dating key events in human evolution.

Here we test the hypothesis that the Toba supereruption at ~74 ka caused an environmental catastrophe in East Africa capable of severely reducing human populations and causing a genetic bottleneck by using plant opal phytoliths and charcoal extracted from continuously sampled Lake Malawi sediment cores that contain the Toba supereruption isochron at subdecadal resolution. We compare simulated climate and vegetation outcomes of recent Toba supereruption models such as the magnitude and duration of the cooling, changes in precipitation, grass and tree cover, and wildfire activity to our record of plant micro remains from a region in East Africa where AMH lived before and after the Toba supereruption.

1.1. The Toba supereruption

1.1.1. The Toba catastrophe hypothesis Ambrose (1998) formally proposed the hypothesis that there is a connection between the youngest Toba supereruption and an effective human population decline to fewer than 10,000 individuals sometime between 50 and 100 ka. He suggested that the Toba eruption caused six years of volcanic winter followed by 1000 years of the coldest, driest climate of the late Quaternary (Greenland Stadial 20), and that this event caused low net primary productivity (NPP) and famine. The development of the Toba catastrophe hypothesis can be traced back to the weak Garden of Eden hypothesis (weak GOE), which is supported by early genomic studies of human mitochondrial DNA. The weak GOE posits that, ~100 ka, AMH spread into separate regions from a restricted source with either an early rapid expansion and subsequent population bottlenecks or early modest population growth and slow expansion (Harpending et al., 1993). Around 50 ka, these dispersed populations, which were genetically isolated from each other, experienced dramatic population growth and expanded with the support of more modern technologies (Harpending et al., 1993). By combining elements of the weak GOE with the Toba supereruption, Ambrose (1998) proposed the volcanic winter/weak GOE model, where rapidly reduced populations induced founder effects on genetic diversity and were a catalyst for subsequent technological innovations and migrations.

Rampino and Ambrose (2000) further refined the volcanic winter/weak GOE hypothesis, incorporating atmospheric modeling of volcanic forcing and possible ecological and environmental effects of the Toba eruption at low latitudes into their discussion. They proposed that the injection of volcanic aerosols after an eruption would have had two major effects on plants, a reduction of light levels due to high-atmospheric opacity and rapid cooling. Light level reductions following the Toba eruption may have ranged between ~75% sunlight transmitted, such as the dim-sun conditions that followed the 1815 Tambora eruption, to ~10% sunlight transmitted (Rampino and Ambrose, 2000). For grasses, a 10% scenario would reduce photosynthesis by ~85% (van Keulen et al., 1975). Rampino and Ambrose (2000) summarized several studies on the effects of rapid cooling in tropical forests and proposed that essentially all above-ground plant tissues would have been killed rapidly during a freeze event, and that chilling events resulting in air temperatures of 10–15 °C for a few days would have severely damaged tropical plants. Simulations of nuclear winter cooling effects on a grassland ecosystem indicate a 3–9 °C decrease for one year would lead to a reduction in grassland NPP from 9 to 42%, respectively; after year two, NPP values would be at 13–51% of normal (Harwell, 1984). Rampino and Ambrose (2000) also suggested that the accumulation of dead woody material from an initial die-off and modeled reductions in precipitation post-Toba eruption might have led to increased wildfire activity. They concluded that severe drought in the tropical rainforest belt and in monsoon regions, and significant reductions in plants and animal populations, especially in the tropics, would have resulted in a global ecological disaster and population crashes of various organisms. Such a scenario is now commonly referred to as the Toba catastrophe hypothesis.

1.1.2. Summary of recent Toba supereruption modeling and geologic evidence There is considerable uncertainty as to what effects the Toba supereruption had on regional and global climate. This is due, in part, to a lack of high fidelity climate records that contain the YTT, which would provide an unambiguous chronological tie point and boundary marker for periods before and after the eruption. In a speleothem stable isotope study from New Mexico (USA), Polyak et al. (2017:843) claimed their data support the hypothesis that the Toba supereruption caused “far-reaching climate change” and possibly triggered the Greenland Stadial 20 cold event. However, the absence of an unambiguous Toba marker in their speleothem record precludes the ability to confidently identify causal relationships for events separated in time by intervals significantly less than the chronological uncertainties of the proxy records themselves. Our high-fidelity Lake Malawi cores with the YTT position securely identified allow us to unambiguously examine the distal effects of the Toba supereruption in East Africa.

Uncertainty as to the climatic effects of the Toba supereruption also arises as a result of limited information about the eruption's intensity, height of plume, and the sulfur yield. It is this last variable, the amount of sulfur injected into the atmosphere, that is the main determinant of global climatic consequences (Oppenheimer, 2002; Timmreck et al., 2012). Volcanic activity releases either sulfur dioxide (SO_2) or hydrogen sulfide (H_2S), which is mostly converted into sulfuric acid (H_2SO_4) and other sulfate aerosols through photochemical reactions with water vapor in the atmosphere (Scaillet et al., 1998). Selecting a SO_2 atmospheric injection load for climate modeling is typically based on petrological evidence and ice core sulfate records, and often expressed in terms relative to the SO_2 release from the 1991 Mt. Pinatubo eruption. Early modeling of Toba volcanic forcing by Rampino and Self (1992), using an approximately 33 times Pinatubo SO_2 injection, produced a global cooling of 3–5 °C. Oppenheimer (2002) used the estimated annual sulfate loading from the Zielinski et al. (1996) high resolution sulfate depositional record from the Greenland Ice Sheet Project II (GISP2) ice core to calculate an annual global cooling of 0.9–1.3 °C over a 6–7.5 year period. Jones et al. (2005), using a coupled atmosphere ocean general circulation model and a 100 times Pinatubo scaling, modeled a maximum cooling of 10.7 °C below normal globally, and 17 °C below normal for Africa. Using two models and a range of sulfur injections from 33 to 900 times Pinatubo, Robock et al. (2009) produced average global cooling values between 8 and 17 °C, but under all of their simulations there was significant climate recovery within a decade. They observed that radiative forcing lasted 4–7 years, which agrees well with the ~6 years of H_2SO_4 deposition in the GISP2 ice core (Zielinski et al., 1996). They concluded that the modeled cooling could have produced great stress on humans and their environment, but that it would have