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Capturing the Extreme in Volcanology: The Case for the Term "Supervolcano"

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Although evocative, the term *supervolcano* has a checkered history of hyperbole and misuse to the point that it seems unprofessional. However, "supervolcano" is firmly embedded in volcanological discourse and we make the case that it is useful if defined and used correctly. To this end we examine the etymology of supervolcano and demonstrate its' dependence on the term supereruption. We build on the work of colleagues to propose that supervolcano be restricted to a *volcano that has been the site of at least one silicic explosive eruption of Magnitude of 8 (M 8) or greater.* Based on this, nine active supervolcanoes are found on the Earth today and although all are calderas, we contend that referring to them simply as large calderas or caldera complexes obviates clear magmatic, volcanological, and structural extremes that distinguish supervolcanoes from other caldera complexes. Such supervolcanoes may produce eruptions that exceed *M* 9 but we stress that *most eruptions from supervolcanoes are actually small effusive eruptions*. Basaltic explosive supereruptions remain enigmatic on Earth and therefore *we advise against the use of supervolcano for any basaltic volcano or province on Earth*.

Keywords: supervolcano, supereruption, VEI, magnitude scale, calderas

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INTRODUCTION

Natural hazards cover a range of scales, and it is common practice in the Earth sciences to differentiate the extremes through the use of superlatives (*superstorms, supercells, superfaults, megafloods, megaquakes, megatsunami, super-greenhouse*, and *super-mountains* among others). This is a double-edged sword. On the one hand superlatives feed into hyperbole and can be open to misuse, most obviously as click-bait headlines or quotes. As aptly put by Janine Krippner of the Global Volcanism Program referring to mega-tsunamis *"Headlines take the smallest hint of truth and turn it into an irresistible bogeyman, causing real stress and harm around the world"*. On the other hand, superlatives have their value. Scientifically their use recognizes the extremes of natural phenomena and conveys the rarity beyond historical experience, but perhaps as important, superlatives ignite public attention and are often the pathway to greater awareness of hazards and the threats they present to society—and of the excitement and importance of Earth Science. Here we look at superlatives in volcanology, in particular the use and abuse of the term *supervolcano*. Like it or not, we find it is here to stay, we accept this, and provide this commentary for its correct use.

THE ORIGINS OF "SUPERVOLCANO"

Volcanologists have tended to shy away from superlatives with the exception perhaps of George Walker's "ultraplinian" eruption (Walker, 1980), which has recently been shown by Houghton et al.

(2014) to be based on an incomplete characterization of a complex deposit emplaced into shifting wind conditions and thus the type no longer exists. The term *supervolcano*, which often raises eyebrows and elicits sighs of disapproval as being corny, clichéd, and unscientific, has a checkered history of misuse. This is primarily in the general media, but includes geologic peer-reviewed journal publications, and has prompted us to write this piece. We note that there are efforts in the blogosphere that attempt to redress the balance and provide some rigour (Andrews, 2018), but these, by their nature, do not provide a scholarly assessment.

The term *supervolcano* goes back quite a long way. Apparently, USGS geologist Frank M. Byers Jr. used the term in a review of a book in 1949, referring to a proposed set of distributed volcanoes around the Three Sisters in Oregon, that turned out to be specious (Wikipedia, 2021). About 2003 the term *supervolcano* was introduced in the eponymous movie being developed by Discovery Channel/BBC TV but with unfortunate hyperbole—*Is Yellowstone overdue?* was the titillating by-line for the movie - and there was no formal definition (Discovery Channel, 2005). Lowenstern (2005) and Lowenstern et al. (2006) appear to have the first formal use and definition of the term which was subsequently modified to the currently accepted formal definition of "supervolcano" in Miller and Wark (2008)—in their introduction to the journal *Elements* Supervolcanoes issue *What makes a volcano super?* There a supervolcano refers to "*a volcano that was the source of at least one supereruption*". The United States Geological Survey has the following formal definition on their website "*The term "supervolcano" implies a volcanic center that has had an eruption of magnitude eight on the Volcano Explosivity Index (VEI), meaning the measured deposits for that eruption is greater than 1,000 cubic kilometers (240 cubic miles)*" (USGS website accessed 5 January 2022). As we will see below, even this definition from a trusted source is problematic.

The concept of *super*-eruptions has been in volcanological discourse since at least 1984 when Bob Christiansen of the USGS (with reference to Yellowstone volcano) wrote "*superexplosive eruptions of magnitudes that have seldom, if ever, been recorded in human history*. . .." (Christiansen, 1984). In 1992, Rampino and Self coined the term *supereruption* in a paper on the Youngest Toba Tuff (YTT), the most recent caldera-forming eruption from Toba caldera, Sumatra, but did not define the term. We note that some works refer to the YTT eruption as a *mega-eruption* (Zielinski et al., 1996) again without any formal definition. It was in a 2005–2006 report and paper (Sparks et al., 2005; Self, 2006) that *supereruption* was defined as one that erupted a minimum 1,000 km^3 of rhyolitic tephra or pyroclastic deposits, which is ~450 km^3 of magma or dense rock equivalent (DRE) or $>1 \times 10^{15}$ kg of felsic/rhyolitic magma.

Two popular classification schemes for volcanic eruptions are 1) the Volcanic Explosivity Index (VEI) of Newhall and Self, (1982), a semi-quantitative logarithmic scale that classifies explosive volcanic eruptions based on erupted volume, eruption column height, and intensity, and 2) the Magnitude scale developed by Pyle (1995, 2000), which is based on the mass of magma erupted. Confusion arises because the term *magnitude* is variously used to imply scale, intensity, volume of magma or deposits, as well as mass of magma in volcanology. It was originally used in the VEI scale as a measure of volume and intensity, hence the above USGS reference to a VEI of magnitude 8. This has unfortunately led to conflation of volume and mass, deposits and magma, in particular. We choose not to enumerate the many instances that we have found, even in peer-reviewed literature, but suggest that, going forward to avoid this, Pyle's measure Magnitude *M*, be the primary measure of magnitude (as a capitalized and italicized *M*). If the term "magnitude" is used in any other way the context should be clearly specified. Thus, in these classification schemes a supereruption has a Magnitude of 8 (*M* 8) or greater and a VEI of eight or greater–we would recommend not using "magnitude" with VEI to avoid confusion.

PROBLEMS, PITFALLS AND INCONSISTENCIES

The definitions above rely on measures (volume, intensity, eruption column height, DRE, *M*) that are unfortunately inconsistent. It is telling that in our best available databases such as LaMEVE (Crossweller et al., 2012) and Mason et al. (2012) more than 50% of the eruptions classifed as ≥ M8 are either missing critical measures or provide inconsistent classification criteria. Most of this is due to the inherent imperfection of the geological record in terms of preservation but there are also methodological inconsistencies.

Volume estimates of pyroclastic deposits are notoriously difficult even in the youngest eruptions due to exposure and preservation and this is compounded with age and environment. Supereruptions, most of which are geologically old (pre-Holocene), and with products that may extend 1,000s of kilometers from source, are even more challenging to measure. Although a few attempts have been made to provide rigorous volume estimates (e.g. Folkes, et al., 2011; Cook et al., 2016), even these require inferences and model-based extrapolations to make these half-an-order-of-magnitude estimates at best. A case in point is for the famous Youngest Toba Tuff eruption which is one of the most infamous supereruptions and the volume estimations are the among the most rigorous that are available. Here the original dense rock equivalent (DRE) magma volume estimate of 2,800 km^3 (Rose and Chesner, 1987) has been reconstructed to 5,300 km^3 DRE by Costa et al. (2014). Both these estimates require assumptions and model-based corrections and rules of thumb that are now common practice and demonstrate that volume estimates of large explosive eruptions are largely reconstructed, with only rare attempts to document uncertainties. The problems are compounded by assumptions made in converting tephra volumes to DRE and those in turn to masses of magma based on densities that are at best averages that attempt to normalize variable tephra densities. Given these issues the community accepts that volume and mass estimates of supereruptions (and all but the smallest explosive eruptions) are at best hemi-order of magnitude estimates.

It should be clear then that the definitions of supervolcano (and supereruption) that specify <u>measured</u> volumes, and include both VEI and Magnitude (*M*), are at best hemi-order of magnitude distinctions that can easily lead to inconsistencies, as cases emerge of eruptions that may have volume estimates that do not classify as VEI 8, whereas *M*, the mass estimate, may.

LARGE BASALTIC ERUPTIONS ARE NOT SUPERERUPTIONS AND THEREFORE THERE ARE NO BASALTIC SUPERVOLCANOES

Another issue in defining supervolcano, is that massive eruptions of flood-basalts have been referred to as supereruptions (Self et al., 2014) because they fit the mass criterion (*M* 8). Work on continental flood basalt provinces (CFBPs) or large igneous provinces (LIPS), such as the Columbia River Basalts (Tolan et al., 1989; Reidel et al., 2013) and other provinces (Self et al., 1998; Self et al., 2008; Bryan et al., 2010) has shown that most eruptions during LIP formation do have dense-rock volumes comparable to those needed for VEI 8 or masses needed for an *M* 8 - due to the density difference between basalt and rhyolite a flood basalt eruption only needs to be >360 km^3 to have a mass of 1×10^{15} kg. In this context, CFBPs and LIPs, could be considered to be supervolcanoes and often are, particularly in the press (e.g., Geolsoc.org, 2013; Forbes.com 2021). However, we propose that this is misleading. The term *supereruption* is synonymous with explosive silicic (*sensu latu* including intermediate compositions like silicic andesite and dacite) volcanism. As such, beyond magnitude, intensity, as a proxy for explosivity, is also a defining criterion. By association, *supervolcano* should also be restricted to volcanoes that produce explosive supereruptions. Under this definition it should be clear that the world's largest volcanoes (e.g., Pūhāhonu (Garcia et al., 2020); Mt. Tamu, Shatksy Rise, (Sager et al., 2013), and the above referred-to Kerguelen Plateau) are not known to have produced a supereruption, and thus should not be referred to as supervolcanoes. Explosive basaltic volcanism (Parfit, 2004; Houghton et al., 2014) is increasingly being recognised in the geological record. Such eruptions maybe an exception, but typically involve magma-water interaction and have not been unequivocally documented to be on the scale of supereruptions. One exception may be the Ash +19 in the North Atlantic Igneous Province (Stokke et al., 2020), but whether this is the product of a single caldera-forming eruption is unclear. Thus, although some flood basalt provinces and LIPS are claimed to have produced basaltic and silicic volcanic volumes that are the products of supereruptions (Bryan et al., 2010) the discrete sites of eruption for these which could be termed supervolcanoes are unknown.

WHAT IS A SUPERVOLCANO?

Based on the foregoing, we propose that a *supervolcano is a volcano that has been the site of at least one silicic explosive eruption of Magnitude 8 (M 8) or greater*. As such the term supervolcano is inexorably linked to the term supereruption and this in turn is at present restricted to silicic explosive eruptions of >M 8. Physically, supervolcanoes differ from other volcanoes not only in that the biggest eruptions are outsized and their impact is potentially far greater than normal eruptions, but the appearance of the volcano itself after eruption is also distinctive: it does not conform to the common image of a volcano. All the volcanoes that fall into this definition are large calderas, often resurgent, and are extensive depressions (100s to 1,000s of km^2 in area). Such

TABLE 1 | Known active† supervolcanoes. †demonstrated eruptive activity <100 kyrs.

Supervolcano	Location	Last *M* 8	DRE volume (km^3)	Mass* ($x10^{15}$ kg)	*M*	Last known eruption reference	DRE volume (km^3)
Toba	Sumatra, Indonesia	74 ka; Youngest Toba Tuff (Storey et al., 2012; Mark, et al., 2017)	~ 5300	12.98	9.1	54.5 ± 8 ka; Lava flow at Pusik Buhit (Mucek et al., 2017)	< 1
Yellowstone	Wyoming, USA	631 ka; Lava Creek Tuff (Christiansen, 2001)	~ 850	2.08	8.3	75 ka; Pitchstone Plateau Flow (Watts et al., 2012)	70
Whakamaru-Taupo	North Island, New Zealand	25.5 ka; Oruanui eruption (Wilson, 2001; Vandergoes et al., 2013)	~ 530	1.29	8.1	1800 yrs B.P.; Taupo eruption (Hogg et al., 2011)	30
Aira	Kyushu, Japan	~ 30 ka; Osumi-Tsuyama eruption (Takarada and Hoshizumi, 2020)	> 430	1.05	8.0	2021 CE; Sakurajima volcano (Japanese Meteorological Association, 2022)	<<<0.1
Kikai	S. Kyushu, Japan	7.3 ka Akahoya eruption (Maeno and Taniguchi, 2007)	>500	1.23	8.1	Active lava dome (Tatsumi et al., 2018)	~32
Aso	Kyushu, Japan	87 ka; Aso-4 eruption (Takarada and Hoshizumi, 2020)	<592	1.45	8.2	2021 CE; Nakadake (Japanese Meteorological Association, 2021)	<<<0.1
Long Valley	California, USA	760 ka (Bishop Tuff Hildreth and Wilson, 2007)	~600-650	1.59	8.2	16 to 17 kyr; western mafic centers (USGS, 2022b)	< 1
Valles	New Mexico, USA	1.2 Ma; Otowi eruption (Cook et al., 2016)	<550	1.34	8.1	74–65 ka; Banco Bonito Rhyolite (Zimmerer et al., 2016)	< 10
Atitlán	Guatemala	74 ka Los Chocoyos (Cisneros de León et al., 2021)	~ 510	1.24	8.1	67 +11/−9 ka (Cisneros de León et al., 2021), I-Fall (Rose et al., 1999)	~7 (Kutterolf et al., 2016)

**assumes magma density of 2450 kg m^{-3}. At this density 450 km^3 of rhyolitic magma (using a bulk deposit volume of 1000 km^3) equates to ~* M *8.*

supervolcanoes are unknown in basaltic provinces. In **Table 1** we have curated a list of the *bona fide* active supervolcanoes of which we are aware.

The list in **Table 1** may at first appear to reflect the potential bias of privilege in the sense that most of the identified supervolcanoes are in resource and opportunity endowed regions. Thus, there might be other supervolcanoes we have not identified in resource and opportunity limited regions that have been less volcanologically explored. However, we would argue that any bias is limited, particularly for young "active" systems. First the geodynamic conditions to develop supervolcanoes are well known and in the last 100,000 years this has not changed. Second, scientific colonization and the advent of satellite monitoring has resulted in flattening of the Earth in terms of the search for interesting active geological phenomena and we would be aware of any interesting anomalies on the continents - beneath the ocean is a different issue, but supervolcanoes are less likely to develop in these settings. Supporting our position that bias is probably limited is that in the compilation of VEI 7 eruptions in Newhall et al. (2018) at least half are in resource and opportunity limited nations.

SUPERVOLCANOES ARE LARGE COMPLEX CALDERAS, SO WHY NOT SIMPLY REFER TO THEM AS SUCH?

Although they are calderas, simply calling supervolcanoes large calderas or caldera complexes (Poland, 2019; Morton, 2021) ignores some key magmatic, volcanological, and structural distinctions from the smaller Krakatau-type (10s of km^2) and nested caldera complexes that form by collapse of the summits of composite volcanoes.

Calderas in general show a size to volume-erupted relationship (Smith, 1979; Spera and Crisp, 1981) indicating a first order relationship between spatial dimensions and geometry of the pre-eruptive magma reservoir and the associated stress field that controls caldera collapse (Lipman, 1997; Gudmundsson, 1998; Folch and Marti, 2004; Kennedy et al., 2004; Scandone and Acocella, 2007). The outsized dimensions of magma reservoirs that birth supereruptions are the result of high crustal magmatic fluxes and long thermal histories that pre-condition the crust to promote storage, growth, and retard eruption in contrast to smaller calderas and caldera complexes (e.g. de Silva, 2008; Karlstrom et al., 2010; Cashman and Giordano, 2014; de Silva and Gregg, 2014). The intersection of these factors is reflected in the magnitude-frequency of large eruptions, >*M* 7 being statistically different from those of smaller eruptions implying different mechanisms controlling these eruptions (Deligne et al.,(2010); Mason et al., 2004; Deligne et al.,(2010); Tatsumi et al., 2018). *M* 8+ eruptions like that of the 74,000 year old Youngest Toba Tuff from the Toba caldera, Sumatra, and the 2.1 Ma Huckleberry Ridge Tuff from the Island Park caldera, Yellowstone, United States, are further distinguished by their magnitude-frequency (Pyle, 1998). These statistical distinctions are consistent with studies that demonstrate that the physical mechanisms of eruption triggering and caldera collapse initiation from such large magma reservoirs are indeed distinct. Field studies that document the characteristics of the deposits from supereruptions and modelling efforts that consider the thermal evolution of caldera-related magmatic system have shown that there is distinction between the largest and smallest systems (Sparks et al., 1985; Gudmundsson, 1998; Christiansen, 2001; Jellinek and DePaolo, 2003; Gregg et al., 2012, 2013; Cashman and Giordano, 2014). To summarize briefly, Krakatau-type calderas are triggered by internal overpressure in magma reservoirs that leads to an initial plinian eruption that evenutally underpressures the reservoir leading to caldera collapse. The magma reservoirs associated with supervolcanoes undergo a different pressure evolution where internal overpressure rarely develops, retarding eruption and promoting growth of the magma reservoir (de Silva and Gregg, 2014). Eventually the dimensions of the magma reservoir reach a threshold where the strength of the reservoir roof is exceeded and eruption is initiated as gravitational roof foundering occurs.

For these reasons, we argue that a term that distinguishes large calderas that are the result of supereruptions is useful as it captures important volcanological distinctions. Like it or not, *supervolcano* has precedence and implicitly includes important volcanological and magmatic distinctions that differentiate these from other calderas and caldera complexes.

NOT ALL ERUPTIONS FROM SUPERVOLCANOES ARE SUPERERUPTIONS

A common source of confusion is that supervolcanoes do not just produce supereruptions. The fact is that *there are no known supervolcanoes that do not emit smaller eruptions as well and the most likely eruption in the near future from any of the restless supervolcanoes on Earth is likely to be a small eruption*. This is an important point of agreement with colleagues who would reject the term supervolcano. The plain fact is that the most frequent eruptions from supervolcanoes are actually small eruptions, most commonly effusive lava eruptions. At Toba, several small effusive eruptions continued for at least 13,000 years after the 74 ka climactic Youngest Toba Tuff supereruption (Mucek et al., 2021). These are individually of the order of only 0.1–1 km^3, four or five orders of magnitude smaller than the climactic eruption. At Yellowstone dozens of lava eruptions have occurred since the supereruption 631,000 years ago, and until as recently as ~70,000 years ago with the most recent having a volume of 70 km^3 (**Table 1**; Christiansen et al., 2007; Watts et al., 2012). The Taupo supervolcano in New Zealand has had one supereruption, the 26.5 ka Oruanui eruption (Wilson, 2001), but has had many smaller eruptions before and since including the famous Taupo Eruption ~1800 years ago that measures approximately as an *M* 6.9 and VEI 5. Small effusive post-climactic eruptions as seen at Toba, are referred to as ring-fracture or post-caldera eruptions (e.g. Smith and Bailey, 1968) and represent leaks of new or remnant magma as the caldera system relaxes after the catastrophic disruption of the climactic eruption. In this sense these eruptions are akin to aftershocks after an earthquake (or megaquake in this case) in that they are the residual effects of the major event - the afterparty to the big dance.

We note that precursors to the "big one" have rarely been described because the evidence is often destroyed and consumed by the climactic eruption. One exception is in the 27 Ma La Garita caldera of the San Juan mountains of Colorado, where the VEI 6 (~200 km^3) Pagosa Peak dacite preceded the massive *M* 9 Fish Canyon Tuff eruption by anywhere from 15 to 78 ka (Morgan et al., 2020). The only evidence for a post-climactic eruption at La Garita is the 1 km^3 Nutras Creek Dacite.

WHAT SHOULD NOT BE CALLED A SUPERVOLCANO?

This goes to the crux of the abuse and misuse of *supervolcano* due to a lack of attention or awareness of the formal definition established by Miller and Wark in 2008 and the conflation of the volume and magnitude measures. There are some caldera volcanoes that over their lifetime have exceeded 450 km^3 in cumulative output of felsic magma, but have never had a *supereruption*, per se. These are not *supervolcanoes.* One of the most common misrepresentations is Campi Flegrei, the famous European or Italian "supervolcano" or "Europe's Yellowstone" (a Google Search brings up many of such comparisons from Newsweek, National Geographic, Wired, and the BBC), which does not fit its' proposed status. The so-called Campanian "supereruption" is currently estimated at 181–265 km^3 DRE, a mass of 4.7–6.9 × 10^{14} kg, a magnitude (*M*) of 7.7–7.8 and a VEI of 7 (Silleni et al., 2020). It is possible that when more work is done, Campi Flegrei may rise to the status of a supervolcano, but at present it does not fit the bill as defined above. However, we do note that given its location, a future eruption with a magnitude comparable to the Campanian Ignimbrite would be even more catastrophic than a true supereruption in a remote region like the Altiplano/Puna of the Andes, for instance.

Other examples of potential supervolcanoes include the Ata Caldera in Kyushu, Japan, the source of the ~110 ka Ata Ignimbrite (Aramaki and Ui, 1966; Matsumoto and Ui, 1987) and the Taal and Laguna de Bay calderas in the Philippines that appear to be associated with major eruptions before ~130 ka ago (Torres et al., 1995); these last two are particularly interesting because they were of dominantly intermediate composition. However, these, and others such as Corbetti-Asawa in Ethiopia which apparently had a massive eruption ~670 ka ago (Newhall et al., 2018), remain insufficiently studied to fully assess their inclusion. There are probably several others, but they are insufficiently documented for us to include them here.

CONCLUDING SUMMARY

The Earth Sciences uses superlatives to emphasize extreme events and phenomena. The subdiscipline of volcanology should not be any different. Although subject to misuse and hyperbole, superlatives bring attention to the real science and can add value. *Supervolcano* is such a term. Rather than throw our hands up in frustration and ignore it, we should recognize that the term is here to stay and work to ensure its correct usage. We believe it is useful and should be retained. The term *supervolcano* is intimately linked to the term *supereruption* defined as *an explosive silicic eruption of Magnitude 8 (M 8) or greater*. We clarify the definition of supervolcano as *a volcano that has been the site of at least one explosive silicic eruption of Magnitude of 8 (M 8) or greater.* The sites of eruption are typically large calderas, but referring to supervolcanoes as simply calderas or caldera complexes (e.g., Poland, 2019) obviates the clear magmatic, volcanological, and structural extremes that distinguish supervolcanoes from other caldera complexes. It is important to understand that whereas the largest supervolcanoes may produce eruptions as large as *M* 9 (10^{16} kg of magma), *most eruptions from supervolcanoes are actually small effusive eruptions*. Basaltic explosive supereruptions remain enigmatic on Earth and their association with catastrophic caldera-formation is unknown; therefore, *we advise against the use of the term supervolcano for any basaltic volcano or province on Earth*.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

SdeS and SS jointly concieved the paper, compiled data, and wrote paper.

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