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COMMENT

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Supereruption doublet at a climate transition

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About 74,000 years ago Earth's climate abruptly transitioned to particularly severe cold and dry conditions, which lasted for several millennia. An incomplete eruption record may be why volcanic eruptions were dismissed as the trigger.

The Youngest Toba Tuff eruption of Toba volcano, Indonesia, is the largest known eruption of the Quaternary with a magnitude of 8.8. Events exceeding a magnitude of 8.0 are those which demonstrate a total erupted mass in excess of 10^{15} kg (~1000 km^3 dense-rock-equivalent), and represent the largest expressions of explosive volcanism on Earth. The eruption date of 73.88 ± 0.32 thousand years ago[1] is within error of the transition into a cold period, recorded in Greenland ice cores as Greenland Stadial 20 with an onset 74.1 ± 0.06 thousand years ago[2]. This coincidence in timing has led to speculation that there may exist a causal link between the Youngest Toba Tuff eruption and Greenland Stadial 20, and that the eruption's exceptional magnitude alongside a release of 1700–3500 Mt of sulfur dioxide (SO_2)[3] was sufficient to have precipitated a cold period in the Northern Hemisphere that lasted for about 2000 years. We know that the 1991 AD Pinatubo eruption released about 18 Mt SO_2 and affected climate globally: the Pinatubo eruption caused a global temperature anomaly of 0.4 °C, and a Northern Hemisphere anomaly of 0.5 °C[4]. The Toba eruption was two orders of magnitude larger than Pinatubo and released between 94 and 194 times as much sulfur into the atmosphere. Additionally, modern aerosol-climate models suggest that direct radiative cooling of 3.5 to 9 °C for multiple years would ensue following an eruption of this size, with significant implications for atmospheric circulation and ocean dynamics[5,6].

The coincidence in the timing between the Youngest Toba Tuff eruption and the onset of Greenland Stadial 20 is tantalizing, with the eruption date within dating uncertainty of the initiation of the cooling. Additionally, positive feedback mechanisms associated with sea ice and oceanic circulation that extend sub-decadal scale aerosol effects to thousands of years have been proposed[7]. However, uncertainty regarding the timing of the Youngest Toba Tuff eruption relative to Greenland Stadial 20, as well as its effective sulfur load[8], contribute to the substantial debate concerning the role Toba played in driving global climate change and the onset of Greenland Stadial 20.

Recent work may hold the key to better understanding the cause of Greenland Stadial 20. Cisneros de León et al.[9] have used zircon (U–Th)/He dating to show that the Los Chocoyos eruption of Atitlán volcano, Guatemala, occurred 75 ± 2 thousand years ago: about 9000 years after the previously accepted eruption time of about 84 thousand years ago. The Los Chocoyos eruption was not only sulfur-rich, but also the third largest eruption of the Quaternary with an estimated magnitude of 8.1[10]. The new eruption date possibly makes the Toba and Atitlán events the first known *doublet* of super-eruptions occurring within ~1000 years of one another, and both are within dating uncertainty of the onset of Greenland Stadial 20. Multiple super-eruptions in the same hemisphere are expected to amplify meridional and dynamical shifts in atmospheric circulation relative to a single eruption, and could act to sustain an ocean-atmosphere feedback favouring cooler, drier conditions in the Northern Hemisphere for hundreds, or even thousands of years. A series of smaller eruptions may have triggered the Little Ice Age during the last millennium[11], and it

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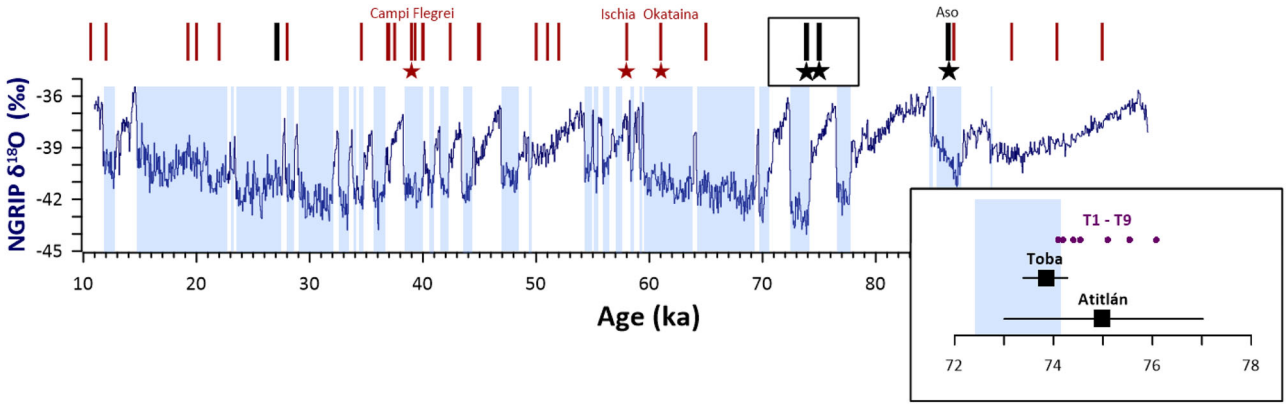

Fig. 1 Timing of known eruptions exceeding magnitude 7, relative to the Greenland $\delta^{18}O$ record. 50-year averaged $\delta^{18}O$ values from the North Greenland Ice Core Project (NGRIP) on the Greenland Ice Core Chronology 2005 (GICC05) model-based extension time scale, with stadials corresponding to cooler temperatures (more negative $\delta^{18}O$) as blue shaded periods[2]. Known very large eruptions are shown as red ($7 < M < 8$) and black ($M > 8$) bars, and stars represent radiometric eruption dates. *Inset:* A comparison of Toba and Atitlán eruption dates, with 1σ errors shown (black bars)[1,9] relative to the timing of Greenland Stadial 20 and bipolar sulfate anomalies (T1-T9; purple points) measured in the NGRIP and EDML ice core[12].

is possible that a series of larger eruptions could have had a larger impact on climate, particularly during a time of transitional climate.

By any metric (such as ice core $\delta^{18}O$, Ca^{2+}, and CH_4[2], stalagmite $\delta^{18}O$ or $\delta^{13}C$), Greenland Stadial 20 was anomalously severe in terms of temperature and hydroclimate compared with the other stadial events of the Last Glacial Period. Interestingly, four different acidity spikes were identified within Greenland ice core record within centuries of the onset of Greenland Stadial 20[12]. Although there is no corroborating tephra in these ice core horizons, it seems likely that at least one of these acidity spikes represents the Youngest Toba Tuff, and we highlight that it is now possible that another represents the Los Chocoyos eruption. Eruption doublets or 'cluster events' have been proposed as a tenable explanation for the occurrence of anomalous cooling events during the Holocene[11]. Greenland Stadial 20 was substantially more severe in expression than any Holocene cooling event, and in most records more severe than other Quaternary stadial events. The occurrence of two >M8 eruptions in such close temporal proximity would provide a plausible explanation for such an anomalous climate response and is indeed exceptional: the global recurrence interval of M8 eruptions is on the order of 10,000 years[13]. Therefore, the probability of two M8 eruptions occurring in such close temporal proximity is very low.

On this note, it remains unclear whether the Los Chocoyos eruption preceded the Youngest Toba Tuff eruption or vice versa, which confounds our ability to establish a precise sequence of events leading to Greenland Stadial 20. Nevertheless, until now research has focussed on whether a single eruption (the Youngest Toba Tuff eruption) forced a notably severe stadial event (Greenland Stadial 20), whereas the new Los Chocoyos eruption date sets the groundwork for a new critical research question: could a doublet of super-volcanic eruptions have triggered Greenland Stadial 20? If this is indeed the case, this result would have broad repercussions, and it would set the scene for a thorough investigation of the origin of other stadials. Perhaps minor stadial events were triggered by positive feedbacks following smaller eruptions, whereas more substantial stadials like Greenland Stadial 20 were triggered by several large sulfur injections that reinforced each other and produced longer lasting or more severe feedbacks. For the last 100,000 years, the climate record is continuous and relatively well-constrained, but the eruption record is far from it. For example, across the past two millennia, we know of two eruptions exceeding magnitude 7, or one about every 1000 years. By contrast, from 100,000 to 10,000 years ago we know of 28, or only one about every 3200 years. Assuming that the frequency of eruptions has not changed, this implies that at least 61 eruptions of magnitudes greater than 7 are simply not known between 100,000 and 10,000 years ago. Moreover, of the eruptions that are known, most lack a high precision, radiometric date (Fig. 1).

We suggest that the recent revision of the Los Chocoyos eruption date shows how improved eruption dates could dramatically change our perspective of the forcing mechanisms of Last Glacial climate change, and potentially lead to an improved understanding of both the long-term consequences of volcanic eruptions and the underlying causes of stadial events.

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Author contributions

A.P., F.W. and J.B. contributed equally to the conceptualization and writing of this Comment.

Competing interests

The authors declare no competing interests.

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