Consequences of Explosive Supereruptions

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Rare but extremely large explosive supereruptions lead to the catastrophic formation of huge calderas, devastation of substantial regions by pyroclastic flow deposits, and ash falls that cover continent-sized areas. The effects of future supereruptions will be felt globally or at least by a whole hemisphere. The most widespread effects are likely to derive from the volcanic gases released, particularly sulfur gases that are converted into sulfuric acid aerosols in the stratosphere. These will remain for several years, promoting changes in atmospheric circulation and causing surface temperatures to fall dramatically in many regions, bringing about temporary reductions in light levels and producing severe and unseasonable weather (‘volcanic winter’). Major disruptions to global societal infrastructure can be expected for periods of months to years, and the cost to global financial markets will be high and sustained.

**KEYWORDS:** supereruptions, ash falls, pyroclastic flow deposits, sulfate aerosols, volcanic winter

**INTRODUCTION**

The geological record contains evidence of rare, explosive supereruptions that have covered whole continents with volcanic ash and have global long-term recurrence intervals estimated to be in the range of 100,000–200,000 years. Supereruptions have been defined as eruptions yielding in excess of $1 \times 10^{15}$ kg of magma (>450 km$^3$; Sparks et al. 2005). Extremely rare examples have produced vast amounts of magma (>1 $\times 10^{16}$ kg, or 4500 km$^3$). Supereruptions lead to caldera collapse, the formation of huge sheets of pyroclastic flow deposits (ignimbrites), as well as very extensive ash-fall layers and injection of noxious gases into the atmosphere. The effects of a future supereruption will therefore be more violent and damaging than those of the considerably smaller eruptions that society has experienced in historic times.

The immediate effects of a supereruption will be almost unimaginably severe. Yet sooner or later, another one will occur, and future societies must be aware of, and prepared for, the consequences. Unlike other extreme natural hazards, there may be some degree of warning of an impending supereruption (Lowenstein and Hurwitz 2008 this issue). Furthermore, supereruptions are potentially long-lasting (continuing at least for many days, and in some cases intermittently for weeks to perhaps years; Wilson 2008 this issue), compared to a brief but intense major earthquake or tsunami. The volcanic ash and gases released high into the atmosphere could have severe worldwide effects on climate and weather. Thus, huge explosive eruptions are one of the few natural phenomena that can produce truly global catastrophic effects. They also differ from other hazards (except meteorite impacts) in producing persistent atmospheric effects for several years after the eruption (Rampino 2002).

This article presents an assessment of the effects of very large explosive eruptions, which could have consequences well beyond those associated with historic volcanic activity. We begin with brief descriptions of the eruption style and the deposits that are produced, the gases that are released, and how we study them. We then turn to the duration, recurrence, and effects of supereruptions, including their atmospheric impact, and consider their potential influence on global temperature and weather. Finally, we discuss issues facing society after a supereruption, including potential socio-economic impacts. Predicting all of the effects of supereruptions is problematic because many are outside modern experience.

**PRODUCTS AND STYLES OF SUPERERUPTIONS**

We have chosen here to assess the effects of a supereruption in the range of 2000–3000 km$^3$ of magma [4–7 $\times 10^{15}$ kg, or Magnitude 8.6–8.8 (Pyle 2000; see Miller and Wark 2008 this issue)], equivalent to 5000–8000 km$^3$ of volcanic ash deposits, an eruption like the largest from the Toba (Indonesia) or Yellowstone (USA) supervolcanoes. All supereruptions are associated with the formation of a caldera, a large collapse depression caused by the inward collapse of the crust above the magma chamber as the magma is evacuated. In the case of Toba, the present lake-filled caldera, formed incrementally by three supereruptions, measures 100 km $\times$ 40 km and covers ~3000 km$^2$ (Figure 2 of Miller and Wark 2008).

**Solid Products**

Explosive supereruptions produce extensive ignimbrite and ash-fall deposits (Wilson 2008). The great size of the ~2800 km$^3$ Toba eruption, which took place 74,000 years ago (Rose and Chesner 1987), was established after deep-sea core studies correlated the widespread deposits across the Indian Ocean and South China Sea (Fig. 1). Ash fall is produced by high ash- and gas-laden atmospheric eruption columns that penetrate through the troposphere and into the stratosphere. The tropopause, separating the troposphere from the stratosphere, is at a height of 17 km over the equator and <10 km at 65° North or South, and it is reached by eruption columns from all very large explosive eruptions.

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The most destructive eruptive phenomena in supereruptions are pyroclastic flows. These flows emanate from collapsing eruptive columns above volcanic vents. They are extremely hot (hundreds of degrees Celsius), rapidly moving mixtures of ash and gas that hug the ground and flow for many tens of kilometres, or in extreme cases for as much as 200 km, laying down ignimbrite deposits (Fig. 2). Major pyroclastic flows such as those that formed Toba’s ignimbrite deposit can cover up to 20,000 km² around the source volcano and bury the landscape with a layer of ash and pumice fragments up to 200 m thick. During emplacement they obliterate everything in their path. The flows typically become partly buoyant during transport, crossing topographic barriers up to hundreds of metres high and feeding fine ash into vigorously convecting co-ignimbrite plumes (Fig. 2B).

The ash from these columns is dispersed by giant ash clouds energetic enough to spread in all directions irrespective of stratospheric winds (Baines and Sparks 2005). This accounts for the extremely wide dispersal of ash-fall deposits, such as those from Yellowstone and Toba; in the latter case, they covered an area in excess of 20 million km², or 4% of Earth’s surface area. With the addition of possible pumicefall deposits from Plinian eruption columns, supereruption ash-fall deposits may be >10 m thick near their source, but they thin down to a few centimetres or less at distances of hundreds to thousands of kilometres downwind. Ash from the supereruptions at Yellowstone is known to have covered much of North America, while ash from Toba is found out over 3000 km from its source, in northern India and offshore Pakistan. Giant ash clouds are also responsible for injecting volcanic gases high into the atmosphere.

**Gaseous Products**

The large eruption rates and extreme explosiveness of supereruptions are driven by the high volatile (gas) content of the magma. The gases are released as the magma rises from the crustal magma chamber to the surface, in the same manner as gas is released when a bottle of carbonated beverage is opened (see Zhang and Xu 2008 this issue). The most abundant gaseous constituents are water (ca. 5% or more of the magma by mass) and carbon dioxide (up to 0.1%), but eruptive emissions of these gases will make little difference to the high concentrations already in the atmosphere. Much moist tropospheric air is also taken up in the eruption columns and transferred to the relatively dry stratosphere. More importantly, sulfur and halogens (Cl, F and perhaps Br) released from the magma cause significant changes to the normal atmospheric concentrations of these gases or of their acids H₂SO₄, HCl and HF (see review by Robock 2000). This is especially so in the stratosphere, where such species normally occur in extremely low abundance. The sulfur content is particularly important because it determines the amount of sulfuric acid aerosols that subsequently form in the stratosphere, increasing the atmospheric opacity and hence having a strong effect on climate.

The pre-eruptive (non-degassed) concentrations of S (and other volatile constituents) in magmatic liquid can be estimated by analyzing tiny (100 µm) inclusions of glass (quenched magmatic liquid) found in crystals that grew within the magma chamber, trapping the liquid and sealing it before it could degas. However, studies of glass inclusions from recent explosive eruptions such as El Chichón (1982) and Pinatubo (1991) have found that the S contents determined this way are insufficient, by 1 to 2 orders of magnitude, to supply the large amounts of SO₂ (7 and 20 × 10¹² kg SO₂, respectively) that Total Ozone Mapping Spectrometer (TOMS) satellites detected in the stratosphere after these eruptions (Bluth et al. 1997). The abundant ‘excess sulfur’ is accounted for by the presence of a S-rich gas phase in the pre-eruptive magma. To estimate the amount of S released from a supereruption such as Toba requires a way of estimating the amount of gas that harbours the excess sulfur and the concentration of S in this gas.

There are two ways in which the S yield of supereruptions can be estimated. The first is to consider supereruptions (none of which has ever been witnessed by scientists) as simply larger versions of smaller eruptions (which have been witnessed and studied). For historic eruptions, TOMS data show a positive correlation between the mass of SO₂ and the mass of magma erupted (Blake 2003). Extrapolating this trend, the amount of SO₂ that potentially could be released by a 2000–3000 km³ supereruption is about 3500 to 20,000 × 10¹² kg of SO₂.

The second method is to quantify the S concentrations in the pre-eruptive magmatic liquid and gas, and then use this information together with the mass fraction of the gas phase to calculate a total S content for the magma. In using this method, it is important to recognise that the partitioning of S between the gas and the magmatic liquid is highly dependent on the oxidation state of the magma. In reduced magmas the partition coefficient given by (mass of S in gas)/(mass of S in magmatic liquid) is about 1, but it is about 1000 in more oxidized magmas (Scaillet et al. 1998). This means that most of the S in an oxidized magma can reside in the gas phase. Using this approach, and assuming 5 wt% gas was present in the magma, Scaillet et al. (2004) estimated that the Bishop Tuff (USA) magma (1.3 × 10¹⁵ kg) held 0.085 wt% S; this would have produced 2.2 × 10¹⁵ kg of SO₂. For Toba, they suggest a S content of 0.022 wt% and, therefore, 1.4 × 10¹² kg of S (2.8 × 10¹² kg of SO₂) would have been released from the 2800 km³ of magma. In contrast, the rhyolite magmas erupted from Yellowstone are considerably more reduced (Carmichael 1991) and can therefore be expected to have low S yields. For Yellowstone’s 2.0 Ma Huckleberry Ridge or 0.6 Ma Lava Creek eruptions (7 × 10¹⁵ kg of magma each; Mason et al. 2004), this approach predicts only 0.2 × 10¹² kg of S (= 0.4 × 10¹² kg of SO₂), despite having unleashed roughly the same amount of magma as Toba. Yellowstone’s supereruptions may therefore have each yielded merely 20 times the amount of SO₂ produced by Pinatubo in 1991, or about
three to four times as much as that produced by the 1783 eruption of basaltic lava at Laki (Iceland) or the 1815 climactic explosive eruption of Tambora.

Although there are considerable uncertainties in the calculation of $S$ emissions from ancient eruptions, the analysis above indicates that a small volume of oxidized magma can release more $S$ than a larger volume of reduced magma.

**DURATION OF SUPERERUPTIONS**

An important question in assessing the effects of a supereruption is “How long would such an eruption last?” This is a difficult question to answer as eruptive histories of past supereruptions are so different that it is probably not appropriate to propose a typical duration (Wilson 2008). What is significant is that the eruption rates (eruptive intensity) during major explosive phases of supereruptions were probably at least similar to the eruption rate at Mount Pinatubo in 1991, where 5 km$^3$ of magma were emitted in the 3.5-hour-long climactic phase, equivalent to almost 1 billion kilograms ($\approx 5 \times 10^5$ m$^3$) of magma erupted each second. The 24-hour-long Tambora eruption also had a similar eruption rate. However, it is expected that eruption intensity and magnitude are linked (Sparks et al. 1997), such that supereruption rates might normally exceed $10^9$ kg s$^{-1}$ of magma. New work on giant ash clouds (Baines and Sparks 2005) indicates that the intensity might approach $10^{10}$ kg s$^{-1}$ in the largest eruptions. One well-studied case (Wilson and Hildreth 1997) is the ~600 km$^3$ Bishop Tuff eruption, which is estimated to have lasted about 6 days with only one short pause (an average eruption rate of $\approx 3 \times 10^9$ kg s$^{-1}$). Other supereruptions may have included several such high-intensity eruptive phases spread over weeks to even years with periods of quiescence in between (Wilson 2008).

**RECURRENCE OF SUPERERUPTIONS**

The question of when the next supereruption might occur is also an important one. The last well-documented supereruption took place ~26,000 years ago, at Taupo volcano, New Zealand – the 530 km$^3$ Oruanui eruption (Wilson 2001, 2008). The most recent eruption approaching the extreme end of the size spectrum is considered to be Toba, which occurred 74,000 years ago. In fact, the number of supereruptions that have occurred in the past is quite small, but our knowledge base is incomplete, making prediction of their recurrence rate problematic. A recent survey of the largest-magnitude explosive eruptions (Mason et al. 2004) shows them to have been very rare, with an average frequency of only one every 100,000–200,000 years. However, global average frequencies are not indicative of the real likelihood of an eruption occurring in a particular area. Different volcanoes have different patterns of activity, and there have been cases when clusters of several very large eruptions occurred within the space of a few thousand years, implying that it is difficult to say how often supereruptions happen.
EFFECTS OF SUPERERUPTIONS

Near- to Mid-Field: Impact of Caldera and Pyroclastic Deposit Formation

We now consider the effects of very large eruptions, beginning at the local scale and extending outwards from the source. Caldera collapse may enlarge, or be encompassed within, a previous collapse structure, depending on the prior history of the volcano. Most supereruption calderas are partly backfilled with pyroclastic deposits (intracaldera ignimbrite). Caldera formation, which takes place catastrophically and engulfs everything on the surface, would destroy any man-made structures within an area of thousands of square kilometres. If it was an island volcano, the collapse could also generate tsunamis (e.g. the 1883 Krakatau eruption, Sunda Strait, Indonesia; Francis and Self 1983).

Ash remains airborne for only a few hours to days, during which time it is an extreme hazard to anything flying, including aircraft (Casadevall 1993). Quite thin ash-fall layers (from a few to 10–15 cm) can cause roof collapse (depending on construction style and standards, and wetting by rainfall), and as little as 1 cm of ash can cause severe disruption to agricultural production if it falls in the growing season. Satellite communication systems may well be highly vulnerable to interruption by ash clouds. Hydroelectric and nuclear power stations could be immobilised due to ash in water intakes, and power lines might be brought down by ash loading and associated electrostatic effects.

Pyroclastic flows are lethal and highly destructive to buildings and other structures. Even areas covered by thin pyroclastic flow deposits would be obliterated, as borne out by the tragic effects of the small-scale flows that went through St. Pierre, Martinique, on May 8, 1902. Only 3 people out of an estimated 30,000 survived, yet the deposits in the town were only centimetres to a few metres thick. After a very large eruption, widespread pyroclastic flow deposits would have to be contended with. These deposits would be many tens, up to several hundreds, of metres thick over areas of thousands to tens of thousands of square kilometres, and they would be thicker in valleys and on plains and thinner over hills. All buildings and man-made structures, indeed all infrastructure, would be buried in thick pumice and ash deposits and would be subjected to high temperatures (400–800°C) and acidic gases and leachates. Rain falling onto fresh volcanic deposits can unleash secondary mudflows (lahars) into rivers and stream catchments, leading to possible damming of rivers and ensuing break-out floods. Lahars caused the highest proportion of death and destruction associated with the Pinatubo eruption, but in the years after the volcanic activity died down.

The low bulk density of parts of most pyroclastic flows also enables them to cross water. During the 1883 eruption at Krakatau, pyroclastic flows crossed 40 km of the sea surface before hitting the coast of southern Sumatra. However, most of the deaths associated with this eruption were apparently caused by tsunamis generated when the pyroclastic flows entered the sea. This serves as a reminder that a supereruption from an island or coastal volcano would previously trigger a series of devastating sea waves.

Far-Field: Global Atmospheric Effects of Large Volcanic Eruptions

The extensive deposits generated by a supereruption may have global consequences. Covering a continent-sized area with white rhyolitic pumice and ash will increase the surface albedo, changing the land–atmosphere energy exchange. A blanketing ash layer will also kill vegetation and alter sources and sinks involved in land–atmosphere gas exchange. If a large mass of ash falls over a wide area of ocean, significant ocean fertilization may occur, causing CO₂ drawdown from the atmosphere.

More-direct global atmospheric changes can be wrought by the volcanic gases injected into the stratosphere. Of these, sulfur gases (mainly sulfur dioxide, SO₂ and sulfuric acid (H₂SO₄) aerosols are the most important atmospheric species, and their effects are quite well known (Robock 2000; Self 2005). Volcanic SO₂ released into the atmosphere is oxidized to form sulfuric acid aerosol particles during reactions that rely on the Sun’s energy. The aerosol droplets of partly frozen H₂SO₄ at low stratospheric altitudes (18–25 km), where conditions are very cold (~ -50°C) and at low pressures, are in the right size range (0.1 to 1 µm) to effectively backscatter and absorb incoming radiation from the Sun. Therefore, the net effect at the Earth’s surface and in the lowest atmosphere is usually cooling.

Well-studied volcanic aerosol events, such as that after Pinatubo in 1991, show how much aerosol is produced, and at what rate, from a known SO₂ release. The Pinatubo aerosol cloud encircled the Earth in less than two weeks, and by three months had spread across much of the globe (Fig. 3). By the end of 1991, spreading polewards, the aerosol cloud had reached high-latitude regions, and it persisted in concentrations sufficient to influence Earth’s radiation budget for more than 3 years. Global temperatures were 0.5°C below normal for two years after the eruption, temporarily offsetting global warming (Hansen et al. 1996).

The much larger S gas releases predicted for supereruptions may imply the formation of greater masses of aerosols, but we do not know how efficient or how fast the conversion of gas to aerosol particles in the atmosphere would be. Some work suggests that much more aerosol would form after massive SO₂ emissions but that the droplets would be larger and would settle out of the stratosphere faster, thus limiting the duration and magnitude of the effects (Pinto et al. 1989). Other work suggests that the chemical reactions forming the aerosols from huge SO₂ clouds would initially dehydrate the stratosphere, thus prolonging the time over which aerosols form (Bekki 1995). With this mechanism, it is possible that the gas-to-particle conversion would take considerably longer than the usual 20–30 days, as exemplified by the carefully monitored post-Pinatubo aerosol cloud. An unknown is the amount and role of water injected into the stratosphere by the eruption column. It is not yet possible to predict with confidence the particle concentration of an aerosol cloud, or its longevity at various concentrations, after a very large eruption. The amount of SO₂ that might be released is considerably larger than for any historic eruption and could lead to an aerosol cloud of unprecedented opacity to incoming radiation. This was the premise of earlier assessments proposing a so-called ‘volcanic winter’ (Rampino et al. 1988) after a very large eruption. Stratospheric aerosols will serve to catalyse ozone loss, increasing the ground-level UV-B flux in high- to mid-latitude regions, the effect lasting a few years after the eruption.

Recently, some of the first attempts were made to assess the effects of a large stratospheric burden of sulfate aerosols. Timmreck and Graf (2005) used an atmospheric model with an SO₂ gas input of 1700 x 10⁶ kg (100 times that of the Pinatubo eruption) from a source at 45° North, similar to the location of Yellowstone volcano. They found that the season of injection is important, with an almost global spread of aerosols from an eruption in the mid-latitude Northern Hemisphere in summer; however, the spread of the aerosol cloud would be restricted to the Northern Hemisphere if the eruption occurred in winter. The results from this study support those of other climate model runs that simulate the...
response to a huge eruption like Toba (Jones et al. 2005). Both studies indicate severe, short-term cooling, with global temperatures plummeting by as much as 10°C, followed by a longer-term (up to 10 years) recovery period. This, combined with much-reduced rainfall predicted by the climate models, could potentially kill off tropical rain forests.

**SOCIETAL IMPACTS OF SUPERERUPTIONS**

We now live in a complex, globally interrelated society that is highly vulnerable to disruption, making the effects and consequences of a large explosive eruption almost entirely detrimental to mankind in the short term. In the past, major historic eruptions have caused famine and disease epidemics (Tanguy et al. 1998). Today, almost 90% of the world’s population lives in the Northern Hemisphere where most food production is concentrated, making the Northern Hemisphere especially vulnerable to the effects of major eruptions. These range from roof collapse due to the weight of an ash layer to the possible disruptive effects of ash and aerosol clouds on satellite communications. Airborne ash would present problems to aviation, especially if the supereruption was of long duration. Ash would block roads, railways and airport runways, causing widespread problems. Ash would also be a health hazard to the eyes and lungs; for example airborne fine volcanic particulates can contain respirable particles of cristobalite (a form of silica) that can cause silicosis (Horwell et al. 2003; Baxter 2005). There are also bound to be effects that we cannot yet anticipate.

![Data from NASA’s Stratospheric Aerosol and Gas Experiment (SAGE II) satellite-mounted instrument show the spread of Pinatubo’s sulfate aerosol cloud; the top-left panel shows the situation before the 1991 eruption; other panels show the situation to January 1994. Colours represent the optical depth (opacity) of the aerosol cloud, with blue being background values and red being the highest concentrations. Note the global coverage by aerosols within a few months of eruption. From McCormick et al. 1995; IMAGE COURTESY OF NASA](image.png)

The consequences of future large-scale eruptions are in detail very challenging to predict because of the variability of volcanic phenomena and the complex interlinking of important societal necessities. Telecommunications and air transport are likely to be extremely vulnerable, and their disruption would significantly compromise the effectiveness of disaster response in the wake of the largest-scale eruptions. The cost of all natural disasters is rising steeply (Smolka 2006), and the effects on world financial markets would likely be acute.

**FINAL THOUGHTS**

Very large explosive eruptions, up to and including supereruptions, are a very small, but real, threat. Many aspects of supervolcanic activity are not well understood as there have been no historical precedents, and such eruptions must be reconstructed from their deposits. Neither is it straightforward to locate or interpret any record of paleo-environmental upheavals in the years to decades after even the most recent supereruptions, several tens of thousands of years ago (Oppenheimer 2002).

Eruptions are unstoppable, and supereruptions are potentially long-lasting (at least several days of intense explosive output from the volcano, and most probably several of these phases spread out over weeks to even years). Further, the effects of each explosive phase will be both immediate (widespread ash fall and pyroclastic flows) and prolonged (due to atmospheric aerosols and debris flows from reworked, unstable, fresh deposits). They will therefore persist and present problems for years after the last major explosive phase. The hazards posed by supereruptions differ from those due to all other natural disasters: although extremely infrequent, they probably present the greatest natural hazard to mankind in terms of the severity and longevity of impact – the ultimate geologic hazard.
It will be necessary to develop strategies to minimise and cope with the effects of future major eruptions. The economic cost of recovery from any future large-scale eruptions will be a major burden on society. As airborne ash and atmospheric sulfate aerosols will bring about the most widespread, long-lasting, and generally hazardous effects of the next large explosive eruption, it is essential to carry out further studies with Earth system models (e.g., coupled atmosphere-ocean general circulation models) to evaluate the potential effects on climate and weather and to assess other possible environmental effects.

Other critical matters that are poorly understood include how long the build-up to such an eruption would be and whether the size and course of events in the impending eruption could be predicted. A large eruption from a geophysically monitored volcano might be predictable to a certain degree, and precursory activity could last for years, if not decades (see Newhall and Dzurisin 1988; Lowenstein and Hurwitz 2008). The difficulty would be to predict whether initial activity might escalate into a catastrophic eruptive phase. There may also be false alarms, with the major phase of an eruption following after years of smaller-scale activity. At present there is no scientific or evidence-based way to determine whether precursor eruptions might be heralding a very large outburst rather than a smaller-magnitude eruption.

Of concern is a situation where a volcano that is currently unrecognized as a potential large-eruption site, or that is evolving towards its first supereruption, or that is not monitored, becomes restless. In these cases scientists and/or the government concerned may not recognize the signs. This uncertainty underlines the fact that we need to know much more about past supereruptions: which volcanoes produced them, what the ages are, what their true size was, and what types of deposits were produced.

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