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The effects and consequences of very large explosive volcanic eruptions

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Every now and again Earth experiences tremendous explosive volcanic eruptions, considerably bigger than the largest witnessed in historic times. Those yielding more than 450 km^3 of magma have been called super-eruptions. The record of such eruptions is incomplete; the most recent known example occurred 26 000 years ago. It is more likely that the Earth will next experience a super-eruption than an impact from a large meteorite greater than 1 km in diameter. Depending on where the volcano is located, the effects will be felt globally or at least by a whole hemisphere. Large areas will be devastated by pyroclastic flow deposits, and the more widely dispersed ash falls will be laid down over continent-sized areas. The most widespread effects will be derived from volcanic gases, sulphur gases being particularly important. This gas is converted into sulphuric acid aerosols in the stratosphere and layers of aerosol can cover the global atmosphere within a few weeks to months. These remain for several years and affect atmospheric circulation causing surface temperature to fall in many regions. Effects include temporary reductions in light levels and severe and unseasonable weather (including cool summers and colder-than-normal winters). Some aspects of the understanding and prediction of super-eruptions are problematic because they are well outside modern experience. Our global society is now very different to that affected by past, modest-sized volcanic activity and is highly vulnerable to catastrophic damage of infrastructure by natural disasters. Major disruption of services that society depends upon can be expected for periods of months to, perhaps, years after the next very large explosive eruption and the cost to global financial markets will be high and sustained.

Keywords: super-eruptions; eruption frequency; eruption magnitude; ash falls; pyroclastic flow deposits; sulphate aerosols

1. Introduction

Volcanic eruptions occur as magma (molten rock) reaches the Earth's surface. There are two major styles of volcanic activity: explosive, yielding fragmented material (ash or pyroclastic deposits) and effusive, which produces lava flows. Both of these eruptive styles display a remarkable range of size, from very small (a few thousand cubic metres of magma) up to the extreme end of the spectrum where eruptive volumes can exceed a thousand cubic kilometres of magma.

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One contribution of 20 to a Discussion Meeting Issue 'Extreme natural hazards'.

Immense, rare explosive eruptions (sometimes called super-eruptions) can cover whole continents with volcanic ash and severely affect global surface and atmospheric processes. Here we focus on explosive activity and will not consider the largest lava eruptions because they are not expected to occur on Earth for many millions of years to come. However, we briefly discuss smaller-scale lava eruptions later in the paper.

The size of volcanic eruptions can be expressed by the volume or mass of magma released (table 1), with super-eruptions yielding in excess of 450 km^3, or more than 1×10^{15} kg, of magma (Sparks *et al.* 2005). Larger-scale explosive eruptions tend to have higher intensities (Carey & Sigurdsson 1989), expressed as the rate of magma release per unit time. They will be more violent and damaging than their smaller counterparts. In contrast, most explosive eruptions of small magma batches from the approximately 150 active volcanoes around the world release on the order of tenths of a km^3 ($1–2\times10^{11}$ kg) or less. The largest eruptions of recent historic times, the most devastating that mankind is familiar with, released between 10 and 30 km^3, or $2–7\times10^{13}$ kg, of magma. Since the eruption of Tambora (Indonesia) in 1815 (approx. 30 km^3 of magma; Self *et al.* 2004), the two biggest eruptions were Krakatau, Indonesia, in 1883 and Katmai-Novarupta, Alaska, in 1912, each releasing about 12 km^3 of magma. Indeed, there may not have been a super-eruption for the past approximately 26 000 years, since the last one at Taupo volcano, New Zealand (the approx. 500 km^3 Oruanui eruption; Wilson 2001). The most recent, recognized eruption approaching the extreme end of the size spectrum (approx. 2800 km^3 of magma) was at Toba (Sumatra) about 74 000 years ago (Rose & Chesner 1987; Rampino & Self 1993).

Huge explosive eruptions are one of the few natural phenomena that can produce global catastrophic effects. The immediate effects of such an eruption will be almost unimaginably severe, yet sooner or later another very large eruption will occur and society must be prepared for its consequences. Moreover, we now live in a complex, globally inter-related society that is highly vulnerable to disruption. Unlike some other extreme natural hazards there should be some degree of warning for an impending super-eruption, but such eruptions are potentially long-lasting (continuing for many days) compared to a brief but intense earthquake or tsunami. They also differ from other hazards (except meteorite impacts—see Morrison 2006) in producing persistent atmospheric effects for several years after the eruption. However, by comparison with meteorite impacts, when the suspected frequency of very large eruptions is compared with the expected frequency of meteorite strikes on Earth that could have similar environmental consequences, it is evident that there is a statistically greater chance of a catastrophe from a future super-eruption than a large impact event (Rampino 2002).

This paper presents an assessment of the effects of very large explosive eruptions that would have consequences well beyond those associated with past, historic volcanic activity. It summarizes what we know and do not know about these eruptions, and how to fill the gaps in our knowledge. We begin with what is known about the size range of explosive eruptions, then examine where very large eruptions have occurred, the frequency of such events and describe the features and deposits that would be produced. We then turn to the atmospheric impact of super-eruptions and consider their effect on global temperatures and weather. Finally, we discuss issues facing society after a super-eruption, including the potential economic impact of such an event.

Table 1. Magnitude, erupted mass, dense magma and bulk deposit volumes, volcanic explosivity index, frequency and probability for a range of explosive eruptions from medium to large size (? indicates that magma volume from eruption is likely to be much larger than presently estimated).

eruption magnitude (M)[a]	minimum erupted mass (kg)	minimum volume magma erupted (km^3)[b]	minimum volume pyroclastic deposits (km^3)	VEI[c]	example of typical eruption[d]	frequency (average number of eruptions per 100 years)	minimum probability of one or more eruptions of this size during 21st century
5	1×10^{12}	0.4	1.0	5	Mount St Helens 1980	$\sim$10	100%
6	1×10^{13}	4	10	6	Krakatau 1883	$\sim$2	100%
7 (low)	1×10^{14}	40	100	7	an eruption bigger than Tambora 1815 (Kuwae 1452)	0.1–0.5 (1 every 200–1000 years)	10–50%
7 (moderate)	2.5×10^{14}	100	250	7	? Kikai-Akahoya, Japan, 7000 ka ago	0.01–0.06 (1 every 1600–10 ka)	1–6%
7 (high)	8×10^{14}	300	750	7	? Campanian Tuff eruption, Italy, 39 000 ka ago	0.001–0.01 (1 every 10–100 ka)	0.1–1%
8 (low)	1×10^{15}	450	1000	8	Oruanui, Taupo, New Zealand, 26 000 ka ago	$<$0.001 (1 every 120–$\sim$200 ka)	$<$0.1%
8 (moderate)	2.5×10^{15}	1000	2500	8	Cerro Galan, Argentina, 2. 2 Myr ago	0.0003 (1 every $\sim$300 ka)	negligible
8 (high)	8×10^{15}	$>$3000	$>$5000	8	an event bigger than Toba (2800 km^3, 74 ka)	$<$0.0001 (less than 1 every million years)	approximately 0%

[a]Magnitude (M), $\log_{10}$ erupted magma mass (kg) -7.0; see Mason *et al.* (2004); also http://www-volcano.geog.cam.ac.uk/database/). Common small eruptions have magnitudes less than five. Only one M9 eruption (greater than 1×10^{16} kg of magma) has been recognized in the past 28 Myr. [b]A deposit of any VEI or M may have a volume ranging from the bulk deposit volume to the equivalent volume of dense magma. Mass–volume conversions made assuming typical magma densities of 2400 kg m^{-3} (M5–6) and 2200 kg m^{-3} (M7–8) and bulk density (that of pyroclastic deposits in the field) of 1000 kg m^{-3}. [c]VEI based on bulk deposit volume alone; data after Decker (1990). [d]ka, one thousand years.

2. The size spectrum of eruptions

Commonly used schemes to describe the size of eruptions are the volcanic explosivity index (VEI; Newhall & Self 1982) and developments of this index based on mass of magma erupted (Pyle 1995, 2000), following the original mass-based magnitude scale suggested by Tsuya (1955). The size-range of eruptions covers many orders of magnitude in volume or mass of magma released (table 1). Magnitude (M) is defined as

$$\mathrm{M} = \log_{10}\,(\text{erupted mass, kg}) - 7.0.$$

A recent survey of the largest-magnitude explosive eruptions (Mason *et al.* 2004) shows them to have been very rare, but past eruptions of immense proportions have occurred and will occur again. Only one eruption rating M9 (1×10^{16} kg, or about 5000 km^3) has been recognized, which occurred 28 Myr ago (Lipman 1997*a*). In this paper, we are mainly concerned with explosive super-eruptions in the range M8 and above, which release more than 1×10^{15} kg of magma, or a minimum of 1000 km^3 of volcanic ash deposits. We will also consider eruptions in the M7–8 range, which are still huge compared to historic events. All of these eruptions are associated with the formation of a caldera. A caldera volcano is a large collapse depression where the crust above the magma chamber collapsed inward as the magma was evacuated (Lipman 1997*b*); in the case of Toba, the present, lake-filled caldera has dimensions of approx. 75×40 km.

Even when the deposits of very large eruptions can be recognized, our estimates of their size are very uncertain. There are difficulties in measuring the volumes of pyroclastic deposits, and thus the amount of magma erupted, because the deposits are affected by various processes after their formation. Many of the caldera volcanoes that have yielded great eruptions are in tropical environments where erosion is very rapid. As an example, about 60% of the new pyroclastic deposits of the 1991 Mount Pinatubo eruption were removed by stream erosion within 3–4 years of the June 1991 event (Daag & van Westen 1996). Alternatively, the eruptions may have occurred at times of colder temperatures and harsher erosion and were subject to extensive re-working, as with the Orunanui eruption products from Taupo volcano (Manville & Wilson 2004). Ancient eruption products can also be covered by dense vegetation or be highly weathered,

Ejecta from eruptions in volcanic arcs (figure 1) are dispersed by primary transport mechanisms (pyroclastic flows and wind-dispersed ash fall) into the sea, usually leading to considerable underestimates of size. For example, the great size of the approximately 2800 km^3 Toba eruption was established after Ninkovich *et al.* (1978) correlated the widespread Toba ash in sea-bottom sediment cores from across the Indian Ocean, although earlier workers had marked the Toba deposit as particularly voluminous (see Oppenheimer 2002). Thus, making estimates of the size of past eruption magnitudes is difficult; realistic original volumes must be reconstructed carefully (e.g. Wilson 1991).

Further uncertainties in magnitude estimates arise because magma expands during an explosive eruption. Wide variations in deposit and magma density in a single eruption lead to a complex relationship between the volume of erupted material and the expelled magma mass. Almost all very large explosive eruptions involve viscous, gas-rich, high-silica magmas (rhyolite and

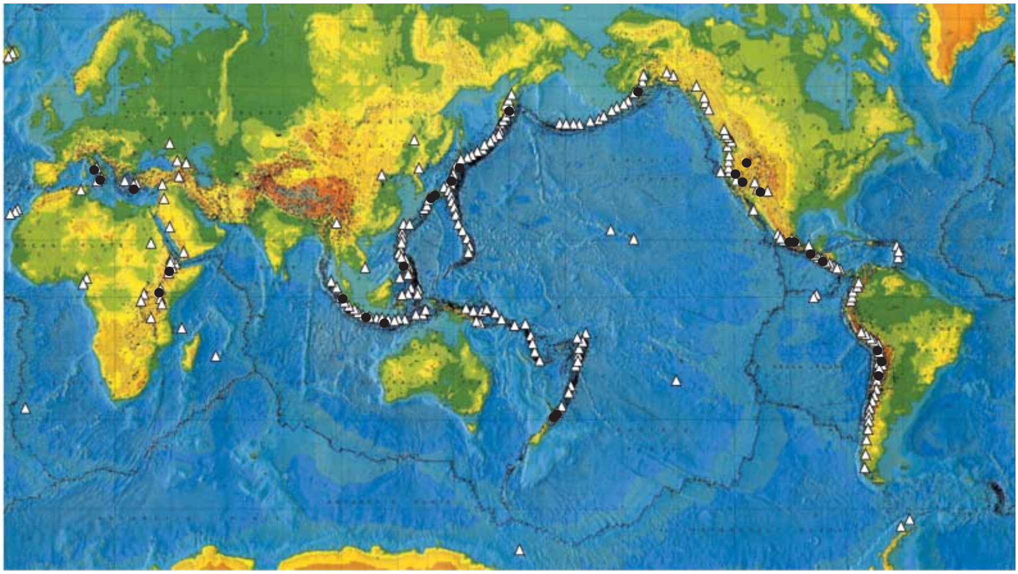

Figure 1. World map showing sites of some volcanoes (black dots) that have produced large explosive eruptions (more than 150 km^3 of magma) within the last one million years. Note concentration around the Pacific tectonic plate margin, the so-called 'Ring of Fire', and also in western interior of continental North America. Pacific plate margin sites are along recognized volcanic arcs and island arcs, defined by lines of active volcanoes (small open triangles). After Sparks *et al.* (2005); base map from www.usgs.gov.

related types) that have densities around 2200 kg m^{-3}. This value has been used in this paper to calculate the masses of eruption deposits exceeding M7 (table 1).

Figure 2 shows estimates of the volumes of magma released by the largest and best-known historic eruptions compared with those from very large eruptions. Even the biggest historic eruptions such as Tambora in 1815 and Kuwae in 1452 (both 30–40 km^3 of magma), and especially recent twentieth century eruptions such as Pinatubo 1991 (5 km^3), are dwarfed by super-eruptions.

3. Where have large explosive eruptions occurred?

The distribution of sites of very large eruptions around the world (figure 1) indicates where future ones might happen. The distribution also demonstrates that they occur in two types of settings. One is from volcanoes in destructive plate margin (subduction zone) settings, as might be expected from knowledge of the ways in which magma is generated. The other main setting is in continental interiors that are, or have undergone, rifting. There have been many huge eruptions on the North American continent and extending into the Sierra Madre Occidental, a Northern Mexican volcanic belt active before about 12 Myr (ago). This region accounts for many of the known M8, and the only M9, eruptions. Most of these North American events are many millions of years old and their calderas are not shown on figure 1; their occurrence is probably irrelevant to present-day assessments of when and where the next very large eruption might occur.

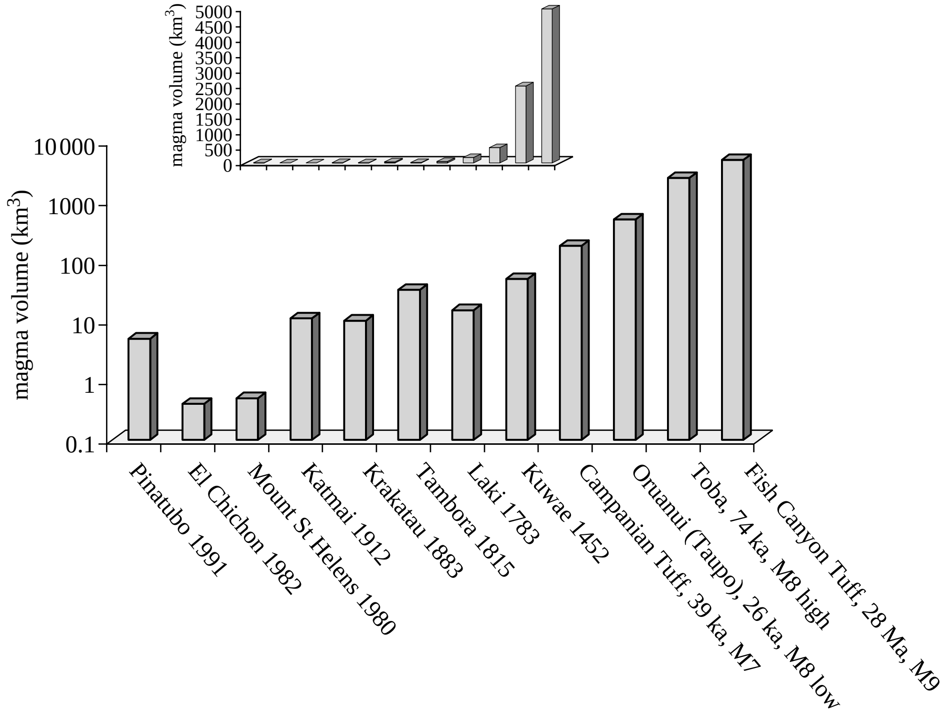

Figure 2. Volumes of magma (plotted on log scale) released by historic eruptions compared with very large eruptions; inset: same data plotted on linear scale. Historic eruptions hardly register against sizes of past very large eruptions of magnitude 7 (exemplified by Campanian Tuff) and magnitude 8 and greater (three examples at right). Ka is thousands of years (ago); Ma millions of years (ago).

Volcanoes located in subduction zone settings, such as continental arcs (e.g. Central America to the Andes) and island arcs (e.g. Japan, Philippines), lead to one of the obstacles to understanding past large eruptions. Much of the volcanic products are deposited into the ocean, as discussed above. Furthermore, as many large explosive eruptions originate from island volcanoes, or from vents within large caldera lakes, the earliest stages may be 'wet' (featuring magma-water explosive interaction; Self & Sparks 1979) and the environmental consequences of these may be different from those of the 'dry' (magmatic) part of an eruption (e.g. Koyaguchi & Woods 1996). In many, but not all, eruptions that have been studied, the dry phase of the eruption seems to be when magma is emitted at the highest eruption rate. Some aspects of these complexities will be briefly discussed later. One other important aspect of the location of a volcano concerns the extent to which eruption clouds are dispersed in the high atmosphere, which affects the atmospheric impact (see §6*b*).

4. Frequency and prediction of large eruptions

Due to the uncertainties in our estimates of deposit volumes, magnitude values for nearly all past eruptions are only approximate. This affects our ability to accurately determine how many past eruptions have occurred in each part of the

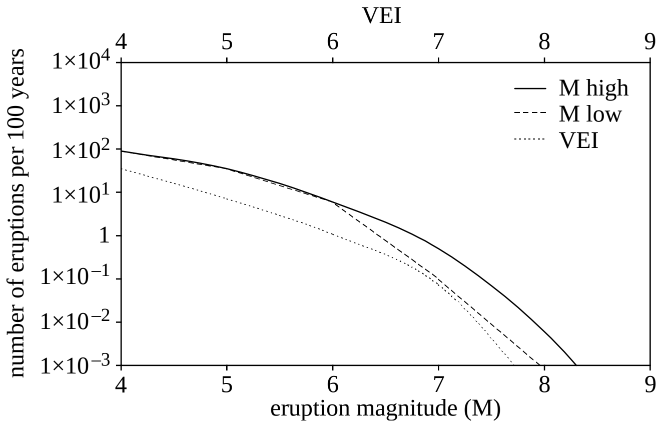

Figure 3. Graph showing numbers of eruptions per 100 years (on log scale) plotted against eruption magnitude (M) and Volcanic Explosivity Index (VEI). Two curves for magnitude 7 and above show current estimates of upper and lower expected numbers of very large eruptions, from analysis by Mason *et al.* (2004). VEI values from Decker (1990) based on volume of pyroclastic deposits. Very large events are rare; M7, one every 200 to 1000 years; M8, one every few tens of thousands of years or longer.

size spectrum. However, a sufficient body of information has been amassed to assess the frequency and size range of large eruptions (figure 3, table 1). Super-eruptions are shown to be very rare, with an average frequency of only one every 100–200 000 years, but those slightly smaller than super-eruptions (the M7 class, yielding $1\times10^{14}-1\times10^{15}$ kg, or approx. 45–450 km^3 of magma) have been more frequent. These can also be assumed to produce severe global effects. A survey of magma masses erupted over time by Pyle (1998) identified those of magnitude 7 as the biggest subaerial explosive eruptions with a high enough frequency to dominate Earth's silicic magma output over long periods, suggesting that they should receive particular attention. Average frequencies are between one every few hundred years for the small end of the range to more than one per 10 000 years for the upper end (figure 3).

Global *average* frequencies are not always 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 in past times when several very large eruptions occurred within the space of a few thousand years. This implies that volcanic eruptions of any particular size may be generally unpredictable on either a short or long-term basis. While there may not have been an eruption of over approximately 500 km^3 of magma in the past 26 000 years, since the Oruanui eruption at Taupo in New Zealand (Self 1983; Wilson 2001), there are notable examples of large eruptions from other volcanic regions in the period between the Oruanui eruption and 18 000 years ago. Moreover, several eruptions in the 150–400 km^3 size-range occurred in the previous 60 000 year interval. These include eruptions at 39 000 years ago at Campi Flegrei caldera in Italy (e.g. Fedele *et al.* 2002) and 84 000 years at Atitlán in Guatemala (Rose *et al.* 1987) that exceeded 150 km^3, while the Toba super-eruption occurred at 74 000 years ago (Rose & Chesner 1987).

Since the last M8 eruption at Taupo, 26 000 years ago, only a few M7 eruptions have occurred. These include the Kikai eruption in Japan about 7000 years ago (Machida & Sugiyama 2002), the Mount Mazama eruption at 6600 years ago in the Cascades of North America, and possibly the late Bronze Age eruption of Santorini and an eruption from an unknown volcano in AD 1257 recorded in ice cores (Oppenheimer 2003). It seems that the presently understood numbers of such eruptions is an underestimate and more will be discovered.

We know a reasonable amount about the deposits and other phenomena that very large explosive eruptions have produced from the study of certain examples. However, there are other critical matters that are poorly understood. These 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 if the volcano had been under surveillance. A large eruption might be predictable to a certain degree, and precursory activity could last for years, if not decades (see Lowenstern 2006). 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 of determining whether precursor eruptions might be heralding a very large outburst rather than a smaller magnitude eruption.

5. Duration and products of large explosive eruptions

Case studies of deposits of very large eruptions help to reconstruct some details of the events and the features formed. Examples of studies include eruptions in the area that is now Europe, such as the Campanian Tuff event (Naples region, Italy, 39 000 years ago (Civetta *et al.* 1997; Fedele *et al.* 2002) and the Kos Plateau Tuff eruption, approximately 160 000 years ago, from a now-submerged volcanic caldera in the Aegean Sea (Allen 2001). An important question is how long would such an eruption last? At a minimum, the eruption rates were probably similar to that at Pinatubo in 1991, where 5 km^3 of magma was emitted in the 3.5 h long climactic phase (Scott *et al.* 1996), equivalent to almost 1 billion (9×10^8) kg s^{-1} (approx. 5×10^5 m^3 s^{-1}). The 24 h long Tambora eruption also had a similar eruption rate. These values are based on relatively small historic eruptions and imply, for example, that a 200 km^3 explosive eruption might

Figure 4. (*Opposite.*) Examples of explosive eruption columns and a large caldera volcano: (*a*) eruption column from Mount Pinatubo on 12 June 1991 (opening explosive phase of 1991 eruption), attaining a height of 22 km and reaching into the base of the stratosphere (US Air Force photo taken from Clark Air Base, Luzon, Philippines); (*b*) pyroclastic flow and associated co-ignimbrite eruption cloud from Mount Pinatubo on 15 June 1991, at beginning of main explosive phase of eruption; giant cloud ultimately rose to 35 km height (US Air Force photo taken from Clark Air Base, Luzon, Philippines); (*c*) Mount St Helens co-ignimbrite ash cloud which rose to 29 km altitude from blast flow at Mount St Helens on 18 May 1980 (see Sparks *et al.* 1997); (*d*) photo of part of Lake Toba, Sumatra (caldera) with 300 m high flat-topped cliffs in background, which represent the caldera rim and the landscape-burying pyroclastic flow deposits produced by the huge eruption 74 000 years ago (photograph by S. Blake); (*e*) cartoon of vertical (Plinian; left) and co-ignimbrite-style eruption columns (collapsing column forming a pyroclastic flow, right) typical of early and later parts of very large eruptions, respectively.

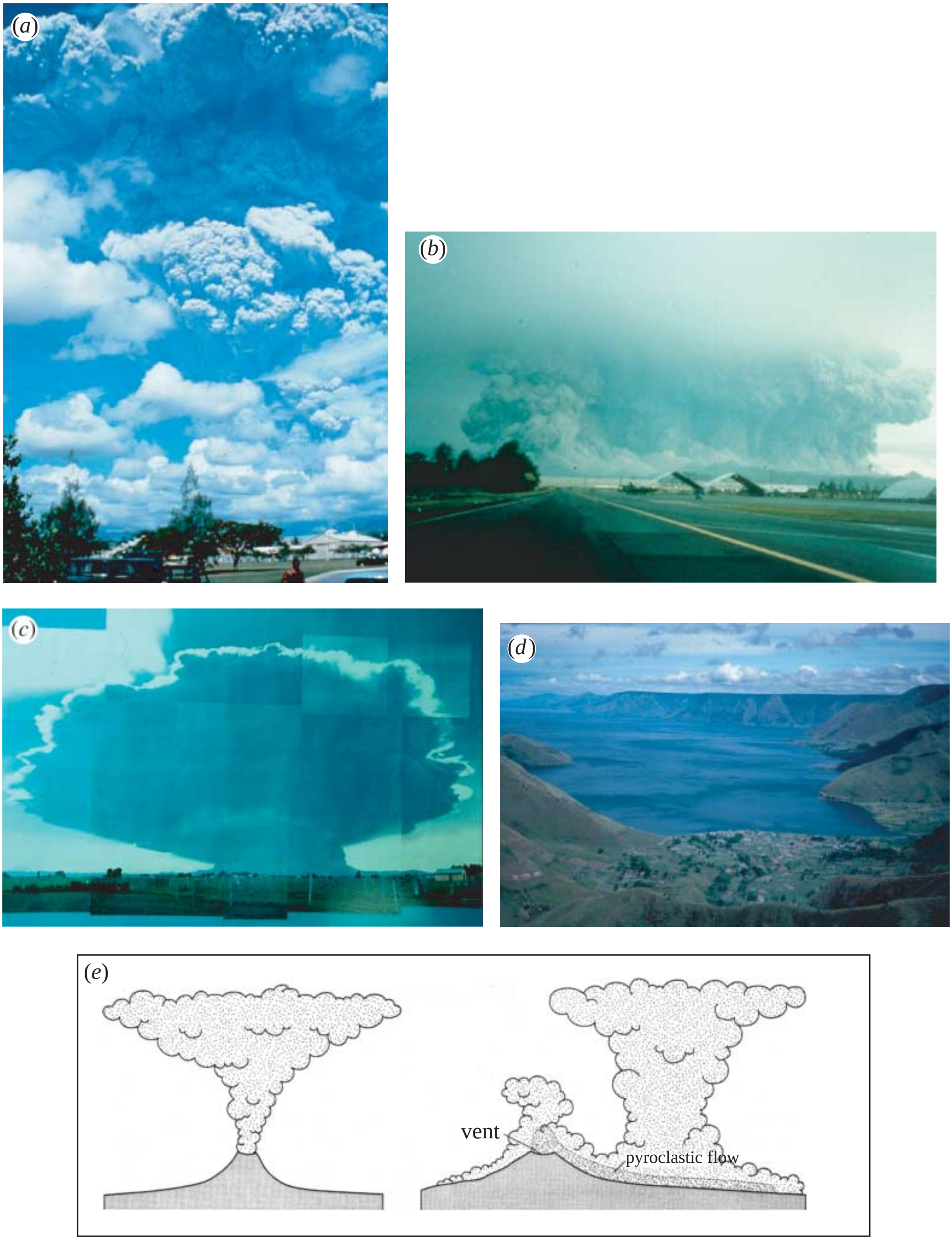

Figure 4. (*Caption opposite.*)

continue for about 5–6 days. However, while it is expected that eruption intensity and magnitude are linked (Carey & Sigurdsson 1989), higher magnitude eruptions always involve the production of large amounts of pyroclastic flow deposits and the rates at which these are produced is less certain. Rates might exceed $1\times10^{9}\,\mathrm{kg\,s^{-1}}$ of magma (as for the pyroclastic-flow-forming phase of the Taupo eruption; Wilson 1985), and higher rates are supported by new work on giant ash clouds (Baines & Sparks 2005). These authors note an increase in ash grain-size with increasing size of the ash clouds and estimate that intensity approaches $1\times10^{10}\,\mathrm{kg\,s^{-1}}$ in the largest eruptions. Implied durations would be more than 2 days to less than 10 days for various combinations of rate and erupted mass in the M8–9 range, a case being the *ca* 450 km^3 Bishop Tuff eruption from Long Valley, California, about 770 000 years ago, which is estimated to have lasted about 4 days (Wilson & Hildreth 1997).

We now consider the products of very large eruptions beginning at the local scale and extending outwards from the source volcano. An eruption of around 450 km^3 of magma would form a caldera at least 15 km diameter, extending up to Toba-size depressions (approx. 100 km) for the largest eruptions. The collapse may enlarge, or be encompassed within, a previous caldera depending on the prior history of the volcano. It may be partly back-filled with pyroclastic deposits depending on when the collapse occurred. Caldera-formation, which takes place catastrophically and engulfs everything on the surface, would destroy any human-made structures in the region over areas of hundreds to thousands of km^2. If it was an island volcano, the collapse could remove part of the land which could also generate tsunamis.

Large explosive eruptions produce high ash- and gas-laden atmospheric columns that penetrate through the troposphere and into the stratosphere (figure 4*a*). The tropopause, separating the troposphere from the stratosphere, is at 17 km height over the equator and less than 10 km at 65° North or South and will be reached by eruption columns from all very large eruptions. From the eruption columns, ash clouds drift downwind in the (usually seasonally varying) wind field. Ash fallout would occur from these clouds to distances of several thousand km downwind, sometimes covering areas well in excess of 1 million km^2 (figure 5). The other main eruptive phenomenon, pyroclastic flows (figure 4*b*), hug the ground and flow for tens of kilometres or in extreme cases for as much as 200 km (Wilson 1985). They typically become partly buoyant during transport, crossing topographic barriers up to hundreds of metres high, and feeding fine ash into vigorously convecting clouds that rise above the flows (Sparks & Walker 1977; Woods & Wohletz 1991; Neri & Macedonio 1996). The ash from these plumes becomes dispersed by the prevailing winds over huge areas, e.g. the ash layer found over Europe and in Mediterranean Sea bed from the Campanian eruption (figure 5*a*). These giant clouds are energetic enough to spread in all directions irrespective of stratospheric winds, accounting for the extremely wide dispersal of ash fall deposits such as those from Yellowstone caldera and Toba (figure 5*b*,*c*).

Major pyroclastic flow deposits can cover up to 20 000 km^2 around the source volcano and bury the landscape with up to 200 m of ash and pumice fragments (figure 4*c*,*d*); during emplacement they will obliterate everything in their path. To put this into perspective, the flow deposits (of an assumed $1000\,\mathrm{kg\,m^{-3}}$ density) produced by a hypothetical eruption of 200 km^3 of magma would completely fill the area enclosed by the M25 London Orbital Motorway (approx. 2000 km^2) with more than 200 m (over 700 ft) thickness, sufficient to engulf the entire topography and everything built upon it!

The low bulk density of some pyroclastic flows, as they travel out from the eruptive vent, also enables them to cross water. During the 1883 eruption of Krakatau (Sunda Straits, Indonesia) pyroclastic flows crossed 40 km of the sea surface and hit the southern Sumatra coast (Carey *et al.* 1996). However, most of the deaths associated with this eruption on an island volcano between Java and Sumatra were apparently caused by tsunami generated when pyroclastic flows entered the sea (Francis 1985). This serves as a reminder that large eruptions can sometimes trigger devastating sea waves. Small pyroclastic flows entering and travelling across the sea are well-documented from the recent eruption of Soufrière Hills volcano, Montserrat (Cole *et al.* 2002).

After, or even during, an eruption, volcanic mudflows (*lahars*) can develop from rains falling onto fresh pyroclastic deposits and by the re-instatement of disrupted rivers and streams. Many areas affected by lahars after a large eruption would already have been effectively devastated by the preceding ash fall and pyroclastic flows. However, lahars can extend beyond the limits of the primary deposits affecting all parts of drainage networks (e.g. Manville & Wilson 2004). Lahars and their deposits are highly disruptive. After the Pinatubo eruption (e.g. Pierson *et al.* 1992), and after Mount St Helens in 1980, lahars reached river mouths and affected coastal ports by build-up of new sediment.

Eruptions also release volcanic gases into the atmosphere. The most abundant gases are water and carbon dioxide, but eruptive emissions will make little difference to the high background concentrations of these gases in the atmosphere. Much moist tropospheric air is also taken up in the eruption columns and emplaced into the relatively dry stratosphere. More importantly, sulphur (S) and volcanic halogen gas releases (chlorine (Cl), fluorine (F) and perhaps bromine (Br; Gerlach 2004)) cause significant changes to the normal atmospheric concentrations of these gases or their acids H_2SO_4, HCl and HF (see review by Robock 2000). This is especially so in the stratosphere, where such species normally occur in extremely low abundance. Using recent eruptions as a guide, an estimate of the amount of SO_2 that could be potentially released by a 450 km^3 eruption is shown on table 2.

As far as the global environmental impacts of large eruptions are concerned, the effects of gas release and its resulting acid aerosols will outweigh that caused by ash fallout over regional to continental-scale areas. Some important issues about which we know very little are related to the atmospheric injection of gases by eruptions that involve explosive activity in flooded calderas. These include whether 'wet' eruption columns are likely to have the soluble gaseous scavenged from them (reducing the amount of gas remaining in the stratosphere), how much water is carried into the stratosphere by 'wet' versus 'dry' eruption columns and whether this can change stratospheric dynamics and if seawater would provide additional S (in the form of sulphate) and Cl to the eruption column.

6. Effects and impacts

(*a*) *Impact of pyroclastic deposits*

Ash fall deposits may be more than 10 m thick near the volcano and thin down to a few centimetres or less at distances of hundreds to thousands of kilometres downwind. Ash from super-eruptions of Yellowstone caldera is known to cover

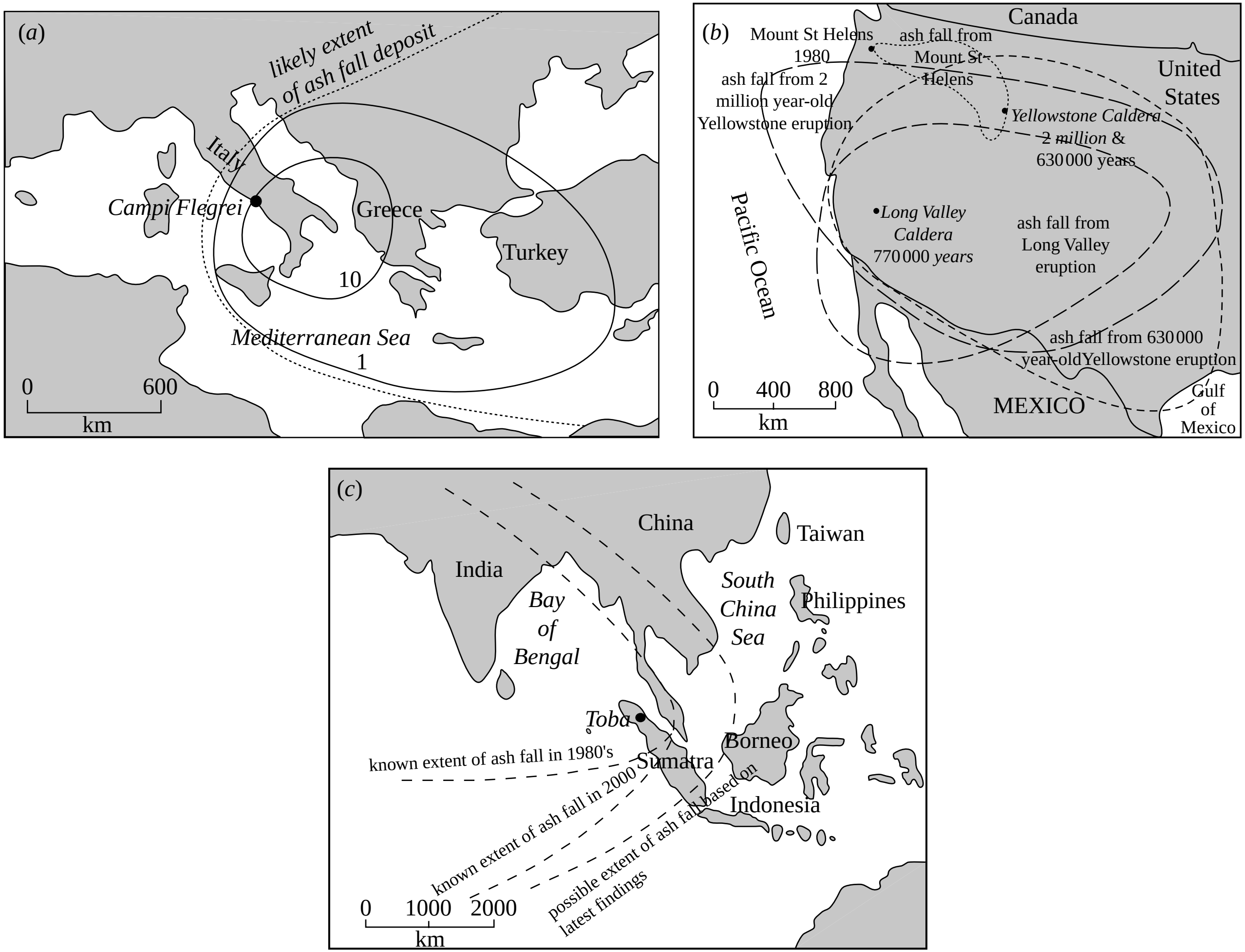

Figure 5. (*Caption opposite.*)

Figure 5. (*Opposite*.) Sketch maps of ash fall deposits associated with formation of large volumes of pyroclastic flow deposits. (*a*) From Campanian eruption approximately 39 000 years ago, derived from Campi Flegrei caldera, Italy, showing lines of equal thickness in centimetres reconstructed from preserved ash deposits on land and in Mediterranean Sea cores (after Fedele *et al.* 2002); possible limit of deposit after D. M. Pyle (2006, personal communication). (*b*) Ash falls that have affected North America include two huge ones from Yellowstone about 2 million and 600 000 years ago and fallout from very large eruption of Long Valley caldera, California, 770 000 years ago; dashed lines show known limits of ash distribution. 1980 Mount St Helens eruption ash fall limits shown for comparison [source: http://volcanoes.usgs.gov/yvo/index.html]. (*c*) Ash fall distribution from Toba super-eruption, Sumatra, 74 000 years ago, showing how the known area of deposition has increased as new knowledge has been gained over past 25 years.

Table 2. Largest volcanic sulphur dioxide releases and sulphate aerosol clouds in past three centuries and mass of SO_2 that could potentially be released from a 450 km^3 (M8) magma batch[a].

historic SO_2 releases		mass SO_2 (10^{12} g or Tg)	mass H_2SO_4 aerosols (10^{12} g or Tg)
Mount Pinatubo, 1991[b] (data from Self *et al.* 1996)		17	28–30
Tambora, 1815 (data from Self *et al.* 2004)		60–70	100–120
Laki, 1783 (data from Thordarson & Self 2003)		122[c]	<200[c]
mass SO_2 from a 450 km^3 eruption[a,b]	mass SO_2 (10^{12} g)	mass magma (10^{15} g)	mass SO_2 for 450 km^3
low S conc. (Mount St Helens)	1	1.2	8×10^{14} g (800 Tg)
moderate (Mount Pinatubo)	20	13	1.5×10^{15} g (1500 Tg)
high (El Chichón)	7	2.3	3×10^{15} g (3000 Tg)

[a]Assuming magma body released sulphur gas in proportions similar to that determined for named historic eruptions with low, moderate and high values. Mass determined from reported mass SO_2 released (from satellite-borne sensors) divided by mass magma erupted (information from various sources) multiplied by mass of 450 km^3 magma (1×10^{15} kg). [b]Manner in which S contained in or around magma body not specified here. [c]Total amounts released/generated over several months.

much of North America, while ash from Toba is found over 3000 km away in northern India and Pakistan, as well as in the south Indian Ocean and China Sea (Oppenheimer 2002). Even a small ash deposit such as that produced on 18–19 May 1980, by the comparatively tiny, magnitude 5 Mount St Helens eruption (Sarna-Wojcicki *et al.* 1981) caused widespread damage and disruption across several states in the USA. The airborne ash is resident for only a few hours to days, during which it is an extreme hazard to anything flying, including birds and aircraft (Casadevall 1993). Quite thin ash fall layers (from a few centimetres to 10–15 cm, depending on construction style and standards) can cause roof collapse (Blong 1984; Sparks *et al.* 1997) and more than 1 cm of ash can cause severe disruption to agricultural production if it falls in the growing season. As an illustration, in an eruption yielding an assumed bulk ash fall volume of approximately 300 km^3 the deposit would be dispersed over immense areas, perhaps exceeding the size of Europe (several million km^2). This implies a very widespread impact, with some of the predicted effects and hazards being given in table 3. Satellite communication systems are vulnerable to interruption by ash clouds.

Table 3. List of phenomena and hazards associated with a hypothetical large explosive eruption (magnitude eight), based on effects of various eruptive phenomena and deposits that would be formed. (Severity of the effects of deposits would depend on distance from source volcano. Impact of atmospheric aerosols in any region will depend on the location of volcano and season of eruption. (Adapted from Sparks *et al.* 2005).)

ash fallout and deposit	*roof collapse* in built-up areas—a local effect out to distances where ash fall is a few centimetres thick (hundreds of kilometres from the volcano). Exacerbated if rain occurs or ash fall is wet.
	agriculture—disruption for at least a growing season over most of area receiving ash fallout. Longer term beneficial changes to soil composition.
	drinking water, *waste disposal*—potential for both chemical and filtration/blockage problems associated with water supply. Blockage of sewage treatment processes.
	aviation—risk to flying aircraft while ash still airborne (days to ?weeks); problems with landing and take-off until airports cleared.
	power generation—effects of ash on hydroelectric and nuclear power plants due to ash in water intakes.
	power distribution—electric pylons and powerlines might be susceptible to ash loading and associated electrostatic effects, possibly exacerbated if ash fall is wet.
	health (see gas and aerosols)
pyroclastic flows and deposits	*burial* of all objects on ground and fires on a local scale, up to perhaps 50–80 km from source volcano.
	refugees—if pyroclastic flows were predicted, widespread evacuation would be required, which, depending on the area, could lead to a large number of persons requiring re-location.
	tsunami—if the volcano is near the coast, pyroclastic flows entering the sea could cause tsunami. In region around the island volcano of Krakatau in 1883, most of 30 000 casualties due to tsunami.
	secondary mudflows (*lahars*) in rivers and stream catchments after rainfall on fresh volcanic deposits. Possible damming of rivers, with ensuing break out floods. (Lahars caused the highest proportions of death and destruction associated with the Pinatubo eruption, but in the years after the activity died down.)
gas and aerosols	*climate change*—dominantly cooler temperatures for a few years after the eruption might change agricultural yields. Some areas may undergo warming, and there might be short-term, very warm spells that could also affect growing crops. Changes in rainfall patterns may influence liability to flooding in certain areas.
	dry-fog and *acid aerosol air pollution*—a Laki-type dry fog in the lower atmosphere (composed of sulphur dioxide gas and sulphuric acid aerosols) could induce respiratory illness, as could fine ash (<10 μm) and other minerals in the ash. Such clouds can attain complete coverage within a hemisphere.
	chemical etching effects of *aerosol particles on aircraft* engines and instrumentation.
	ozone depletion—stratospheric aerosols will serve to catalyse ozone loss, permitting higher UV-B flux to the ground in high–mid-latitude regions, the effect lasting a few years after the eruption.
general	*disruption of national and international relief efforts and cooperation, and of some communications* (satellite-borne instruments may not be able to perform normally due to ash and/or aerosols situated in atmosphere between sensor and Earth's surface).
	effects of all the above on world financial markets.

Pyroclastic flows are extremely hot (hundreds of degrees centigrade), rapidly moving mixtures of ash and gas. They are lethal and highly destructive to buildings and other structures (Valentine 1998; Baxter 2005). Even areas covered by parts of a pyroclastic flow that leaves thin deposits would be obliterated, as borne out by the tragic effects of the small-scale flows that went through St Pierre, Martinique, on 8 May 1902 (Boudon & Lajoie 1989). Only three people out of an estimated 30 000 survived (Tanguy *et al.* 1998), yet the deposits in the town are only centimetres to a few metres thick.

After a very large eruption, the widespread pyroclastic flow deposits will have to be contended with. These can be many tens, up to several hundreds, of metres thick over areas of hundreds to thousands of km^2, thicker in valleys and on plains, and thinner over hills. All buildings and human-made structures, indeed, all infrastructure, will be buried in thick pumice and ash deposits and subjected to high temperatures.

There are major issues in predicting the behaviour of pyroclastic flows and the total potential devastation of any eruption from its precursory activity. On a smaller scale, the Mount St Helens 1980 blast flow and the Taupo AD 180 pyroclastic flow (Wilson 1985) represent this problem. The 1980 blast was not predicted due to the available knowledge at the time and most probably the great extent of the Taupo flow (approaching 20 000 km^2) would not have been predicted from the styles of activity earlier in the eruption. An important question that cannot be answered at present is whether any population at risk could be evacuated from the critical area before the next large explosive eruption occurs.

Rather than dwell on the stark realities of the hazards of pyroclastic fall and flow deposits, which have been covered in several texts such as Blong (1984) and Scarpa & Tilling (1996), we will now consider the long-lasting and global-scale effects of a very large explosive eruption.

(*b*) *The widespread atmospheric effects of large volcanic eruptions*

Sulphur gases (mainly sulphur dioxide, SO_2) and sulphuric acid (H_2SO_4) aerosols are the most important atmospheric species and their effects are quite well known (Self 2005). Volcanic SO_2 released into the atmosphere is oxidized to form sulphuric acid (sulphate) aerosol particles during reactions that rely on the sun's energy (figure 6). The aerosol droplets of partly frozen H_2SO_4 at low stratospheric altitudes (18–25 km), where conditions are very cold (approx. $-50\,^{\circ}C$) and at low pressures, are in the right size range (0.1–1 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. Apart from sulphur, however, the influence of volcanic eruptions on atmospheric chemistry has not been explored in any detail. Chlorine (and HCl in gaseous or aerosol form) may, for example, be very important after some eruptions (Tabazadeh & Turco 1993).

Well-studied volcanic aerosol events, such as that after Pinatubo 1991, show how much aerosol is produced, and at what rate, from a known SO_2 release (e.g. Zhao *et al.* 1996). Pinatubo is a sub-tropical volcano and the gas and aerosol clouds generated spread into both hemispheres. If a volcano is within 15° north or south of the Equator, a stratospheric-high eruption cloud can spread gas and aerosols into both hemispheres. Aerosol dispersal is also dependent on season of

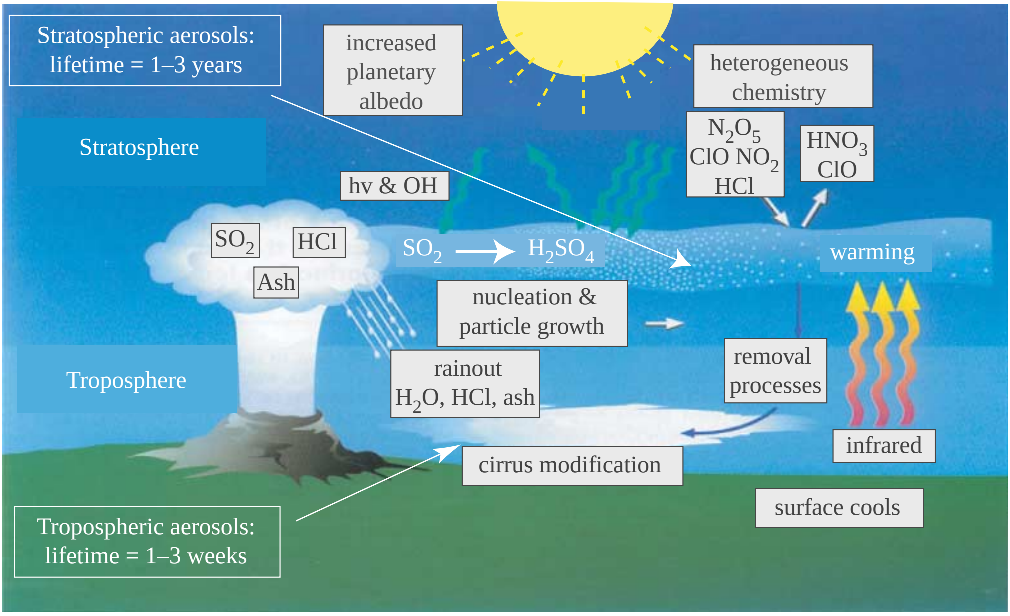

Figure 6. Schematic diagram of various volcanic inputs to atmosphere and their interaction, fates, and radiative impact, including the formation of sulphuric acid (sulphate) aerosols (after McCormick *et al.* 1995; Robock 2000). See text for description of processes illustrated.

the eruption and atmospheric circulation cycles. From higher latitudes than that, up to about 30° from the Equator, aerosol clouds are predominantly distributed into only one hemisphere. However, there will still be significant amounts of aerosols in the opposite hemisphere. North or south of 30° latitude an eruption cloud and its gas and aerosols will usually be limited to the relevant hemisphere. The Pinatubo aerosol cloud, still forming from SO_2 gas, encircled the Earth in less than two weeks, and by three months had covered much of the global atmosphere (McCormick *et al.* 1995). 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 2 years after the eruption, slightly offsetting global warming (Hansen *et al.* 1996).

In terms of changing weather patterns, the effects of past eruptions of volcanoes located in the tropics can give us an indication of what might happen after a much larger event. It has been noted from surface and lower atmosphere temperature data collected after several explosive eruptions that summer temperatures are lower, often by up to several degrees centigrade locally, and very cool summer conditions occur in some regions (Robock 2000). Winter temperatures in the Northern Hemisphere (where 90% of the world's population lives) are colder generally but warmer than average in some high latitude regions (Stenchikov *et al.* 2002).

The much larger aerosol clouds formed by emissions of SO_2 from M7 and M8 eruptions would also rapidly attain hemispheric or global coverage of the atmosphere. What we do not know is how efficient and fast the conversion from gas to aerosol particles in the atmosphere would be after a much bigger SO_2 release. Some work suggests that much more aerosol would form after massive

SO_2 emissions but that the droplets would be larger and would settle out of the stratosphere faster, thus self-limiting the duration and magnitude of the effects (Pinto *et al.* 1989). Other work has suggested that the chemical reactions forming the aerosols from huge SO_2 clouds would initially dehydrate the stratosphere, thus prolonging the time over which aerosols form (Bekki 1995). By 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 development. 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 what the particle concentration of an aerosol cloud, or its longevity at various concentrations, would be after a very large eruption. Referring to table 2, the amounts of SO_2 that might be released are considerably larger than for any historic eruption and could lead to aerosol clouds of unprecedented opacity to incoming radiation. This was the premise of earlier assessments proposing so-called 'volcanic winter' (Rampino *et al.* 1988) after very large eruptions. Cooler conditions usually imply poorer weather and possibility lower agricultural productivity (Engvild 2003).

Recently, some of the first attempts have been made to assess the effects of a large stratospheric burden of sulphate aerosols. Timmreck & Graf (2005) have used an atmospheric model with an SO_2 gas input 100 times that of the Pinatubo eruption (1700 Tg) from a source at 45° North, similar to that of Yellowstone volcano, which last produced a super-eruption 630 000 years ago (Lowenstern 2006). They found that the season of injection is important, with almost global spread of aerosols from an eruption in the mid-latitude Northern Hemisphere in summer, but with the aerosol cloud more 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) and which have starting conditions with a large aerosol loading. 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 year) recovery period.

There are many other aspects of the effects of volcanic aerosols and ash fallout to be taken into consideration, some of which we are only just discovering. These include more efficient photosynthesis and effective tree growth due to the abnormally diffuse light in the 3–4 years after an eruption (Gu *et al.* 2003), and the possible effects of ash on the sea surface causing biological changes that affect the CO_2 cycle. Also, for eruptions occurring in shallow submarine environments or lakes, there may be more water introduced into the stratosphere than with a 'dry' volcanic eruption column. This may promote extra high-altitude cloudiness, which will also have an impact on the radiation budget, and may influence the mass of aerosols generated.

Another important effect of volcanic sulphate aerosols is on high-altitude ozone concentrations. It has been suggested that due to the presence of chlorofluorocarbons (CFCs) in the stratosphere since 1950 (Solomon 1999), interactions between free chlorine molecules (and possibly other halogens such as fluorine) from the CFCs and ozone molecules on the surface of the volcanic sulphate aerosol particles had detrimental effects on ozone levels in the upper atmosphere. Mid-latitude ozone depletion almost doubled for the two years after Mt Pinatubo erupted in 1991 (Prather 1992) and extensive ozone 'holes' persisted in the polar atmosphere for 3–4 years. Less ozone, of course, means that more ultraviolet radiation (particularly UV-B) reaches the Earth's surface with a possible deleterious impact on the health of living organisms. The potential direct effect of volcanic chlorine has only been touched upon in a couple of model studies (Tabazadeh & Turco 1993; Textor *et al.* 2003) and little is known about how much chlorine or HCl gas remains in the stratosphere after a large eruption. Furthermore, it may be that in 'wet' eruptions, with the inclusion of vapourized sea water, the gases injected into the upper atmosphere may be richer in ozone-depleting elements such as chlorine, although to date no work has been done on such aspects. Much is yet to be learned about the effects of volcanic gases and aerosols on ozone. Even a small eruption from Hekla (Iceland) in the year 2000 led to a substantial local ozone depletion (Hunton *et al.* 2005).

7. Societal relevance of very large eruptions

Major historic eruptions have caused mass starvation in vulnerable regions. The vulnerability of agriculture to volcanic phenomena may not now be as great as it was before the twentieth century, but most of the world's population live in the Northern Hemisphere where most food production is concentrated. Thus the Northern Hemisphere could be particularly threatened by the effects from major eruptions. Today's globalized society is heavily dependent on communications and other technologies that are highly susceptible to disruption, and many areas are now densely populated. The effects of a large explosive eruption (table 3) are almost entirely detrimental to humankind in the short term. 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. Ash will block roads, railways and airport runways, causing widespread problems. Ash will also be a visibility and respiratory health hazard, and airborne fine volcanic particulates can contain toxic silica (Horwell *et al.* 2003). There are also bound to be effects that we cannot yet predict, and assessing the risks posed by future large-scale volcanic eruptions requires details of the consequences and frequency (Clement 1989) that are not presently available.

The consequences of future large-scale eruptions are in detail very difficult to predict because of the variability of the volcanic phenomena and the complex interlinking of important societal necessities. Telecommunications and air-transport are likely very vulnerable, and, realistically, effective disaster response will be very difficult for the largest scale eruptions. The cost of all natural disasters is rising steeply (Smolka 2006) and effects on world financial markets will be a very significant factor.

Besides the direct effect of pyroclastic flows, ash clouds, and their deposits, discussed above, the most far-reaching effects of a future large explosive eruption will be related to the atmospheric opacity and longevity of the sulphate aerosol cloud and its influence on incoming solar radiation (i.e. its impact on climate and weather). In this regard, it will not necessarily take a super-eruption to cause a Northern Hemispheric environmental disaster. A repeat of even a modest, Tambora-sized eruption (M6, or up to 45 km^3 of magma) in the appropriate location can be expected to cause a severe, widespread effect from ash and aerosols. Two examples are worth consideration. The tropical eruption of Tambora itself in 1815 caused global atmospheric effects, so far only known for the cooler global temperature in 1816 (approaching −1 °C; Robock 2005) and reports of awful weather, crop failures, and mass starvation in 1815–1816. It is not possible to put a figure on the number of casualties worldwide but probably more than 50 000 people perished in the Indonesian region alone (Tanguy *et al.* 1998). The other case is, surprisingly, a smaller magnitude, largely lava-producing eruption. When the Laki fissure out-breaks occurred in Iceland in 1783–1784 it caused a major air-pollution and crop-failure disaster in Europe, being directly downwind from the source (Thordarson & Self 2003). Despite the fact that only a proportion of the gases, and thus aerosols, were in the stratosphere, the persistent activity for many months and the high SO_2 yield of the eruption caused a considerable tropospheric sulphate aerosol burden. This appears to have caused high mortality in some areas (Grattan *et al.* 2003; Witham & Oppenheimer 2004) and food shortages, and these contributed to political unrest in Europe. In the event of a repeat of a similar eruption from Iceland, there would be considerable disruption to Northern Hemisphere communications and air transport for several months due to ash and aerosol clouds.

8. What needs to be done? Improving our current understanding

In order to detect when a large magma body may be coming to life, we can use geophysical techniques to image the chamber under a volcano and to investigate changes that go on inside and around it. For example, there may be density changes as the proportion of crystals changes through time or crystals settle down towards the bottom. Intrusions of fresh magma into an existing chamber can also be detected by geophysical means either directly or by measuring the effects in the overlying water table. Such work provides a proxy estimate of the state of a magma chamber because changes will occur before an eruption (Lowenstern 2006). Much current research seeks to interpret the geophysical signatures of ongoing persistent activity at caldera volcanoes; are these signs of 'normal' caldera unrest due to movements of subsurface hot water and small magma intrusions (e.g. at Campi Flegrei caldera; Orsi *et al.* 1999), or the precursors to an eruption? If the latter, will that eruption be large or small, and explosive or not? Better resolution seismic images might help to determine the amount of eruptible magma in a chamber, and whether there is the possibility of a large eruption.

If a known and monitored volcano is building towards a future large eruption there might be adequate signs over a sufficient time period (years–decades) to provide a reasonable warning (Newhall & Dzurisin 1988), but at present we cannot be sure. Of concern is a situation where a volcano that is presently unrecognized as a potential large-eruption site, or that is evolving towards its first super-eruption, or that is not monitored, becomes unrestful. 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 super-eruptions: which volcanoes have produced them, what the ages are, what their true size was and what types of deposits were produced. With this basic information, better long-term, global predictions can be made of when the next event might occur (IAVCEI 2004). Moreover, from the same information, hazard maps can be prepared from which mitigation plans can be started. In some cases these maps will have to cross international boundaries, which will take considerable effort and organization.

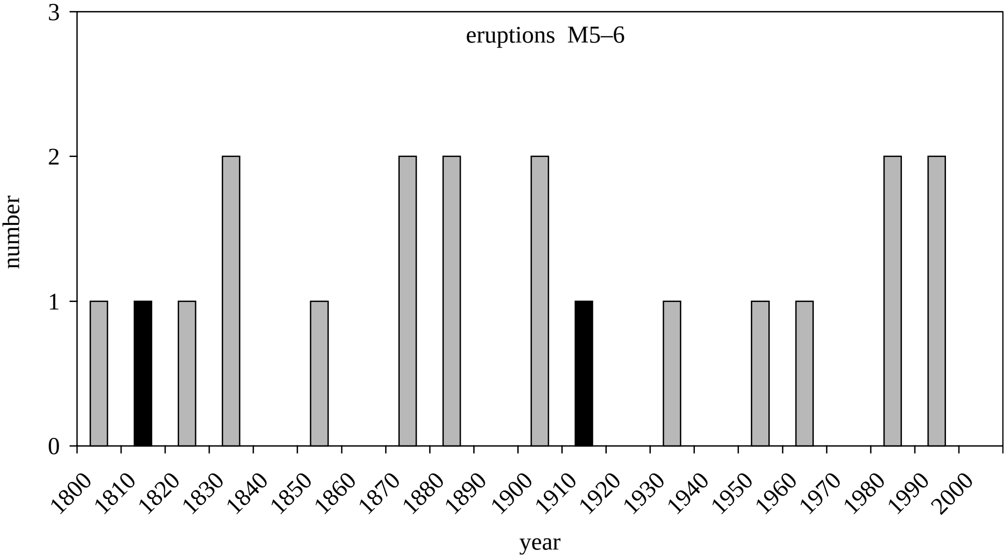

Figure 7. Plot of number of eruptions of magnitude (M) 5 (light bars) and 6 (dark bars), representing magma volumes in the range more than 1 to approximately 30 km^3, per decade since AD 1800. Note spasmodic distribution and how few eruptions occurred between 1910 and 1980; except Krakatau 1883, Mount St Helens (1980) and Pinatubo (1991) all eruptions took place far from populated areas. Eruption in 1809 is possible M5 known from its ice-core acidity record only (see Self 2005 and references therein). M6 eruptions are Tambora (Indonesia) 1815 and Katmai-Novarupta (Alaska) 1912.

The reason that the above effort is needed is that very large eruptions are rare enough that they are not on the 'radar screen' of our society. Even much smaller, yet locally devastating, eruptions have been few and far between in recent centuries. Figure 7 shows that that the biggest eruptions since 1800, producing approximately 0.5–5 km^3 of magma (M5–6), have occurred spasmodically. During the large time gaps between them, generations of people have been unaware of any severe volcanic threat. Before the 1850s and the widespread advent of telegraphic communications, news of distant disasters reached the 'civilized world' many months after they occurred. The news had little impact on society, even in well-educated circles. Eruptions of large size could recur quite soon and with little warning. Apart from Tambora and Krakatau, the few volcanic disasters with many tens of thousands of deaths in the past 200 years have come from small-volume eruptions (M4–5) where an at-risk population has been in the wrong place at the wrong time rather than from the larger explosive events. Other M5–6 eruptions have mainly been from volcanoes in isolated, low-population locations (Simkin & Siebert 2001) .

9. Summary

There is a very small, but real, threat from very large volcanic explosive eruptions up to, and including, magnitude (M) 8 in size (yielding in excess of 450 km^3 of magma or 1000 km^3 of pyroclastic deposits). Many aspects of very large-scale volcanic activity are not well understood as there have been no historical precedents, and such eruptions must be re-constructed from their deposits. The deposits are not straightforward to understand, and some important parameters such as the duration of an eruption are difficult to ascertain. The global average repeat period for such eruptions is long (currently estimated at one every approx. 100 000 years or more) but averages hide the fact that the interval between very large eruptions in the geological record has sometimes been quite short (a few thousand years or less).

There are almost certainly several unrecognized Tambora-size or larger eruptions (more than 30 km^3) within the past few millennia. This affects the statistics of the frequency and future probability of eruptions smaller than super-eruptions (in the M7 class), which still pose a considerable hazard to society. Future estimates of their frequency will almost certainly be revised, revealing them to be more common than we currently appreciate. Moreover, the frequency of eruptions that can have severe widespread effects is much greater than that of a potential meteorite impact that would have the same effects.

Eruptions are unstoppable, and a very large one is potentially long lasting (several days of intense explosive output from the volcano). Further, the effects are both immediate (widespread ash fall, pyroclastic flows) and also of longer-duration (due atmospheric aerosols, re-sedimentation of fresh deposits by lahar activity), persisting and presenting problems for years afterwards. In these ways, the hazards posed by explosive eruptions differ from those due to all other natural disasters. It will necessary to develop strategies to minimize 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. Finally, as airborne ash and atmospheric sulphate aerosols will bring about the most widespread, long-lasting and generally hazardous effects of the next large explosive eruption, it will be essential to carry out further studies with global circulation atmospheric models to evaluate their potential effects on climate and weather, and other potential feedbacks with global environmental cycles. Some currently unanticipated consequences will surely be found.

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