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Environmental and Societal Impacts in New England Following a Potential Yellowstone Eruption

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Abstract

Yellowstone National Park is famously known for its history of "super-volcano" eruptions. From the evidence of volcanic deposits, scientists know that the ash cloud that erupted from Yellowstone covered most of the western U.S. states, but until recently, models have not shown the ash could also have reached eastern states. The scope of this investigation is to determine what would happen to New England if Yellowstone were to erupt today in terms of health, agriculture, transportation, relocation, economy, and climate. In order to do so, three significant eruptions during human history are considered as case studies in order to compare their impacts to those of a potential Yellowstone eruption. In addition, ash fall models are created to predict the amount of ash that could reach New England. These models suggest that 0-30 mm of ash could cover New England and global temperatures could decrease by 3-5°C. This would have devastating impacts on agriculture in New England, leading to starvation and other issues that could ricochet across the globe. Although Yellowstone is unlikely to erupt during the 21st century, there are numerous other less closely-monitored caldera systems on the planet that could erupt, and therefore it is important to have mitigation strategies in place to decrease the harmful effects of potential volcanic cataclysms.

Introduction

One of the most beautiful places in the world is also one of the deadliest, yet Americans have created an entire ecotourism system around it. They cleared campgrounds, made hiking trails and walkways, sold t-shirts and hats, and named hydrothermal features "Old Faithful" (Photos 1 and 2), which is very telling of what lies beneath the surface. Yellowstone National Park lies within the states of Wyoming, Montana, and Idaho and was the first national park in the world. Wallace Stegner called national parks "the best idea we ever had. Absolutely American, absolutely democratic, they reflect us at our best rather than our worst." Is it absolutely American to sell mugs and make TV shows based on a place that could wreak havoc across the United States?

Photo 1 (left): Old Faithful Geyser in Yellowstone National Park erupting. Photo 2 (right): Morning Glory Pool in Yellowstone National Park with elaborate, bright colors from the microorganisms in the water. Photos taken by Joseph Licciardi.

Yellowstone lies within a caldera, which is a volcanic feature that forms during an eruption of high magnitude as magma exits the chamber at high speeds and creates a depression in the ground (Williams, 1951). The Yellowstone caldera covers an area of 80x50km (Hurwitz and Lowenstern, 2014). Yellowstone's super-volcano is known to have erupted three times in the past: 2.029 +/- 0.004 Ma, 1.285 +/- 0.004 Ma, and 0.639 +/- 0.002 Ma (Lanphere et al., 2002). The first eruption of the Island Park Caldera produced approximately 2500 km^3 ejecta known as the Huckleberry Ridge Tuff, the second eruption of the Henry's Fork Caldera produced ~280 km^3 ejecta known as the Mesa Falls Tuff, and the third eruption of the Yellowstone Caldera (Figure 1) produced approximately 1000 km^3 ejecta known as the Lava Creek Tuff (Shapiro and Koulakov, 2015). Volcanic ash deposits from the three eruptions are evident around the park and across 1/3 of the continental United States, but mostly from the larger Lava Creek and

Huckleberry Ridge Tuffs (Figure 2) (Mastin et al., 2014). From the geologic evidence of the past eruptions, we can begin to understand the environmental impact of this scale of eruption. However, there is no analog for volcanic eruptions of this magnitude during human history. Therefore, it is more difficult to predict the impact on society if Yellowstone were to erupt again.

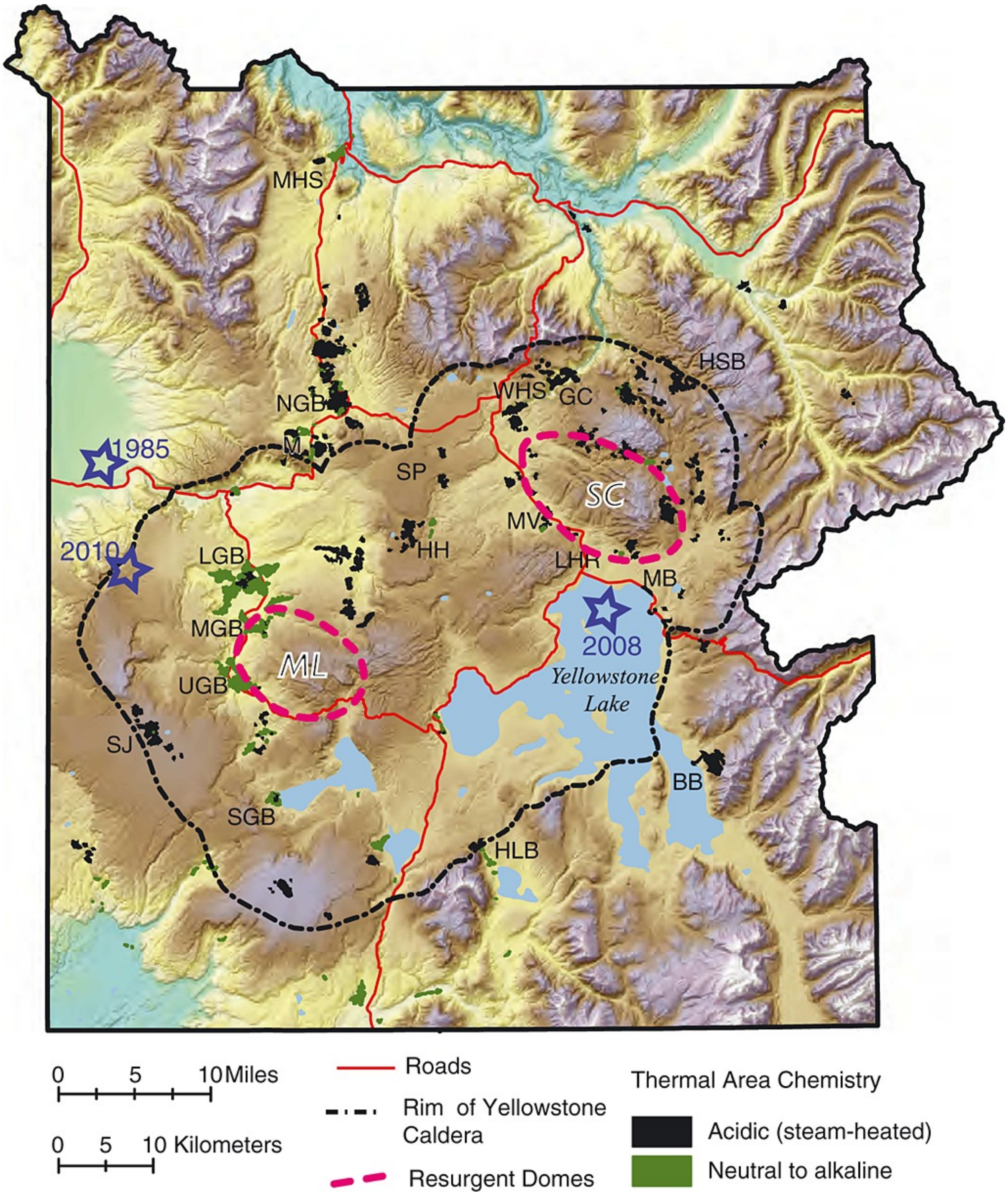

Figure 1: Shaded relief image of Yellowstone National Park from Hurwitz and Lowenstern (2014). Yellowstone Caldera boundary is the feature that formed the Mesa Falls Tuff ~0.639 Ma. Thermal features and resurgent domes are also shown.

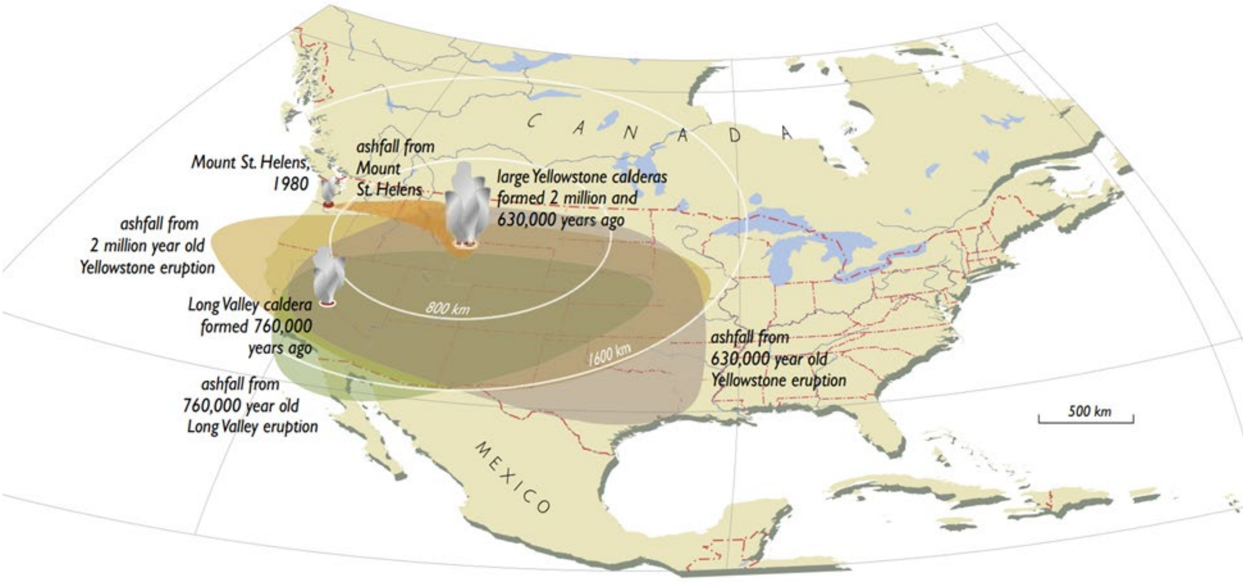

Figure 2: Ash falls from the two larger Yellowstone eruptions as well as other historic eruptions for comparison. The Yellowstone eruption deposits cover the greater part of the western United States and have not been found in the eastern states. Figure reproduced from Sparks and Self (2005).

The most directly affected places will be those closest to the eruption and will experience high volumes of ash and extensive pyroclastic flows. Volcanic hazard assessments usually discuss the impacts on locations close to the source or the globe as a whole. However, what might happen to locations further from the vents that are often ignored in ashfall models? Hazards such as changes in climate and ashfall can have substantial impacts on places much further from the vents, but the distance and less immediate effects of the eruption explain why hazard assessments rarely or briefly mention the far-flung locations. The New England region includes 6 states–Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut–and is bordered by the Atlantic Ocean and Canada. According to the United States Census Bureau as of 2021, the total area is 186,455 km², of which 24,086 km² is water. As of July 1st, 2019, there were 14,845,063 residents estimated by the 2019 Census. Although New England will not experience immediate hazards, the region could still experience ash fall. However, more issues will arise after the eruption that impact the environment and society. These issues likely include impacts on climate, travel, agriculture, livestock, water quality, human health, economy, and human displacement. If Yellowstone's super-volcano were to erupt today, then New England would mainly be impacted by changes in climate in the years following the eruption as well as the changes forced upon society. In order to determine the impact of the eruption, research studies and models must be used to explain the consequences of an eruption on New England.

Planning for the outcomes of an eruption should not be placed on the backburner, as signs of an impending eruption could occur at any moment, and we do not have the current knowledge to know the timeframe between pre-eruptive signs and the eruption itself. The importance of knowing what could happen will allow us to better prepare appropriate mitigation strategies based on scientific studies that are effectively communicated to government officials and the public.

The History of the Yellowstone Hotspot

On March 1st, 1872, President Ulysses S. Grant signed into law the first United States National Park – Yellowstone (Jackson, 1942). The part of the park that resides within a caldera was formed by hotspot volcanism. Hotspots are areas where volcanism occurs without the presence of a plate boundary. Hotspots are stationary, however, the tectonic plates overriding the hotspots move and produce volcanic chains (Morgan, 1971). The track of the Yellowstone hotspot appears to have moved towards the northeast, however, the overriding North American Plate is moving towards the southwest in comparison to the fixed hotspot (Figure 3). The plume of Yellowstone's hotspot is thought to have originated as far back as 56 Ma with volcanism and the accretion of an oceanic terrane off the western coast of the U.S. (Camp and Wells, 2021). Another example of hotspot volcanism is the Hawaiian Islands; however, the volcanism of the islands is less explosive than that of Yellowstone, and more effusive in nature. Effusive eruptions produce lava flows while explosive eruptions produce material such as ash and pyroclastic deposits (Self, 2006). The differences in explosivity have to do with several factors, one being the type of rock the magma would have to move through to reach the surface. The Hawaiian hotspot interacts with a thinner, basaltic oceanic crust that is more mafic than the magma moving through it, therefore the magma can remain buoyant and ascend to the surface quickly as effusive basaltic flows (Shapiro and Koulakov, 2015). The Yellowstone hotspot, however, must travel through thicker, more felsic continental crust, which can cause the melts to stall within the crust and form reservoirs of magma that can grow for thousands to millions of years. These reservoirs are generally in the upper 40 km of the Earth's crust and consist of the intruding basaltic melts and melting felsic crust, creating a more silica-rich melt that can rise toward the surface (Lowenstern et al., 2006). If the chambers are unable to reduce pressure by means of magma leaking through the surface in small and frequent eruptions, then the system may develop the capabilities of a highly explosive eruption. What makes continental hotspot plumes more explosive than oceanic hotspot plumes is the high silica (SiO_2) content in the melt, enough dissolved gases to cause a forceful ejection of magma during the initial eruption, and high viscosity and surface tension to resist flow and trap gases. Since the gases are under high pressure, the eruption will rapidly degas, fragmenting the magma into clouds of ash particles, which are composed of magmatic glass, that can reach into the stratosphere as well as masses of ash that move radially away from the center of the eruption.

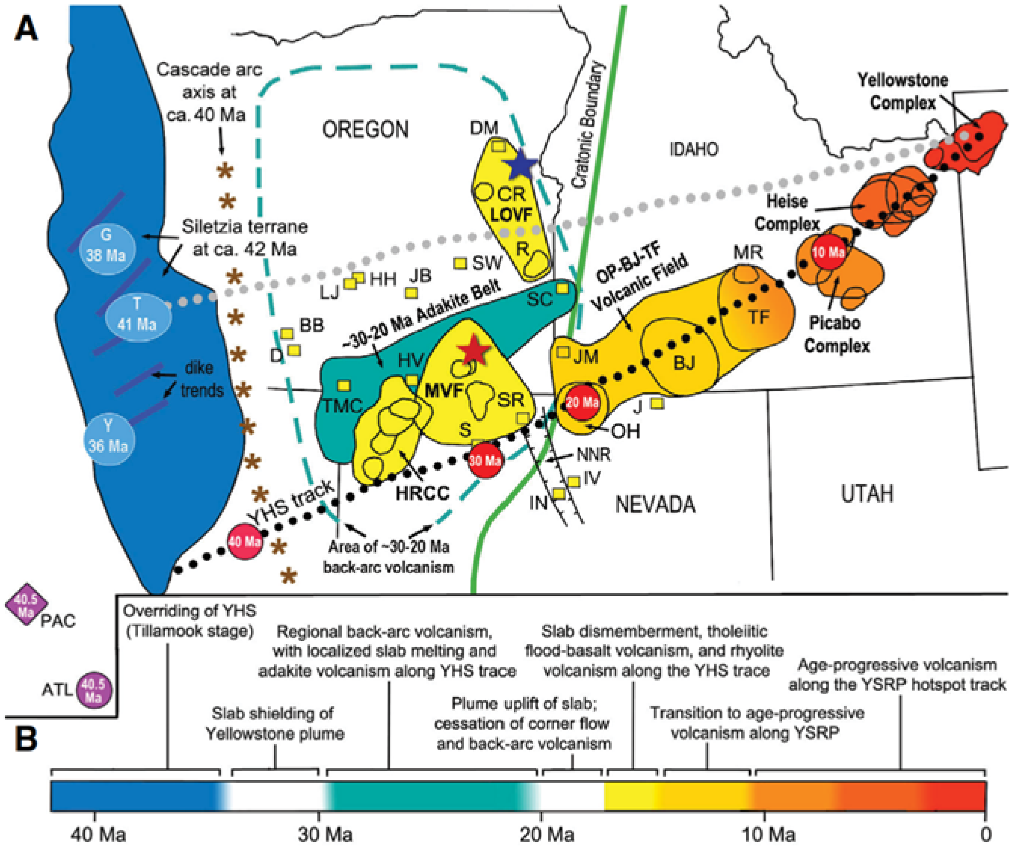

Figure 3: (A) History of the Yellowstone hotspot track from Camp and Wells (2021). Evidence for the track suggests its evolution began just off the western coast of the U.S. and, as the overriding North American plate has moved over time, the hotspot is now on the border of Wyoming, Montana, and Idaho as the Yellowstone Complex. (B) Timeline of tectonomagmatic events along the Yellowstone hotspot track.

A "super-volcano" is a term commonly associated with Yellowstone but in actuality it is informal, like calling a rainforest a 'jungle.' The term has been accepted over the years in the scientific community as a way to convey to the public that the eruptions around Yellowstone and other calderas have been exceedingly large. A more scientific term to use for Yellowstone's super-volcano would be a rhyolitic caldera system. The volcanic field is also referred to as the Yellowstone Plateau Volcanic Field (YPVF) (Hurwitz and Lowenstern, 2014) A super-volcano has come to be classified as at least 300 km³ of magma rapidly escaping from a subsurface magma chamber in an explosive manner (Sparks et al., 2005). 300 km³ of magma would have a value of 7 on Volcanic Explosivity Index (VEI), which is a logarithmic scale used to rank eruptions based on the volume of ejected material and height of the eruptions plume (Lowenstern et al., 2006). The scale goes from VEI 1 to 8, with eight being eruptions with greater than or equal to 1000 km³ of ash deposits. Super eruptions are the least common type of eruption generally occurring every 100-200,000 years, but smaller and more frequent eruptions can still have severe impacts (Self, 2006). The magma reservoir below Yellowstone is inferred through geophysical and geochemical evidence to have at least 15,000 km³ of crystal-melt mush currently (Lowenstern et al., 2006). Evidence such as a geothermal anomaly located at a depth of 8-18 km as well as the size of the caldera were used to derive this estimate. Whether or not a super eruption could take place depends on the melt fraction of the crystal-melt mush, but as of right now evidence suggests there is not an eruptible volume of magma at this time.

Evidence that Yellowstone's super-volcano formed from hotspot volcanism is that the area's high terrain flares outward and ahead of the volcanic progression in a bow-wave pattern (Pierce and Morgan, 2009). Geological evidence shows that rhyolitic formations are younger the closer one is to Yellowstone, indicating the hotspot has moved over time and its most recent location is in Yellowstone (Armstrong et al., 1975). Also, just northeast of the Yellowstone Plateau is the highest geoid anomaly in the United States, indicating that a process underneath Yellowstone must be the cause of the swell in the area, and only a deep mantle plume can adequately explain the anomaly (Pierce and Morgan, 2009). The continental divide currently crosses through Yellowstone, but in the Oligocene, the divide was much closer to the Pacific coast, meaning the change in topography over the last 34-23 Ma has shifted eastward, much like the hotspot track. The plume driving the hotspot track is thought to extend to a depth of at least 1000 km because the volcanism created by the Yellowstone hotspot would require a plume to reach below the transition zone of the upper and lower mantle.

Even though Yellowstone is currently considered "dormant", components of the system are still highly active (Lowenstern et al., 2006). Yellowstone has abundant geothermal activity due to the caldera system and magma chamber within the crust, which provides evidence for the possibility of another Yellowstone eruption in the future. Hydrothermal features and related processes include geysers, hot springs, mud pots, fumaroles, hydrothermal explosion craters, surface rising and subsidence, and earthquakes. Nearly half of the world's 1,000 geysers reside in Yellowstone (Rinehart, 1980). Seismic tomography also indicates a deep-sourced mantle plume beneath the caldera, which is further backed by the timing and location of volcanism, faulting, and uplift (Pierce and Morgan, 2009). Yellowstone's active hydrothermal system is created by water that is between the Earth's surface and the magma chamber, so the magma is heating the water and forming steam (Lowenstern et al., 2006). The Yellowstone region also experiences abundant precipitation due to its high-altitude location in the northern Rocky Mountains, which recharges the aquifers below the surface. The aquifer can interact with heat and gases rising from the magma chamber below, creating waters that form hydrothermal fluids and can precipitate minerals as the fluids flow. Minerals such as silica sinter, travertine, and sulfur tend to precipitate from discharged fluid through biotic and abiotic processes (Hurwitz and Lowenstern, 2014). Degassing through soil, bubbling pools, and fumaroles allows volatiles to enter the atmosphere from the ground. 70 out of 9000 km^2 within the park are covered with boiling thermal features with an estimated convective heat flow of 5-6 GW combined, which is 30 times greater than the average North American heat flow value (Smith and Braile, 1994). The soil-gas flux is also one of Earth's most abundant sources of CO_2 as the system releases more than 45,000 tons per day (Lowenstern et al., 2006). It is unknown whether the high gas flux indicates the system is heating up with the addition of magma into the subsurface or is cooling down. Yellowstone has also erupted 80 smaller, separate rhyolitic flows since the super eruption 640,000 years ago, the last of which was 70,000 years ago.

When Christiansen and Blank (1972) discovered the Yellowstone area had experienced three highly explosive eruptions, they also identified "resurgent domes" in the center of Yellowstone caldera (Lowenstern et al., 2006). They found that the calderas center had risen approximately 80 cm since the 1920s, but by the 1990s the domes had subsided. With GPS and

InSAR data, researchers found that different parts of the caldera will experience uplift while other parts experience subsidence. Intrusion of magma or migration of hydrothermal fluids could be the main mechanism driving these deformation changes; however, it is difficult to pinpoint an exact cause due to the lack of monitoring geochemical proxies. Yellowstone has uplifted 1 km over the past 8 million years; therefore, the uplift rate is approximately 0.1-0.125mm/year (Pierce and Morgan, 2009).

The Yellowstone region experiences 1000-3000 detectable earthquakes every year, most of which follow the trend of the ring-fracture system that formed during the collapse of the 2.1 Ma eruptions caldera (Lowenstern et al., 2006). Seismic activity can be an indicator of a possible eruption, especially if that activity changes or increases in frequency or intensity. None of the large magnitude earthquakes have led to a volcanic eruption since an eruption 70,000 years ago, but the impacts of an earthquake cannot be ruled out as a 2002 earthquake in Alaska caused smaller earthquakes and changes in the hydrothermal system in Yellowstone as a result. Earthquake swarms are earthquakes clustered in space and time (Smith et al., 2009), and three large swarms have occurred since 1985 in Yellowstone. The transition from inflation to deflation of the surface could also coincide with earthquake swarms because of the movement of hydrothermal fluids and pressure releases within the caldera (Hurwitz and Lowenstern, 2014) as changes in pressure can result in uplift or subsidence.

Geochemical monitoring would also be useful for Yellowstone's hydrothermal system, which includes geysers and hydrothermal features, to track any changes in the fluid chemistry that could indicate a potential eruption (Lowenstern et al., 2006). Hydrothermal explosions eject rock fragments and, over the past 30 years have formed craters a few meters in diameter (Muffler et al., 1972). However, hydrothermal explosion craters found from the last 15,000 years are assumed to have been much larger as they have diameters of 100-3000m. Hydrothermal explosions occur when confining pressure in a system is reduced, which allows water to quickly change to steam (Hurwitz and Lowenstern, 2014). They are considered the most dangerous natural features within the park (excluding confrontations with bison and grizzly bears). In September of 1989, reservoir temperature had increased by 10°C since 1962, which is inferred to have caused a hydrothermal explosion in the Norris Geyser Basin of Yellowstone (Fournier et al., 1991). In May of 1888, the largest hydrothermal explosion within historical times in Yellowstone occurred in the Midway Geyser Basin where 0.3m diameter blocks were ejected over 150m from the explosion site (Hurwitz and Lowenstern, 2014). Earthquakes, gas emission changes, or reduced pressure from drought or deglaciation may be the causes of hydrothermal explosions (Lowenstern et al., 2006).

Eruptions during Human History

Super eruptions have not taken place during human history, but smaller magnitude eruptions have severely impacted the climate and human life. Mount St. Helens erupted less than one cubic kilometer of magma in 1980, Vesuvius (AD 79) erupted approximately five cubic kilometers of magma, and Tambora erupted 25-150 cubic kilometers of magma. Super eruptions can erupt thousands of cubic kilometers of magma. The largest super-eruption found in the geologic record is the eruption of La Garita in Colorado, USA, which formed the Fish Canyon

Tuff 28 million years ago and produced about 5,000 cubic kilometers of deposits. The entirety of magma erupted by Mount St. Helens could be erupted in a few minutes during a super eruption. A few case studies of eruptions during human history include Mount Tambora, which is the largest eruption in human history and caused many deaths, Pinatubo, where the government handled the eruption well but struggled with helping displaced communities and mitigating lahar hazards, and Eyjafjallajökull when aviation was halted in the northern hemisphere due to high quantities of ash in the atmosphere (Figure 4).

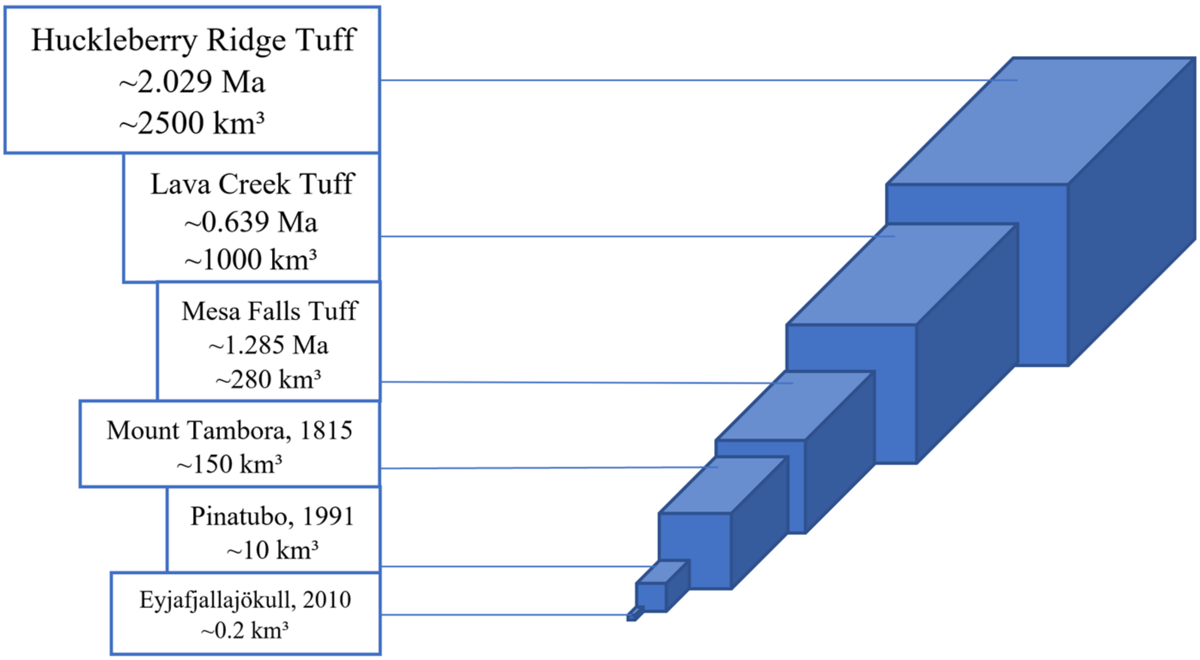

Figure 4: The rectangular prisms represent the volume of eruptive material for the three Yellowstone hotspot eruptions compared to the eruptions of Mount Tambora, Pinatubo, and Eyjafjallajökull. Figure modified from Smith and Braille (1994).

Mount Tambora

The eruption of Mount Tambora on the Indonesian island of Sumbawa during the year 1815 was the largest in recorded history (Boers, 1995). Mount Tambora erupted as a caldera and resulted in a six-kilometer-wide caldera where the top third of the mountain once existed. Mount Tambora erupted for 24 hours at a rate of one billion kilograms of magma per second (Self, 2006) and ejected 25 to 150 km^3 of volcanic material (Figure 4) (Shapiro and Koulakov, 2015). Three years before Mount Tambora erupted, there were signs of a possible eruption such as a cloud that increasingly grew darker over time above the summit as well as a loud rumbling noise until the eruption occurred (Boers, 1995). Initially, a pyroclastic flow ran down the slope of the mountain that destroyed and killed anything in its path immediately, devastating any nearby villages and leaving an initial death toll of 10,000 people. Several minutes after the eruption, a tsunami occurred on the Sanggars northern coast and destroyed even more villages and resulted in more deaths. Eventually, the ash settled over the land from 0.6 to 1.2 meters in thickness, killing 95% of the rice crop, 75% of the livestock, and polluting the water supplies. The leading cause of all 117,000 deaths was starvation, as there was barely any food or water that was not polluted by ash to sustain the population of Sumbawa. The death toll does not even include the deaths that occurred in nearby areas when diseases spread from the initially impacted island. The Indonesian economy collapsed and approximately 37,000 people left Sumbawa to immigrate elsewhere. Island inhabitants resorted to eating dry leaves and poisonous vegetation, selling themselves to escape the island, selling their children to be able to afford food, scavenging from the dead littering the island, digging up graves to steal the valuable items buried with the dead, and resorting to killing their children in order to save them from the extended pain of starvation. For those that passed away, a funeral service was unlikely as there were too many people that died and too few who survived or remained on the island to bury them. The effects of the famine were intensified by epidemics and rat-borne diseases, sending the island into severe poverty.

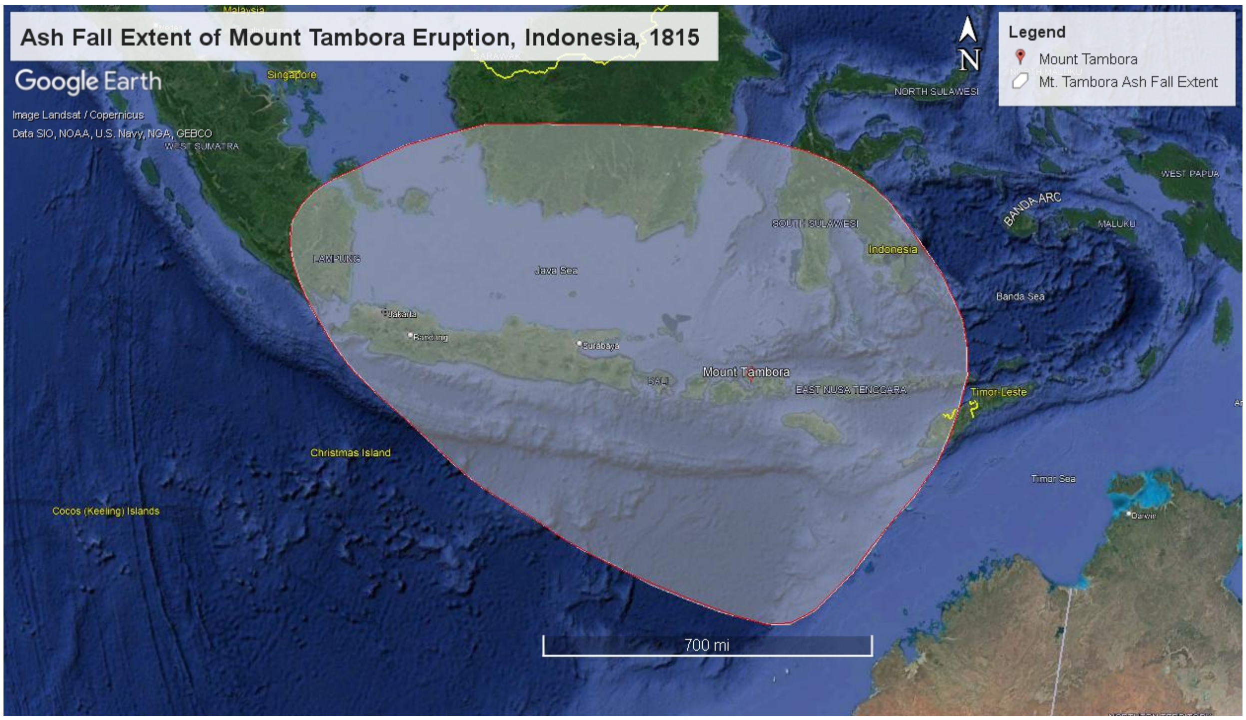

Figure 5: Shaded area represents the ash fall extent of the Eruption of Mount Tambora, Indonesia, 1815, according to Zollinger (1855) and Petroeschevsky (1949). Modified from Boers (1995).

Many animals suffered due to the eruptions as they were either incinerated by falling ash, disease stricken, experienced famine, or drank polluted water, causing a reported 75% of livestock to die. Wild birds and bees were also severely impacted by the ash fall (Boers, 1995). Birds, bees, and horses were some of the main commodities to come from Sumbawa, therefore the economy collapsed from the eruption and the people had to rely on imported goods.

Within the next year, the global mean temperature decreased by 0.5°C due to the increased albedo caused by sulfuric aerosols released into the atmosphere from the explosion (Boers, 1995). The decrease in temperature may not seem significant, but the northern hemisphere was largely impacted by the change. The year after the eruption, 1816, was called "the year without summer," as many places experienced rainy weather and colder temperatures. The northeastern U.S. and Europe had a frost cover its summer harvest that killed the crops, leading to famine. Altogether, the eruption led to the worst famine of the 19th century (Oppenheimer, 2003). The weather of the summer of 1816 was so gloomy and stormy that it even inspired Mary Shelley to write her novel *Frankenstein* and Lord Byron to write his poem *Darkness* (Sparks and Self, 2005). The eruption of Mount Tambora devastated Indonesia and impacted the climate on a global scale. Also, Indonesia was drier between 1816 to 1818 because it was cooler which means there was less condensation and precipitation. Tree rings from Indonesia also show thinner rings for the years 1816-1818, meaning the years were unusually dry (Boers, 1995).

The crops in eastern Sumbawa could be harvested for the first time five years after the eruption (Boers, 1995) but due to the easterly monsoon winds pushing more ash west, western Sumbawa crops took longer to recover (Figure 5). The short-term consequences are devastating, but one good thing did come from the eruption – the soil was more fertile than ever on any of the islands that received significant ash fall, such as Bali, Lombok, and South Sulawesi. Bali and Lombok were the largest exporters of rice a few years later. The eruption also allowed the island of Flores and its Manggarai people to stop paying tribute to the Sultan of Bima for many years until the Bimanese seized power again.

When Mount Tambora erupted, it created a caldera 6 km in diameter – in comparison, Yellowstone's caldera is ~65 km in diameter at its widest point. If the eruption in Indonesia was able to decrease global temperatures by 0.5°C within a year (Boers, 1995), imagine what would happen if a super volcano like Yellowstone were to erupt. Also, at the time of the eruptions, Indonesia had a population of 10 million and today the population is well over 200 million. The number of lives impacted by the eruption of Mount Tambora would be much larger today than in 1815.

Pinatubo

On June 12th, 1991, in the Philippines, Mount Pinatubo began its eruption that created some of the largest ash clouds observed since the onset of satellite use (Minnis et al, 1993). 5-7 km^3 (Figure 4) of pyroclastic material was deposited on the slopes of Pinatubo, thus allowing many lahars to occur with rainfall, which threatened 770 km^2 of the Philippines (Leone and Gaillard, 1999). The magma was emitted for 3.5 hours during the Pinatubo eruption of 1991, meaning almost one billion kg/s of magma was released in that time frame (Self, 2006). A 2.5 km diameter caldera was formed and aerosols spread around the globe, affecting global temperatures for 2-3 years afterwards (Sigurdsson et al., 2015). The highest proportion of deaths and destruction for the Pinatubo eruption were lahars (Photo 3), which are mobilized and travel downslope when new volcanic deposits are influenced by rainfall (Self, 2006) and can move 50 km/hr for tens of kilometers (Hansell et al., 2006). After Pinatubo erupted, lahars reached rivers and were transported downstream to block the river mouths from the build-up of new sediment. Lahars also continued to occur annually for many years after the eruption in 1991. From 1991 to 1997, total sediment delivery was estimated as 3,209 Mm^3, dead and/or missing was estimated as 1,209, 957 of which were recorded in 1991, and almost 150,000 homes were damaged (PHIVOLCS, 1997). The estimated cost of this eruption is US$ one billion and over 2.1 million people were affected (Leone, 1996)

The management of the eruptions and proceeding lahars had many associated strengths and weaknesses (Leone and Gaillard, 1999). During the first phases of the eruption, populations were put into a state of alert by a warning given on time, allowing people to sufficiently evacuate the areas deemed risk zones based on the volcano's historic and geologic events. The activity of the volcano was also discovered early in August of 1990 as rumblings, fissures, and landslides, allowing plenty of time for the authorities to plan for the impending eruption. The populations were made aware of the danger of the eruption based on effective awareness films and information provided by the Philippine Institute of Volcanology and Seismology and the USGS. The warning system was later improved to include warnings for lahars and floods. The evacuated populations are moved into evacuation centers as the first step to providing people with funds for immediate relief, establishing communities, providing employment opportunities, and repairing/reconstructing infrastructure. However, many families had to remain in evacuation centers with poor hygiene and living conditions, overcrowding, and food, water, and medicine shortages for months to years because of a lack of qualified workers. High levels of stress and trauma were common as evacuations persisted for many years. By December 1997, 42,396 families were accommodated in the resettlement centers (Leone and Gaillard, 1999). Although the evacuated population responded well to the initial warnings, they were not consulted on measures of how to deal with the lahars, which created resentment between the people and the government (Figure 6). Dikes were constructed to try to control the flow of lahars, but some construction was politicized. One 'megadike' had reinforced portions constructed to protect certain cities due to political reasons while 60% was not reinforced, which led to many breaches and endangerment of the public.

Figure 6: Cartoon in the *Philippine Daily Inquirer* (08/26/1993) showing the ineffective and expensive protective measures prioritized by authorities for possibly political reasons, much to the detriment of important resettlement programs for displaced people (Leone and Gaillard, 1999).

Photo 3: Only the top of this church in Bacolor is exposed, as the lower parts are covered by a lahar flow. Photo taken by F. Leone, June 1996. (Sparks and Self, 2005).

Eyjafjallajökull

Eyjafjallajökull is a stratovolcano on the southern coast of Iceland (Peterson, 2010). Unrest was observed for the year prior to the eruption that began on March 20th, 2010. At first, only a small amount of ash was produced during the small-scale eruptions, so people were able to visit the volcano to see the flowing lava in person. Earlier ash falls impacted local farms to the southeast of the mountain badly and the fine ash covered the landscape (Lund and Benediktsson, 2011). However, the event was dealt with in an orderly fashion as a disaster plan was practiced several days before the eruption. Locals were evacuated and the damage was quickly repaired. The ash fall covering the local area did increase anxiety, but no one was injured or killed, and the rest of Iceland was largely unaffected. On April 14th, the eruption changed as the ice-filled main caldera began a more explosive eruption with an ash column 9.5 km in height (Peterson, 2010) that was carried northeastward over Europe. Reykjavik is 150 km away from the eruption site and was impacted very little due to the prevailing wind directions (Photo 4) (Lund and Benediktsson, 2011). When magma with certain chemical compositions interacts with water, high quantities of ash are produced. Ash and tephra amounts were estimated at a total of 0.2 km^3 magma (Figure 4) was released over 59 days (Peterson, 2010). This resulted in the largest air-traffic shutdown since World War II, as 80% of the European aviation network closed (Figure 7), and about 10 million passengers were stranded due to the cancellation of over 100,000 flights (Lund and Benediktsson, 2011). Heathrow airport outside of London, one of the world's busiest airports, was shut down for five days. Local communities were immersed in a one-kilometer-thick ash cloud (Peterson, 2010). By the end of May, ash production stopped and tremor activity decreased. The Eyjafjallajökull eruption produced 6-10 Tg of fine ash and had an estimated economic impact of five billion USD (Sigurdsson et al., 2015).

Photo 4: Taken by Joseph Licciardi. View of Eyjafjallajökull ash cloud with prevailing wind direction to the East.

Ash can not only decrease visibility (so long as the ash itself is visible) but is dangerous for aircraft. When ash particles enter an engine, the heat melts the ash into a viscous substance that clogs airflow openings in the engine (Sigfusson et al., 2010). In 1982 a Boeing 747 lost power between Kuala Lumpur and Perth after the aircraft flew through a cloud of volcanic ash from the Mount Galungguang eruption in west Java (Diamond, 1986). Volcanic eruptions are commonplace in Iceland (Peterson, 2010), but even experience with volcanism cannot prepare everyone for the multitude of dangers that arrive with eruptions. Our extreme dependability on the mobility of our world is very vulnerable to high quantities of ash present in the troposphere and stratosphere.

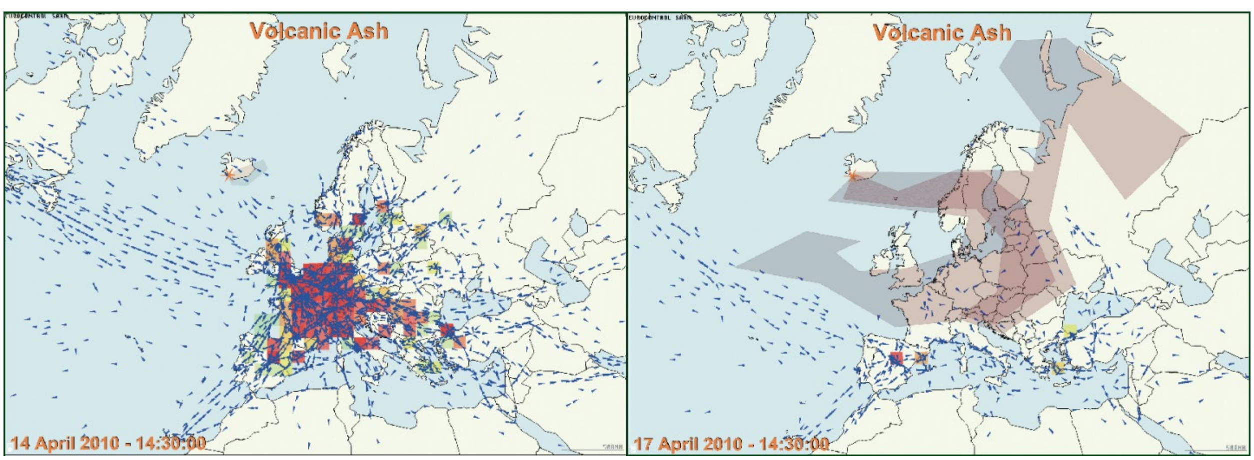

Figure 7: Air traffic in European before and during the Eyjafjallajökull eruption in Iceland. Lines and colors represent air traffic on April 14th and shaded area represents closed air space on April 17th. Figure from (Lund and Benediktsson, 2011).

Volcanic eruptions in human history have also inspired many artists. When sulfate aerosols enter the atmosphere, they scatter most of the shortwave radiation while the longwave radiation is mainly absorbed and can lead to bright red sunsets (Harris, 2008). For example, when Krakatau erupted in 1883 it caused brilliant sunsets over Oslo, leading the artist Edvard Munch to paint "the Scream"; he was quoted saying, "… I stood there trembling with anxiety and I sensed an infinite scream passing through nature," (Sigurdsson et al., 2015).

Eruption Warning Signs and Immediate Impacts

Tremors are possible indicators of an impending eruption as continuous, low-frequency seismic activity has been observed to occur before and during many explosive eruptions (Lowenstern et al., 2006). Over the last two decades, there have been more than 25 successful forecasts of eruptions based on monitoring of seismic activity and infrasound (sound waves where most volcanic acoustic energy is concentrated) (Sigurdsson et al., 2015). Yellowstone's seismicity, ground deformation, water temperature, and chemistry are closely monitored. These are monitored for well-known super volcanoes, but it is speculated that many other potentially hazardous super-volcanoes exist that are not well-known or monitored (Sparks and Self, 2005) In the case of Mount Pinatubo, monitoring of seismic activity occurred just a week before the eruption, allowing officials to plan the evacuation of locals. However, there are still large challenges when it comes to providing adequate warnings to communities since we still lack knowledge of potential warning signs for higher-magnitude eruptions (Lowenstern et al., 2006). Calderas that are known to have erupted multiple times in the past, like Yellowstone, are especially important to monitor as we do not yet fully understand the warning signs of highly explosive eruptions. About every 100,000 years, at least one super-eruption large enough to cause global disaster occurs (Sparks and Self, 2005). Also, as a rule of thumb, the longer a volcano is dormant, the larger the eruption will be in magnitude and intensity. Therefore, a super eruption will happen eventually, and civilization will reach a point where the devastating impacts can no longer be ignored, but preemptive measures can be put in place to diminish those impacts. It is important to establish a baseline of seismic activity for volcanoes in order to understand when there is a change in the system (Sigurdsson, et al. 2015). Changes can forecast the size and timing of eruptions, based on prior knowledge. Eruptions tend to follow earthquake swarms or tremors. Some well-monitored volcanoes, one of which is Mount St. Helens, have more than six seismic stations around the volcano to detect earthquakes and disturbances beneath the surface, even at low magnitudes.

The movement, size, and composition of volcanic plumes is imperative to know in order to invoke effective hazard mitigation strategies (Sigurdsson et al. 2015). Magma migrating upward and a long-term accumulation of magma in the subsurface can indicate an eruption is in progress). The movement of magma causes changes in pressure within the volcanic system and can result in ground deformation. GPS, InSAR, and surveying techniques can be used to measure changes caused by that deformation.

The most dangerous immediate impact of an explosive volcanic eruption is pyroclastic density currents or flows that move at incredibly fast speeds with high temperatures, destroying anything in their path (Sigurdsson et al., 2015). Pyroclastic flows are clouds of hot gas and tephra that can move at speeds of 350 km/hr or more and reach several hundred degrees Celsius, ultimately killing anything in its path (Hansell et al., 2006). During the Mont Pelee eruption of

1902, pyroclastic flows moved at speeds of 160 km/hr and killed 29,000 people within minutes. Pyroclastic flows cause deaths of heat-induced fulminant shock or “boiling brains”, asphyxia from plugged airways, lung injury from the heat, and deep burns. Also, local fires, lahars and other landslides, tsunamis, and earthquakes are all immediate hazards that can be caused by an explosive volcanic eruption. Pyroclastic flows and other immediate hazards from a Yellowstone eruption most likely will not reach New England, but the displacement of locals likely will occur.

Volcanic Ash Coverage

When eruptions produce ash that can penetrate the stratosphere, tephra can be carried downwind and travel several thousand kilometers before falling out and covering areas over 1 million km^2 (Self, 2006). Tephra is any fragmented material that was emitted from a volcano and ash is a tephra particle less than 2 mm in diameter (Hansell et al., 2006). The hazards of tephra to humans include inhalation, abrasion, roof collapse due to build up, pollution to aquatic environments, and damage to agriculture/vegetation. Ash can also disperse in any direction depending on the explosivity of the eruption and wind patterns and have very wide ash dispersal deposits. Ashfall deposits near the volcano can be over 10 meters in height and decrease as the distance from the volcano increases, sometimes thousands of kilometers away where the ash fall layer is very thin. Even if ash is only a few centimeters thick, the ash can still cause roofs and powerlines to collapse, pollute water sources, and destroy agricultural areas, and this is exacerbated if the ash is wet. One centimeter of ash is enough to destroy agriculture, especially if it falls during the growing season and a few millimeters can destroy many types of crops (Sparks and Self, 2005).

In a paper by Mastin et al. (2014), the ash fall of a potential Yellowstone eruption was modelled examining the long-distance expansion of an umbrella cloud-shaped plume as well as the dispersal of erupted material in the varying wind field. The model has the super volcano erupting a fixed value of 330 km^3, which was chosen by compiling the tuff volumes of the last three caldera-forming eruptions as well as including a fraction of that volume to represent ash deposited further than where deposits can be found today. The wind field data is from the year 2001, when wind patterns were not strongly influenced by El Nino/Southern Oscillation. The height and vertical distribution of mass were constant throughout eruption. The model simulated an umbrella cloud with a top at 25 km, but they also tested tops at 15 km and 35 km. These umbrella cloud heights were used because they are similar to ones observed; for example Pinatubo reached a plume height of 40 km but its umbrella cloud spread out around 18-25 km.

The model from Mastin et al (2014) compared the ash distribution over three days, one week, and one month for four different times during the year. The models also have different grain size distributions. A heavily aggregated grain size distributions is more dense and larger relatively, moderately aggregated is of medium density and size, and weakly aggregated is less dense and smaller in size. In Figure 8, New England was covered in 3 to 30 mm of tephra deposits and the most effective parameter in dispersing ash is the grain size distribution.

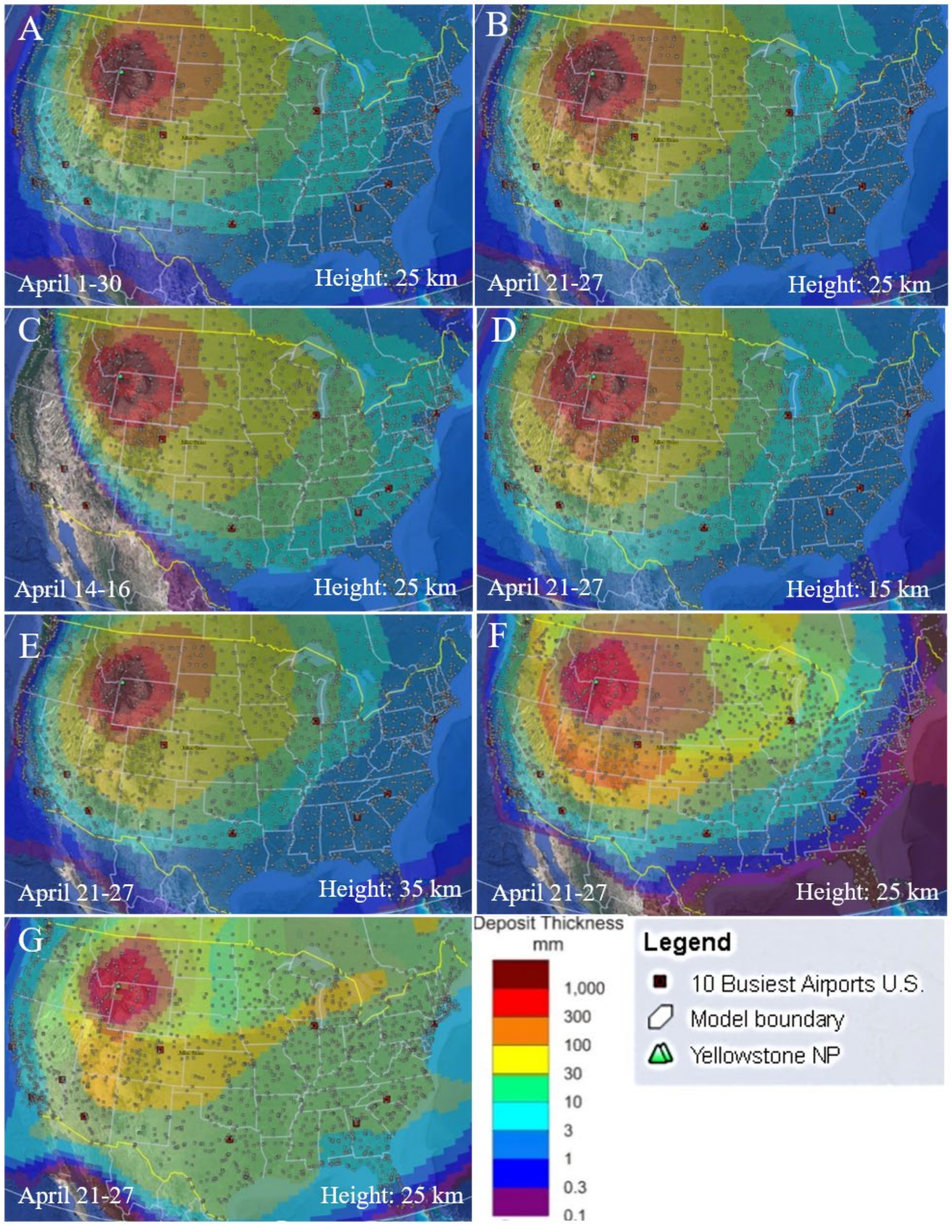

Figure 8: A-G represents the simulated tephra fall thickness from a Yellowstone eruption under various circumstances. Airports in the US are also shown, and the ten busiest US airports are shown in red to show the effects on air travel in the US. With these simulations, New England is supposed to receive some ash fall. A-C represents simulated tephra fall thickness from a Yellowstone eruption of 330 km3 with April 2001 wind fields, an umbrella cloud height of 25 km, and heavily aggregated grain size distribution. (A) represents a month-long eruption, (B) represents a week-long eruption from April 21-27, and (C) represents a 3-day long eruption from April 14-16. (D) represents an umbrella cloud height of 15 km for a week-long eruption. (E) represents an umbrella cloud height of 35 km for a week-long eruption. (F) represents tephra with a moderately aggregated grain size distribution for a week-long eruption. (G) represents tephra with a weakly aggregated grain size distribution for a week-long eruption. Data from Mastin et al. (2014).

Topography has been found to be the most important factor in controlling large-scale atmospheric flow (Pausata et al., 2011). The Mastin et al. (2014) study used wind patterns during the year 2001, which is in the current interglacial period. If the Yellowstone eruptions occurred during glacial periods, the wind patterns could be very different due to the different topography introduced by ice sheets. During the Last Glacial Maximum, a simulation by Pausata et al.

(2011) found a stronger and sharper northward-shifted 200-hPa zonal wind maximum, suggesting that ice sheet topography plays a dominant role in altering atmospheric circulation, especially around 40-50 degrees latitude north, in the same latitudinal zone as Yellowstone. Any alterations in wind pattern could therefore change the ash distributions and explain why we do not see evidence of Yellowstone's past eruptions in New England. Evidence also may not be seen in New England because of erosive processes over time, such as the advancement and retreat of the Laurentide Ice Sheet during the Last Glacial Maximum. However, larger eruptions tend to be less sensitive to wind fields than smaller eruptions (Mastin et al., 2014), so the effects of wind patterns could be negligible.

The model shows three different grain size distributions because volcanic ash is not the same for volcanism around the world as they have a variety of sizes and compositions (Sigurdsson et al., 2015). Most ashes are 30-100% volcanic silicate glass and can contain many minerals that are typically silicates. Larger particles are greater than 1 mm in diameter and fall from the atmosphere within 30 minutes of ejection. Finer ash particles are less than 1 mm in diameter and have an atmospheric residence time greater than 30 minutes. Very fine ash particles are less than 30 micrometers in diameter and can have a residence time up to several days. Particles of ash finer than the diameter of human hair (1-30 micrometers) can take several months to fall out of the atmosphere depending on the height of the plume and wind patterns.

Health Hazards

The eruption of Mt. Saint Helens in 1980 sparked research into the health hazards associated with volcanic ash (Hansell et al., 2006). Such research revealed that tephra contained crystalline silica, which can expose people to silicosis (a lung disease caused by inhalation) and chronic obstructive pulmonary disease (which obstructs airflow to the lungs). The UK Department for International Development conducted a risk assessment in 2003 for developing symptoms of silicosis. They found that the population in areas highly affected by ash over long periods of time had a just over 1% risk of developing silicosis. However, people who worked outdoors had a 2-3% risk and even up to 10% risk in some cases over the long exposure period. Other health effects of ash would include increased cases or intensity of asthma, bronchitis, and pneumonoconiosis, irritation to the eyes and skin (especially in the presence of acid rain), exposure to polluted water that could result in fluorosis, and mesothelioma (cancer generally associated with asbestos exposure). Gas emissions could cause increased or worsened cases of bronchoconstriction, respiratory diseases, eye and skin irritation, asphyxiation from CO_2 and H_2S, and lung cancer from long-term exposure to radon. Areas that experienced high levels of airborne ash had a 2-3-fold increase in hospital admissions and a 3-5-fold increase in respiratory cases in emergency rooms. Overall, the ash irritated the affected population's airways, leading to increased mucous production and inflammation. The size of the ash particles can also impact human health differently, where larger particles (4-10 micrometers) impact the upper airways and finer particles (less than 4 micrometers) can enter deeper parts of the lungs. The more free silica available in the ash composition, the more hazardous the ash is to human health. Also, the higher the iron content, the more free radicals can adhere to the surface of the particles. However, most cases of people affected by volcanic ash and volatiles had pre-existing respiratory conditions, but understanding the longer-term effects is still unclear. Volatiles emitted during an eruption can also be dangerous, and include gases like CO, CO_2, SO_2, HCl, HF, H_2S, and radon as well as several types of metals like mercury and lead (Hansell et al., 2006). However, only 1-4% of volcano-related deaths are due to volcanic gases (Sigurdsson et al., 2015).

Risks to human health and safety are not limited to ash and volatile exposure. Car accidents, disease, starvation, and mental health issues are all side effects to human populations in the event of a volcanic eruption. The risks of future volcanic eruptions continue to increase as the global population increases, especially in areas surrounding volcanoes (Hansell et al., 2006).

Impacts on Agriculture, Livestock, and Water Quality

The most severe impact of a Yellowstone eruption would be its effect on agriculture as millions of square miles of farmland would be covered by ash to a depth of meters to centimeters and the changes in climate could decrease the crop yield (Photo 5). Most food production is concentrated in the Northern Hemisphere, where most of Earth's population is as well. If a Northern Hemisphere super eruption were to take place, mass starvation would be expected, especially in vulnerable regions (Self, 2006). From 1600 to 1982, volcanic gases caused 40% of volcano-related deaths indirectly due to the destruction of crops by means of starvation and disease (Sigurdsson et al., 2015). Not only would humans be impacted, but so would wildlife and domesticated animals. Gases and metals in the environment and from the eruption can adhere to the surfaces of volcanic particles and when the fall out of the particles occurs, the toxic particles could end up being consumed by grazing animals or contaminate surface waters. At least several years after the eruption, the soil will be very fertile from the volcanic deposits which could lead to high crop yields under certain circumstances.

One element that would be of major concern if high enough amounts were present in an eruption would be fluoride because highly fluoride-contaminated water consumed for many years can cause chronic skeletal fluorosis. Chronic skeletal fluorosis results in weakening of bones and stiffening of and pain in joints. Such circumstances have been reported in Vanuatu, where a volcano that regularly degassed the contaminates would adhere to rain particles and be collected by the islanders for drinking water. Also, chemical and filtration/blockage issues in the water supply as well as blockage of sewage treatment processes could occur (Self, 2006). If sediment were to build up in waterways, for example the lahars entering waterways after Pinatubo erupted, then that sediment would need to be dredged in order for transportation to continue. The build-up could also change the hydrology of the region by damming certain waterways and thus affecting local people, animals, and plant life that rely on that water.

Another impact of volcanism on water quality has to do with acid rain. When volcanoes emit sulfur compounds and hydrochloric acid (HCl), those gases interact with water particles in the atmosphere by lowering the water particle's pH (Johnson and Parnell Jr., 1986). Once the particles precipitate with the HCl and/or sulfur, the rain has a pH around 2.5 to 5 rather than the neutral pH of 7. This change in pH is enough to kill vegetation locally to the rain, which can further damage crops, harm animals, and decrease the useability of local water sources as the acidity would need to be neutralized before consumption is safe. Once the HCl and sulfur are no longer in the atmosphere, then the pH of the rain will return to its normal value.

Photo 5: Ashfall on crops in Karo, Sumatra, Indonesia after the eruption of Mt. Sinabung in 2014. Photo from USGS.

Impact on Air Travel and the Economy

When Eyjafjallajökull volcano erupted in 2010, air traffic was disrupted for several days to weeks depending on distribution of ash, and this was considered a moderate eruption (Shapiro and Koulakov, 2015). If Yellowstone were to have a super-eruption larger in magnitude than Eyjafjallajökull, then its impacts on air travel would be even more significant than in 2010. For example, the over 550 airports within the U.S. would have to be closed while ash fall is still occurring across the U.S., as shown in most of the models in Figure 8. Air traffic would not be able to continue at these airports until the ash in the atmosphere is safe to fly through and the ash deposited at the airports is removed. Photo 6 shows Quito International Airport in Ecuador after an eruption in 2002. The airport was covered in 3-5 mm of ash, which is within the range of ash New England would receive, and it took 8 days to clean up. Any more ash deposited would take much longer to remove and if that demand is occurring at all airports around the country, then the process may take even longer to clean. A Yellowstone eruption would also halt air traffic not just within the U.S., but all around the world because of the large amounts of material released that would circulate and spread around the globe. The eruption and aftereffects would also have a huge economic impact around the world.

Natural disasters are expensive to recover from. Every effect a Yellowstone eruption could have on health, agriculture, travel, and climate would all impact the world markets (Sparks and Self, 2005), especially given the role the U.S. plays within those markets.

Photo 6: Quito International Airport during eruption of Reventador Volcano covered with 3-5 mm ash on 3 November 2002. Airport was closed for 8 days for cleanup. Photo from USGS.

Changes in Climate

The potentially most dangerous effect of a volcanic eruption larger than those seen in human history is the impact that eruption could have on the climate. If very large amounts of sulfurous gases are emitted into the atmosphere and react with water particles, cooling will occur on Earth's surface (Harris, 2008). When a volcano erupts, aerosols (any suspended particles in the atmosphere) are injected into the atmosphere and can reach the stratosphere, which is the atmospheric layer above the troposphere (where humans live) at about 12-30 km altitude (Sigurdsson et al., 2015). There is very little vertical motion and no precipitation in the stratosphere, so volcanic aerosols can remain there circulating the globe at a fast rate for up to two years until they settle out over time. Aerosol clouds are usually limited to the hemisphere of the eruption when the eruption takes place more than 30 degrees from the equator, but aerosols themselves can spread around the globe (Self, 2006). Since Yellowstone is not located within 30 degrees N and 30 degrees S, the spread of ashes and gases could happen slower than volcanoes within those latitudes (Sparks and Self, 2005). When Pinatubo erupted, the aerosols circled the Earth in 22 days (Harris, 2008). Sulfate aerosols, or sulfuric acid H_2SO_4, decrease the effects of incoming solar radiation (insolation) by scattering shortwave radiation and, in turn, lead to a cooling of Earth's average temperature. The aerosols are formed by sulfur dioxide SO_2 present in the eruption reacting with hydroxide OH^- present in the atmosphere. For example, Mount Pinatubo decreased global average temperature by 0.5 °C a year after the eruption took place. It has also been well-documented that some areas experience a warmer/milder winter while other areas will experience cooling (Hansell et al., 2006). However, volcanism-induced climate change is only short-term and has been observed to return to its pre-eruption state three to four years later (Sparks and Self, 2005). Therefore, a volcanic eruption could be helpful in that it would temporarily pause the impacts of human-induced global warming.

Increased stratospheric aerosols from volcanism would also decrease the amount of ozone, thereby allowing an increased ultraviolet radiation (UV-B) flux to reach the Earth's surface in high-to-mid latitude regions for several years after the eruption occurs (Self, 2006). This can severely impact the health of life on Earth. Two years after Pinatubo erupted, mid-latitude ozone depletion almost doubled and 'holes' persisted for a few more years.

Since volcanic eruptions release abundant amounts of greenhouse gases like CO_2 and H_2O (Sigurdsson et al., 2015), one would think that an explosive eruption would result in an average warming of the planet. However, atmospheric concentrations of those gases are already high, so the injection of more from a volcano could be considered negligible. In fact, the globally averaged emissions of CO_2 per year from volcanic eruptions are at least 100 times smaller than CO_2 emissions from human activities, based on data collected since 1750. Models have been used to understand the climatic impacts of super eruptions and found that the average surface cooling could be 3-5 degrees Celsius, which may not sound like much, but a change in 4°C that lasts over a long period could cause a new ice age (Sparks and Self, 2005). However, climate models are very complicated and always need improvement to obtain more reliable results.

Effects on New England

New England is a region in the northeastern corner of the U.S., a fair distance from Yellowstone (> 3000 km) compared to the rest of the country. There is no evidence found so far that tephra from the past three super-eruptions of Yellowstone reached New England, hence the region has been left off ash fall distribution maps for many years. However, recent model simulations show that ash could reach New England under various parameters, leaving the region covered with 0-30 mm of ash (Mastin et al., 2014). This would have lasting impacts on New England in terms of health, agriculture, travel, and economy, not to mention the variety of other issues that an eruption of this scale would cause pertaining to the climate and influx of residents.

Health

Those with pre-existing respiratory conditions are the most vulnerable to health conditions related to ash such as silicosis and chronic obstructive pulmonary disease. Those without pre-existing conditions are likely to experience inflammation in their airways and irritation of their eyes and skin. The deaths caused by the ash and other gases alone would be devastating, but the secondary effects of the eruption, such as overpopulation and starvation, could be the main driver for injuries and fatalities among New England residents. Since residents from the western states will have to move to the less affected eastern states, the overpopulation in an area that is already highly developed and populated will allow disease to spread more easily. Imagine the COVID-19 pandemic, but with the entire U.S. population concentrated along the east coast, a portion of which would now be in New England. The amount of trash and human waste would also increase and contribute to the exposure of disease. New Englanders will also experience water pollution. This could have negative effects on the wildlife in the region, killing off animals that humans in that region rely on for food and/or money. If humans are exposed to the polluted water for long enough, they may experience changes in their tooth enamel due to increased fluoride content in the waterways.

Agriculture

Crops that are exposed to ash are at risk for becoming contaminated with materials that are harmful to ingest or at risk of being destroyed in general. Also, previous eruptions that impacted local agricultural lands have shown that it is cheaper to restart the growing process than it is to treat and clean the ash covered plants. Also, livestock would be highly affected by ash fall as their grazing land would become contaminated with the ash as well as their water supply.

New England has 3,730,000 acres (~15,000 km^2) of operating farmland as of January 1, 2021, and the U.S. as a whole has 896,600,000 acres (USDA, 2021). From this farmland, there are 32,770 farm operations in New England and 2,019,200 farm operations in the U.S. total. At lot of crops would be destroyed (and businesses losing profit), leading the U.S. residents and countries the U.S. supplies food to losing those crops. This would lead to starvation across the United States as well as other locations around the world that agricultural products are sent to from the U.S.

Climate

Given what has been seen from eruptions such as Mount Tambora and Pinatubo, we would expect a Yellowstone super-eruption to change the global average temperatures by a minimum of 0.5°C or up to 5°C, as climate models have suggested (Sparks and Self, 2005). A sustained increase of 4°C or more could lead the world into another ice age. Not only would the remaining crops in New England be destroyed by unseasonably cold weather and frosts, like when Mount Tambora decreased the average global surface temperature, but this effect would be seen around the world, leading to mass starvation all over the United States and in many other countries as well. This predicted cooling is also averaged across the entire planet, so localized temperatures could be more or less extreme based on weather patterns.

Transportation

Boston-Logan International Airport is the 18th busiest airport in the U.S. (CY 2014 Preliminary Airports). The presence of this busy airport helps bring in domestic and international visitors, who spend $24.2 billion during their travels and support 153,000 jobs and $5.6 billion in wages and salaries in the New England state of Massachusetts as of the 2019 MOTT Annual Report. All of this income would be put on pause in New England as air traffic cannot continue while ash particles remain in the atmosphere due to the damage ash can inflict on aircraft and visibility changes.

Not only is ash dangerous to fly through, but it is also dangerous to drive on as it reduces the traction of the roads. Roadways around New England would have to be closed until the ash fall ceases and the roads can be cleared. This process may take a while, as the ash fall could continue for an extended period of time and paths to access hospitals and retrieve necessary materials would be prioritized.

Economy

Every effect a Yellowstone super-eruption would have on New England would also impact the economy. Not only would New England be affected, but the entire world as well given the role the U.S. plays in the world market.

Some major financial impacts to New England would involve the loss of agricultural products. In 2020, the New England State of Vermont produced the most maple syrup in the U.S. with 2,220,000 gallons and the total value of New England maple syrup production was valued at $81,264,000 (Agricultural Statistics Bulletin, 2021). In Strafford County, New Hampshire (where the University of New Hampshire is located), agricultural products had total sales of $10,479,000 in 2017 (USDA, 2017). The state of Maine has been the national leader in wild blueberry production since the 1950s, producing a crop valued at $26,028,000 as of 2021 as well as producing potatoes valued at $160,968,750 (USDA, 2021). Massachusetts was responsible for over 25% of cranberry production in the U.S. as of 2020 that is valued at $58,991,000 (Noncitrus Fruits and Nuts, 2020). As of January 1st, 2021, the USDA claims the total value of New England cattle is $428,031,000, the value of milk produced in New England is $750,493,000, and the value of alfalfa hay and other hay products is valued at $333,738,000. It can be assumed that if a Yellowstone super-eruption were to occur, all of these agricultural industries would be severely impacted financially, as well as many other industries outside of agriculture.

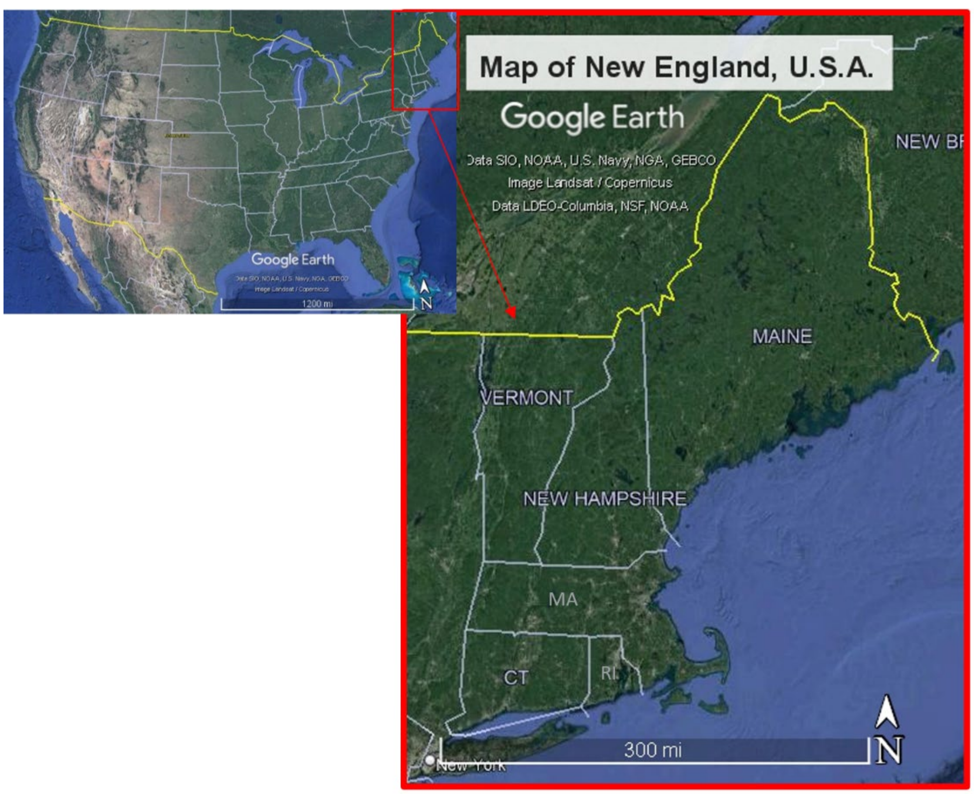

Figure 9: Map of New England and its location in the United States of America. Images from Google Earth Pro.

Mitigation Strategies

In order to decrease the risks of future eruptions, monitoring of hazardous volcanoes needs to be increased (Lowenstern et al., 2006). Only a small number of highly threatening volcanoes on Earth are monitored closely enough to provide reliable and predictable signs of an impending eruption. If a volcano erupts that is not being monitored well beforehand, society will not be able to gain knowledge of the signs of future eruptions. Scientists, emergency-management networks, politicians, and an informed public will need to collaborate and learn from each other in order to prepare for a super eruption. Even with preparation, however, the loss of infrastructure, agricultural lands, money, and lives will be detrimental. Scientists especially need to establish efficient and effective monitoring systems for the variety of geophysical and geochemical signals produced by volcanoes.

There are few if any strategies available today to allow populations to mitigate the impacts of a potential super-eruption (Sparks and Self, 2005). A volcanic warning system would have to be put in place to detect the impending danger as well as convey that information to everyone at risk (Sigurdsson et al., 2015). The U.S., and the world as a whole, will need to implement Volcanic Ash Advisory Centers (VAACs), such as those that were initiated after Pinatubo's eruption, to provide efficient warnings and advice about the volcanic ash clouds. There are three main phases to any crisis management: first we must prepare for the event, second we must respond to the crisis, and third we must recover. To prepare for the event of a volcanic eruption, a monitoring and alert system must be in place, plans must be made and practiced if the eruption were to occur, risk assessments must be made to determine who needs to be evacuated and who can remain where they are, and scientists must provide advice to the public, government, and first responders. When an event occurs, the practiced management strategies must be put into action based on scientific advice, roadways must be cleared so supplies and hospitals are accessible, masks and eye protection need to be distributed, western residents need to be moved to evacuation centers in New England and other eastern states, livestock must be relocated for protection, funds need to be organized for immediate relief, and unnecessary transportation needs to be halted. Once the initial eruption is over, the proper authorities must determine whether the danger of the eruption has ended and when displaced people can return home. If the displaced people cannot return home, then funds need to be organized to establish recovery communities and create jobs. In the event of a larger eruption such as Yellowstone, the recovery process will be long and the effects will be global.

Investment into research regarding high magnitude eruptions needs to increase in order to prepare for an eruption and to better understand the signs of an upcoming eruption to efficiently warn people (Sparks and Self, 2005). The International Association of Volcanology and Chemistry of the Earth's Interior (IAVCEI) has worked on an inventory of super-eruptions over the recent two million years as a step towards proactively creating mitigation plans for which super-volcanoes need to be highly monitored, and increasing knowledge on the frequency of potential super-volcano eruptions. By improving monitoring, raising awareness, and implementing research-based planning, the suffering of millions and perhaps even billions of people can be reduced.

Conclusion

After discussing the detrimental effects of a potential Yellowstone super-eruption on New England and the world as a whole, it is important to note there is a 99.9% confidence that Yellowstone will not experience a super-eruption in the 21st century (Mastin et al., 2014). However, that is not to say that other caldera systems around the world pose no danger (Figure 10). Given that Yellowstone lies within a developed western country such as the U.S., the caldera system is very well monitored by many experts in volcanism. However, other active caldera systems around the world are less well-monitored and some may still remain unknown to humans today. Therefore, not only is it important to have mitigation strategies in place for a future Yellowstone eruption, but it is also important to have those strategies known and ready to implement for other active calderas around the world in the event that a highly explosive eruption takes place in the future.

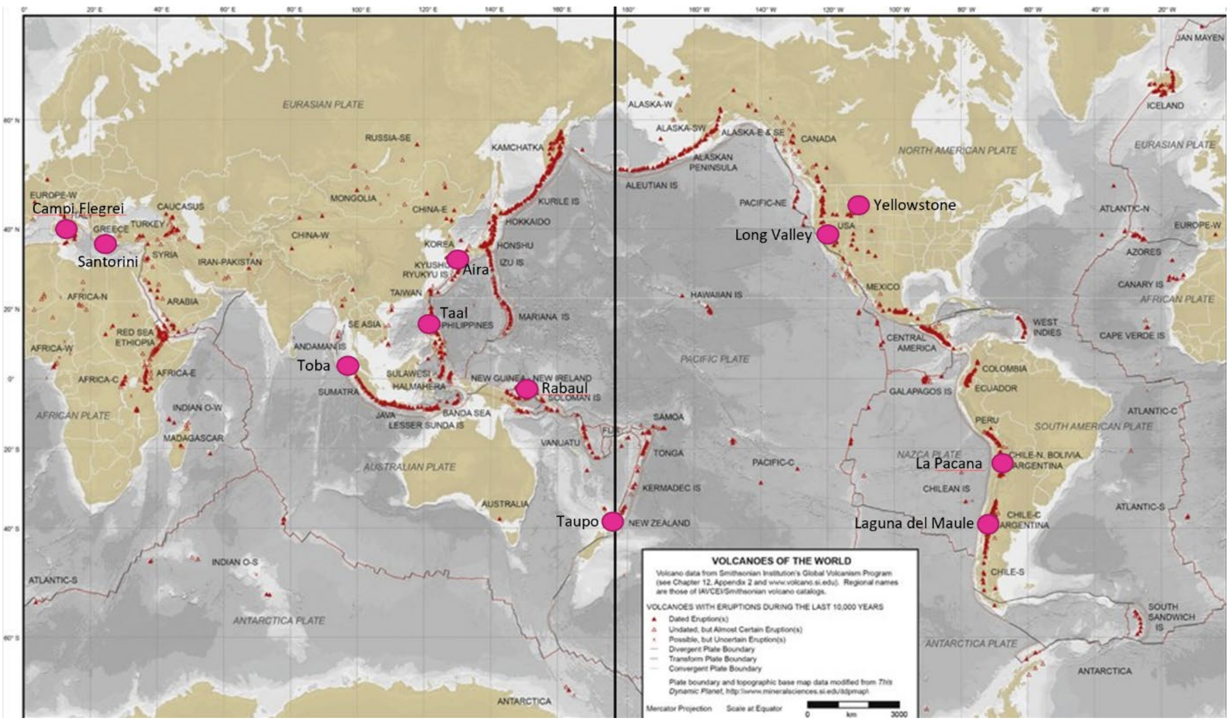

Figure 10: Volcanoes considered active around the world that have erupted during the last 10,000 years. The pink ovals represent some of the largest calderas in the world still considered to be active systems (cf. Mason et al., 2004) such as Toba (Indonesia), Yellowstone (U.S.), La Pacana (Chile), Taupo (New Zealand), Long Valley (California, U.S.), as well as other active systems such as Aira (Japan), Rabaul (Papua New Guinea), Taal (Philippines), Campi Flegrei (Italy), Santorini (Greece), and Laguna del Maule (Chile). Extinct caldera systems are not included. Figure modified from Sigurdsson et al. (2015).

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Works Cited

Agricultural Statistics Annual Bulletin: New England, 2020-2021. (2021, September). United States Department of Agriculture, National Agricultural Statistics Service: New England Field Office. NewEng_Annual_Bulletin_2020.2021.pdf (usda.gov)

Armstrong, R.L., Leeman, W.P., Malde, H.E. (1975). K–Ar dating, Quaternary and Neogene rocks of the Snake River Plain, Idaho. American Journal of Science. Vol.275, pp. 225–251.

Boers, Bernice de Jong. (1995). Mount Tambora in 1815: A Volcanic Eruption in Indonesia and Its Aftermath. *Indonesia*, *60*, 37–60. https://doi.org/10.2307/3351140

Camp, Victor E. and Wells, Ray E. (2021, January). The Case for a Long-Lived and Robust Yellowstone Hotspot. The Geological Society of America. Vol. 31, no. 1, pp. 4-10. https://doi.org/10.1130/GSATG477A.1. CC-BY-NC.

Christiansen, R. L. and Blank Jr, H. R. (1972) Volcanic stratigraphy of the Quaternary rhyolite plateau in Yellowstone National Park. *US Geological Survey Professional Paper*. Vol. 729-B, p. 145. Washington, DC: US Government Printing Office

"CY 2014 Primary Airports -- Preliminary Data" (PDF). Faa.gov. Retrieved 13 April 2022.

Diamond, J. (1986). Down to a sunless sea: The anatomy of an incident. *The Log*, Apr.: 13–16.

Erickson, Kristen. (2019, June 17). What is a Volcano. *NASA Space Place*. NASA Science. https://spaceplace.nasa.gov/volcanoes2/en/

Farms and Land in Farms: 2020 Summary. (2021, February). United States Department of Agriculture, National Agricultural Statistics Service. Farms and Land in Farms 2020 Summary 02/19/2021 (cornell.edu)

Fournier, Robert O. (1991), The transition from hydrostatic to greater than hydrostatic fluid pressure in presently active continental hydrothermal systems in crystalline rock. *Geophysical Research Letters*. Vol.18, no.5, pp. 955–958, doi:10.1029/91GL00966

Global Volcanism Program, 2013. Volcanoes of the World, v. 4.10.6 (24 Mar 2022). Venzke, E (ed.). Smithsonian Institution. Downloaded 14 Apr 2022. https://doi.org/10.5479/si.GVP.VOTW4-2013.

Hansell, A.L., Horwell, C.J., and Oppenheimer, C. (2006). The Health Hazards of Volcanoes and Geothermal Areas. Occupational and Environmental Medicine. Vol. 63, No. 2, pp. 149-156. Doi: 10.1136/oem.2005.022459.

Harris, Bethan. (2008, August). The potential impact of super-volcanic eruptions on the Earth's atmosphere. *Weather*. Vol. 63, No. 8, pp. 221-225. Doi: 10.1002/wea.263.

Hurwitz, Shaul and Lowenstern, Jacob B. (2014, August 11). Dynamics of the Yellowstone hydrothermal system. *Reviews of Geophysics*, 51, 375-411. doi:10.1002/2014RG000452.

Jackson, W. T. (1942). The Creation of Yellowstone National Park. *The Mississippi Valley Historical Review*, Vol. *29*(2), 187–206. https://doi.org/10.2307/1896270

Johnson, Noye & Parnell JR., R. A. (1986). Composition, distribution and neutralization of "acid rain" derived from Masaya volcano, Nicaragua, Tellus B: *Chemical and Physical Meteorology*, 38:2, 106-117, DOI: 10.3402/tellusb.v38i2.15086

Lanphere, M. A., D. E. Champion, R. L. Christiansen, G. A. Izett, and J. D. Obradovich (2002), Revised ages for tuffs of the Yellowstone Plateau volcanic field: Assignment of the Huckleberry Ridge Tuff to a new geomagnetic polarity event, *Geol Soc Amer Bull*., 114, 559–568, doi:10.1130/0016-7606(2002)114<0559:RAFTOT>2.0.CO;2

Leone, F. (1996) Impacts et gestion des crises liés à l'éruption du volcan Pinatubo (1991-1996). Contribution à l'analyse du système institu- tionnel philippin de réponse aux catastrophes volcaniques. *PANGEA, Bulletin du Centre International pour la Formation et les Echanges en Géosciences* (CIFEG), Orléans, France, n. 26, Décembre 1996, pp. 13-34.

Leone, F. and Gaillard, J.C. (1999). Analysis of the Institutional and social responses to the eruption and the lahars of Mount Pinatubo volcano from 1991 to 1998 (Central Luzon, Philippines). *GeoJournal*. Vol. 49, No. 2. https://www.jstor.org/stable/41147418?seq=1

Lowenstern, Robert B., et al. (2006, August 15). Monitoring Super-Volcanoes: Geophysical and Geochemical Signals at Yellowstone and Other Large Caldera Systems. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*. Vol. 364, no. 1845, pp. 2055-2072. doi:10.1098/rsta.2006.1813.

Lund, K. A. and Benediktsson, K. (2011). Inhabiting a risky Earth: The Eyjafjallajökull eruption in 2010 and its impacts. *Anthropology Today*. Vol. 27, No. 1.

Mason, B.G., Pyle, D.M. & Oppenheimer, C (2004). The size and frequency of the largest explosive eruptions on Earth. *Bull Volcanol* **66,** 735–748. https://doi.org/10.1007/s00445-004-0355-9

Massachusetts Office of Travel and Tourism. (2020, May). 2019 MOTT Annual Report. 2020_Annual_Report.pdf (visitma.com)

Mastin, L. G., A. R. Van Eaton, and J. B. Lowenstern (2014). Modeling ash fall distribution from a Yellowstone supereruption. *Geochem. Geophys. Geosyst*., 15, 3459–3475, doi:10.1002/ 2014GC005469.

Minnis, et al. (1993). Radiative Climate Forcing by the Mount Pinatubo Eruption. *Science*. Vol. 259, No. 5100, Pp. 1411-1415. https://www.jstor.org/stable/2880784

Morgan, W.J. (1971). Convection Plumes in the Lower Mantle. *Nature*. Vol. 230, 42-43. https://doi.org/10.1038/230042a0

Muffler, L. J. P. et al. (1971). Hydrothermal explosion craters in Yellowstone National Park. *Geological Society of America Bulletin*. Vol. 82, pp. 723-740.

Noncitrus Fruits and Nuts 2019 Summary. (2020, May). United States Department of Agriculture, National Agricultural Statistics Service. Noncitrus Fruits and Nuts 2019 Summary 05/05/2020 (cornell.edu)

Oppenheimer, C. (2003), Climatic, environmental and human consequences of the largest known historic eruption: Tambora volcano (Indonesia) 1815. *Prog. Phys. Geogr*. Vol. 27(2), 230–259, doi:10.1191/0309133303pp379ra.

Pausata, F.S.R., et al. (2011). The key role of topography in altering North Atlantic circulation during the last glacial period. *Climate of the Past*. Vol. 7, 1089-1101. Doi: 10.5194/cp-7-1089-2011.

Peterson, G. N. (2010). A short meteorological overview of the Eyjafjallajökull eruption 14 April-23 May 2010. *Royal Meteorological Society*. Vol. 65, No. 8. doi: 10.1002/wea.634.

*The Philippine Journal (*1997): Evacuation order to come only from RDCC- PHIVOLCS, 06/04/97.

Pierce, Kenneth L. and Morgan, Lisa A. (2009, July 28). Is the track of the Yellowstone hotspot driven by a deep mantle plume? – Review of volcanism, faulting, and uplift in light of new data. *Journal of Volcanology and Geothermal Research*. Vol. 188, pp. 1-25. doi:10.1016/j.jvolgeores.2009.07.009

Population Estimates. (2019, July 1) United States Census Bureau. https://data.census.gov/cedsci/table?q=New%20England%20Division&tid=PEPPOP2019.PEPANNRES

Rinehart, J. S. (1980), Geysers and Geothermal Energy, Springer–Verlag, New York.

Self, S. (2006). The Effects and Consequences of Very Large Explosive Volcanic Eruptions. *Philosophical Transactions: Mathematical, Physical and Engineering Sciences*, 364(1845), 2073–2097. http://www.jstor.org/stable/25190315

Shapiro, Nikolai M. and Koulakov, Ivan. (2015, May 15). Probing the underbelly of a supervolcano: Seismic imaging of Yellowstone provides a better understanding of large volcanic systems. *Science, New Series*. Vol. 348, no. 6236, pp. 758-759. http://www.jstor.org/stable/24747533

Sigfusson, T.I. et al. (2010). First results of experiments with the effect of volcanic ash from Eyjafjallajökull Volcano on aircraft turbines. *A report to the Icelandic Civil Aviation Administration*. Available at http://www.nmi.is (accessed 4 Nov. 2010).

Sigurdsson, H., et al. (2015). *The Encyclopedia of Volcanoes*. Academic Press.

Smith, Robert B. and Braile, Lawrence W. (1994). The Yellowstone hotspot. Journal of Volcanology and Geothermal Research. Vol.61, no.2-4, pp. 121–129, 135–187, doi:10.1016/0377-0273(94)90002-7

Smith, Robert B., et al. (2009). Geodynamics of the Yellowstone hotspot and mantle plume: Seismic and GPS imaging, kinematics, and mantle flow. Journal of Volcanology and Geothermal Research. Vol. 188, no. 1-3, pp. 26–56, doi:10.1016/j.jvolgeores.2009.08.020

Sparks, S. et al.. (2005, June). Super-Eruptions: Global Effects and Future Threats. *Geological Society of London.* 2nd Edition. https://www.geolsoc.org.uk/~/media/shared/documents/education%20and%20careers/Su per_eruptions.pdf?la#:~:text=An%20area%20the%20size%20of,food%20supplies%2C%20and%20mass%20starvation.

Sparks, S. & Self, S., et al. (2005). Super-eruptions: global effects and future threats. Report of *Geological Society of London Working Group.* 2nd (print) Ed., Original (Web) edition available at www.geolsoc.org.uk/supereruptions.

State Area Measurements and Internal Point Coordinates. (2021, December 16). United States Census Bureau. https://www.census.gov/geographies/reference-files/2010/geo/state-area.html

United States Department of Agriculture. 2020 New England Regional Agricultural Report. (2021, May).. Microsoft Word - NE2021_StateAgProfile.docx (A).docx (usda.gov)

Williams, H. (1951). VOLCANOES. *Scientific American*, Vol. *185*(5), 45–53. http://www.jstor.org/stable/24950523

2017 Census of Agriculture County Profile: Strafford County, New Hampshire. United States Department of Agriculture, National Agricultural Statistics Service. cp33017.pdf (usda.gov)