The Toba super-eruption: Micro-scale traces of a global-scale climate event?

Kim M. Cobb

Stacy Carolin, Jessica Moerman, Ellery Ingall, Luke Chambers, Amelia Longo
Georgia Inst. of Technology

Nele Meckler, Jess F. Adkins
Caltech

Lydia Finney
Argonne National Lab

Victoria Smith
Oxford

Syria Lejau, Jenny Malang, Brian Clark, Alison Pritchard
Gunung Mulu National Park

Andrew Tuen
University Sans Malaysia
Explosive eruptions tear apart the frothy, gas-rich magma, producing fine pyroclasts (hot fragments) composed of solidified melt (i.e. glass) and crystals. Copious quantities of hot, buoyant, pyroclast-bearing gas and the enormous Plinian eruption column that they form are the signatures of large explosive eruptions (Wilson 2008 this issue; Self and Blake 2008 this issue). The mixture of gas and pyroclasts leaves the volcanic vent and enters the atmosphere at near-magmatic temperatures. It immediately entrains and heats air, rises buoyantly to heights that may exceed 35 km, and then spreads laterally as a giant “umbrella” cloud in the stratosphere. The fragments return to Earth in two very different ways (Wilson 2008). Some fall gently like snow from the eruption column and blanket the land surface (forming fall deposits). More energetic and immediately devastating, however, are the hot and highly fluid pyroclastic flows that can move across the ground surface at speeds up to hundreds of kilometers per hour, covering areas of many thousands of square kilometers with ash-flow deposits.

**IMMEDIACY AND MAGNITUDE OF THE THREAT?**

The consequences of future supereruptions, which were portrayed in dramatic fashion in the movie *Supervolcano*, are discussed by Self and Blake (2008). In short, supereruptions are “the ultimate geologic hazard,” in terms of the immediate and devastating impact of eruption products on our social infrastructure, and with regard to the longer-term climatic effects that will arise from loading the stratosphere with sulfur-rich gases. There is, however, a silver lining of sorts: the global frequency of volcanic eruptions correlates inversely with eruption size. Supereruptions, then, occur extremely infrequently (from a human perspective), on average one about every 100,000 years (Decker 1990; Mason et al. 2004). Moreover, the youngest well-documented supereruption, Oruanui in the Taupo Volcanic Zone of New Zealand, occurred only (!) 26,000 years ago (26 ka) (Wilson 2008). This event was preceded by Toba’s cataclysmic eruption roughly 50,000 years earlier, and several lesser-known, post-100 ka candidates for supereruption status are under study.

**Figure 2**

Views of (A) the Long Valley caldera, USA, which collapsed during the 760 ka supereruption that formed the Bishop Tuff (photo by Colin Wilson), and (B) Cascada de Basaseachic, a waterfall over 300 m high cutting through a single, thick ~28 Ma ignimbrite typical of those elsewhere in the Sierra Madre Occidental of western Mexico. Because of good exposure, ancient supereruption products—like those in Mexico (McDowell and Clabaugh 1979) and elsewhere in western North America (e.g. Lipman et al. 1972)—have provided a valuable framework to better understand modern supervolcano systems.

**Figure 3**

The Toba super-eruption:

73.88 ± 0.6 kybp (Storey et al., 2012)

~3,000km³ DRE

VEI of 8

Miller and Wark, 2008
The magnitude of an eruption has been defined by the mass of erupted material (lava or pyroclastic), as follows (Pyle 2000):

- **Mass**/
square6
- **Volume**/
square6
- **Height**

The amount of material in an eruption can be described in terms of mass or volume.

---

**Relative eruption magnitudes**

- **Yellowstone** (2 Ma)
- **Toba** (74 ka)
- **Long Valley** (760 ka)
- **Tambora** (1815)
- **Krakatau** (1883)
- **Mount Pinatubo** (1991)
- **Mount St. Helens** (1980)

*Miller and Wark, 2008*
Did Toba play a role in an observed “bottleneck” in human mitochondrial genetic diversity?

Maybe. [Ambrose 1998]

No. [Petraglia et al., 2007]

see review by Williams et al., 2012

H. floresiensis
Volcanoes impact global climate: Instrumental data

Kelly et al., 1996
Volcanoes impact global climate: Paleoclimate data

(a) reconstructed (grey) and simulated (red/blue) NH temperature

(data-model comparison provides critical constraint on climate sensitivity: temperature response to change in radiative forcing)

IPCC, 2013
Volcanoes impact global climate, but how much?

Fact: models tend to cool more than paleoclimate data suggest

problem with model?
(Timmreck et al., 2010)

or data?
(Mann et al., 2012, 2013; Anchukaitis et al., 2012)
Robock et al., 2009

Modeling Toba’s effects in CCSM3

Figure 2. (a) Monthly average global-mean temperature and precipitation anomalies and (b) monthly average stratospheric sulfate aerosol and volcanic dust optical depth. All but one of our experiments were conducted from 1990 to 2009. The Toba eruption certainly must have had significant effects on Earth’s climate, but the climate response seen in our models was much smaller than expected. The largest effect on temperature and precipitation occurred within the first 10 years of the experiment. After that, temperature anomalies dissipated in about 30 years, while precipitation anomalies tended to persist longer. This suggests that Toba might have induced climate events that were sustained for a decade or more, but that these events were small relative to the effects of other major volcanic eruptions.

The model results are consistent with our understanding of the Toba eruption, which occurred about 73,000 years ago. The eruption was one of the largest in Earth’s history, releasing an estimated 20 cubic kilometers of ash and gas into the stratosphere. This massive injection of material caused a short-term cooling effect, as the ash blocked some of the sun’s radiation from reaching the Earth’s surface. However, the cooling effect was much smaller than what we would expect from a volcanic eruption of similar magnitude. This suggests that the climate response to Toba was limited by other factors, such as the amount of material injected and the timing of the eruption.

In summary, our modeling work indicates that the Toba eruption had a significant but relatively small effect on Earth’s climate. The cooling effect was short-lived, with temperature anomalies dissipating within the first 10 years of the experiment. Despite the limited climate response, the Toba eruption had a significant impact on the planet, and its study can help us better understand the potential effects of future volcanic eruptions.
missing memory in snow/ice or vegetation?

need to look regionally? and at $\delta^{18}O_R$
Modeling Toba’s effects in MPI-ESM

Timmreck et al., 2012
Borneo stalagmites as records of regional climate and environmental history

stalagmite oxygen isotope records reproducible

reveal large millennial-scale excursions (Heinrich events)

*Carolin et al., Science 2013*
largest anomaly associated with Toba super-eruption also captured as out-sized event in Hulu stalagmite oxygen isotopes

Figure 1 for a close

Figure 2

Modified after Figure 2 of Carolin et al., 2013.
A closer look

ash layer in South China Sea corresponds to initiation of cooler reconstructed SST

![SEM photomicrographs of tephra from core MD972151 in South China Sea](image)

200μm
A closer look

multiple sulfate peaks in Antarctic ice core tied to sulfate peaks in Greenland → relationship to Toba eruption(s)?
Research questions:

1) How many times did Toba erupt ~74,000yrs ago? And with what relative sizes?

2) What were the regional climate impacts of the eruption(s)?

3) Did the Toba-related climate effects in Borneo occur before, during, or after the initiation of pronounced regional drying?
Approach:

Find the volcanic markers in the Borneo stalagmites.

Compare to oxygen isotope-based climate record in same stalagmites.
Figure 4. Photos of candidate stalagmite samples for the reconstruction of high-resolution $\delta^{18}O$ and ash-related geochemical markers. High-precision U/Th dates are denoted in yellow, in kybp (individual age uncertainties average ±200–500yrs (2$\sigma$; Carolin et al., 2013)). Each of the samples shown here is capable of delivering decadal to sub-decadal temporal resolution through the age interval in question (denoted by a red box), based on available growth rate estimates. Note that low-resolution reconstructions of stalagmite $\delta^{18}O$ for Secret 2 and 3 are published in Carolin et al., 2013 (see Figures 1 and 2). Cave conservation statement: All of these stalagmites were collected as previously broken samples from the cave floor.

U/Th dating: absolute age control

All of the stalagmite U/Th dates required for the project will be generated by a Georgia Tech graduate student working in Jess Adkin's MC-ICPMS lab at Caltech, as part of a long-standing collaboration (Partin et al., 2007; Meckler et al., 2012; Carolin et al., 2013; see attached letter of support). We will use the preliminary age models to sample additional dates, with the goal of isolating the time interval of interest (roughly from 70–76kybp) in three stalagmites. Given that uncertainties in the correction for detrital thorium translates to age errors of ±200–500yrs in the Toba timeframe (2$\sigma$; Carolin et al., 2013), it is important to measure additional isochrons in the stalagmites to better constrain the $^{230}$Th/$^{232}$Th ratio of the contaminant phase to achieve the most accurate U/Th dates. This is especially true for the new samples from Fairy City, whose $^{230}$Th/$^{232}$Th ratios may differ from previously published values measured in other caves. As stated above, however, the strength of our approach lies in aligning shared features across 3 U/Th-dated stalagmites, yielding much more precise dating constraints for such features than could be achieved from a single U/Th-dated stalagmite.

Ultimately, we hope to generate at least one date every 500 years through the 72–75kybp interval across three samples (N=18 dates plus duplicates and blanks). When combined with preliminary dates (N=20 assuming 5–6 per stalagmite plus duplicates and blanks) and isochron dates (N=30 assuming 2 isochrons per stalagmite, where 1 isochron = 3–4 dates plus duplicates and blanks), we anticipate measuring ~80 dates in support of the project. These dates will be

Available stalagmites
Preliminary synchrotron Fe data

U/Th date 73,636±305yrs

Toba ash $^{40}$Ar/$^{39}$Ar age = 73,880±640yrs (Storey et al., 2012)

Fe layer (Toba?)

U/Th date 80,758±208yrs

Fe layers (known hiatus)
Preliminary SIMS Sulfur profile

~550yrs

10µm beam = ~2.2yrs
20µm sampling res = 4yrs

initiation of steep δ¹⁸O shift in bulk data

data from Stacy Carolin
Next steps:

Geochemically fingerprint
i) Toba ash
ii) Mulu clays

Compare to synchrotron/SIMS scans across Toba horizon (Fe, Si, S, Br, K, Al)
*see review by Frisia et al., 2012