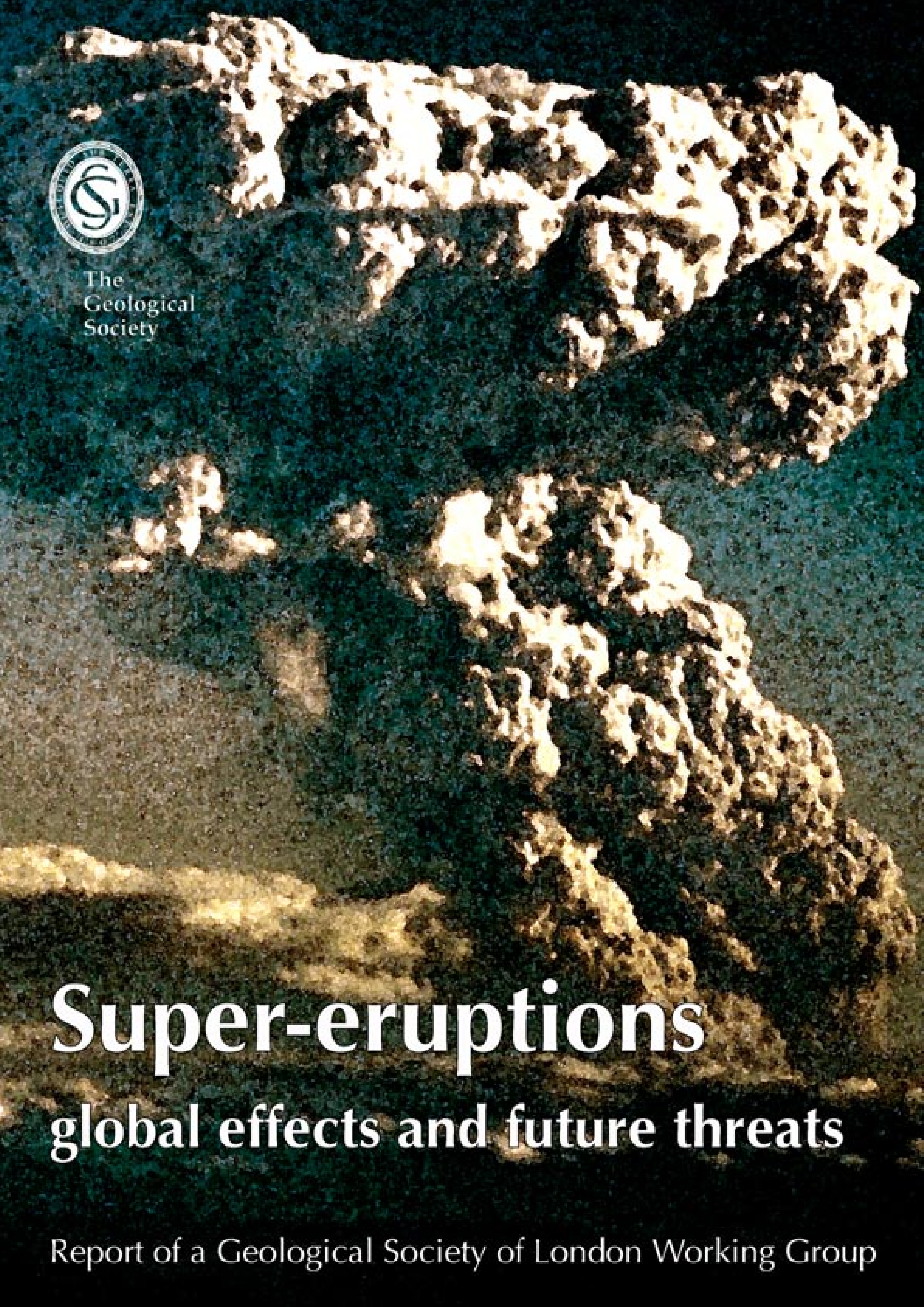


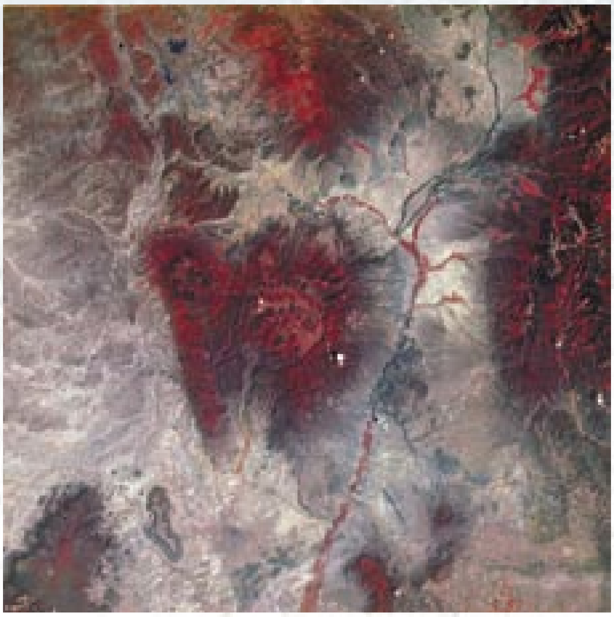
The Geological Society

Super-eruptions

global effects and future threats

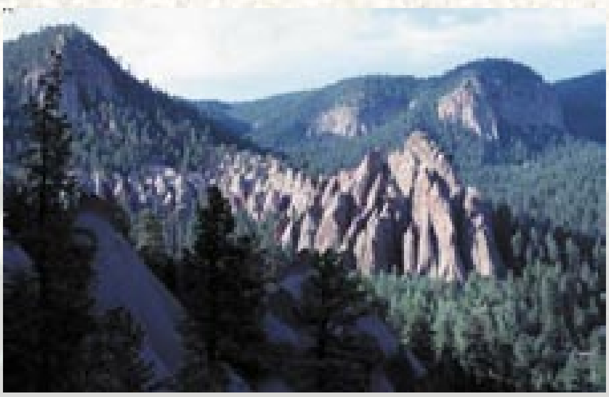
Report of a Geological Society of London Working Group

The Jemez Mountains (Valles Caldera) super-volcano, New Mexico, USA.



Many super-eruptions have come from volcanoes that are either hard to locate or not very widely known. An example is the Valles Caldera in the Jemez Mountains, near to Santa Fe and Los Alamos, New Mexico, USA. The caldera is the circular feature (centre) in this false-colour (red=vegetation) Landsat image, which shows an area about 80 kilometres across of the region in North-Central New Mexico. The collapsed caldera is 24 kilometres in diameter and is the result of two explosive super-eruptions 1.6 and 1.1 million years ago (i.e., 500,000 years apart).

All rocks in the photo below are part of the 250 metre thick deposits of the older of the two super-eruptions at the Valles Caldera.



“Many large volcanoes on Earth are capable of explosive eruptions much bigger than any experienced by humanity over historic time. Such volcanoes are termed **super-volcanoes** and their colossal eruptions **super-eruptions**. Super-eruptions are different from other hazards such as earthquakes, tsunamis, storms or floods in that – like the impact of a large asteroid or comet – their environmental effects threaten global civilisation.”

“Events at the smaller-scale end of the super-eruption size spectrum are quite common when compared with the frequency of other naturally occurring devastating phenomena such as asteroid impacts. The effects of a medium-scale super-eruption would be similar to those predicted for the impact of an asteroid one kilometre across, but super-eruptions of this size are still five to ten times more likely to occur within the next few thousand years than an impact.”

“Although at present there is no technical fix for averting super-eruptions, improved monitoring, awareness-raising and research-based planning would reduce the suffering of many millions of people.”

Executive summary

Some very large volcanoes are capable of colossal eruptions with global consequences. Such eruptions are quite frequent on a "geological" time scale, but one has not occurred in the short time that our interdependent human civilisation has existed. Our present civilisation depends on global trade and food production, with much reliance on air travel and space-borne communications, all of which could be at considerable risk if a super-eruption occurred.

In the past, several super-eruptions sufficiently large to cause a global disaster have occurred, on average, every 100,000 years. This means super-eruptions are a significant global humanitarian hazard. They occur more frequently than impacts of asteroids and comets of comparable potential for damage.

Several of the largest volcanic eruptions of the last few hundred years (Tambora, 1815; Krakatau*, 1883; Pinatubo, 1991) have caused major climatic anomalies in the two to three years after the eruption by creating a cloud of sulphuric acid droplets in the upper atmosphere. These droplets absorb and reflect sunlight, and absorb heat from the Earth, warming the upper atmosphere and cooling the lower atmosphere. The global climate system is disturbed, resulting in pronounced, anomalous warming and cooling of different parts of the Earth at different times.

Super-eruptions, however, are hundreds of times larger than these recent events and their global effects are likely to be much more severe. An area the size of North America or Europe could be devastated, and pronounced deterioration of global climate would be expected for a few years following the eruption. Such events could result in the ruin of world agriculture, severe disruption of food supplies, and mass starvation. The effects could be sufficiently severe to threaten the fabric of civilisation.

Problems such as global warming, impacts by asteroids and comets, rapid use of natural resources, and nuclear waste disposal require world leaders and governments to address issues with very long-term consequences for the global community. Sooner or later a super-eruption will happen on Earth and this is an issue that also demands serious attention. While it may in the future be possible to deflect asteroids or somehow avoid their impact, we know of no strategies for reducing the power of major volcanic eruptions. Even science fiction cannot produce a credible mechanism for averting a super-eruption. We can, however, work to better understand the mechanisms involved in super-eruptions, with the goal of being able to predict them ahead of time and provide a warning for society. Preparedness is the key to mitigation of the disasterous effects of a super-eruption.

** Krakatau is the correct Javanese spelling of the name of the island more commonly known in English as Krakatoa.*

The Working Group recommends:

Investment in research to improve our understanding of regional and global impacts of major volcanic eruptions.

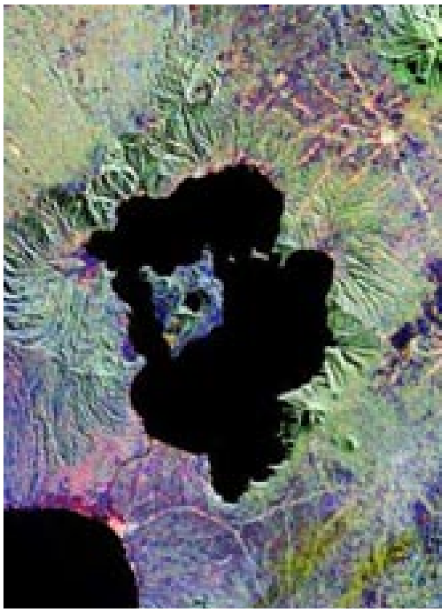
Research to determine more accurately the composition and amounts of volcanic gases and dust released in super-eruptions;these are the major factors governing widespread environmental effects.

An expanded programme to produce a comprehensive inventory of large magnitude explosive eruptions in recent geological times, such as the initiative started under the auspices of the International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI).

Initiatives to improve public understanding of the nature of volcanic hazards.

Establishment of a multidisciplinary Task Force to consider the environmental, economic, social, and political consequences of large magnitude volcanic eruptions.

For more detailed recommendations, see page 21.


Taal, Philippines


Cerro Galan, Argentina

The four images shown here are sites of volcanoes that have produced super-eruptions.


Atitlán, Guatemala


Toba, Sumatra

Introduction

There are certain natural events that, as a consequence of their enormous size and catastrophic energy release, can have major adverse global effects. They may seriously threaten the stability of the world economy and order, and could well threaten the lives of billions of people.

Impacts of asteroids and comets ("Near Earth Objects" or NEOs), and eruptions from super-volcanoes, are the two prime examples of such potentially disastrous natural events. NEOs have received much recent publicity through Hollywood movies and these have helped prompt an investigation instigated by the UK Minister of Science, resulting in a report on potentially hazardous NEOs that was finally presented to the UK Government in September 2000. By contrast, volcanic hazards on a global scale have not (until recently) received much attention outside specialist scientific circles.

Such catastrophic eruptions are rare, and so their probability of occurrence in terms of a human life span is small. When viewed over longer periods of time, however, such eruptions are surprisingly common, and on the time scales of civilisations (hundreds to thousands of years) become quite likely. It is inevitable that huge eruptions with potentially catastrophic consequences for humanity will happen again on Earth.

In this report we consider the nature and size-range of super-eruptions, estimate how often they occur, identify parts of the world where dormant super-volcanoes are located, and assess the environmental impact of these eruptions, with particular emphasis on climate. Not all large volcanoes are capable of producing super-eruptions. The largest volcanic edifices, such as Mauna Loa and Mauna Kea on the island of Hawaii, the highest and widest volcanoes on Earth (some 200 kilometres across and over 12 kilometres tall), will never produce a super-eruption because they cannot store up the amount of magma and pressure needed for a massive explosive eruption. Our knowledge is currently limited, because the source vents of super-eruptions are often hard to locate and many volcanoes that have the potential for producing future super-eruptions still go unrecognised.

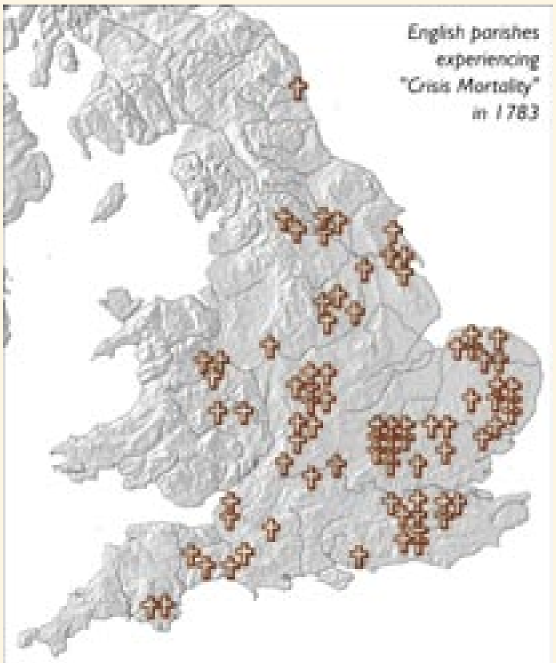
Humans and their civilisation are very vulnerable indeed to unexpected natural events with global impact. The dramatic success of the human species has placed enormous stress on the Earth's ecology, with consequences familiar to all – like global warming and falling biodiversity. Key factors seem to be population explosion (mostly over the last two centuries) and unprecedented advances in science and technology that have allowed humans to utilise Earth resources on a huge scale.

In the last 200 years the use of hydrocarbons has released enormous quantities of carbon dioxide into the atmosphere, changing its composition as fast as at any known time in Earth history. Some artificial chemicals have harmful effects on the ozone layer, which protects life from damaging ultraviolet light from the Sun. The economic, political and social institutions of humanity have also advanced dramatically, even though the proportion of the world's population who benefit greatly from these advances remains relatively small. As stock market crashes show, even the economic institutions that help deliver great wealth and well-being to many people, can be vulnerable. Such institutions are sustained as much by perceptions of progress and advance as by the underlying natural and human resources that underpin wealth creation.

The United Kingdom is located away from the Earth's major destructive plate boundaries, and consequently does not suffer directly from the effects of large-scale explosive volcanism. However, two of the UK's Overseas Territories (Montserrat and Tristan da Cunha) are active volcanoes. Moreover, the UK lies downwind from volcanoes that have caused major eruptions in Iceland, so the UK should have a direct interest in the primary effects of volcanic activity. As a member of the European Community, the UK would be vulnerable economically to the effects of super-eruptions in Italy or Greece.

The continuing eruption of the Soufrière Hills volcano on Montserrat encouraged a partnership between the geoscience community and government to address the problems caused. However, the UK is an integral part of the global community, with influence beyond its size due to its recent history and position as one of the world's wealthiest countries. As we will demonstrate, a huge eruption elsewhere in Europe, or in New Zealand, Indonesia, or Alaska could have serious consequences for the UK. Another large-volume lava eruption in Iceland, with its accompanying major atmospheric pollution would create major environmental problems for the whole of the Northern Hemisphere, as well as serious disruption to commercial air traffic across the Atlantic for several years.

The Lakagigar (Laki) AD 1783–4 eruption: the threat from Iceland



One impact of the Laki gas and aerosols over the UK during 1783 was to increase deaths, possibly due to respiratory disorders, as shown by the map above of distribution of English parishes experiencing "Crisis Mortality", much-above-average numbers of deaths per month, during the Laki fissure eruption.

"There seems to be a region higher in the air over all countries, where it is always winter, where frost exists continually, since, in the midst of summer on the surface of the earth, ice falls often from above in the form of hail... During several of the summer months of the year 1783, when the effect of the sun's rays to heat the earth in these northern regions should have been greatest, there existed a constant fog over all Europe and a great part of North America. This fog was of a permanent nature; it was dry, and the rays of the sun seemed to have little effect towards dissipating it, as they easily do a moist fog, arising from water... The cause of this universal fog is not yet ascertained… or whether it was the vast quantity of smoke, long continuing to issue during the summer from Hecla in Iceland, or that other volcano…"

The Laki fissure, Iceland

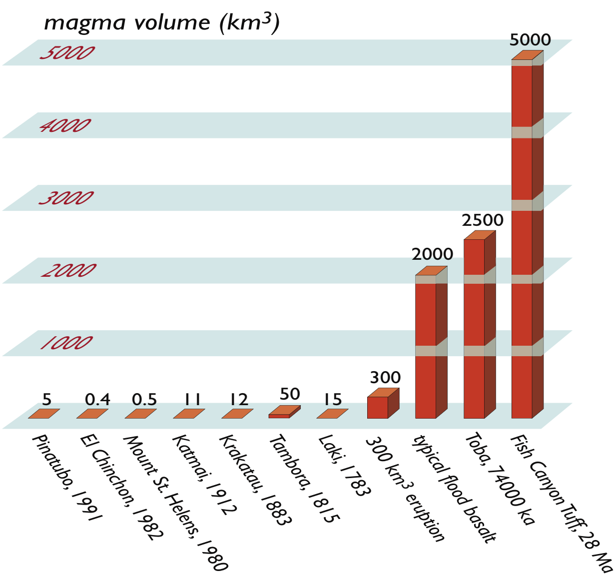
Extract from Meteorological Imaginations and Conjectures, *by Benjamin Franklin, LL.D., Fellow R. Soc., and Acad. Reg. Sci. Paris Soc. etc., communicated by Dr. Percival Read December 22, 1784, to the Manchester and Liverpool Philosophical Society. Franklin was in Paris, France, in the summer of 1783 as U S Ambassador.*

Super-volcanoes and super-eruptions

Most volcanoes that produce super-eruptions are very long-lived (active over millions of years), produce very large explosive eruptions, and remain dormant for long periods (from thousands to hundreds of thousands of years) between major eruptions. In general, the longer the dormancy ("repose period") the larger the eventual eruption.

Volcanologists use two measures of eruption size: the **magnitude** of the eruption (the volume or mass of magma erupted) and the **intensity** (the rate of magma eruption). (Magma is the hot, molten, often gas-laden rock material stored under volcanoes.) In principle, these two parameters are independent, but there is good evidence that they are linked. Thus, super-eruptions are not only huge (high magnitude), but also very violent (high intensity).

To give some comparison, Mount St. Helens in 1980 erupted less than one cubic kilometre of magma. Vesuvius (AD 79) erupted about five cubic kilometres, and Krakatau (1883) about 12 cubic kilometres. The biggest eruption of the past several hundred years, that of Tambora volcano (Indonesia, 1815), released about 50 cubic kilometres of magma. But even Tambora was small in comparison with a super-eruption, which may involve the release of thousands of cubic kilometres of magma. The biggest super-eruption recognised so far produced approximately 5000 cubic kilometres of deposits, creating the so-called "Fish Canyon Tuff event" in Colorado, USA, about 28 million years ago.



There is no strict definition of a super-volcano, because in reality there is a continuum of volcanoes and volcanic eruptions from the very small and weak to the very large and violent. However, the definition of a super-eruption, a term introduced to describe the Toba eruption, has value in that it encapsulates the fact that there have been explosive volcanic eruptions very much larger than eruptions that have so far affected humanity in the short course of recorded history.

Tambora volcano, forming the Sanggar Peninsula, Indonesia, viewed from the NASA Space Shuttle, showing the 7 kilometre-wide caldera depression formed in 1815.

The super-eruption of Toba volcano, Sumatra, some 74,000 years ago, ejected about 300 times more volcanic ash than the eruption of Tambora in Indonesia in 1815. Tambora's eruption had significant impact on global climate, producing the "Year Without a Summer" (1816) when Lord Byron wrote his poem *Darkness* and Mary Shelley wrote *Frankenstein*. Unusually cool summers prevailed in the Northern Hemisphere for the following two years.

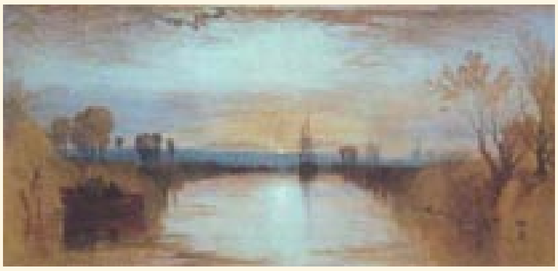
It is easy to imagine that an eruption on the scale of Toba would have devastating global effects. A layer of ash estimated at 15 centimetres thick fell over the entire Indian sub-continent, with similar amounts over much of SE Asia. Most recently, Toba ash has been found in the South China Sea, implying that several centimetres also covered southern China. Just one centimetre of ash is enough to devastate agricultural activity, at least when it falls in the growing season. An eruption of this size would have catastrophic consequences. Many millions of lives throughout most of Asia would be threatened if Toba erupted today. The UK might not receive any ash fall directly, but it would be affected by the impact on global economic and political stability, as well as by worldwide climatic effects.

For the purposes of this report, we consider that an eruption of over 300 cubic kilometres

The great Tambora eruption of 1815 and its aftermath

The bright sun was extinguish'd and the stars
Did wander darkling in the eternal space,
Rayless, and pathless, and the icy earth
Swung blind and blackening in the moonless air;
Morn came and went – and came, and brought no day…

An extract from Darkness *by Lord Byron, written in June 1816 on the shores of Lake Geneva in the midst of the 'Year Without a Summer', 14 months after the great eruption of Tambora in Indonesia.*



A J.M.W. Turner landscape (of the Chichester Canal) shows skies of typical turbidity for the post-Tambora period, including, possibly, a secondary glow at sunset caused by stratospheric aerosols.

Vesuvius erupting in 1944: a typical small-scale explosive event from this volcano, which colours our perception of its eruptive behaviour. The small-magnitude AD 79 eruption of Vesuvius was violent, and destructive because of the Roman towns scattered at its foot. It is highly unlikely that Vesuvius will ever produce a super-eruption, but across the Bay of Naples lies Europe's only proven super-volcano, which has erupted in the past 100,000 years (there may be another in the Aegean Sea). The map, below, based on a satellite image of the Neapolitan–Campanian area, shows the area of the Phlegrean Fields (inside yellow box), a caldera volcano that produced a super-eruption about 35,000 years ago. This eruption covered large areas of southern Europe with an ash deposit, mostly derived from pyroclastic flows, that spread out over southern Italy and crossed part of the Appenine Mountains. Now many millions of people live in the same area.

Vesuvius, the AD 79 eruption and the local super-volcano

"It was not clear at that distance from which mountain the cloud was rising (it was afterwards known to be Vesuvius); its general appearance can best be expressed as being like an umbrella pine, for it rose to a great height on a sort of trunk and then split off into branches, I imagine because it was thrust upwards by the first blast and then left unsupported as the pressure subsided, or else it was borne down by its own weight so that it spread out and gradually dispersed. In places it looked white, elsewhere blotched and dirty, according to the amount of soil and ashes it carried with it."

Part of Pliny the Younger's description of the eruption column from Vesuvius in AD 79 and its collapse

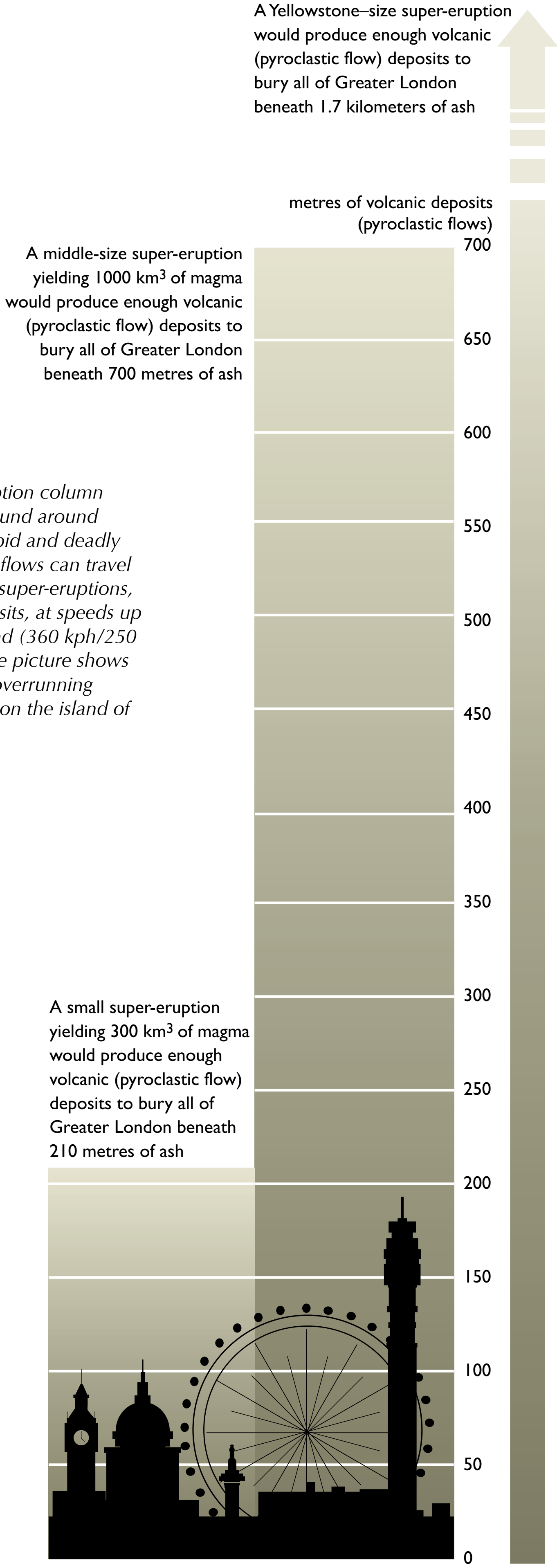
of magma (equivalent to about 750 cubic kilometres of volcanic ash) would produce effects that would have global consequences, and can be taken as representing the smallest scale end of the super-eruption spectrum. This is ten times larger than the Tambora eruption, but, interestingly, we do not have a firm idea of how many such eruptions have taken place in the past. We probably have to go back at least 6000 years, and perhaps 10,000 years, before we can recognise eruptions approaching this size range (which occurred in Japan, Oregon (USA), and Kamchatka (Russia)). In the last 40,000 years, super-eruptions with magma volumes in the 300 cubic kilometre range occurred in Italy, New Zealand, and Japan.

Intensity (effectively, the "violence") of an eruption is measured in cubic metres, or mass, of magma erupted per second. In AD 79, Vesuvius erupted a staggering one hundred thousand cubic metres of magma per second over a 24-hour period. Yet this pales into insignificance alongside super-eruptions, where intensities of tens to even one hundred million cubic metres per second have been deduced from geological evidence and models. The entire volume of magma erupted at the Soufrière Hills volcano, Montserrat, in five years (about one third of a cubic kilometre) can be discharged in a few minutes during a super-eruption.

Denser parts of the eruption column collapse back to the ground around the volcano, forming rapid and deadly pyroclastic flows. Such flows can travel up to 100 kilometres in super-eruptions, as revealed by the deposits, at speeds up to 100 metres per second (360 kph/250 mph) or even faster. The picture shows small pyroclastic flows overrunning farmland and dwellings on the island of Montserrat in July 1997.

To envisage the scale of the deposits left by a super-eruption, we can consider this familiar (but unlikely) example. A super-eruption in Trafalgar Square, London, yielding 300 cubic kilometres of magma would produce enough volcanic (pyroclastic flow) deposits to bury all of Greater London to a depth of about 210 metres. A larger super-eruption (1000 cubic kilometres) would bury the same area to a depth of 700 metres. These thicknesses do not include extensive ash-fall deposits, which could cover an area greater than all of Europe.

However, the severity of environmental effects is not simply determined by the amount of erupted material. The mass of erupted gas, which is related to the mass of magma, is crucial. It is now known that the most important factor in determining the impact of eruptions on global climate is the amount of sulphur and halogen gases (chlorine and fluorine) erupted. Not all volcanoes erupt magmas with large amounts of sulphur or halogen gas. Therefore a critical scientific issue is the mass of these key gases released, which is unfortunately not yet well constrained.



Frequency, location and types of super-eruptions

Two types of super-eruption occur on Earth: huge outpourings of lava and great explosive eruptions. Geological processes presently operating within the Earth are capable of producing only the explosive type; but the Laki, Iceland, eruption of AD 1783–84 is considered to have been a small-scale example of the type of activity that has formed huge lava flows in the geologic past.

Fortunately, there is an inverse relation between frequency and size of eruption; the bigger they are, the less often they go off. Eruptions obey an approximate law similar to that for earthquakes – of which you can also say the larger the magnitude, the less frequent. There are only one or two eruptions the size of Pinatubo (five cubic kilometres of magma) or Krakatau (12 cubic kilometres) every century. Three to five eruptions with a volume of a few tens of cubic kilometres, such as Tambora, occur every thousand years. The great Bronze Age eruption of Santorini, Greece, is another example in this size range.

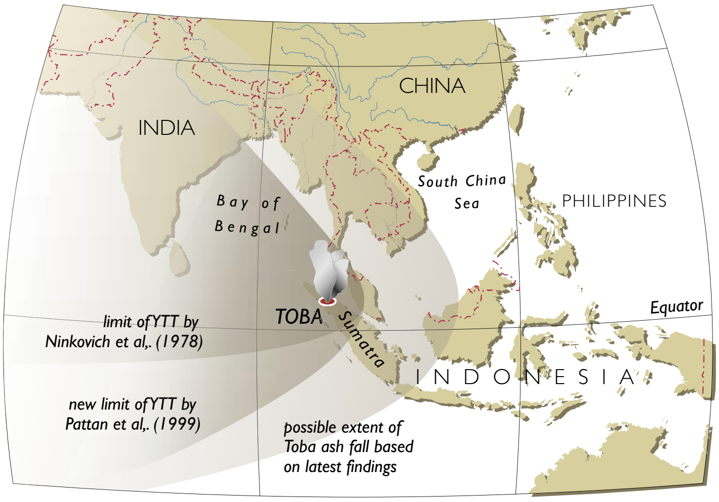
The table below gives the magnitude of eruptions, expressed as the Volcanic Explosivity Index (VEI), a logarithmic–based scale of erupted mass, as well as past examples, estimated frequency and probability. It includes large eruptions from 40 cubic kilometres in magma volume up to the largest super-eruptions known.

Eruption magnitude or VEI (Volcanic Explosivity Index)	Minimum erupted mass (kg)	Minimum volume of magma erupted (km^3)	Minimum volume of ash (km^3)	Example of typical eruption	Frequency (average number of eruptions per 100 years)	Minimum probability of one or more eruptions of this size during 21st century
7 (low)	1×10^{14}	40	100	An event a little larger than Tambora, 1815	0.1 – 0.5	10 – 50%
7 (moderate)	2.5×10^{14}	100	250	Possibly Kikai, Japan, 6000 years ago	0.01 – 0.06	1 – 6%
7 (high)	8×10^{14}	300	750	Campanian, Italy, 35,000 years ago	0.001 – 0.01	0.1 – 1%
8 (low)	1×10^{15}	400	1000	Taupo caldera, New Zealand, 26,000 years ago	<0.001	0.1%
8 (high)	8×10^{15}	3200	>5000	A Toba-size event	0.0001	Approximately 0%

The frequency of a volcanic eruption of any size falls by about a factor of 7 for every ten-fold increase in eruption size. For this reason, volcanologists describe the sizes of volcanic eruptions using a logarithmic scale (in just the same way that earthquakes are described by the logarithmic Richter scale of magnitude). The largest eruptions shown are very rare indeed.

Note: Volumes of ash ejected during a volcanic eruption are typically two to three times greater than the equivalent volume of magma. This is a source of frequent confusion: for example, the Krakatau eruption in 1883 produced a total of about 30 cubic kilometres of ash, or12 cubic kilometres of magma.

By defining the low end of the super-eruption size spectrum as "those exceeding 300 cubic kilometres of magma erupted" we bring attention to events common enough to have reasonable odds of recurring within a human lifetime, but which are rare enough not to have been witnessed by our civilisation. We expect that such an eruption would produce significant, widespread and devastating effects affecting the whole globe if it came from a volcano located within a zone between 30°N and 30°S – where many volcanoes lie.



As well as the huge volume of pyroclastic flow deposits, Toba's eruption formed a very widespread ash fall deposit over the equatorial oceans and southern Asia – its known distribution shown by the extent of the shaded areas on the map above. New scientific reports are published nearly every year about finding Toba's ash fallout further afield, thus our appreciation of the size of the deposit grows.

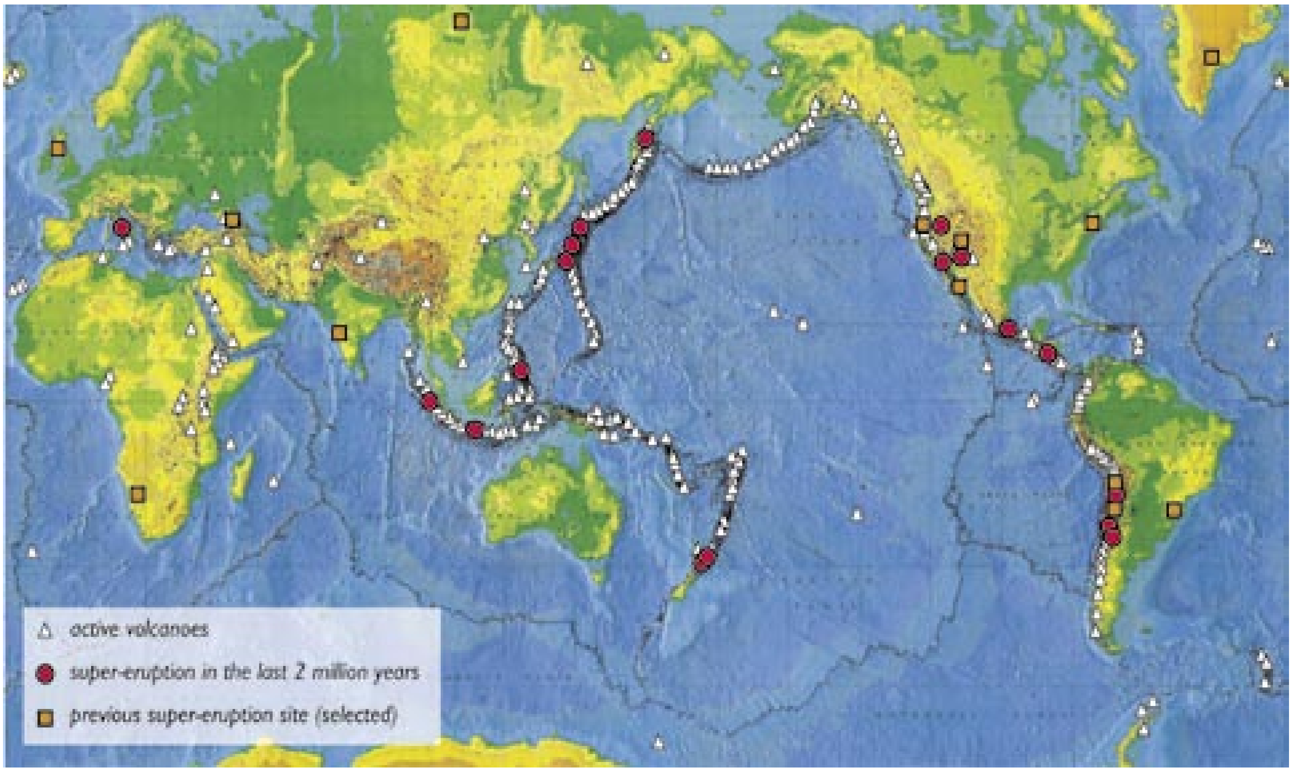
A false-colour Landsat satellite image of the 45 x 75 kilometre caldera formed by the Toba eruption 74,000 years ago.

The number of past eruptions exceeding this size is poorly known, for various reasons. Our current understanding is that average recurrence rates could well be as high as one such eruption every 3000 years. There is, therefore, a 1 in 10 to 1 in 6 chance that an eruption of this scale could occur during the 21st century. One eruption in the size range 200–300 cubic kilometres is estimated to occur every 10,000 years, resulting in a 1 in 100 chance of such an eruption occurring in this century. The largest eruptions, such as that which created Toba caldera (Sumatra, Indonesia) or the largest of the Yellowstone (USA) eruptions, are very rare indeed – perhaps one every 500,000 years.

The Toba pyroclastic flow deposit probably accumulated quite quickly; for example, by comparison, up to 200 metres of pyroclastic flow deposit accumulated in only 3.5 hours during the 15 June 1991 Mount Pinatubo eruption in the Philippines. A fresh exposure of these new deposits is shown below.

Where are the source vents of super-eruptions?

The sites of super-eruptions are mostly found where the Earth's tectonic plates collide or where hot material wells up from the deep Earth's interior below a continent. Yellowstone volcano in the USA, the Phlegrean Fields volcano west of Naples, Italy, and Lake Taupo in New Zealand are three examples of active volcanoes capable of producing super-eruptions. However, there are many other areas of the Earth where such volcanoes are found or suspected, including Indonesia, the Philippines, several Central American countries, the Andes, Japan, and the Kamchatka Peninsula in eastern Russia. A key point is that super-volcanoes are often located within or near continents. World population expansion means that these vents are often close to areas with dense populations.



The world's active volcano distribution is shown by the triangles. Source volcanoes of known super-eruptions that have happened within the last 2 million years are shown as red dots. Note the concentration around the Pacific tectonic plate margin – the so-called "Ring of Fire". Yellow squares mark previous super-eruption sites, including those of some of the great, but ancient, flood lava provinces.

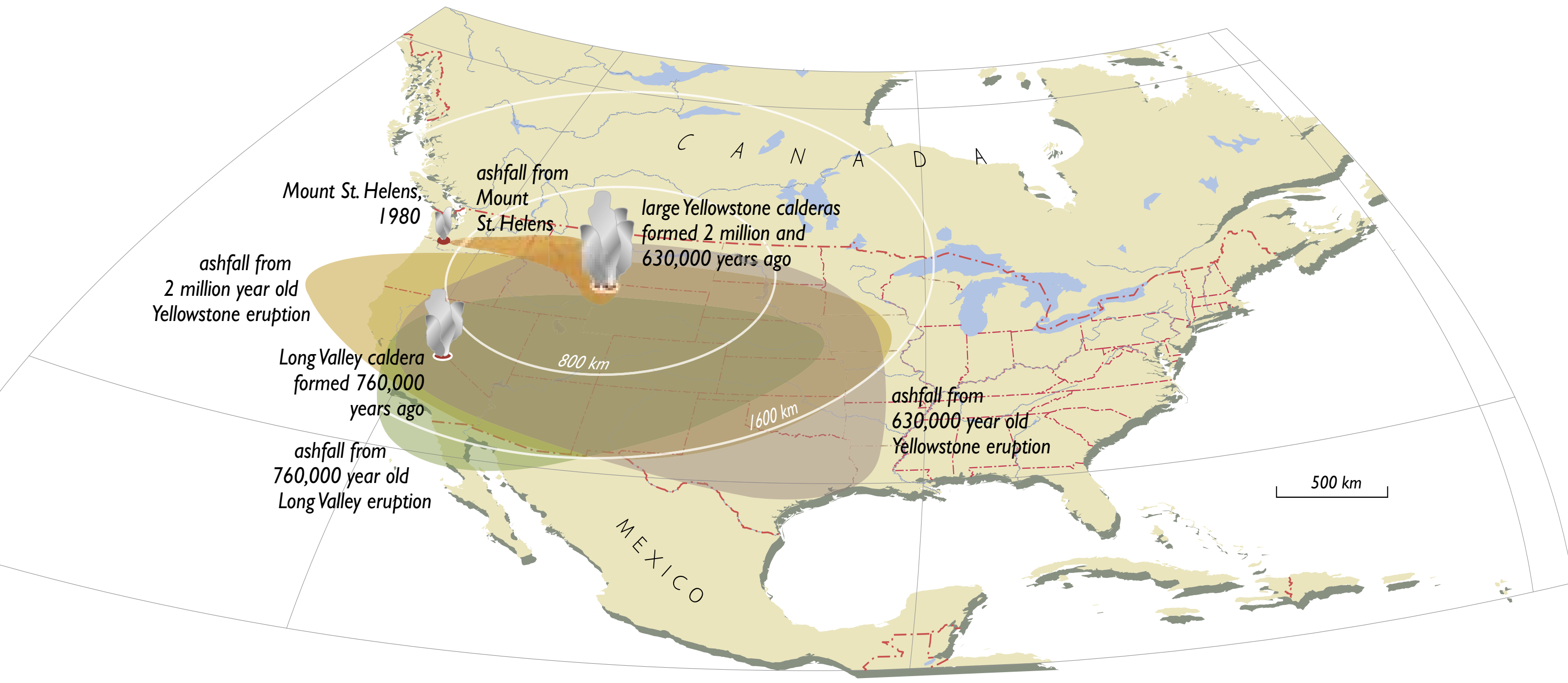
As to non-explosive eruptions involving the outpouring of copious amounts of lava, the most likely place for such an eruption today is Iceland; and so this kind of eruption is of particular interest to Europe. The last one began in 1783 when the Laki fissure disgorged about 15 cubic kilometres of lava over eight months (see p.5). Enormous quantities of sulphur dioxide were released and caused climatic anomalies in Europe and North America, including a dry acid fog over Europe, and severe crop failures. Many of the livestock in Iceland died from poisoning by halogen gases (chlorine and fluorine). As a consequence about one third of the Icelandic people died from famine. Related food shortages in France may even have been one of the factors that eventually triggered the French Revolution. Eruptions of this scale seem to take place on Iceland on average every 1000 years. The next large lava eruption on Iceland will not be of super-eruption scale by the definition given here, but it could be environmentally and economically devastating for Europe.

The effects of a super-eruption on the areas in the immediate vicinity of the volcano are completely catastrophic. Explosive super-eruptions produce huge incandescent hurricanes known as pyroclastic flows, which can cover thousands to tens of thousands of square kilometres in thick deposits of hot ash. No living beings caught by a pyroclastic flow survive. However, these dramatic local effects are not of greatest worldwide concern. Globally, most repercussions will come from the effects of the volcanic ash and volcanic gases suddenly released into the atmosphere.

Volcanic ash fallout from a super-eruption will probably have severe effects over areas the size of a large continent. One centimetre thickness of volcanic ash is easily enough to disrupt most forms of agriculture, and lesser amounts (a few millimetres) can destroy many kinds of crops. A super-eruption can cover tens of millions of square kilometres in several centimetres of ash.

The most vulnerable areas are North and South America and Asia, when account is taken of locations of such volcanoes. Europe has at least one supervolcano (the Phlegrean Fields). It is possible that the area around Kos and Nisyros in the Aegean Sea might be a super-volcano. If such an eruption were to take place at any of these sites, then a substantial part of the global economy would inevitably be devastated and many parts severely incapacitated. Any technologically advanced city would be very vulnerable to the effects of ash, including pollution of water supplies, disruption of transport systems, and failure of electronic equipment. There would also be severe disruption of aviation.

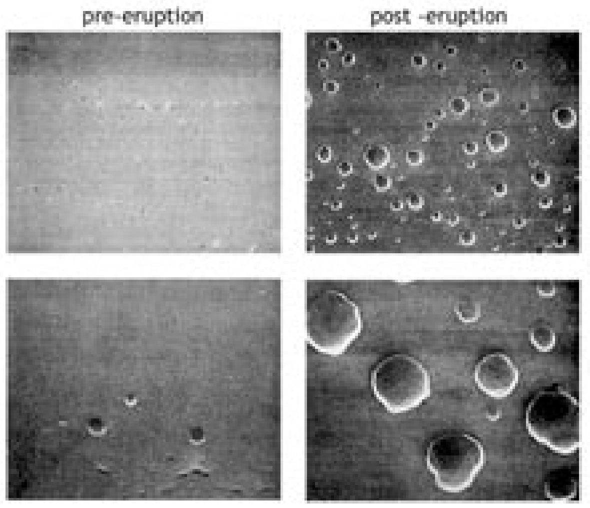
The most significant global threat from super-eruptions is, however, to global climate and weather. Large explosive volcanic eruptions eject huge amounts of volcanic dust and gas into the stratosphere. The gases are dominated



The map shows ash falls that have affected North America, from the small-volume 1980 Mount St. Helens fallout, to huge ones from Yellowstone about two million and 600,000 years ago. Also given is the area of fallout from the eruption of Long Valley super-volcano, California, but not included are the two ash deposits from the Jemez Mountains (Valles Caldera – see inside front cover) volcanic centre at 1.6 and 1.1 million years ago, because the far-flung ash deposits have not yet been recognised. The whole of the USA has been covered by ash in the geologically recent past.

by water vapour, but also commonly include significant amounts of sulphur dioxide, carbon dioxide and chlorine. A great deal has been learnt over the last few decades on the effects of volcanic dusts and gases about climate, from careful examination of climate records and observations on eruptions. The eruption of Mount Pinatubo (Philippines,1991) allowed some of these ideas to be tested in detail.

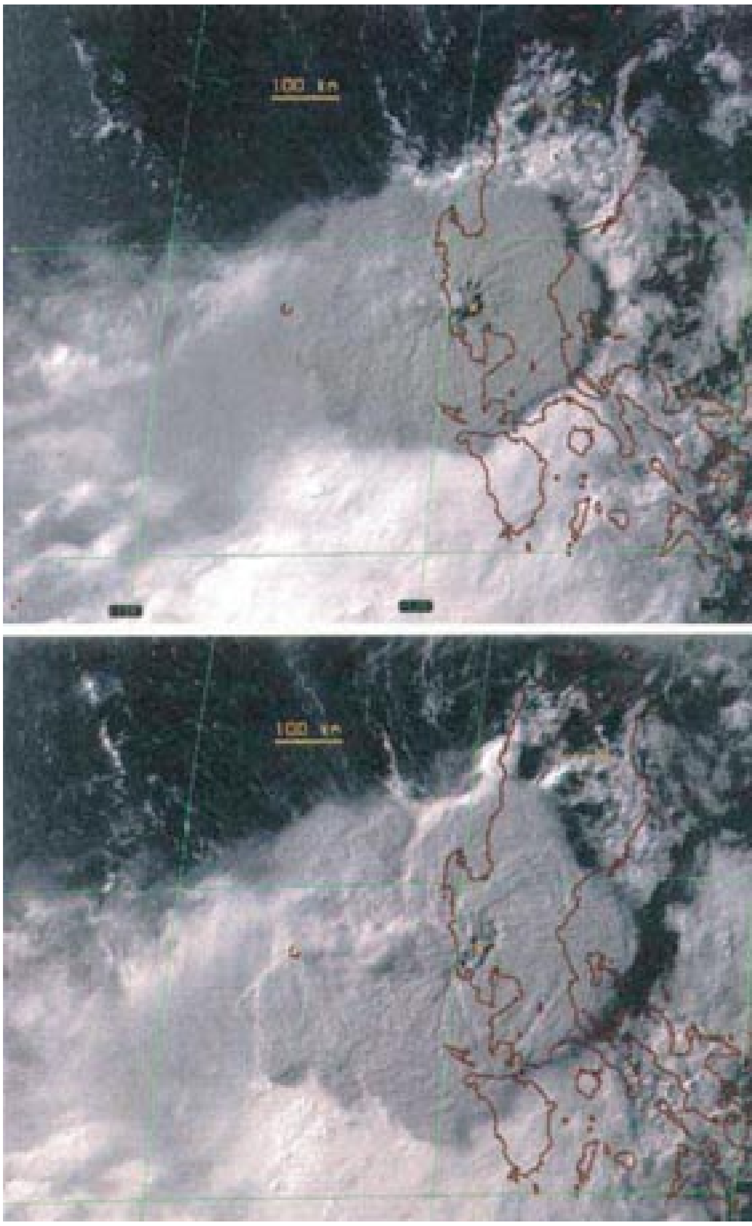
Dust and gases injected by an eruption into the stratosphere reflect solar radiation back to space and absorb heat themselves, cooling the lower atmosphere. This fact has led to the concept of 'volcanic winter'. Silicate dust (made of tiny ash particles) is thought to be less important, because its residence time in the stratosphere is quite short (only a few weeks to months at most). The main factor causing global cooling after a major eruption is sulphur dioxide gas, which reacts with water to form tiny droplets of sulphuric acid, and these remain in the stratosphere for two or three years as an aerosol.



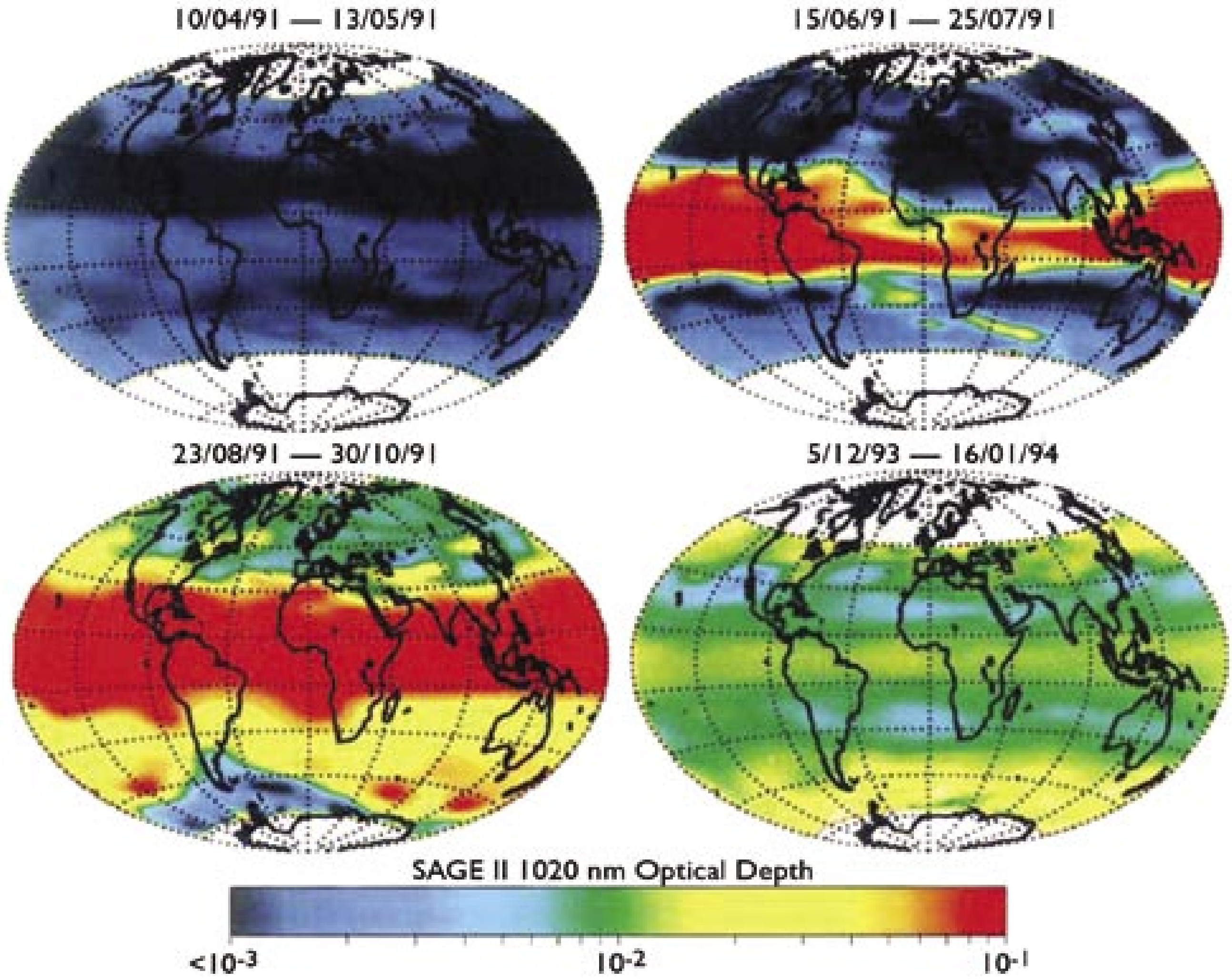
An example of volcanic sulphuric acid aerosol droplets in the 0.5-1 micrometer size-range sampled on filters carried by high-flying aircraft after the El Chichón eruption of 1982. The filters on the left are from pre-eruption flights and those on the right are from post-eruption missions.

Measurements of the Pinatubo sulphur dioxide injection by satellite-borne instruments showed that the aerosol plume encircled the globe in only three weeks, and then slowly dispersed to cover much of the Earth in the following two years. Eventually the circulation pattern of the upper atmosphere causes the aerosol particles to fall back to the surface in the polar regions. Stratospheric aerosols absorb heat so that, on average, the upper atmosphere is heated and the lower atmosphere is cooled significantly. However, the response of the atmosphere is complex, so that there are areas of both highly anomalous heating and cooling in the few years following an eruption.

There is compelling evidence from meteorological records and tree-rings that eruptions like Tambora (1815), Krakatau (1883) and Pinatubo (1991) caused substantial and measurable cooling in the Northern Hemisphere. In these cases the lower atmosphere cooled by an average of 0.5 - 1°C in the subsequent two years. This averaged cooling masks significant anomalies, such as frosts in the middle of the summer of 1816 in New England (the so-called "Year Without a Summer" that followed the Tambora eruption).



Visible wavelength view of the top of the Mount Pinatubo eruption cloud as it was spreading out in the stratosphere about 1.5 hours after the start of the climactic eruption on 15 June, 1991 (top) and two hours later (bottom). By this stage it had already reached over 700 kilometres across, and it eventually reached over 1200 km across!



Satellite data from NASA's SAGE sensor map shows the atmospheric aerosol cloud that developed around the globe following the climactic eruption on June 15. The four panels show the amount of aerosols (blue – low; red – highest concentration) in the period before the eruption (top left), 2 weeks after (top right), 2–3 months after (bottom left), and 30 months later (bottom right). Note that most of the atmosphere is covered by a thick aerosol veil after only about 3 months, and that even after more than 2 years has passed, the stratosphere is still dominated by a thinning cloud of Pinatubo's aerosols. The aerosols reduce incoming solar radiation and cause temperature changes on Earth.

With an eruption at low latitudes, like Pinatubo, these fluctuations are caused by the increased temperature difference in the stratosphere between high and low latitudes. The results of detailed atmospheric studies after Pinatubo indicate quite complex patterns of pronounced summer cooling in many parts of the Northern Hemisphere but also pronounced winter warming in continental interiors. For example there were a few degrees of summer cooling over the US and Europe, and winter warming over Northern Europe and Siberia. The change in climate, however, is a short-term phenomenon. For moderate-sized eruptions climate returns to the pre-eruption situation once the global aerosol has disappeared (after about three to four years).

It is not clear how the understanding and observations of relatively small historic eruptions, like Krakatau and Pinatubo, can be extrapolated to super-eruptions. It can safely be assumed that their effects will be more severe, but the Earth's climate system is not well enough understood for us to be very confident in detailed predictions. In principle, putting twice as much aerosol in the stratosphere should double the predicted climatic effect. But climate systems are complex, with important feedback processes. Thus the consequences of very much larger injections of volcanic gas cannot be forecast with much confidence.

It is also possible that other components (dust and non-sulphurous gases) may have a much more significant role when injected into the stratosphere in much larger amounts. As in many situations with global climate there are forcing factors that might inhibit and forcing factors that might magnify the effects of a super-volcano eruption on climate. Understanding can best be advanced by investigating the effects of large volcanic injections in global climate models. Encouragingly, such models showed good agreement with observations made of the effects of Pinatubo.

Recently, observations from ice cores have been made on the possible effects of the Toba super-eruption, 74,000 years ago. If these data do reflect the Toba event, they suggest that aerosol formation and fallout lasted for six years. The volcanic winter would not only be more severe than for a Pinatubo-scale eruption, but would last much longer. Models suggest that a Toba-sized super-eruption would inject so much sulphur gas into the atmosphere that the stratosphere chemistry would be substantially perturbed – allowing for more prolonged climate-forcing. Some models suggest super-eruptions can cause cooling of 3–5°C, which in global climate terms represents a catastrophic change.

It may not sound like much, but a mere 4°C cooling, sustained over a long period, is enough to cause a new Ice Age. However, great caution is needed in attributing causes and effects in a system as complex as global climate, and more detailed modelling research is required. Initial computer climate-model runs by scientists at the UK Meteorological Office's Hadley Centre for a Toba-sized eruption suggest Northern Hemisphere temperature drops of 10°C. This would freeze and kill the equatorial rainforests.

These important issues are still in the hypothesis stage because our detailed knowledge of the timing of events 74,000 years ago, of the complex physical and chemical processes involved, and of the applicability of current climate models to such scenarios, needs to be significantly improved.

Other effects typical of large eruptions were detected after Mount Pinatubo blew in 1991. The presence of volcanic aerosols can accelerate ozone-destroying reactions and affect changes in nitrogen in the stratosphere as well as tropospheric carbon monoxide concentrations. Ozone is destroyed by anthropogenically-released chemicals, and it appears that volcanic aerosols can act to catalyse these reactions. While the ozone layer remains vulnerable, a super-eruption could further adversely affect the deterioration of the ozone layer, which is essential for life on Earth because it shields us from severe ultraviolet radiation.

Major changes in the increases in methane and carbon dioxide concentrations in the troposphere were also observed after the Mt Pinatubo eruption. These changes are not yet fully explained but show that eruptions can affect the biosphere and the carbon cycle on a global scale.

Comparison with impacts by Near Earth Objects

The recent concern in UK Government about NEOs impacting the Earth raises the question of whether super-eruptions are a comparable threat. Prof. Michael Rampino, New York University, has estimated that a large (1000 cubic kilometres of magma) super-eruption would have global effects comparable to an object 1.5km in diameter impacting the Earth.

According to the recent report by the UK Task Force on Near Earth Objects, the best available estimates suggest that such impacts occur about once every 400,000–500,000 years. The present estimate of recurrence rates for large super-eruptions is around one per 100,000 years. Thus, the probability of the Earth having a global-scale natural disaster from a super-eruption could be as much as four to five times greater than for a large impact.

Comparisons with nuclear winter

Study of large volcanic eruptions' climatic effects was boosted during the 1980s by the issue of the potential long-term environmental effects of thermonuclear war. From this research, the concept of "nuclear winter" – pronounced cooling in the few years following such a war – emerged. In a nuclear war, large amounts of dust and smoke would be injected into the atmosphere. Data from volcanic eruptions like Mount Pinatubo later provided opportunities to test "nuclear winter" models. It emerged that the main cause of disaster would be destruction of global agriculture and food supply. After a year of severely reduced food supply, there would be mass starvation. Because a nuclear winter might last two or three years, scientists concluded that this would threaten the continued existence of civilisation (and possibly even our species). Casualties from the immediate consequences of nuclear winter due to direct destruction and radioactive contamination would be few compared with those due to mass starvation. This apocalyptic depiction of the consequences of nuclear war by the scientific community had a profound influence in governmental efforts to reduce the world's nuclear arsenals and the threat of conflict.

The possibility that super-eruptions might have the same effects as nuclear war, by causing severe volcanic winters, is one reason why our working group wishes to draw attention to this natural volcanic phenomenon.

There is probably no greater problem facing modern politicians and decision-makers than dealing with scientific uncertainty and perceptions of risk. A few years ago the UK Government banned the sale of beef-on-the-bone, based on an assessment of an exceedingly low risk. Politicians felt obliged to act more on the basis of public risk perception than scientific evidence. Policy towards genetically modified food, biotechnology and nanotechnology has likewise been influenced by public perceptions of risk.

A comparison can be made between the levels of risk to which the nuclear waste disposal industry must work, and the risk from super-eruptions. Here the comparison is interesting in that both have to be viewed over geological time scales.

Risk is commonly presented in terms of annualised probabilities of a fatality. So, for example, to make a safety case for burying intermediate level nuclear waste near Sellafield, Cumbria (UK), UK Nirex were required to demonstrate a risk of less than one in 100,000 fatalities. Further, the safety case had to be made over a 100,000-year period because of the very long decay time of the radioactive waste.

In the same period of 100,000 years there are likely to be several super-eruptions. It is possible that each of these eruptions will affect many millions of people. Let us suppose, conservatively, that such an eruption directly or indirectly killed one million people. The annual probability of a significant super-eruption might only be 1 in 10,000, but the consequence is 10,000,000 deaths.

Thus over 100,000 years it is likely that tens of millions of people will die because of super-eruptions, while a handful of people may die because of the storage of existing nuclear waste over the same time period (assuming that the required safety standards are met).

Of course, the huge time periods involved make such comparisons difficult. Over the same period considerable numbers of people will die from transport accidents. However, neither road nor aeroplane accidents, nor accidents with nuclear waste, will ever threaten civilisation and the global community. Enormous amounts of human effort and financial resources are allocated to the nuclear waste problem, which with existing technology is only likely to lead to a small number of deaths over a period 30 times longer than recorded human history. In contrast, natural events, which are inevitable and could even threaten civilisation, are currently not recognised as a problem.

The next super-eruption: forecasting and potential effects

Any eruption on the scale considered would be characterised by abundant and obvious precursor activity, so humankind should not be taken by surprise. Our recent civilisation has not suffered from a super-eruption and so large-scale volcanic symptoms have not been experienced. The time scales and types of super-eruption signals around a candidate volcano can be understood by scaling up from smaller events. The expected signs are seismic unrest, ground heating and swelling, change in groundwater temperature and chemistry, and in the composition and flux of volcanic gas. Many of these changes are nowadays routinely measured at super-volcanoes such as the Phlegrean Fields, Italy, and Yellowstone and Long Valley, USA. However, other potentially active super-volcanoes are not currently monitored.

The list below illustrates the aspects of our lives that would be influenced by a future explosive super-eruption. Except in the case of atmospheric aerosols, the severity of the effects would depend on the distance from the source volcano.

Ash fall (deposit)

Roof collapse in built-up areas – a local effect out to distances where ash fall is a few centimetres thick (tens of kilometres from the volcano). Exacerbated if rain occurs or ash fall is wet.

Agriculture – devastation and disruption for at least a growing season over most of the area receiving ash fallout. Longer-term changes to soil composition.

Drinking water – potential for both chemical and filtration/blockage problems associated with water supply.

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 unknown.

Power distribution – electric pylons and power lines might be susceptible to ash loading and associated electrostatic effects. Possibly exacerbated if ash fall is wet.

Health (see *Gas and aerosols*)

Secondary mudflows (lahars)

These occur in rivers and stream catchments after rainfall on fresh volcanic deposits. Possible damming of rivers, with ensuing breakout floods. Lahars caused the highest proportions of death and destruction associated with the Pinatubo eruption, but died down in the years after the activity.

Pyroclastic flows and deposits

Burial of all objects on ground and fires on a local scale, up to perhaps 50–80 kilometres from source volcano.

Refugees – if pyroclastic flows were predicted, widespread evacuation would be required. This, depending on the area, could lead to a large number of persons requiring relocation.

Tsunamis – if the volcano is near the coast, pyroclastic flows entering the sea could cause tsunamis. Around the island volcano of Krakatau in 1883, most of the 30,000 casualties were due to tsunamis sweeping ashore.

Gas and aerosols

Climate change – dominantly lower 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 liablilty 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 microns) 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 is a little understood aspect.

Ozone depletion – stratospheric aerosols will serve to catalyse ozone loss, permitting more 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.

Disruption of some communications (satellites may not be able to recieve or transmit information normally due to ash and/or aerosols in the lower atmosphere.

Possible effects of all the above on **world financial markets.**

Mitigation

The fact that there are natural events (super-eruptions, meteorite impacts) with global rather than local or regional impact is now fully recognised in the scientific community. The impact of population growth, globalisation, and ecological stress on the Earth is causing issues with very long time scales to emerge as topics for serious political debate and action. Global warming and nuclear waste disposal are examples of this, with time frames varying from decades to many millennia. These are now being addressed with utmost seriousness by individual governments and the international community. When such a super-eruption happens, as is inevitable, it will be a severe threat to the global human civilisation of the time and could, in the extreme case, endanger our species. This could happen tomorrow or in ten thousand years. If it happened now the results would be catastrophic. We are certain that humanity will, at some stage, need to deal with this unavoidable threat.

It is conceivable that technology could provide mechanisms for stopping or diverting NEOs from colliding with Earth. However, at least at the present time, there is no way of preventing a super-volcano from erupting.

What can be done? The most immediate tasks will involve action from the scientific community with support from national and regional agencies supporting fundamental research. In the UK the Research Councils provide the main way of supporting research to improve knowledge of these eruptions and their environmental effects. The European Union Framework Programme is an example of a regional agency that can co-ordinate, promote and support research. The UK is in a strong position to contribute to the international efforts, as there is considerable strength in relevant disciplines such as volcanology, petrology, meteorology and the economic studies of natural disasters. We provide below some recommendations of research that should be encouraged. International organisations also have an important role to play.

The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) represents international volcanological science. IAVCEI is being proactive in a number of ways, including a project of the IAVCEI Commission on Explosive Volcanism to make a comprehensive inventory of super-eruptions over the last two million years of Earth history. Recently, most of the members of this Working Group met and the possible effects of super-eruptions were discussed for the first time.

Inter-governmental agreements, like the Kyoto and Montreal Protocols, which attempt to develop global agreements related to the environment, and the United Nations, provide another approach. The resources placed into organisations like UNESCO for international programmes of research, or efforts in mitigation of natural hazards, are currently small. Our world is repeatedly surprised by natural catastrophes, such as the recent Asian tsunami, floods in Bangladesh, and earthquakes in Italy, Iran, or Turkey, which are local or regional rather than global in scale. Global warming has been taken seriously, but global natural hazards have hardly featured as a recognised problem. The recognition by the UK Government that impacts of NEOs are more than science fantasy is encouraging. Now is a good opportunity for the threat of super-eruptions to be similarly recognised.

A significant step forward would be for the international community of governments to recognise that global natural catastrophes are not only possible but inevitable, in the same way that global warming is now taken seriously. Solutions and mitigation can only be found through greatly strengthened international organisations, like the United Nations, support by governments of international scientific programmes, and by international agreements. In the foreseeable future, a super-eruption may be predicted but not prevented. Thus, just as individual countries have natural disaster preparation plans, the world community needs preparation plans. What might happen if several billion people needed evacuation from most of Asia, and, simultaneously, three or four years of severe volcanic winter threatened agriculture throughout North America and Europe? This is not fanciful, but the kind of acute problem and inevitable consequence of the next super-eruption.

There should be investment in research to improve our understanding of large magnitude explosive eruptions and the regional and global impacts of such eruptions.

A major focus of this research should be on collaboration between volcanologists and climate modellers, in particular in relation to investigating the effects of large magnitude aerosol injections into the stratosphere using global climate models. There is also a need to understand much better the controls on the masses of volcanic gas and ash released in such eruptions.

One of the key problems is that there is no systematic inventory of the previous occurrences of super-eruptions. A great deal of research has been done in many parts of the world on the history of volcanism but none of this work has been integrated together systematically. An inventory of potential super-volcanoes would provide the basis for identifying which volcanic centres should be studied intensively. An inventory of the frequency of the occurrences of super-eruptions over the recent geological past (the last one million years), as begun by IAVCEI, [http://www-volcano.geog.cam.ac.uk/database/] would allow the frequency-magnitude relationship to be much better constrained.

There should be initiatives to improve public understanding of the nature of volcanic hazards that have regional and global effects.

The establishment of a Task Force to consider the environmental, economic, social, and political consequences of large magnitude volcanic eruptions. As in the case of Near Earth Objects, these proposed activities will be best developed and served by international collaboration.

Further reading

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The peaceful waters of Lake Taupo in the North Island of New Zealand belie its origin as a volcanic caldera. The northern part of the lake basin was formed by collapse during a 500 km^3 (magnitude 8) super-eruption about 26,000 years ago. Taupo is still an active volcano but it is expected that its next eruption will not be as large as the caldera-forming one. The impressive stratovolcanoes at the southern end of the lake, some 60 km from where the photo was taken, were formed gradually by very small eruptions. Mount Ruapehu (with snowcap) was the site of New Zealand's latest active volcanic episode in 1994–1997.

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PDF files of all brochures in the series *The Earth in our Hands*, each highlighting a geoscientific issue of high societal relevance, can be found at www.geolsoc.org.uk under Teaching Resources, where the 1st (Web) edition of this document also sits.
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Front Cover: Mount St Helens , 22 July 1980, **James Vallance, USGS.**
Inside front cover: Valles Caldera satellite image, **NASA;**
Valles Caldera rocks, **Stephen Self, Open University.**
Page 2: Super-volcano calderas: Taal satellite radar image, **NASA;** Cerro Galan satellite image,**NASA;**
Toba, **Stephen Blake, The Open University;** Atitlán, **Stephen Self.**
Page 5: Crisis mortality map, after **John Grattan, University of Wales.**
Laki fissure, **Stephen Self.**
Page 6: Magma volume graph, **Stephen Self;** Satellite image of Tambora. **NASA.**
Page 7: Painting of Chichester Canal,**Tate Gallery, London**;
Vesuvius eruption, **Time-Life Books;** Phlegrean Fields satellite image, **NASA.**
Page 8: Soufrière Hills pyroclastic flow, **Paul Cole, Coventry University;**
Depth of ash graphic, **Stephen Self and John Taylor.**
Page 9: Frequency table, after **Mason, B.G. *et al*. Bulletin of Volcanology 66, 2004.**
Page 10: Toba ash map, after **Patten, J.N. *et al*., Current Science 80, 2001;**
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Page 11: World map base, **USGS.**
Page 12: North America ash fall map, after **USGS.**
Page 13: Aerosol droplets, **Eos, Transactions of the American Geophysical Union;**
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Page 14: Pinatubo aerosol cloud maps, SAGE satellite data, **NASA.**
Page 17: Old Faithful, **USGS.**
Page 22: Lake Taupo, **Stephen Self.**
Inside back cover: Mount Pinatubo eruption, **US Air Force;**
Southern Luzon satellite image, **SPOT, France.**

Beginning of Mount Pinatubo eruption, June 12, 1991, photographed from Clark Air Base. A huge eruption column of ash and gas is rising to heights in excess of 20 kilometres into the atmosphere.

Mount Pinatubo, on Luzon Island, Philippines, is shown circled on this 1996 SPOT satellite image. The area devastated by pyroclastic and mudflows in June 1991 is the grey region around the volcano. Pinatubo is located close to an area of still active but slumbering super-volcanoes. SE of Pinatubo, across Manila Bay, lie two large lakes – both are sites of little known super-eruptions that occurred within the past 1-2 million years. Taal, the 30-kilometre-diameter lake with an island in the centre, has had frequent historic eruptions and is an active super-volcano that has the capability to produce another large eruption. About two million people live within 20 kilometres of Lake Taal, and Manila has a population in excess of 10 million. Next to Manila lies Laguna de Bay, the central part of which is the source of extensive volcanic deposits, suggesting that Laguna de Bay might also be the site of a super-volcano.