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Tambora 1815, super-volcano eruptions, and the future volcanic threat

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1. Introduction

While the 1883 Krakatoa eruption is coincident in many people's minds with the ultimate in volcanic devastation, most remain unaware of the great explosion of another Indonesian volcano, Tambora (Fig. 1) — five times bigger and nearly 70 years earlier. This is hardly surprising given the kick-start that the burgeoning global telegraph business gave to the Krakatoa blast, spreading the news swiftly across the planet and installing it permanently in the catastrophe mindset. When Tambora blew itself apart in 1815, the first working telegraph was still 12 months away, so word of the event leaked only slowly and sporadically in the direction of Europe and North America. At a time when it took 45 days for a letter to reach London from Singapore, knowledge of Tambora seeped rather than exploded onto the world stage, and general awareness of the event has suffered ever since. Nonetheless, the impact of Tambora on the climate and on society greatly outweighed that of the lesser blast at the other end of the 19th century.

Scoring a seven on the Volcano Explosivity Index, the 1815 Tambora eruption was the largest in recorded history. As well as causing devastation on Sumbawa and neighbouring islands, the legacy of the blast was a serious deterioration in weather across Europe and eastern North America, which resulted in wholesale harvest failure. This in turn triggered famine and civil unrest in what economic historian, John Post, has termed the "the last, great, subsistence crisis in then western world." The severe impact of the Tambora eruption on agriculture and its deleterious ramifications hold important lessons for future volcanic events on this scale and flag potentially serious consequences for economy and society.

2. Setting the scene

The global volcanic threat is significant, with more than 1,550 volcanoes having erupted during the Holocene (approximately the last 10,000 years). In addition, there is perhaps a comparable number of volcanoes that show no evidence of Holocene activity, but which may have the potential to erupt again. Around 550 volcanoes have erupted in recorded history, of which between 50 and 70 are active every year, and on any single day, about 20 volcanoes can be expected to be in eruption. Indonesia is the most volcanically active nation on the planet, boasting 78 historically active volcanoes, including — in Krakatoa and Tambora — two of the biggest volcanic explosions of modern times.

While the absence of effective global communication hindered the immediate spread of news about the Tambora eruption, the presence of a particular individual ensured that knowledge of the event was ultimately preserved. British diplomat, Thomas Stamford Bingley Raffles — later Sir Stamford Raffles — was, at the time of the eruption, the Lieutenant Governor of Java, and so perfectly placed to record the details of the event and its local consequences, which he did in his *History of Java*, published in 1817. Further details of the eruption are contained in Raffles' biography, written by his daughter Sophie and published in 1830, and in issues of the *Asiatic Journal* from 1816. These contemporary sources provided invaluable material for a 2003 review of the eruption and its impacts by Clive Oppenheimer and a recent (2014) book marking the bicentennial by Gillen D'Arcy Wood.

Figure 1 Aerial view of the summit of Tambora (courtesy Jialiang Gao. Licensed under the Creative Commons Attribution-Share Alike 3.0 Unported; https://en.wikipedia.org/wiki/Mount_Tambora#/media/File:Caldera_Mt_Tambora_Sumbawa_Indonesia.jpg).

3. Anatomy of a catastrophe

Tambora is a classic subduction-related stratovolcano located above the Java Trench. With an age of 57,000 years, it is also relatively young. Nonetheless, it formed an impressive mountain and prior to the 1815 eruption is estimated to have stood 4,300m tall, making it, at that time, the highest peak in the East Indies. It certainly would have towered above the surrounding landscape and dominated the northern end of Sumbawa's Sanggar Peninsula. It is highly likely that those living in the volcano's shadow had no idea that the volcano was active and presented a threat to life and livelihoods; the last eruption occurring more than 2,500 years earlier in 740 BC.

The first signs of unrest are recorded in 1812, indicating that fresh magma was on the move within the volcano; but it was another three years before this reached the surface. It did so violently on April 5th, with a major blast that hurled a column of ash tens of kilometres into the atmosphere. Just five days later the climactic phase of the eruption began at 19:00 (local time) on April 10th, and lasted for close to 24 hours. Activity then slowly subsided until the eruption ended sometime the following month. While the local and regional impacts were immediate, remote climatic effects took longer to take hold, so that it was 1816 that became known — in Europe and eastern North America — as 'the year without a summer'.

Tambora has been relatively quiet for the last couple of centuries; the last minor eruption occurring in 1967. Recently, however, the volcano has shown increased signs of unrest, resulting,

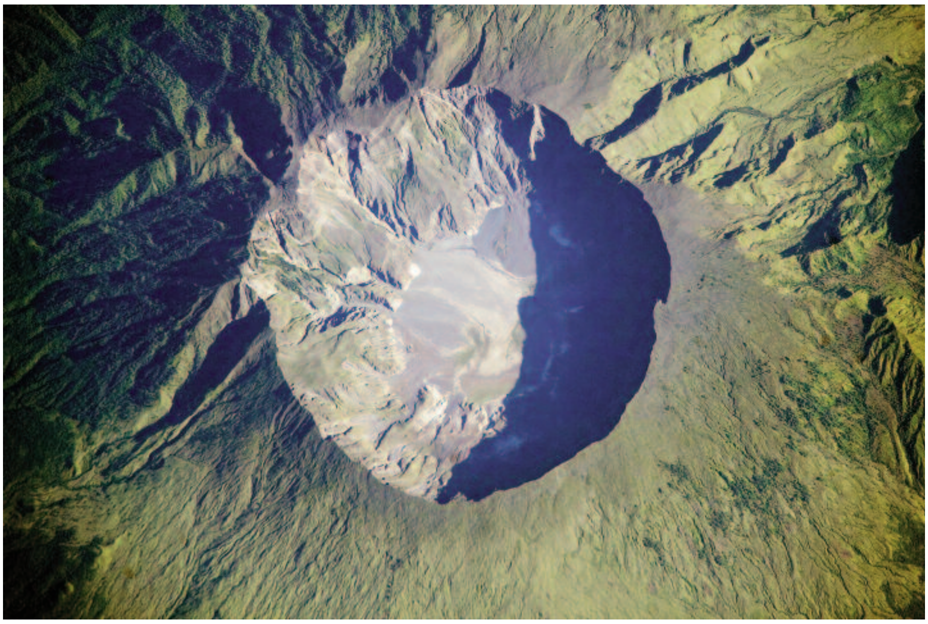

Figure 2 Vertical view of the Tambora summit caldera formed in 1815, taken by the NASA Expedition 20 crew (courtesy NASA; http://eoimages.gsfc.nasa.gov/images/imagerecords/39000/39412/ISS020-E-06563_lrg.jpg).

in 2013, in the alert level being raised to 2 (on a scale of 1–4). While another blast on the scale of 1815 is unlikely in the extreme, a moderate eruption in the near- to medium-term is certainly not out of the question.

The numbers of the 1815 explosion are truly staggering. One hundred and forty gigatonnes of pulverised rock was ejected, mostly within the 24-hour long climactic phase. The volume of erupted material was on the order of 100km^3, translating to a dense rock equivalent (DRE) of *c.* 41km^3. Ash and pumice left the vent at an estimated rate of 1.3km3 an hour, feeding an eruption column that climbed to an altitude of 43km. The biggest detonations were heard more than 2,000km away and ash fall was so heavy that many places within 600km of the volcano were in complete darkness for up to two days. Much of Sumbawa was buried beneath 0.5m or more of ash, while pumicious pyroclastic flows (ignimbrite flows) scoured the landscape up to 30km from Tambora's summit. Fully 95 per cent of the ejected mass took the form of pyroclastic flows; the remaining five per cent taking the form of ash making up a Plinian eruption column. The entry of pyroclastic flows into the sea also generated tsunamis with run-ups as high as 4m, which caused considerable damage to some coastal communities.

The eruption itself is estimated to have taken *c.* 12,000 lives, mainly due to immolation or asphyxiation by pyroclastic flows. Famine following the destruction of crops and loss of livestock resulted in the loss of a further 59,000 lives as a consequence of starvation and disease, including respiratory problems and fluorine poisoning. The eruption took its toll on the volcano too, reducing its height by 450m and opening a caldera 6km across and a kilometre deep (Fig. 2).

4. The Year Without a Summer

The Tambora eruption is best known not for its devastating impact on the local population and environment, but for the manner in which it affected the climate and impinged detrimentally upon countries half a world away. The eruption lofted an estimated 60 megatonnes of sulphur gases into the stratosphere, forming a veil of sulphate aerosols that significantly reduced the level of incoming solar radiation. The resulting cooling of the troposphere and surface reached a peak of about 1°C in 1816. The same year also saw the second coldest northern hemisphere summer in 600 years; just the first of a string of anomalously cold summers that persisted for at least three years. Analysis of the temperature curve for the time indicates another significant fall in northern hemisphere temperatures in 1812, which is assumed to have been triggered by another large volcanic event that has yet to be identified. The appalling summer of 1816 seems, therefore, to have been a legacy of the cooling effects of these two eruptions combined.

In eastern North America, the weather in the year following the eruption was dire. Across New England, severe frosts and snow were still evident in June, while 300mm of snow fell in Quebec. Hard frosts continued throughout the summer months, halving the growing season and leading to almost total crop failure across the region. Farm losses were so great throughout the north-eastern states of the US that they supposedly contributed towards the first big migration to the interior.

The situation in Europe was, if anything, worse. Summer temperatures in 1816 were up to 3°C down on the 1951–1970 average, and this, alongside extremely wet weather, drove harvest failure on a scale comparable to that experienced in North America. The European economy was still struggling to recover in the aftermath of the Napoleonic Wars, and the consequences of a failed harvest conspired to promote unrest among an already fractious population. Bread prices reached levels that were unaffordable even to those on an average wage, prompting riots in the UK, Germany and elsewhere. Disease, in particular typhus, was rampant, taking as many as 40,000 lives in Ireland alone.

The conditions of economic hardship and social unrest continued at least until 1817, spawning financial turmoil and depression across post-Napoleonic Europe. They also probably played a part in the last armed uprising in England, which began in the Derbyshire village of Pentrich in June 1817. From here, up to 300 disaffected and armed men, led by Jeremiah Brandreth, set off towards the seat of government in London. The column was supposed to sweep up more supporters on the way, but they were informed upon and only made it as far as the village of Giltbrook in the next county — Nottinghamshire. Here the march was broken up by soldiers and the ring leaders captured, later to be hanged for high treason or deported.

The aftermath of the 1815 eruption also appears to have had some other unlooked for consequences. The gloom and cold of the 1816 summer is widely held to have played a key role in prompting Mary Shelley to begin her great gothic masterpiece, *Frankenstein*, and to push Byron to pen his bleak poem, *Darkness*. In Germany, the prohibitive cost of animal feed in 1817 persuaded Karl von Drais to invent the 'Dandy Horse', or Draisine, a pedal-less, two-wheeled vehicle that ultimately gave

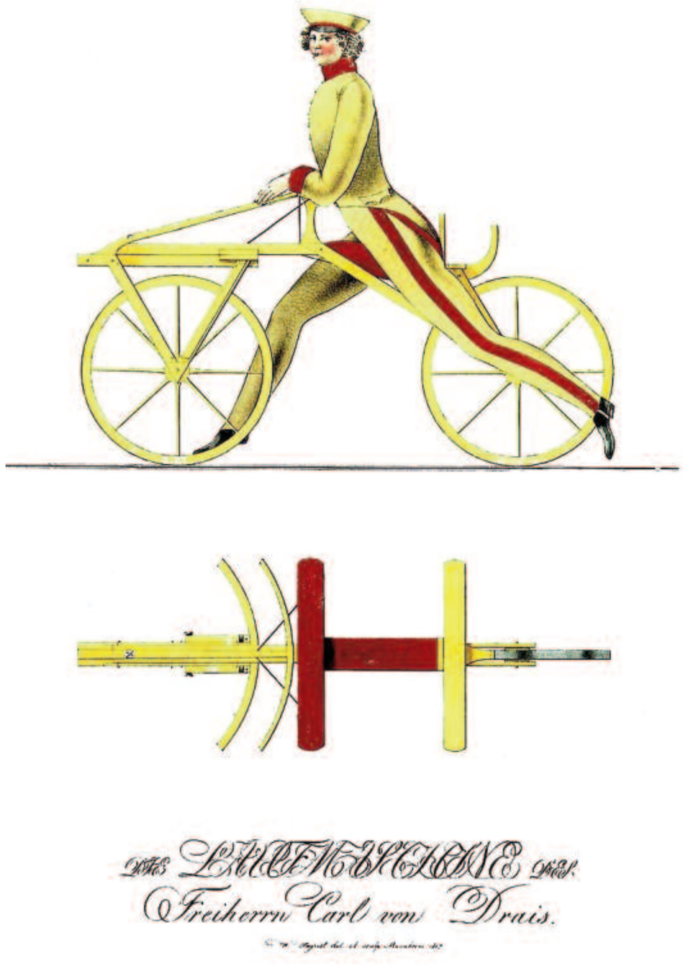

Figure 3 The Dandy Horse or Draisine, invented in 1817 by Karl Drais (https://en.wikipedia.org/wiki/Dandy_horse#/media/File:Draisine1817.jpg).

rise to the modern bicycle (Fig. 3). The brilliant sunsets of some of J. M. Turner's landscapes have also been attributed to the effects of volcanic dust in the atmosphere in the years following the eruption, although this is difficult to verify.

5. Tambora in context

There is no doubt that the 1815 Tambora eruption constituted a major volcanic event that had severe consequences, both locally and across the world. As volcanic eruptions go, however, it was far from the biggest. On the Volcano Explosivity Index (VEI), on which the scale of volcanic events is measured, the Tambora blast scores an impressive 7, a ranking reserved for eruptions that eject a volume on the order of 100km^3 of material. The VEI is logarithmic, so that a VEI 7 is ten times bigger than a VEI6 and ten times smaller than a VEI8. The 1815 eruption was therefore about 100 times bigger than the 1980 eruption of Mount St. Helens (Washington State, USA) (VEI5) and 10 times bigger than the 1991 eruption of Pinatubo (Philippines) (VEI6). On the other hand, it pales into insignificance when compared with VEI8 events (*see* Table 1). Such events erupt at least 1,000km^3 of material and include the 640,000y BP eruption of Yellowstone (1,000km^3), the 74,000y BP Toba (Indonesia) blast (2,800km^3) and the colossal 30-million-year-old Wah Wah Springs eruption (5,000km3) in Utah, USA.

Such so-called 'super-eruptions' are extremely rare and probably have return periods as long as 50,000 years or even longer. Nonetheless, they are important from a risk viewpoint, as they have massive impacts at the global scale. Volcanoes capable of hosting super-eruptions require a certain magma 'recipe' and so are also geographically restricted. Magma must be sufficiently rich in silica to promote high viscosity and gas contents and severely restrict bubble expansion so that enormous overpressures accumulate as magma rises towards the surface. Conditions also need to prevail that allow or promote the accumulation of a very large body of magma and then permit its release (or at least the release of a substantial fraction of it) in one go. Broadly speaking all the conditions required for a super-eruption are satisfied primarily around the Pacific Rim and in South East Asia.

The huge volumes of material ejected require the climactic phases of super-eruptions to have durations of a week or more, resulting in regional devastation, but it is their remote consequence that attract the greatest interest. In this context, they are like Tambora writ large. The quantity of sulphate aerosols that load the stratosphere after a super-eruption are prodigious and may reach 5,000 megatonnes. This is sufficient to cause a global temperature fall of several degrees Celsius, triggering what has become known as a 'volcanic winter.'

The Yellowstone super-eruption of 640,000y BP saw ash fall as far away as what is now Los Angeles (California) and El Paso (Texas). Even 1,500km from the eruption site, compacted ash deposits were 20cm thick. Ashy horizons in drill cores from the Caribbean attest to wholesale reworking of the ash fallout by the major river systems, which may well have become clogged resulting in widespread flooding. The impact of the eruption on global temperatures has not been established, but would have been considerable.

Nearer to the present day, the impacts of the Toba (Indonesia) super-eruption at 74,000y BP — which was almost three times bigger than the Yellowstone explosion — are even more impressive. In the process of excavating one of the largest volcanic craters on the planet, 100mm or more of ash was dumped on at least one per cent of the Earth's surface. Five gigatonnes of sulphate aerosol introduced into the stratosphere caused northern hemisphere temperatures to tumble by 3–5°C and brought about a severe volcanic winter that lasted for five to six years. There were immediate temperature falls close to or below zero degrees centigrade in the tropics, and hard freezing at mid-latitudes, while modelling of the effects of the eruption suggest that perhaps one-third of the planet could have been covered by ice and snow. The consequence for our human ancestors may have been

Table 1 Selected VEI ('super') eruptions

volcano	*location*	*eruption date ('000y)*
Cerro Galan	Argentina	2200
Yellowstone	USA (Wyoming)	2000
Toba	Indonesia (Sumatra)	790
Long Valley	USA (California)	700
Yellowstone	USA (Wyoming)	640
Toba	Indonesia (Sumatra)	74
Oruanui	New Zealand (North Island)	26.5

close to terminal, and there is a school of thought that a human population bottleneck at around this time may be traced to the eruption. It appears that the human population may have been reduced to a pool of just a few thousand individuals for a couple of centuries, bringing our race within a whisker of extinction.

6. The next Tambora

The rarity of super-eruptions counts against such an event happening in the short- to medium-term, although this can never be completely ruled out. The probability, in the not to distant future, of another Tambora-scale blast is, however, significantly greater. One estimate of the likelihood of another Tambora is 1 in 10 in the next 50 years, but the return period for climate perturbing eruptions may be as short as a few centuries (*see* Table 2). Bearing this in mind, how would we fare if another eruption on the scale of Tambora happened today?

In relation to widespread harvest failures, the received wisdom is that globalisation will make it easier to cope. It could well be argued, however, that this very interconnectedness of world markets could make things worse. Harvest failures in North America, Europe and perhaps elsewhere could be expected to drive huge hikes in the cost of grain, pricing out many — particularly in developing countries or in the disadvantaged of industrial societies. In addition, competition for reduced food commodities could be expected to drastically reduce the range of available products, compromise supply and distribution systems and bring about a collapse of the 'just-in-time' production and delivery mechanism so beloved of large, modern food suppliers. As in the years following Tambora, the end product could be serious civil unrest, but potentially on a far wider scale.

Clearly, there will be another climate-perturbing eruption on the scale of Tambora, or even larger, and the key to coping successfully with the consequences is to be prepared. Unfortunately, while at least some elements of the scientific community might be aware of the future volcanic threat, key stakeholders are not. Governments have other day-to-day priorities and tend to have time horizons limited by the date of the next election. Aid agencies have enough on their plates with countless wars and civil problems, while emergency managers and planners are inevitably concerned with more immediate situations. All this translates into a relationship with hazardous natural phenomena — including volcanic eruptions — that is dominated by a reactive rather than proactive approach; in other words response still dominates thinking, much to the detriment of effective preparedness. The 2010 Eyjafjallajökull eruption provides an excellent example of this. We only need to look back to 1947 for the last time that Icelandic ash impinged upon UK airspace, yet the National Risk Register contained no mention of a threat from Icelandic eruptions. As a reaction to the aviation mayhem arising from the events of 2010, Icelandic ash hazard has now been added to the register.

Table 2 Selected eruptions of the last 10,000 years, sufficiently large to have had significant climate-perturbing effects

volcano	*location*	*eruption date*
Kurile Lake	Russia (Kamchatka)	8470y BP
Crater Lake	USA (Oregon)	7600y BP
Kikai	Japan (Ryukyu Islands)	6300y BP
Taupo	New Zealand (North Island)	AD 180
Baitoushan (Mt. Paektu)	China-North Korea border	AD 1030
Unknown	—	AD 1258
Kuwae	Vanuatu	AD 1452
Tambora	Indonesia (Sumbawa)	AD 1815

Given that a major eruption on a scale sufficient to have a significant impact on the climate is certain at some point in the future, is there anything in the pipeline? Two volcanoes that are well worth watching are Uturuncu in Bolivia and Laguna del Maule in Chile. Both have hosted enormous eruptions in the past and both are once again demonstrating clear signs of restlessness. At Uturuncu, a 70km wide bulge has been growing steadily since the early 1990s, as fresh magma intrudes beneath the volcano. Farther south, the Laguna del Maule volcano is swelling at the astonishing rate of 250mm a year above a large body of magma just 6km down. There can be no certainty, in either case, that such unrest will translate to an eruption, nor that if it does the eruption will be large enough to seriously impact upon the climate, but the risk is not insignificant. So, in conclusion, do keep smiling … but don't say I didn't warn you.

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