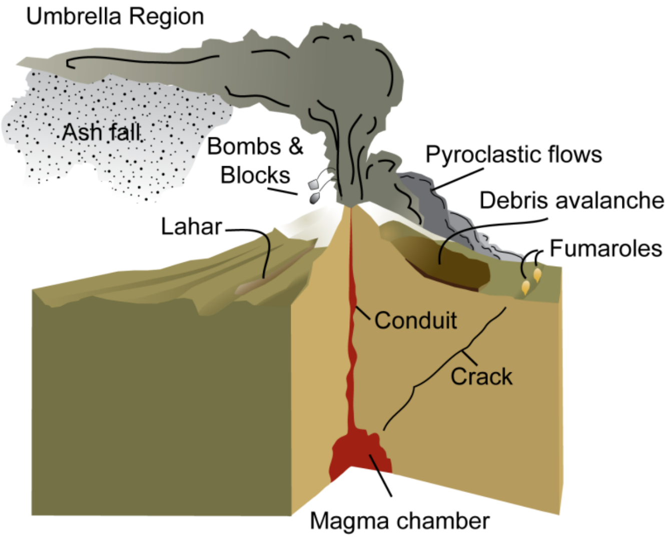
Chapter 3
Volcanic Hazards

Introduction

The natural hazards associated with volcanic eruptions include lava flows, falling bombs and blocks, lightening, ash falls, pyroclastic flows, debris avalanche (landslides), and lahars (volcanic mud flows) (Figure 1). In addition, fumaroles and poisonous gas (limnick) eruptions can occur, and some large volcanic eruptions can produce tsunamis and climate change



Note: Volcanic summits are commonly covered with snow & glaciers as depicted in this scene.

Figure 1. The common hazards associated with volcanic eruptions. Others include lava flows, limnic eruptions, tsunami, and climate change.

Fumaroles

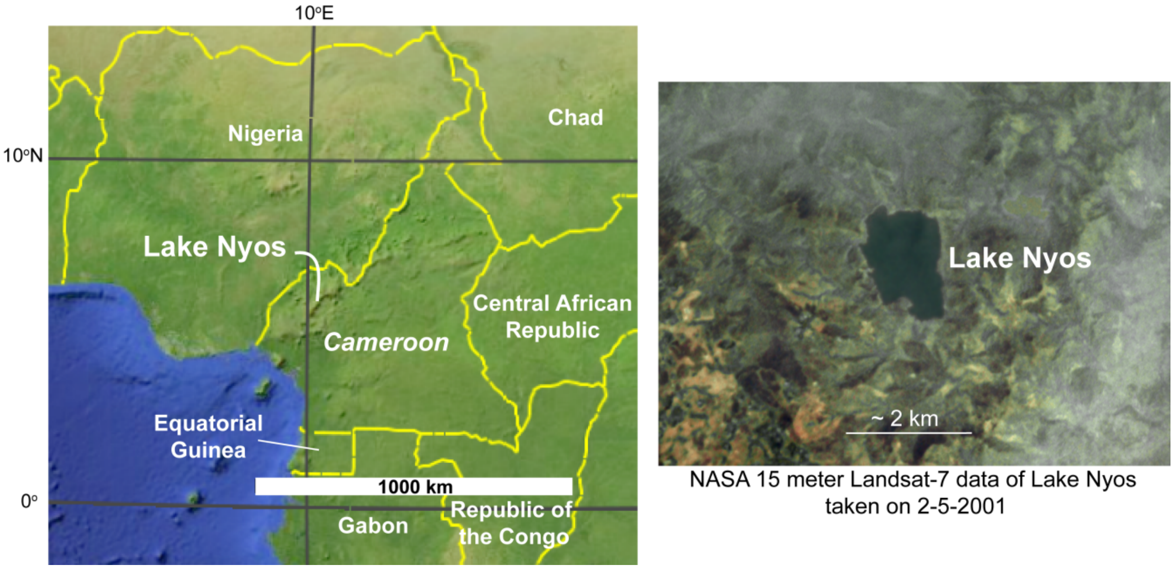
Fumaroles are openings such as small vents or cracks in or around a volcano that emit steam and gases such as carbon dioxide (CO_2), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S) (Figure 2) at temperatures varying between ~100^o and ~1000^{o}C. They may persist for centuries or decades if they lie above a persistent heat source, e.g., an underlying sub-volcanic magma chamber.

CO_2 is an odorless, tasteless, and colorless gas that is extremely dangerous. For example, breathing air with more than 11% CO_2 will produce unconsciousness in a minute or less. In contrast to carbon dioxide, SO_2 has a pungent smell and can cause inflammation and burning of the eyes and respiratory tract, and difficulty in breathing. When SO_2 mixes with water vapor it forms sulfuric acid (H_2SO_4), a constituent of acid rain. Once formed, acid rain can cause severe damage or destruction of vegetation, and severe irritation of the eyes, nose, and throat. H_2S is a toxic gas that smells like rotten eggs. Breathing H_2S can cause a variety of ailments including headaches, fatigue, dizziness, excitement, diarrhea, and eye irritation. Inhaling large amounts of H_2S gas can cause paralysis of the respiratory system and death. CO_2 and H_2S are denser than air and may accumulate in low-lying areas. Hence, if fumarolic activity is suspected, then low-lying areas such as hollows should be avoided, and gas masks should be worn or readily available.

Figure 2. Fumarole on Kilauea Volcano, Hawaii. Escaping sulfur vapor cools and forms yellow-colored crystals around the margins of the fumarole. Photograph by R.L. Christiansen, United States Geological Survey, 27 July 1973

Limnic Eruptions

Volcanoes release various types of gases including SO_2 and CO_2. As described in the preceding section, the latter is an odorless and colorless gas that can suffocate people. On October 21, 1986, a 914 m (3000 foot) wide and 914 m high cloud of CO_2 was released from Lake Nyos, a lake lying within a volcanic crater, in the Cameroon, Africa (Figure 3). The CO_2 was fed to the lake waters from magma lying ~213 m (~700 feet) beneath the surface. Being denser



NASA 15 meter Landsat-7 data of Lake Nyos taken on 2-5-2001

Figure 3. Earth Explorer 5.0 DEM of Lake Nyos, Cameroon, western Africa.

than the atmosphere, the cloud hugged the ground and flowed silently down the slopes of the volcano where it asphyxiated ~1700-1800 sleeping villagers.

For limnic eruptions to occur, lake waters have to be saturated with CO_2. At the bottom of lakes susceptible to limnic eruptions pressures are greater and temperatures are colder than at shallower lake levels. Hence, CO_2 is kept in solution. However, if some event, such as a landslide disturbs this setting, and causes the deep CO_2 saturated waters to rise, then as they rise they will travel through shallower levels of the lake where pressures are less and temperatures are warmer. Under these conditions, the CO_2 will come out of solution (exsolves), and over time be released into the atmosphere becoming a potentially deadly killer.

Lava Flows

Basaltic lava like that in Hawaii is very hot, reaching temperatures of ~1600^{o}F (871^{o}C) to 2200^{o}F (1204^{o}C). In photographs and in movies of basaltic lava flowing out of one of the volcanoes in Hawaii, red colors are typical of temperatures around 1600^{o}F (871^{o}C), orange of temperatures of ~1800^{o}F (982^{o}C), and yellow of temperatures of ~2000^{o}-~2200^{o}F (193^{o}C –

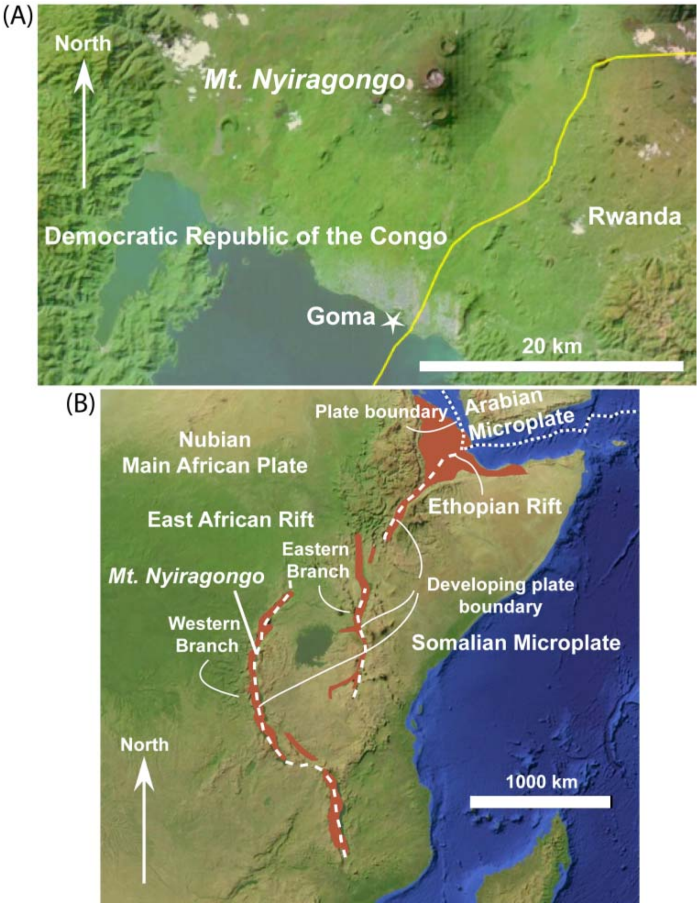


Figure 4. (A) Earth Explorer 5.0 DEM of Mt. Nyiragongo. Note crater at summit. (B) Mt. Nyiragongo within East African Rift.

1204^{o}C). Though Hawaiian lava flows move at rather slow speeds (a few meters to a few kilometers per hour), that is not always so at other locations. For example, Mt. Nyiragongo, a stratovolcano in the Democratic Republic of the Congo, lies within the West Branch of the East African Rift (Figure 4). It is well known for the lava lakes that form within its crater. On January 10, 1977, the lava lake existing at that time breached its walls as they fractured, releasing the relatively low SiO_2, very fluid, mafic lava. The resulting lava flow is estimated to have traveled at ~90 kilometers per hour (60 miles per hour) down the slopes of Mt. Nyiragongo. Because of its rapid speed, the lava overwhelmed nearby villages and killed 70 people. A similar event occurred in 2002, resulting in the destruction of 1200 homes and 100 deaths in Goma (Figure 4A).

Basaltic lava in Hawaii is less fluid than that lying in the crater of Mt. Nyiragongo. Though it moves slowly it is relentless. For example, in 1990, lava flowed discontinuously from the Kupaianaha vent of Kilauea volcano for nearly 6 months. It ended up burying the coastal village of Kalapana under about 18.3 meters (60 feet) of lava destroying 100 homes.

Falling Bombs and Blocks

Though the smallest volcanic bomb is about the size of a baseball or tennis ball, bombs or blocks can be much larger, sometimes reaching the size of an automobile. Moreover, they can be blasted out more than about 805 meters (half a mile) from the crater. Rosaly Lopes of the Jet Propulsion Laboratory in Pasadena, California relates the story in Sci-Trek's *Volcanoes* where during one of the recent modern eruptions of Mount Etna (Figure 5) blocks blasted from the volcano struck and killed nine people.

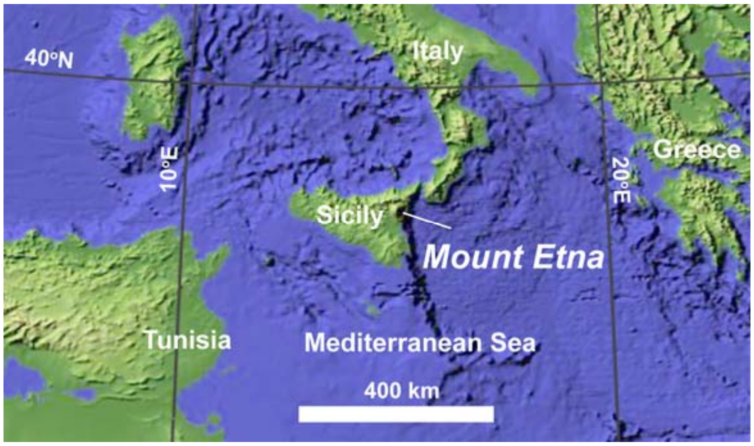


Figure 5. Earth Explorer 5.0 DEM showing location of Mt. Etna in NE Sicily, Italy

Lightning

Though the details of how electrical charges are built up within the eruption column are not yet known, we do know that lightning is an electrostatic discharge between variously charged areas of the column or between charged areas of the column and the ground. Within the eruption column, tephra tumbles and bumps into each other building up an electrostatic charge. Somehow this process leads to various areas within the eruption column being negatively charged while other areas are positively charged. As these areas grow and become more distinct an electrical field is set up and grows stronger the farther apart the two positive and negatively charged portions of the eruption cloud become. Eventually, the electrical field grows great enough, that a current of electricity forces a path between the two differently charged areas. Along its path, the current makes a good connection with some object, and as a result is discharged as a stroke of lightning. On the ground, beneath the eruption column an area of positive charge accumulates. This area is responsible for column-to ground lightning strikes.

Mt. Etna, a stratovolcano on the northeast coast of Sicily (Figure 5), is the largest volcano in Europe. It is almost in a constant state of eruption. Since 2000 lightning strikes near the summit of the volcano have killed four tourists.

Ash Clouds and Ash Falls

Ash is not soft, but is hard and abrasive consisting mostly of pulverized rock and silica. It does not dissolve in water, is mildly corrosive, and conducts electricity when wet. Winds can carry ash vertically and horizontally great distances, and thus can create economic and health hazards in unexpected areas. One common danger involves the flight of airplanes into unexpected ash clouds.

The melting temperature of silica in an ash cloud is similar to the internal temperature of a modern jet engine. When ash is ingested into a jet engine it melts, and then is sucked into cooler regions of the engine where it creates a “flame out”, i.e., total engine failure. There are reports of as many as 100 jets having encountered ash clouds. For example, in 1982, a 747 encountered a volcanic cloud at 11,278 meters (37,000 feet) over Indonesia, and experienced total engine failure in all four of its engines. The plane fell 7,010 meters (23,000 feet) before the pilots were able to restart the engines.

In addition to the above danger, in areas blanketed by ash falls, people commonly seek shelter from the suffocating affects of the fallout. However, ash is dense and its density increases when wet. As a result, even a 10 centimeter (~four inch) layer can carry sufficient mass to flatten many shelters. Finally, even after an eruption is long over, fallen ash can be stirred up by human activity and winds and thus pose a long-term health and economic hazard.

Lahars

Lahar, an Indonesian term, *describes a hot or cold mixture of water and volcanic rock fragments flowing down the slopes of a volcano or river valley*. Such features are commonly described as resembling a mass of wet cement. Particles included in lahars vary in size from less than ~0.004 mm (clay) to boulders over 10 m in diameter.

Lahars vary widely in size but can reach up to ~30 feet or more (tens of meters) in thickness and ~330 feet or more (hundreds of meters) in width. Such large flows can travel at speeds in excess of ~30 feet/second (tens of meters per second).

Lahars are common features associated with stratovolcanoes. Such volcanic structures erupt explosively, stand tall above their surrounding landscape, and build steep-sided cones that are (a) covered with snow and ice, (b) topped with a crater lake, and/or (c) constructed of weakly consolidated volcanic rock debris that is easily eroded or internally weakened by hydrothermal activity. The initiation of a lahar on a stratovolcano is most commonly the result of the eruption of one or more pyroclastic flows. As the pyroclastic flows move down the snow and ice covered summits of a stratovolcano, they erode and mix with the snow and ice substrate that they are traveling over, cutting channels and melting significant proportions of the snow and ice field. The resulting mixtures of water, ice, pumice, and other rock debris then move down the flanks of the volcano through its network of channels and valleys.

If the lahars traveling down valleys and gullies incorporate more water, rock, and sediment debris from the channels that they flow through, then they can continue to grow in size sometimes increasing their volume by up to 4 times their initial size. In some cases lahars have traveled ~62 miles (100 km) or more from their site of initiation.

Let’s look briefly at Mount Rainier, an example of a stratovolcano located in the NW continental United States that appears to be prone to lahars. Significantly, it lies near numerous urban centers including Seattle and Tacoma (Figures 6 and 7).

Figure 6. Mount Rainier as seen from Paradise, Mount Rainier National Park.
USGS Photograph taken in 1975 by Lyn Topinka.

Mount Rainier

Mount Rainier is located in the state of Washington about 72.4 kilometers (~45 miles) SE of Tacoma and about 93.3 kilometers (~58 miles) SE of Seattle (Figure 7). It is an active stratovolcano that reaches ~4392 meters (~14,410 feet) in elevation. At its summit numerous glaciers and snow fields cover rocks derived from andesitic lava flows and coarse pyroclastic materials. Though the earliest preserved deposits are 2,900,000 to 840,000 year old, Mount Rainier last erupted in 1894-95.

The U.S. Geological Survey believes that lahars initiated on Mount Rainier pose a greater risk to surrounding regions than would an actual volcanic eruption. The greater risk from lahars stems from geologic data indicating that lahars (i.e., volcanic mudflows) have occurred relatively often in the past, and the fact that future lahars likely will travel down valleys that currently transect several dense population centers (Figure 7). For example, during the past several thousand years large lahars initiated on Mount Rainier have reached the Puget Sound lowland on average at least once every 500 to 1000 years. If large lahars continue to occur at rates similar to those of the past, then there is roughly a 1-in-10 chance of a lahar reaching the Puget Sound lowland during an average human lifespan.

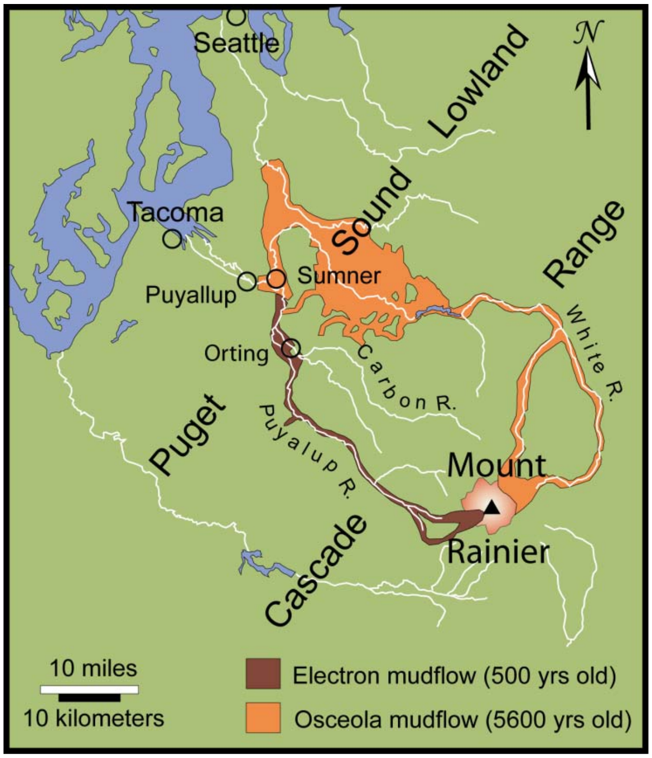


Figure 7. Generalized map showing the distribution of Osceola and Electron mudflows. Map is based on sources listed in references.

Before proceeding I encourage you may to first review videos and images of lahars found at the Michigan Technological Institute Volcanoes web site. It can be found at the following url.

http://www.geo.mtu.edu/volcanoes

There are two possible types of lahars that could be generated on Mount Rainier that would threaten surrounding areas. The first is what the US Geological Survey refers to as *melt water-generated* and the second as *landslide-generated*. In the first case, pyroclastic flows melt and mix with melting snow and ice generating lahars in a process like that described earlier in this section. In the second case, landsides are triggered by magma rising into the volcano and destabilizing it, or are initiated by large earthquakes produced by magma movement beneath the volcano. In addition, large parts of Mount Rainier have been hydrothermally altered. This type of alteration occurs when magma lying beneath the volcano releases gases and heat creating hot acidic ground water that in turn converts volcanic rock into mechanically weak clay-rich material. When such hydrothermally altered and weakened material gives way during a landslide along a steep to over steepened slope it is rapidly transformed into a lahar, and thus represents another type of land-slide generated lahar.

The west side of Mount Rainier contains the largest amount of hydrothermally weakened and altered rock. Hence, communities along the Puyallup River with its headwaters in this hydrothermally weakened clay-rich region have the highest probability of being subjected to a lahar initiated on Mount Rainier (Figure 7).

Osceola & Electron Mudflows

As shown in Figure 7, the Electron mudflow which occurred about 500 years ago, and the Osceola mudflow which occurred about 5600 years ago, are examples of what may occur in the future. The Electron mudflow (lahar) was produced by a landslide originating along the west flank of Mount Rainier. The landslide quickly transformed into a volcanic mudflow (lahar) that traveled down the Puyallup River. As it raced down the narrow stretches of this drainage it reached depths (thicknesses) up to 164 feet (50 m). Below the community of Electron, the lahar spread out leaving a blanket of debris as thick as ~33 feet (~10 m), and near the current community of Orting buried an old-growth forest (see Figure 7).

In contrast to the Electron mudflow, the Osceola mudflow or lahar originated from the northeast side of Mount Rainier. It too began as a landslide that transformed quickly into a mixture of rapidly moving volcanic rock, snow, and ice. It traveled rapidly down the west and main forks of the White River, and eventually reached the Puget Sound more than 31 miles (50 km) downstream of its site of origin (see Figure 7).

Geologists have identified 55 lahars younger than 10,000 years that have originated from Mount Rainier. In the past 5600 years 6 and possibly 13 have occurred. These observations and data suggest a recurrence interval of 500 to 1000 years. If you lived in one of the valleys extending from Mount Rainier would you be concerned? In your life time will another lahar occur in this beautiful setting? Are Seattle and Tacoma safe from such natural disasters?

Debris Avalanche

As volcanoes grow they build large shield or conical shaped structures. The slopes on such features can be very steep, gravitationally unstable, and can be underlain by layers of weak, fragmented, volcanic rocks. In addition, hot acidic ground water can alter some of these rocks into weak clay minerals, and thus weaken them further. Under such conditions material on steep unstable slopes may suddenly collapse under the influence of gravity, and move very rapidly down slope. During such rapid movement large initially coherent blocks break or disintegrate into smaller blocks and these smaller blocks in turn break into yet smaller fragments, the whole mass becoming an unsorted chaotic mixture of various sizes. A debris avalanche is thusly defined by the United States Geological Survey as *a gravitationally induced* *flowing or sliding, incoherent and chaotic, wet or dry mixture of soil and rock debris moving away from its source of origin at high speeds*. During movement flowage may occur in a dry or wet state or possible both. If the debris avalanche contains water, then after the coarsest portion of the avalanche has come to rest the remaining finer portions may continue as a lahar. Deposits derived from debris avalanche are commonly thick and have a chaotic hummocky surface morphology (Figure 8). They can extend as far as several tens of kilometers from a volcano and cover an area of a few tens of square kilometers.

Figure 8. Photograph of a view looking downstream of the North Fork Toutle River valley Mt. St. Helens. Hummocky material in foreground is part of the nearly 2.3 cubic kilometers (2/3 cubic miles) of debris avalanche that slid from Mt. St. Helens on May 18, 1980. The avalanche traveled ~24 kilometers (~15 miles) downstream at a velocity exceeding 240 kilometers/hour (150 miles/hour). USGS photograph taken on November 30, 1983, by Lyn Topinka.

There are two general types of debris avalanche. A cold debris avalanche is the result of failure along a steep gravitationally unstable slope, while a hot debris avalanche is the direct result of volcanic activity such as earthquakes produced by magma movement within the interior of the volcano, or the high level injection of magma. An example of the latter occurred during the early eruptive stage at Mt. St. Helens when magma injected into the north flank of the volcano created a bulge that became gravitationally unstable and failed as a debris avalanche during an earthquake (see Chapter 4). In contrast, the lahars at Mount Rainer described in the preceding section began as cold debris avalanches.

Tsunami

According to the National Oceanic and Atmospheric Administration (NOAA), "…a tsunami is a set of ocean waves caused by any large, abrupt disturbance of the sea-surface". Most are generated by earthquakes, but others are caused by volcanic eruptions, landslides, undersea slumps, or meteor impacts. The magnitude of an earthquake is a measure of the amount of energy it released, while the focus is the point of initiation of the earthquake beneath the Earth's surface or seabed. Most major tsunamis are produced by large (>7) magnitude, shallow focus (< 30 km) earthquakes along convergent margins. We will study these types of tsunami in a later chapter. Here we focus on tsunami produced by explosive volcanic activity (e.g., Krakatoa) and by landslides or slumps derived from the failure of the gravitationally unstable flanks of a volcano (e.g., Mauna Loa).

The term tsunami comes from the Japanese and literally means "harbor wave". The plural is tsunamis. In the past, tsunamis have sometime been referred to as tidal waves. However, though they can resemble a tidal bore, they have nothing to do with the 4 tides produced by the interaction of the gravitational fields of the Earth, Moon, and Sun with the inertial force produced by the spinning Earth-Moon pair.

A tsunami can be produced when a large mass of material is suddenly displaced into a large body of water like an ocean. The result of this displacement is the tsunami, a series of waves that radiate out from the central area of disturbance. A common day analogy is throwing a stone into a tranquil lake. The ripples that radiate outward from where the stone hits and disturbs the once tranquil lake surface represent the tsunami.

In two dimensions, the **crest** of a tsunami is the highest point on the wave while the **trough** is the lowest point (Figure 9). The **wavelength** is the distance from crest to crest or trough to trough. The **wave height** is the vertical distance from trough to crest. The **period** is the time it takes two successive crests to past a stationary point.

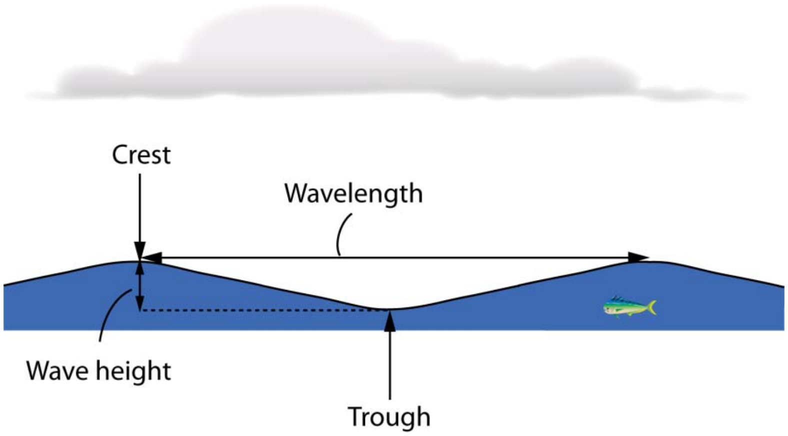


Figure 9. Wave characteristics of a tsunami.

In the deep oceans, tsunamis have wavelengths ranging from ~100 meters (~328 feet) to over ~500 kilometers (~311 miles), and periods, ranging from 10 minutes to 2 hours. In addition, wave height is commonly less than ~ 1 m (~3 feet). In contrast, common everyday wind-generated waves have wavelengths of about 100 to 200 meters (300 to 600 feet), periods between about 5 and 20 seconds, and wave heights around 2 m (7 feet).

The speed of typical wind-generated waves is about 40 kilometers per hour (~25 miles per hour) but ranges up to about 90 kilometers per hour (~56 miles per hour). In contrast, the speed of a tsunami depends on ocean depth. It can exceed ~966 kilometers per hour (~600 miles per hour) in the deep ocean but typically tsunamis slow to ~32 to ~48 kilometers per hour (~20 to ~30 miles per hour) in shallow water near land. A tsunami can cross the entire Pacific Ocean in less than 24 hours.

Just prior to a tsunami coming ashore sea level appears to drop, a phenomenon referred to as **drawdown**. Because of their long wavelengths, following drawdown tsunamis commonly come ashore more like a flood or a tidal surge than a wind-generated wave. **Runup**, that is the maximum vertical height above normal high tide reached by the tsunami as it travels over the land surface, can be extreme sometimes extending up to ~30 meters (~100 feet) above sea level.

Volcanoes grow by piling up layers of tephra and/or lava and are relatively common adjacent to oceans, especially where they form intraoceanic island arcs (e.g., Indonesia) or islands in intraplate settings (e.g., Hawaii; Figure 10). An ultimate result of such growth is that volcanoes sometimes become unstable as they grow larger and higher. For example, the south flank of Mauna Loa volcano in Hawaii, the largest volcano in the world with a volume of 42,000 cubic kilometers, collapsed ~120,000 years ago into the Pacific Ocean (Figure 10). This collapse moved a huge mass (~120 cubic miles or ~500 cubic kilometers) of the volcanoes flank into the adjacent Pacific Ocean and is known as the Alika 2 landslide (Figure 10). The Alika 2 landside created a giant tsunami with a runup of more than 400 meters (~1312 feet) for more than 6 kilometers (~3.7 miles) inland. Giant landsides like the Alika occur about every 200,000 years in Hawaii.

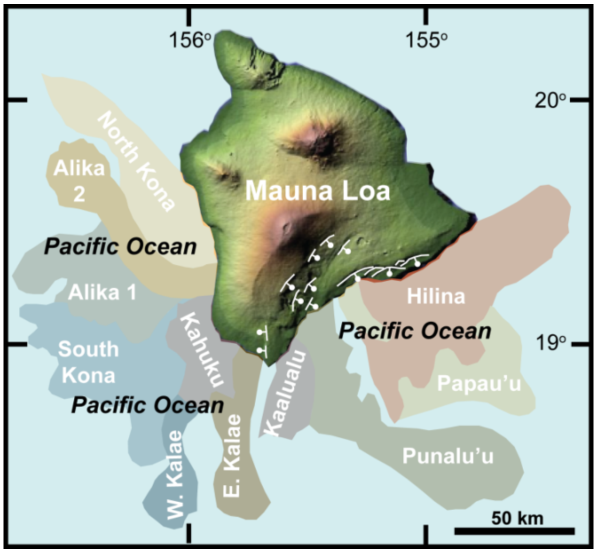


Figure 10. Earth Explorer 5.0 DEM of Mauna Loa showing positions of giant subsea landslides mapped and discussed by Moore et al. (1994).

Another famous example of a volcano eruption creating tsunamis is the 1883 eruption of Krakatoa (also spelled Krakatau) in the Sunda Straights of Indonesia. I discuss this eruption again in the section below entitled Climatic Change. During 1883 eruption much of the volcano was destroyed and blasted into the atmosphere. The final culminating blast was equivalent to exploding 210 tons of TNT, and was so loud that it was heard 4500 kilometers (2858 miles) away. The results of the Krakatoa eruption produced a series of tsunamis that devastated the surrounding coastal areas destroying some 165 villages and killing over ~36,000 people.

Pyroclastic Flows

Pyroclastic flows are relatively common during eruptions of felsic to intermediate composition magma. They are mixtures of hot gases, tephra, and rock debris. Perhaps the most famous pyroclastic flow formed during the eruption of Mount Pelée, Martinique, a French Caribbean island in the Lesser Antilles (Figure 11). Martinique is part of an intraoceanic island arc that formed as the result of the subduction of the North American plate beneath the Caribbean plate.

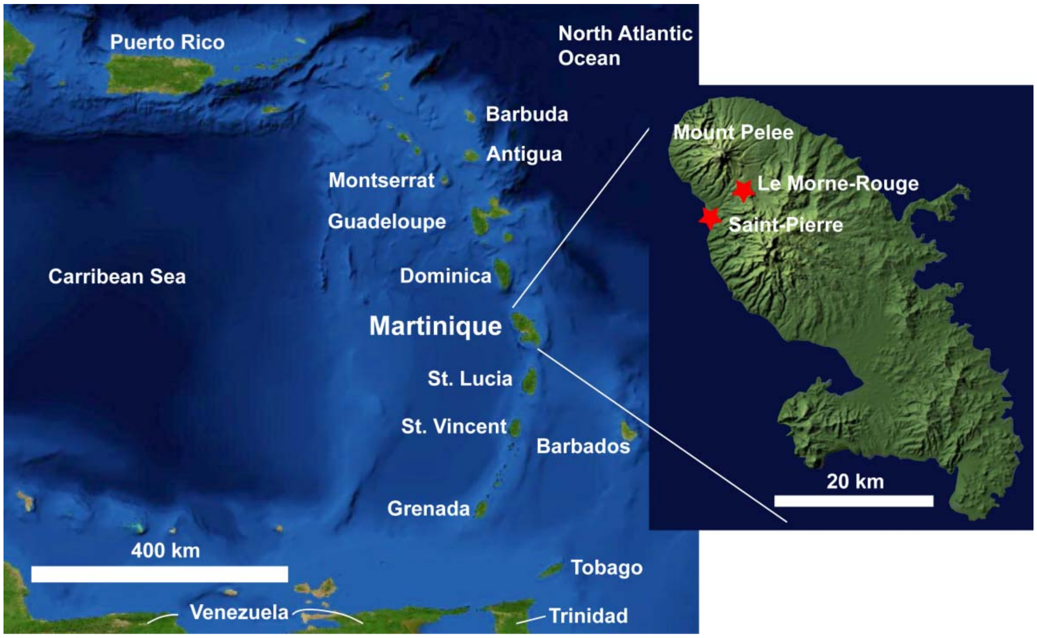


Figure 11. Earth Explorer 5.0 DEM of Lesser Antilles. Inset shows Mount Pelée in northwestern Martinique.

From January through May 1902 there were numerous observations of volcanic activity on Mount Pelée. For example, in January fumarole activity increased in the summit crater, and in March sulfuric gas was observed coming from several sources within the crater. On April 23, a small eruption occurred, and by April 27 a lake had formed within the crater. From April 27 through May 4 explosions continued within the crater. On May 5, the water that had accumulated in the crater suddenly burst free and flowed into the valley of the Riviere Blanche where it picked up loose debris and became a mudflow (lahar) traveling at 90 kilometers per hour (56 miles per hour). Near the coast the lahar encountered a rum distillery burying all but its smoke stacks and killed 24 workers. The lahar then continued to the coast where it entered the Caribbean Sea generating a tsunami with 3 to 4 meters (9.8 to 13.1 feet) high waves that flooded the low lying parts of St. Pierre. From May 6 through the 7 ash erupted and several small pyroclastic flows moved down the slopes of Mount Pelée. Unfortunately, these early warning signs were ignored by the citizens of St. Pierre, and the worst part of the erupting volcano was yet to happen.

On May 8, 1902, at 7:50 am Mount Pelée erupted violently and a pyroclastic flow ripped down the south slope of the volcano toward the coastal community of St. Pierre (Figure 11). The pyroclastic flow reached speeds of 100 mph and temperatures around 1300^{o}F. At these speeds it took only a few minutes for the pyroclastic flow to travel the 6 kilometers (4 miles) to St. Pierre and its 29,000 inhabitants. When it reached St. Pierre it had sufficient force to knock down brick houses and twist steel girders. It also was so hot that it ignited a firestorm. Upon reaching the sea its winds were strong enough to damage twenty ships which either capsized or caught fire due to the intense heat.

Of the 29,000 people living in St. Pierre only two survived the pyroclastic flow of May 8. One of the survivors was a shoemaker hiding in a basement on the outskirts of St. Pierre, and, as it turns out, on the very fringe of the pyroclastic flow. The second survivor was a criminal named Louis Cyparis. Cyparis was in solitary confinement in the prison dungeon.

On May 20 another pyroclastic flow swept down the south slope of the volcano and over the now dead community of St. Pierre. Finally, on May 30 a third pyroclastic flow moved down the slopes of Mount Pelée, but this time it took a different path and engulfed not only St. Pierre, but also the inhabitants of Morne-Rouge (Figure 11): it killed another 2,000.

Climate Change

Large sustained eruptions eject into the atmosphere large quantities of fine ash (< 0.063 mm; <0.0025 inches), called dust, and sulfur dioxide (SO_2) gas that can affect global climate. Molecules of sulfur dioxide gas combine with water vapor to form droplets of sulfuric acid. In the atmosphere these tiny droplets along with volcanic dust form an aerosol, i.e., fine solid particles and liquid droplets suspended in a gas. Such aerosols reflect sun light back into space, and thus can cause a global lowering of Earth's surface temperature. An example of this effect may have been caused by the 1883 VEI 6 plinian eruption of Krakatoa.

Lying in the Sunda Straights between Java and Sumatra, Indonesia, Krakatoa during the August 1883 eruption ejected an estimated ~10 cubic kilometers (~2.4 cubic miles) of dacitic rock, ash, and pumice into the atmosphere (Figure 12). The eruption column reached the stratosphere and climbed to heights of 25 to 36 kilometers (15.5 to 22.5 miles). The culminating explosive eruption on August 27 literally tore the volcano apart and was heard 4,500 kilometers (2,858 miles) away at Rodriguez Island in the Indian Ocean. The shock wave produced during this event traveled around the globe seven times.

The cloud of sulfuric acid droplets and volcanic dust from the eruption of Krakatoa formed a stratospheric aerosol that was distributed by wind around the globe. The aerosol cloud reduced the amount of sunlight reaching the Earth's surface, producing erratic weather and vividly red and orange sunsets and sunrises throughout the world for many months following the eruption. During the year following the eruption, it is estimated that the global temperature dropped on average by 0.5^{o}C. Weather patterns apparently remained chaotic for years and the global climate did not return to normal until about 1888.

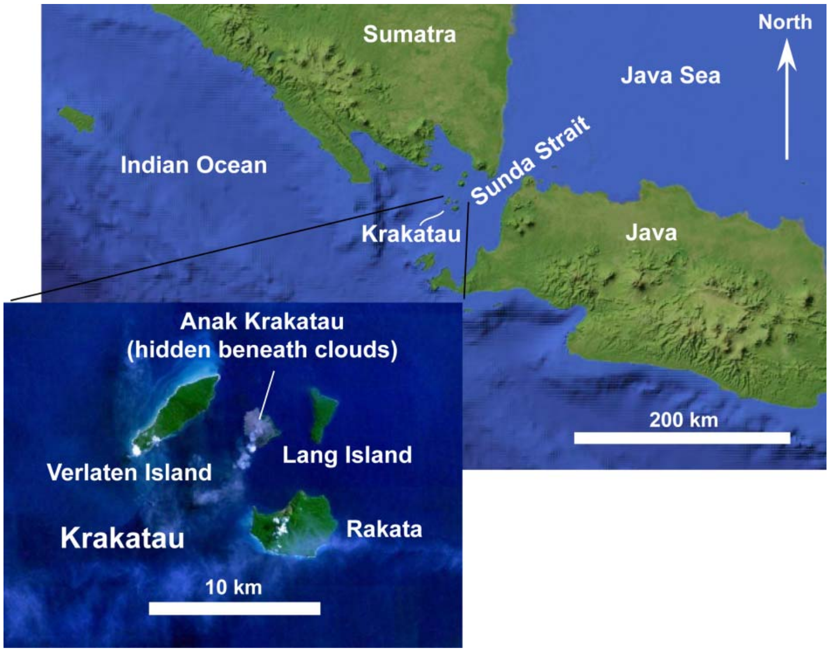


Figure 12. Earth Explorer 5.0 satellite image (inset) and DEM of Krakatau. On modern maps Krakatoa is referred to as Krakatau. It consists of Verlaten Island, Lang Island, Rakata, and Anak Krakatu.

A more modern day example of a volcanic eruption influencing climate is the June 15, 1991 eruption of Mt. Pinatubo in the Philippines (Figure 13). According to Max Rosenberg (About.com) and the National Geographic Society it is estimated that during this eruption 20 to 21 million tons of sulfur dioxide was dispersed ~34 kilometers (~21 miles) into the stratosphere. There it combined with water vapor and fine volcanic ash to form an aerosol that within two

Figure 13. Mt. Pinatubo, Philippines. Photograph from United States Geological Survey.

weeks encircled the globe, and within the year covered the entire planet. The aerosol cloud reduced the amount of sunlight reaching the Earth's surface, and, as a result, it lowered global temperatures. In fact, according to the National Geographic Society, in 1992 and 1993, the average global temperature was reduced 0.4^{o}F (~0.23^{o}C). As with Krakatoa unusually vivid sunsets and sunrises occurred around the globe during the two years following the eruption of Mt. Pinatubo.

Summary

Volcanoes are the principal method by which heat is removed from the Earth's interior. They therefore are ubiquitous features of the Earth's surface, and, as a result, can greatly affect the landscape and the living inhabitants of planet Earth. For example, it is estimated that some 600 million people live in or near an active volcano, are therefore in imminent danger. It therefore is imperative that we educate as many of our fellow citizens of the perils of living near such features. In the next chapter I will review the most significant historical explosive volcanic eruption in the conterminous United States. Hopefully, you will gain further insight into how the many and varied processes discussed in this chapter might interact in a complex way during a given volcanic eruption.

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