Encyclopedia of

Volcanoes

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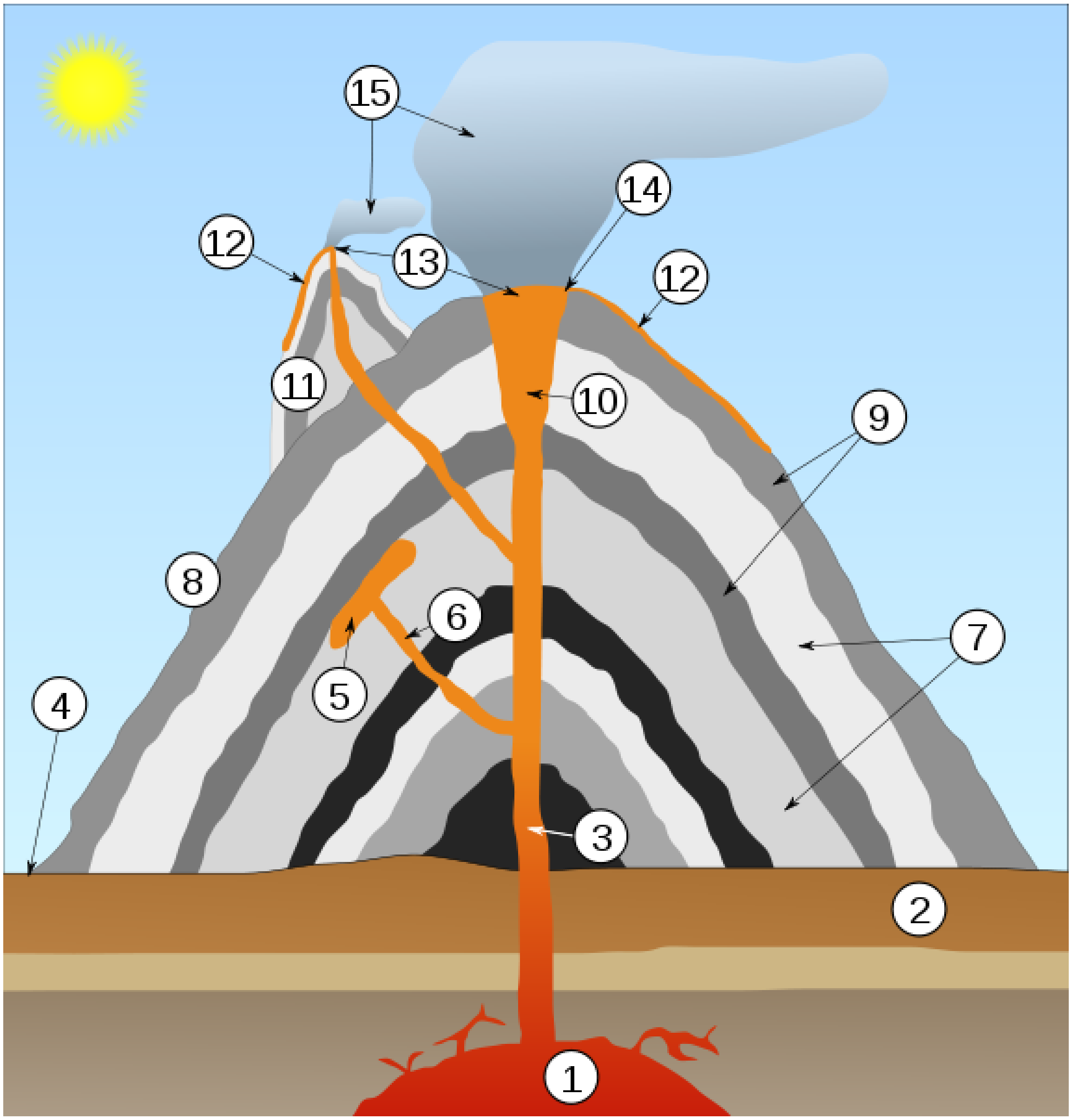
Introduction to Volcano

Cleveland Volcano in the Aleutian Islands of Alaska photographed from the International Space Station, May 2006



Cross-section through a stratovolcano (vertical scale is exaggerated):

1. Large magma chamber
2. Bedrock
3. Conduit (pipe)
4. Base
5. Sill
6. Dike
7. Layers of ash emitted by the volcano
8. Flank
9. Layers of lava emitted by the volcano
10. Throat
11. Parasitic cone
12. Lava flow
13. Vent
14. Crater
15. Ash cloud

Pinatubo ash plume reaching a height of 19 km, 3 days before the climactic eruption of 15 June 1991

A **volcano** is an opening, or rupture, in a planet's surface or crust, which allows hot magma, ash and gases to escape from below the surface.

Volcanoes are generally found where tectonic plates are diverging or converging. A mid-oceanic ridge, for example the Mid-Atlantic Ridge, has examples of volcanoes caused by divergent tectonic plates pulling apart; the Pacific Ring of Fire has examples of volcanoes caused by convergent tectonic plates coming together. By contrast, volcanoes are usually not created where two tectonic plates slide past one another. Volcanoes can also form where there is stretching and thinning of the Earth's crust (called "non-hotspot intraplate volcanism"), such as in the East African Rift, the Wells Gray-Clearwater volcanic field and the Rio Grande Rift in North America.

Volcanoes can be caused by mantle plumes. These so-called hotspots, for example at Hawaii, can occur far from plate boundaries. Hotspot volcanoes are also found elsewhere in the solar system, especially on rocky planets and moons.

Etymology

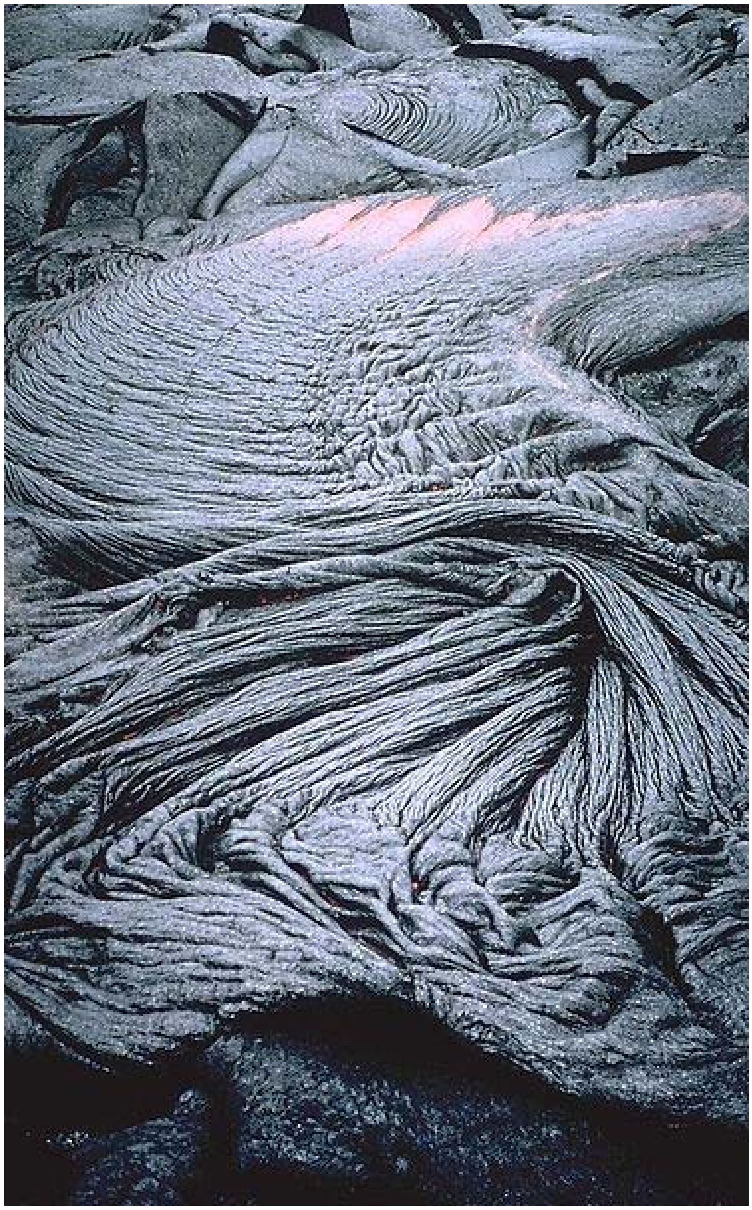
The word *volcano* is derived from the name of Vulcano, a volcanic island in the Aeolian Islands of Italy whose name in turn originates from Vulcan, the name of a god of fire in Roman mythology. The study of volcanoes is called volcanology, sometimes spelled *vulcanology*.

Erupted material

Pāhoehoe Lava flow on Hawaii. The picture shows overflows of a main lava channel

The Stromboli volcano off the coast of Sicily has erupted continuously for thousands of years, giving rise to the term strombolian eruption.

Mafic basalt lava flows created the Deccan Traps near Matheran, east of Mumbai, one of the largest volcanic features on Earth.



Pāhoehoe lava from Kīlauea, Hawaii

Lava composition

Another way of classifying volcanoes is by the *composition of material erupted* (lava), since this affects the shape of the volcano. Lava can be broadly classified into 4 different compositions (Cas & Wright, 1987):

- If the erupted magma contains a high percentage (>63%) of silica, the lava is called felsic.
  - Felsic lavas (dacites or rhyolites) tend to be highly viscous (not very fluid) and are erupted as domes or short, stubby flows. Viscous lavas tend to form stratovolcanoes or lava domes. Lassen Peak in California is an

example of a volcano formed from felsic lava and is actually a large lava dome.
    - Because siliceous magmas are so viscous, they tend to trap volatiles (gases) that are present, which cause the magma to erupt catastrophically, eventually forming stratovolcanoes. Pyroclastic flows (ignimbrites) are highly hazardous products of such volcanoes, since they are composed of molten volcanic ash too heavy to go up into the atmosphere, so they hug the volcano's slopes and travel far from their vents during large eruptions. Temperatures as high as 1,200 °C are known to occur in pyroclastic flows, which will incinerate everything flammable in their path and thick layers of hot pyroclastic flow deposits can be laid down, often up to many meters thick. Alaska's Valley of Ten Thousand Smokes, formed by the eruption of Novarupta near Katmai in 1912, is an example of a thick pyroclastic flow or ignimbrite deposit. Volcanic ash that is light enough to be erupted high into the Earth's atmosphere may travel many kilometres before it falls back to ground as a tuff.
- If the erupted magma contains 52–63% silica, the lava is of *intermediate* composition.
    - These "andesitic" volcanoes generally only occur above subduction zones (e.g. Mount Merapi in Indonesia).
    - Andesitic lava is typically formed at convergent boundary margins of tectonic plates, by several processes:
        - Hydration melting of peridotite and fractional crystallization
        - Melting of subducted slab containing sediments
        - Magma mixing between felsic rhyolitic and mafic basaltic magmas in an intermediate reservoir prior to emplacement or lava flow.
- If the erupted magma contains <52% and >45% silica, the lava is called mafic (because it contains higher percentages of magnesium (Mg) and iron (Fe)) or basaltic. These lavas are usually much less viscous than rhyolitic lavas, depending on their eruption temperature; they also tend to be hotter than felsic lavas. Mafic lavas occur in a wide range of settings:
    - At mid-ocean ridges, where two oceanic plates are pulling apart, basaltic lava erupts as pillows to fill the gap;
    - Shield volcanoes (e.g. the Hawaiian Islands, including Mauna Loa and Kilauea), on both oceanic and continental crust;
    - As continental flood basalts.
- Some erupted magmas contain <=45% silica and produce ultramafic lava. Ultramafic flows, also known as komatiites, are very rare; indeed, very few have been erupted at the Earth's surface since the Proterozoic, when the planet's heat flow was higher. They are (or were) the hottest lavas, and probably more fluid than common mafic lavas.

Lava texture

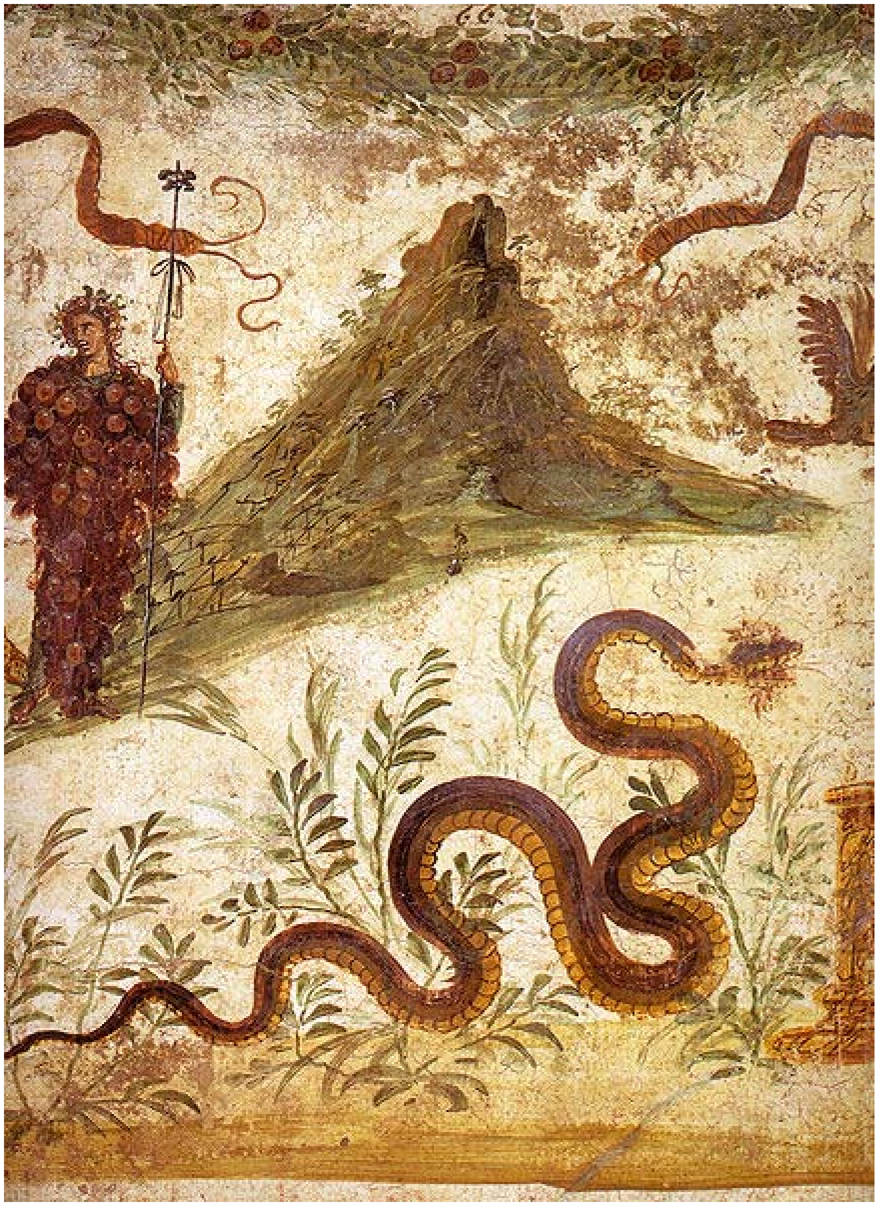
Two types of lava are named according to the surface texture: ʻAʻa and pāhoehoe, both Hawaiian words. ʻAʻa is characterized by a rough, clinkery surface and is the typical texture of viscous lava flows. However, even basaltic or mafic flows can be erupted as ʻaʻa flows, particularly if the eruption rate is high and the slope is steep.

Pāhoehoe is characterized by its smooth and often ropey or wrinkly surface and is generally formed from more fluid lava flows. Usually, only mafic flows will erupt as pāhoehoe, since they often erupt at higher temperatures or have the proper chemical make-up to allow them to flow with greater fluidity.

Volcanic activity

Active volcano Mount St. Helens shortly after the eruption of 18 May 1980

Damavand, the highest volcano in Asia, is a potentially active volcano with fumaroles and solfatara near its summit.



Fresco of Bacchus and Agathodaemon with Mount Vesuvius, as seen in Pompeii's House of the Centenary.

Fourpeaked volcano, Alaska, in September 2007, after being thought extinct for over 10,000 years.

Scientific classification of volcanoes

The Philippine Institute of Volcanology and Seismology provides a scientific classification system for volcanoes.

Active - Eruption in historic times - Historical record - 500 years - C14 dating - 10,000 years - Local seismic activity - Oral / folkloric history

Potentially Active - Solfataras / Fumaroles - Geologically young (possibly erupted < 10,000 years and for calderas and large systems - possibly < 25,000 years). - Young-looking geomorphology (thin soil cover/sparse vegetation; low degree of erosion and dissection; young vent features; +/- vegetation cover). - Suspected seismic activity. - Documented local ground deformation - Geochemical indicators of magmatic involvement. - Geophysical proof of magma bodies. - Strong connection with subduction zones and external tectonic settings.

Inactive No record of eruption and its form is beginning to change by the agents of weathering and erosion via formation of deep and long gullies.

Popular classification of volcanoes

Active

A popular way of classifying magmatic volcanoes is by their frequency of eruption, with those that erupt regularly called **active**, those that have erupted in historical *times* but are now quiet called **dormant**, and those that have not erupted in historical times called **extinct**. However, these popular classifications—extinct in particular—are practically meaningless to scientists. They use classifications which refer to a particular volcano's formative and eruptive processes and resulting shapes, which was explained above.

There is no real consensus among volcanologists on how to define an "active" volcano. The lifespan of a volcano can vary from months to several million years, making such a distinction sometimes meaningless when compared to the lifespans of humans or even civilizations. For example, many of Earth's volcanoes have erupted dozens of times in the past few thousand years but are not currently showing signs of eruption. Given the long lifespan of such volcanoes, they are very active. By human lifespans, however, they are not.

Scientists usually consider a volcano to be **erupting** or **likely to erupt** if it is currently erupting, or showing signs of unrest such as unusual earthquake activity or significant new gas emissions. Most scientists consider a volcano *active* if it has erupted in holocene times. **Historic times** is another timeframe for *active*. But it is important to note that the span of recorded history differs from region to region. In China and the Mediterranean, recorded history reaches back more than 3,000 years but in the Pacific Northwest of the United States and Canada, it reaches back less than 300 years, and in Hawaii and New Zealand, only around 200 years. The Smithsonian Global Volcanism Program's definition of *active* is having erupted within the last 10,000 years (the 'holocene' period).

Presently there are about 500 active volcanoes in the world – the majority following along the Pacific 'Ring of Fire' – and around 50 of these erupt each year. The United States is home to 50 active volcanoes. There are more than 1,500 potentially active volcanoes. An estimated 500 million people live near active volcanoes.

Extinct

Extinct volcanoes are those that scientists consider unlikely to erupt again, because the volcano no longer has a lava supply. Examples of extinct volcanoes are many volcanoes on the Hawaiian – Emperor seamount chain in the Pacific Ocean (extinct because the Hawaii hotspot is centered near the Big Island), Hohentwiel, Shiprock, and Paricutin (which is monogenetic). Otherwise, whether a volcano is truly extinct is often difficult to determine. Since "supervolcano" calderas can have eruptive lifespans sometimes measured in millions of years, a caldera that has not produced an eruption in tens of thousands of years is likely to be considered dormant instead of extinct.

Dormant

It is difficult to distinguish an extinct volcano from a **dormant** one. Volcanoes are often considered to be extinct if there are no written records of its activity. Nevertheless volcanoes may remain dormant for a long period of time, Yellowstone has a repose/ recharge period of around 700 ka and Toba of around 380 ka. Vesuvius was described by Roman writers as having been covered with gardens and vineyards before its famous eruption of AD 79, which destroyed the towns of Herculaneum and Pompeii. Before the catastrophic eruption of 1991, Pinatubo was an inconspicuous volcano, unknown to most people in the surrounding areas. More recently, the long-dormant Soufrière Hills volcano on the island of Montserrat was thought to be extinct before activity resumed in 1995. Another recent example is Fourpeaked Mountain in Alaska, which, prior to its eruption in September 2006, had not erupted since before 8000 BC and was long thought to be extinct.

Notable volcanoes

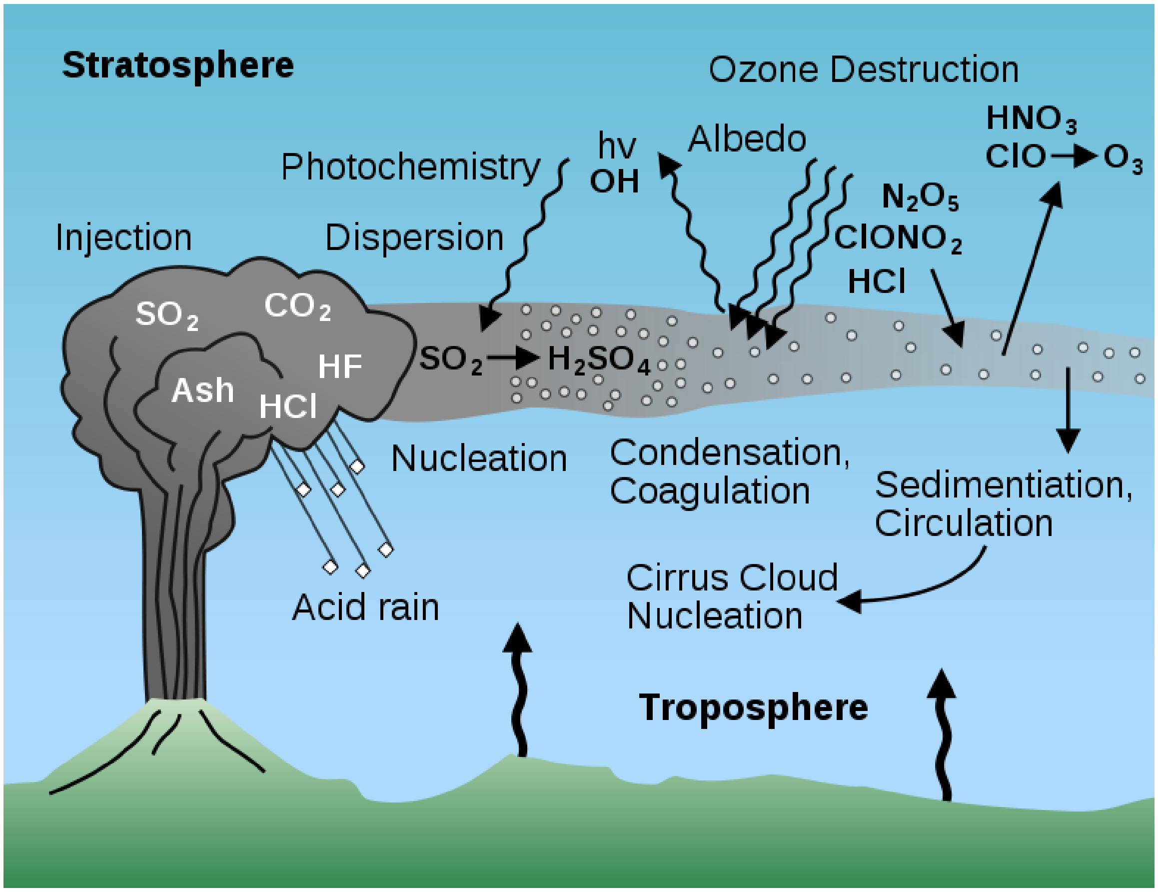
Koryaksky volcano towering over Petropavlovsk-Kamchatsky on Kamchatka Peninsula, Far Eastern Russia.

Mount Teide on the island of Tenerife (Spain)

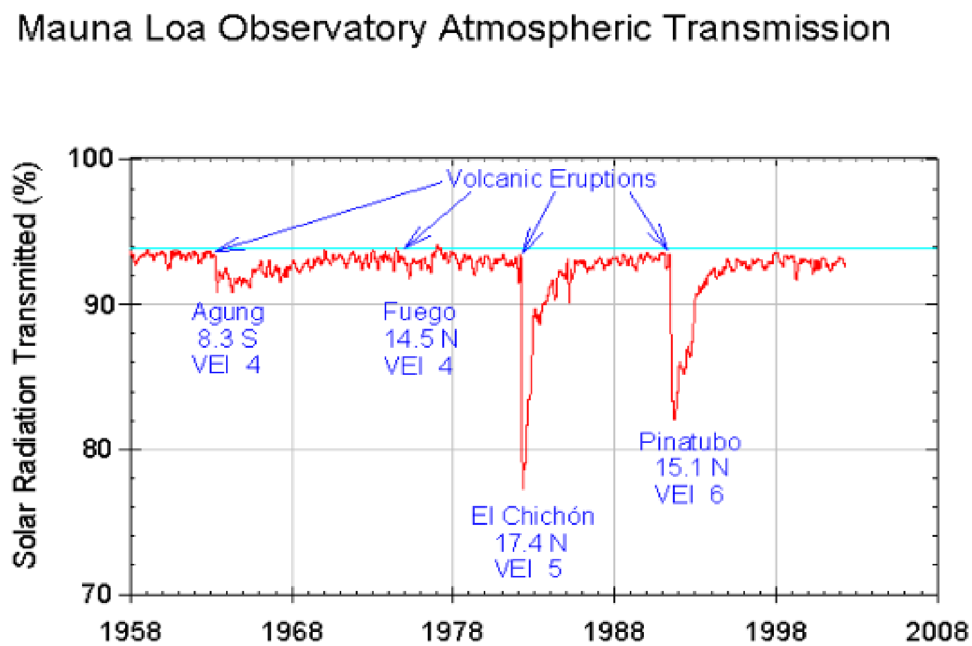
The 16 current Decade Volcanoes are:

- Avachinsky-Koryaksky, Kamchatka, Russia
- Nevado de Colima, Jalisco and Colima, Mexico
- Mount Etna, Sicily, Italy
- Galeras, Nariño, Colombia
- Mauna Loa, Hawaii, USA
- Mount Merapi, Central Java, Indonesia
- Mount Nyiragongo, Democratic Republic of the Congo
- Mount Rainier, Washington, USA
- Sakurajima, Kagoshima Prefecture, Japan
- Santa Maria/Santiaguito, Guatemala
- Santorini, Cyclades, Greece
- Taal Volcano, Luzon, Philippines
- Teide, Canary Islands, Spain
- Ulawun, New Britain, Papua New Guinea
- Mount Unzen, Nagasaki Prefecture, Japan
- Vesuvius, Naples, Italy

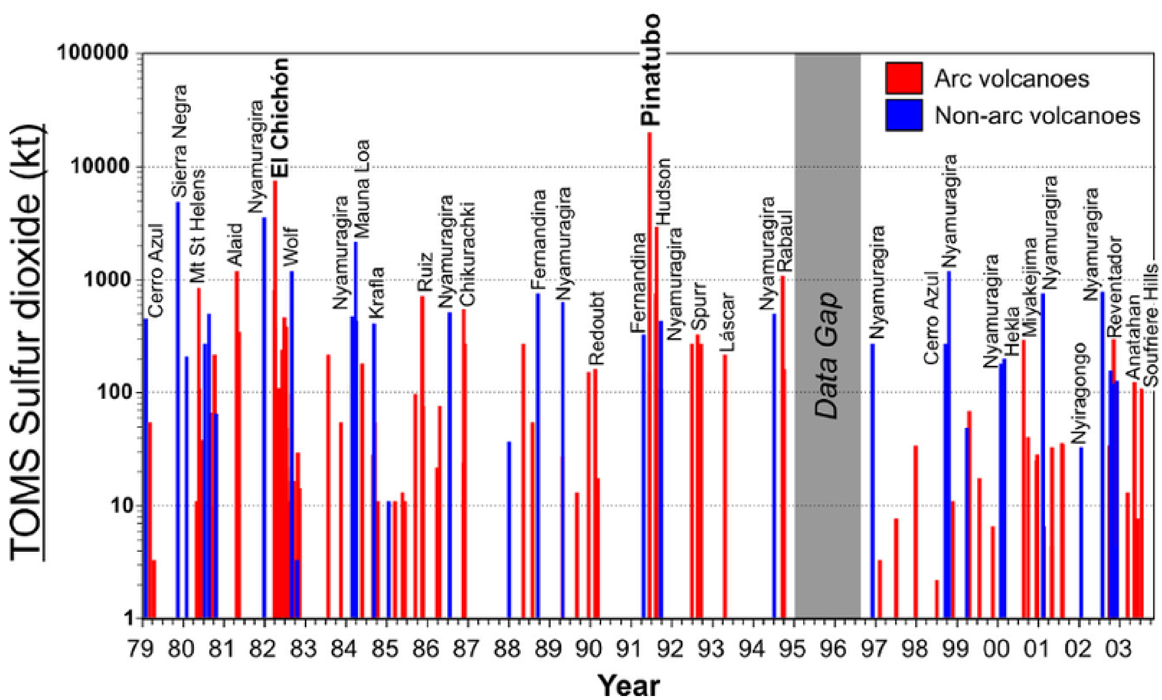
Effects of volcanoes



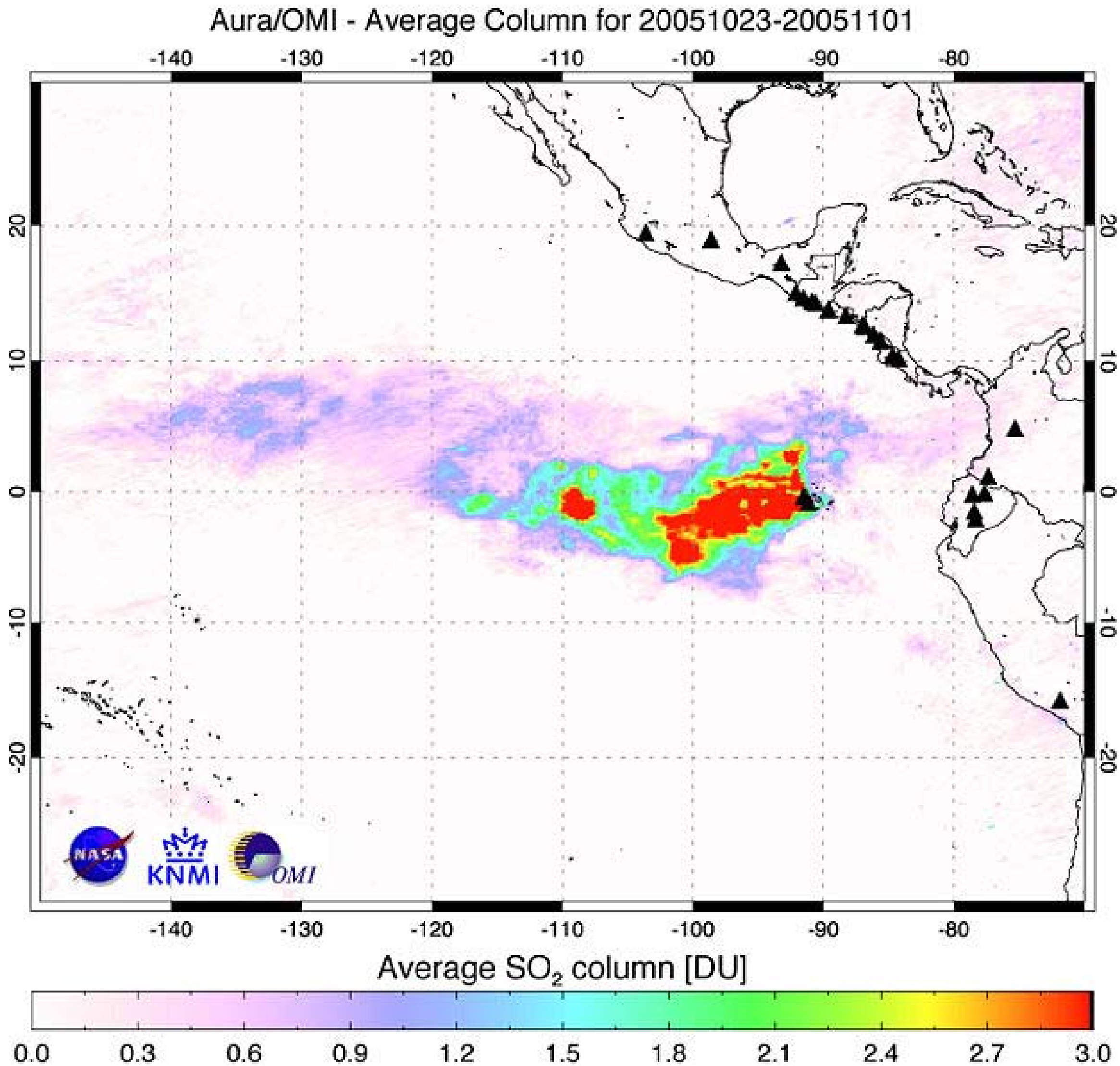
Volcanic "injection"



Solar radiation reduction from volcanic eruptions



Sulfur dioxide emissions by volcanoes



Average concentration of sulfur dioxide over the Sierra Negra Volcano (Galapagos Islands) from October 23–November 1, 2005

There are many different types of volcanic eruptions and associated activity: phreatic eruptions (steam-generated eruptions), explosive eruption of high-silica lava (e.g., rhyolite), effusive eruption of low-silica lava (e.g., basalt), pyroclastic flows, lahars (debris flow) and carbon dioxide emission. All of these activities can pose a hazard to humans. Earthquakes, hot springs, fumaroles, mud pots and geysers often accompany volcanic activity.

The concentrations of different volcanic gases can vary considerably from one volcano to the next. Water vapor is typically the most abundant volcanic gas, followed by carbon dioxide and sulfur dioxide. Other principal volcanic gases include hydrogen sulfide, hydrogen chloride, and hydrogen fluoride. A large number of minor and trace gases are also found in volcanic emissions, for example hydrogen, carbon monoxide, halocarbons, organic compounds, and volatile metal chlorides.

Large, explosive volcanic eruptions inject water vapor (H_2O), carbon dioxide (CO_2), sulfur dioxide (SO_2), hydrogen chloride (HCl), hydrogen fluoride (HF) and ash (pulverized rock and pumice) into the stratosphere to heights of 16–32 kilometres (10–20 mi) above the Earth's surface. The most significant impacts from these injections come from the conversion of sulfur dioxide to sulfuric acid (H_2SO_4), which condenses rapidly in the stratosphere to form fine sulfate aerosols. The aerosols increase the Earth's albedo—its reflection of radiation from the Sun back into space - and thus cool the Earth's lower atmosphere or troposphere; however, they also absorb heat radiated up from the Earth, thereby warming the stratosphere. Several eruptions during the past century have caused a decline in the average temperature at the Earth's surface of up to half a degree (Fahrenheit scale) for periods of one to three years — sulfur dioxide from the eruption of Huaynaputina probably caused the Russian famine of 1601 - 1603.

One proposed volcanic winter happened c. 70,000 years ago following the supereruption of Lake Toba on Sumatra island in Indonesia. According to the Toba catastrophe theory to which some anthropologists and archeologists subscribe, it had global consequences, killing most humans then alive and creating a population bottleneck that affected the genetic inheritance of all humans today. The 1815 eruption of Mount Tambora created global climate anomalies that became known as the "Year Without a Summer" because of the effect on North American and European weather. Agricultural crops failed and livestock died in much of the Northern Hemisphere, resulting in one of the worst famines of the 19th century. The freezing winter of 1740-41, which led to widespread famine in northern Europe, may also owe its origins to a volcanic eruption.

It has been suggested that volcanic activity caused or contributed to the End-Ordovician, Permian-Triassic, Late Devonian mass extinctions, and possibly others. The massive eruptive event which formed the Siberian Traps, one of the largest known volcanic events of the last 500 million years of Earth's geological history, continued for a million years and is considered to be the likely cause of the "Great Dying" about 250 million years ago, which is estimated to have killed 90% of species existing at the time.

The sulfate aerosols also promote complex chemical reactions on their surfaces that alter chlorine and nitrogen chemical species in the stratosphere. This effect, together with increased stratospheric chlorine levels from chlorofluorocarbon pollution, generates chlorine monoxide (ClO), which destroys ozone (O_3). As the aerosols grow and coagulate, they settle down into the upper troposphere where they serve as nuclei for cirrus clouds and further modify the Earth's radiation balance. Most of the hydrogen chloride (HCl) and hydrogen fluoride (HF) are dissolved in water droplets in the eruption cloud and quickly fall to the ground as acid rain. The injected ash also falls rapidly from the stratosphere; most of it is removed within several days to a few weeks. Finally, explosive volcanic eruptions release the greenhouse gas carbon dioxide and thus provide a deep source of carbon for biogeochemical cycles.

Rainbow and volcanic ash with sulfur dioxide emissions from Halema`uma`u vent

Gas emissions from volcanoes are a natural contributor to acid rain. Volcanic activity releases about 130 to 230 teragrams (145 million to 255 million short tons) of carbon dioxide each year. Volcanic eruptions may inject aerosols into the Earth's atmosphere. Large injections may cause visual effects such as unusually colorful sunsets and affect global climate mainly by cooling it. Volcanic eruptions also provide the benefit of adding nutrients to soil through the weathering process of volcanic rocks. These fertile soils assist the growth of plants and various crops. Volcanic eruptions can also create new islands, as the magma cools and solidifies upon contact with the water.

Ash thrown into the air by eruptions can present a hazard to aircraft, especially jet aircraft where the particles can be melted by the high operating temperature. Dangerous encounters in 1982 after the eruption of Galunggung in Indonesia, and 1989 after the eruption of Mount Redoubt in Alaska raised awareness of this phenomenon. Nine Volcanic Ash Advisory Centers were established by the International Civil Aviation Organization to monitor ash clouds and advise pilots accordingly. The 2010 eruptions of Eyjafjallajökull caused major disruptions to air travel in Europe.

Past beliefs

Many ancient accounts ascribe volcanic eruptions to supernatural causes, such as the actions of gods or demigods. To the ancient Greeks, volcanoes' capricious power could only be explained as acts of the gods, while 16th/17th-century German astronomer

Johannes Kepler believed they were ducts for the Earth's tears. One early idea counter to this was proposed by Jesuit Athanasius Kircher (1602–1680), who witnessed eruptions of Mount Etna and Stromboli, then visited the crater of Vesuvius and published his view of an Earth with a central fire connected to numerous others caused by the burning of sulfur, bitumen and coal.

Various explanations were proposed for volcano behavior before the modern understanding of the Earth's mantle structure as a semisolid material was developed. For decades after awareness that compression and radioactive materials may be heat sources, their contributions were specifically discounted. Volcanic action was often attributed to chemical reactions and a thin layer of molten rock near the surface.

Panoramas

Mount Bromo, East Java, Indonesia

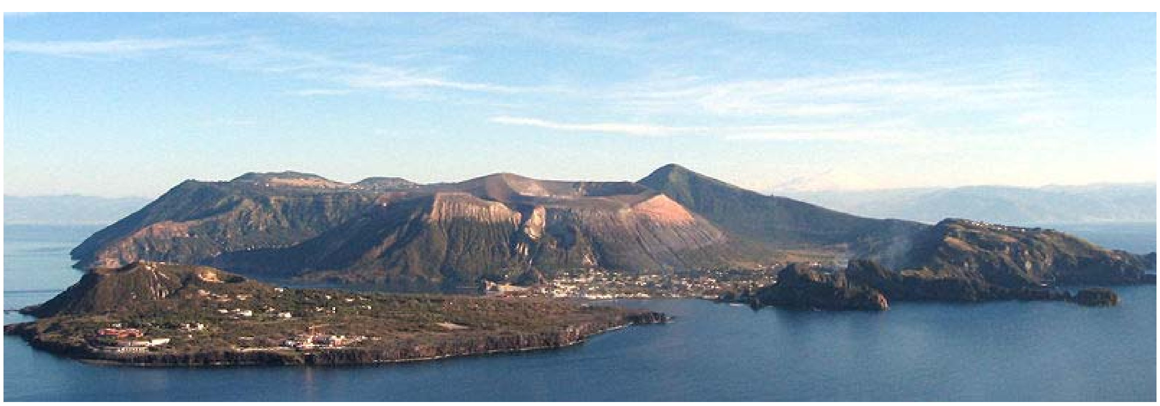
Crater of Mount Tangkuban Perahu, West Java, Indonesia

Irazú Volcano, Costa Rica

Black Rock Volcano an extinct cinder cone near Fillmore, Utah

Taal Volcano, Philippines

Crater of Sierra Negra volcano, Isabela island, Galapagos, Ecuador



Vulcano island with the north coast of Sicily in the background

Chapter- 2

Plate Tectonics and Hotspots

Divergent plate boundaries

In plate tectonics, a **divergent boundary** or **divergent plate boundary** (also known as a **constructive boundary** or an **extensional boundary**) is a linear feature that exists between two tectonic plates that are moving away from each other. These areas can form on the end of continents but eventually form ocean basins. Divergent boundaries within continents initially produce rifts which produce rift valleys. Therefore, most active divergent plate boundaries are between oceanic plates and are often called **mid-oceanic ridges**. Divergent boundaries also form volcanic islands which occur when the plates move apart to produce gaps which molten lava rises to fill. Thus creating a shield volcano which would eventually build up to become a volcanic island.

Although still an area of active research, it appears that according to complex convection within the Earth's mantle material rises to the base of the lithosphere beneath the divergent plate boundary. This supplies the area with vast amounts of heat and a reduction in pressure that melts rock from the asthenosphere (or upper mantle) beneath the rift area forming large flood basalt or lava flows. Each eruption occurs in only a part of the plate boundary at any one time, but when it does occur, it fills in the opening gap as the two opposing plates move away from each other. The average rate of movement is comparable to how fast human fingernails grow, (both about 2.5 cm per year).

Over millions of years, the plates have moved many hundreds of kilometers away from both sides of the divergent plate boundary. Because of this, rocks closest to the boundary are younger than rocks further away on the same plate.

Description

Bridge across the Álfagjá rift valley in southwest Iceland, that is part of the boundary between the Eurasian and North American continental tectonic plates.

At divergent boundaries, two plates move apart from each other and the space that this creates is filled with new crustal material sourced from molten magma that forms below. The origin of new divergent boundaries at triple junctions is sometimes thought to be associated with the phenomenon known as hotspots. Here, exceedingly large convective cells bring very large quantities of hot asthenospheric material near the surface and the kinetic energy is thought to be sufficient to break apart the lithosphere. The hot spot which may have initiated the Mid-Atlantic Ridge system currently underlies Iceland which is widening at a rate of a few centimeters per year.

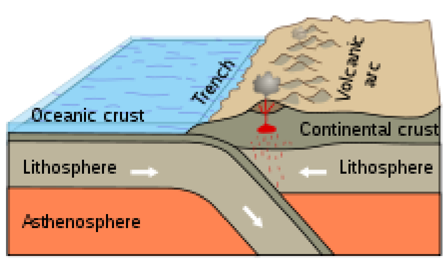
Divergent boundaries are typified in the oceanic lithosphere by the rifts of the oceanic ridge system, including the Mid-Atlantic Ridge and the East Pacific Rise, and in the continental lithosphere by rift valleys such as the famous East African Great Rift Valley. Divergent boundaries can create massive fault zones in the oceanic ridge system. Spreading is generally not uniform, so where spreading rates of adjacent ridge blocks are different, massive transform faults occur. These are the fracture zones, many bearing names, that are a major source of submarine earthquakes. A sea floor map will show a rather strange pattern of blocky structures that are separated by linear features perpendicular to the ridge axis. If one views the sea floor between the fracture zones as conveyor belts carrying the ridge on each side of the rift away from the spreading center the action becomes clear. Crest depths of the old ridges, parallel to the current spreading center, will be older and deeper (from thermal contraction and subsidence).

It is at mid-ocean ridges that one of the key pieces of evidence forcing acceptance of the seafloor spreading hypothesis was found. Airborne geomagnetic surveys showed a strange pattern of symmetrical magnetic reversals on opposite sides of ridge centers. The pattern was far too regular to be coincidental as the widths of the opposing bands were too closely matched. Scientists had been studying polar reversals and the link was made by Lawrence W. Morley, Frederick John Vine and Drummond Hoyle Matthews in the Morley-Vine-Matthews hypothesis. The magnetic banding directly corresponds with the Earth's polar reversals. This was confirmed by measuring the ages of the rocks within each band. The banding furnishes a map in time and space of both spreading rate and polar reversals.

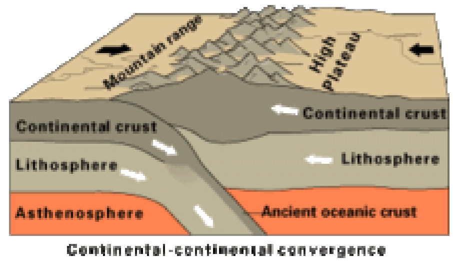
Convergent plate boundaries

n plate tectonics, a **convergent boundary** also known as a **destructive plate boundary** (because of subduction), is an actively deforming region where two (or more) tectonic plates or fragments of lithosphere move toward one another and collide. As a result of pressure, friction, and plate material melting in the mantle, earthquakes and volcanoes are common near convergent boundaries.

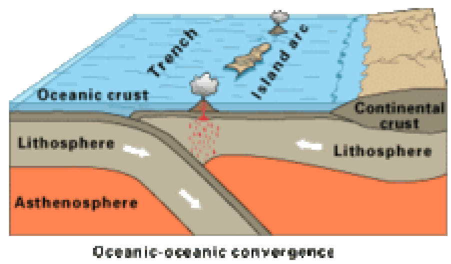
When two plates move towards one another, they form either a subduction zone or a continental collision. This depends on the nature of the plates involved. In a subduction zone, the subducting plate, which is normally a plate with oceanic crust, moves beneath the other plate, which can be made of either oceanic or continental crust. During collisions between two continental plates, large mountain ranges, such as the Himalayas are formed.



Oceanic-continental



Continental-continental



Oceanic-oceanic

Description

The nature of a convergent boundary depends on the type of lithosphere in the plates that are colliding. Where a dense oceanic plate collides with a less-dense continental plate, the oceanic plate is typically thrust underneath because of the greater buoyancy of the continental lithosphere, forming a subduction zone. At the surface, the topographic expression is commonly an oceanic trench on the ocean side and a mountain range on the continental side. An example of a continental-oceanic subduction zone is the area along the western coast of South America where the oceanic Nazca Plate is being subducted beneath the continental South American Plate.

Surface volcanism (volcanoes at the ocean floor or the Earth's surface) typically appears above the melts which form directly above downgoing plates. There is still debate in the geologic community as to why this is. However, the general consensus from ongoing research suggests that the release of volatiles is the primary contributor. As the subducting plate descends, its temperature rises driving off volatiles (most importantly water) encased in the porous oceanic crust. As this water rises into the mantle of the overriding plate, it lowers the melting temperature of surrounding mantle, producing melts (magma) with large amounts of dissolved gases. These melts rise to the surface and are the source of some of the most explosive volcanism on Earth because of their high volumes of extremely pressurized gases (consider Mount St. Helens). The melts rise to the surface and cool, forming long chains of volcanoes inland from the continental shelf and parallel to it. The continental spine of western South America is dense with this type of volcanic mountain building from the subduction of the Nazca plate. In North America the Cascade mountain range, extending north from California's Sierra Nevada, is also of this type. Such volcanoes are characterized by alternating periods of quiet and episodic eruptions that start with explosive gas expulsion with fine particles of glassy volcanic ash and spongy cinders, followed by a rebuilding phase with hot magma. The entire Pacific Ocean boundary is surrounded by long stretches of volcanoes and is known collectively as the Pacific ring of fire.

Where two continental plates collide the plates either buckle and compress or (in some cases) one plate delves under or the other. Either action will create extensive mountain ranges. The most dramatic effect seen is where the northern margin of the Indian Plate is being thrust under a portion of the Eurasian plate, lifting it and creating the Himalayas and the Tibetan Plateau beyond. It may have also pushed nearby parts of the Asian continent aside to the east.

When two plates with oceanic crust converge they typically create an island arc as one plate is subducted below the other. The arc is formed from volcanoes which erupt through the overriding plate as the descending plate melts below it. The arc shape occurs because of the spherical surface of the earth (nick the peel of an orange with a knife and note the arc formed by the straight-edge of the knife). A deep undersea trench is located in front of such arcs where the descending slab dips downward, such as the Mariana trench near the Mariana Islands. Other good examples of this type of plate convergence would be Japan and the Aleutian Islands in Alaska.

Plates may collide at an oblique angle rather than head-on to each other (e.g. one plate moving north, the other moving south-east), and this may cause strike-slip faulting along the collision zone, in addition to subduction or compression.

Not all plate boundaries are easily defined. Some are broad belts whose movements are unclear to scientists. One example would be the Mediterranean-Alpine boundary, which involves two major plates and several micro plates. The boundaries of the plates do not necessarily coincide with those of the continents. For instance, the North American Plate covers not only North America, but also far northeastern Siberia, plus a substantial portion of the Atlantic Ocean.

Convergent margins

A subduction zone is formed at a convergent plate boundary when one or both of the tectonic plates is composed of oceanic crust. The denser plate, made of oceanic crust, is subducted underneath the less dense plate, which can be either continental or oceanic crust. When both of the plates are made of oceanic crust, convergence is associated with island arcs such as the Solomon Islands.

An oceanic trench is found where the denser plate is subducted underneath the other plate. There is water in the rocks of the oceanic plate (because they are underwater), and as this plate moves further down into the subduction zone, much of the water contained in the plate is squeezed out when the plate begins to subduct. However, the recrystallization of ocean floor rocks, such as Serpentine, which are unstable in the upper mantle, recrystallize into Olivine, causing dehydration through loss of hydroxyl groups. This addition of water to the mantle causes partial melting of the mantle, generating magma, which then rises, and which normally results in volcanoes. This normally happens at a certain depth, about 70 to 80 miles below the Earth's surface, and so volcanoes are formed fairly close to, but not right next to, the trench.

Some convergent margins have zones of active seafloor spreading behind the island arc, known as back-arc basins.

When one plate is composed of oceanic lithosphere and the other is composed of continental lithosphere, the denser oceanic plate is subducted, often forming an orogenic belt and associated mountain range. This type of convergent boundary is similar to the Andes or the Cascade Range in North America.

When two plates containing continental crust collide, both are too light to subduct. In this case, a continent-continent collision occurs, creating especially large mountain ranges. The most spectacular example of this is the Himalayas.

When the subducting plate approaches the trench obliquely, the convergent plate boundary includes a major component of strike-slip faulting within the over-riding plate. The best example of this is the Sumatra convergent margin, where orthogonal convergence on the Sunda megathrust is occurring intermixed with movement on the Great Sumatran fault.

Examples

- the collision between the Eurasian Plate and the Indian Plate that is forming the Himalayas.
- subduction of the northern part of the Pacific Plate and the NW North American Plate that is forming the Aleutian Islands.
- subduction of the Nazca Plate beneath the South American Plate to form the Andes.
- subduction of the Pacific Plate beneath the Australian Plate, and vice versa forming the complex New Zealand to New Guinea subduction/transform boundaries.
- collision of the Eurasian Plate and the African Plate formed the Pontic Mountains in Turkey.
- Mariana Trench
- subduction of the Juan de Fuca Plate beneath the North American Plate.

Other types of plate boundaries

- Divergent boundary
- Transform fault

Hotspot (geology)

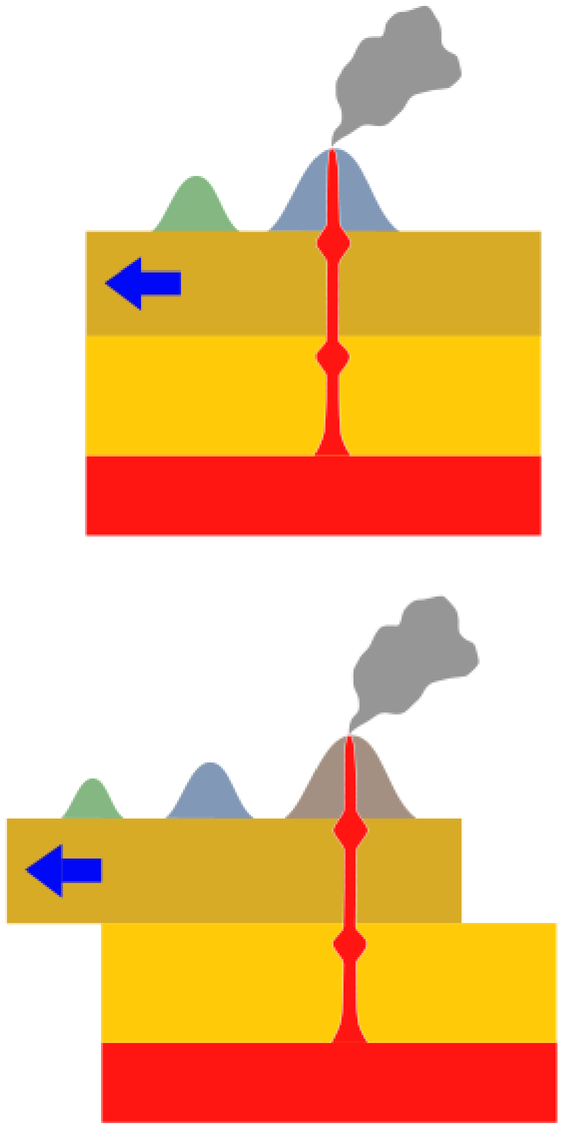


Diagram showing a cross section though the Earth's lithosphere (in yellow) with magma rising from the mantle (in red)

In geology, a **hotspot** or **hot spot** is a portion of the Earth's surface that may be far from tectonic plate boundaries and that experiences volcanism due to a rising mantle plume or some other cause.

Characteristics

J. Tuzo Wilson postulated in 1963 that volcanic chains like the Hawaiian Islands result from the slow movement of a tectonic plate across a fixed hot spot deep beneath the surface of the planet. Hotspots are thought to be caused by a narrow stream of hot mantle convecting up from the Earth's core-mantle boundary called a mantle plume, although some geologists prefer upper-mantle convection as a cause. This in turn has re-raised the antipodal pair impact hypothesis, the idea that pairs of opposite hotspots may result from the impact of a large meteor. Geologists have identified some 40–50 such hotspots around the globe, with Hawaii, Réunion, Yellowstone, Galápagos, and Iceland overlying the most currently active.

Most hotspot volcanoes are basaltic because they erupt through oceanic lithosphere (e.g., Hawaii, Tahiti). As a result, they are less explosive than subduction zone volcanoes, in which water is trapped under the overriding plate. Where hotspots occur under continental crust, basaltic magma is trapped in the less dense continental crust, which is heated and melts to form rhyolites. These rhyolites can be quite hot and form violent eruptions, despite their low water content. For example, the Yellowstone Caldera was formed by some of the most powerful volcanic explosions in geologic history. However, when rhyolitic magma is completely erupted, it may eventually be followed by eruptions of basaltic magma coming up through the same weaknesseses in the crust. An example of this activity is the Ilgachuz Range in British Columbia, which was created by an early complex series of trachyte and rhyolite eruptions, and late extrusion of a sequence of basaltic lava flows.

The theory of hotspot generation is just a part of the Wilson Cycle theory. The origin of a primary hotspot is a subducted seafloor that gets instable above the core/ mantle boundary (it gets a buoyancy by its heating up). If the magma encounters a continent upon rising up, it accumulates under it (plume head), causing a regional domal uplift of c. 1,000 m and geoid upswelling of a diameter of more than thousand kms. This gives origin to three rifts c. 120° apart and to basalt floods from the rifts. This begins crust movement/ seafloor spreading (similar to "landslides") from the top of the uplift, many times on two of the rifts only. The plume tail on the other hand could give origin to a primary hotspot with a deep origin.

The plume tail of a hotspot is deflected by the convection "wind" of the upper and lower mantle. Then one seafloor plate disappears the convection "wind" direction can change. Hotspots wander at a ten times slower velocity as the tectonic plates but there has been up to 50 mm/a motion between the two hemispheres prior to 50 Ma.

Some types of intraplate volcanism

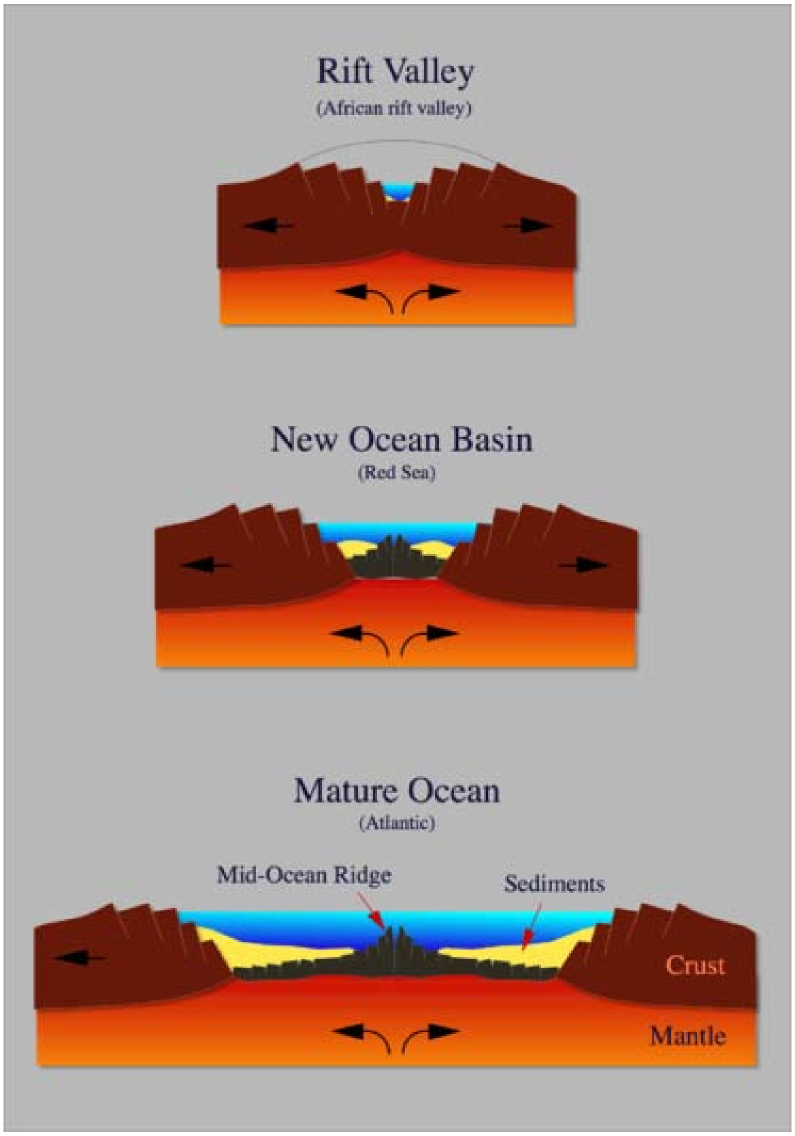


Diagram of Great Rift Valley, shows will form a sea in the future

There are four types of linear chain of volcanoes in the direction of the tectonic plate movement.

- All volcanoes have a similar age, volcanism is caused by faulting.
- Volcanism has a shallow origin caused by extension, e.g.: Basin and Range Province.
- Secondary Hotspots: Volcanism originates on the top of plume domes near the transition zone of the Upper Mantle/ Lower Mantle boundary.
  - Examples: hotspots over the superplumes under French Polynesia and Western Africa.
- Primary hotspots originating from the D'' Core-mantle boundary zone.

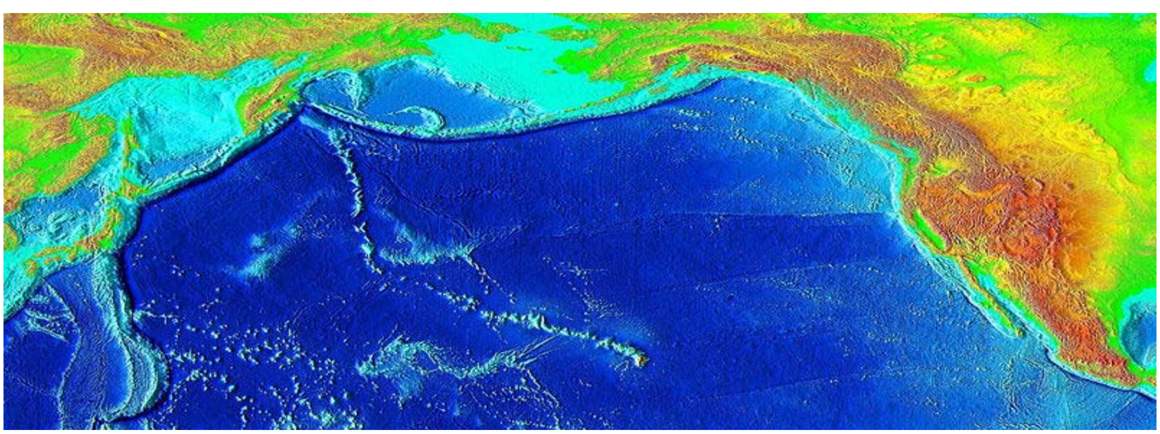
Examples

- Central Atlantic Magmatic Province (c. 200 Ma)
    - Rifts: Mid-Atlantic Ridge and Gulf of Mexico, the separation of South America and Africa occurred later on.
- Equatorial Atlantic Magmatic Province (139-81 Ma)
    - Rifts: Mid-Atlantic Ridge and Niger River estuary/ Benue River (Benue Trough).
- Paraná and Etendeka traps (c. 132 Ma)
    - Rifts: Mid-Atlantic Ridge
        - Ribeira Valley, Ribeira de Iguape river (North of the state border: São Paulo/ Paraná) ends where the extrapolated oldest part of the Rio Grande Rise (c. 25°S) would be.
    - Gough/Tristan hotspot: Walvis Ridge (East of the Mid-Atlantic Ridge), the plume tail could have forked.
- Deccan Traps (main events: 68.5-65 Ma)
    - Rifts: Central Indian Ridge and Narmada River (Narmada-Son and Gop rift).
    - Réunion hotspot: Réunion-Chagos-Maldives-Laccadive islands.

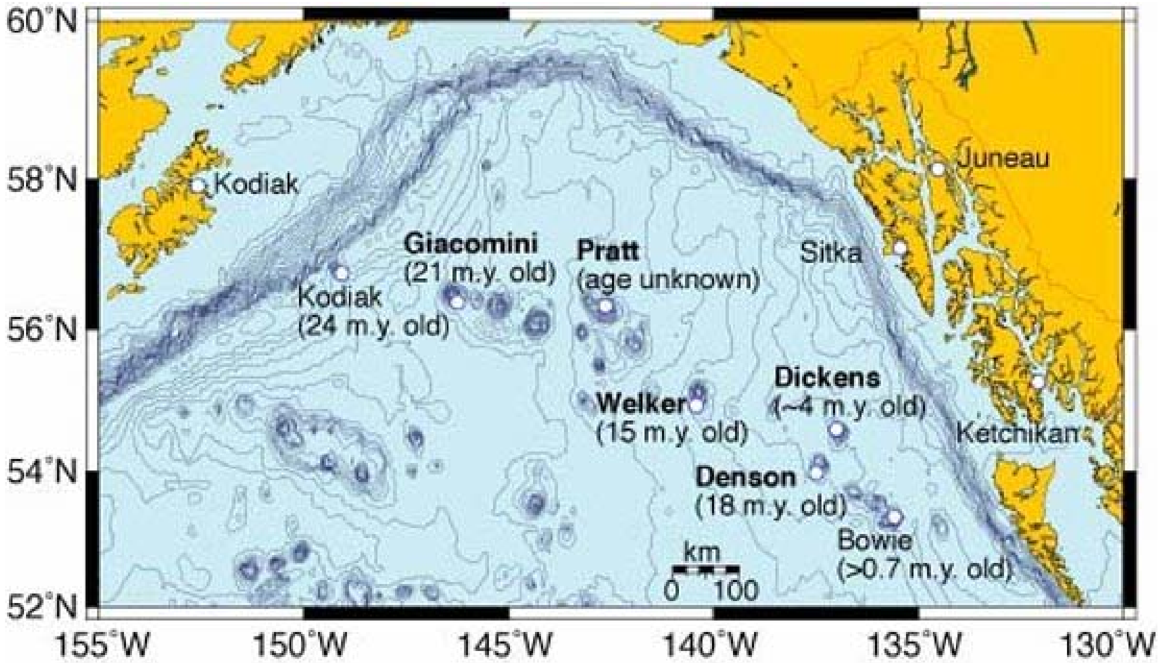
Comparison with island arc

Hotspot volcanoes should not be confused with island arc volcanoes. While each will appear as a string of volcanic islands, island arcs are formed by the subduction of converging tectonic plates. When one oceanic plate meets another, the denser plate is forced downward into a deep ocean trench. This plate, as it is subducted, releases water into the base of the over-riding plate, and this water causes some rock to melt. It is this that fuels a chain of volcanoes, such as the Aleutian Islands, near Alaska.

Trail



Over millions of years, the Pacific Plate has moved over the Hawaii hotspot, creating a trail of underwater mountains that stretch across the Pacific



Over millions of years, the Pacific Plate has moved over the Bowie hotspot, creating the Kodiak-Bowie Seamount chain in the Gulf of Alaska

As the continents and seafloor drift across the mantle plume, hotspot volcanoes generally leave unmistakable evidence of their passage through seafloor or continental crust. In the case of the Hawaiian hotspot, the islands themselves are the remnant evidence of the movement of the seafloor over the hotspot in the Earth's mantle. The Yellowstone hotspot emerged in the Columbia Plateau of the US Pacific Northwest. The Deccan Traps of India are thought to be the result of the emergence of the hotspot currently under Réunion Island, off the coast of eastern Africa.

Geologists use hotspots to help track the movement of the Earth's plates. Such hotspots are so active that they often record step-by-step changes in the direction of the Earth's magnetic poles. Thanks to lava flows from a series of eruptions in the Columbia Plateau, scientists now know that the reversal of magnetic poles takes about 5,000 years, fading until there is no detectable magnetism, then reforming in near-opposite directions.

Notable hotspot trails

- Hawaiian-Emperor seamount chain (Hawaii hotspot)
- Louisville seamount chain (Louisville hotspot)
- Walvis Ridge (Gough and Tristan hotspot)
- Kodiak-Bowie Seamount chain (Bowie hotspot)
- Cobb-Eickelberg Seamount chain (Cobb hotspot)
- New England Seamount chain (New England hotspot)
- Anahim Volcanic Belt (Anahim hotspot)

- Mackenzie dike swarm (Mackenzie hotspot)
- Great Meteor hotspot track (New England hotspot)
- St. Helena Seamount Chain - Cameroon Volcanic Line (Saint Helena hotspot)
- Réunion-Chagos-Maldives-Laccadive islands (Réunion hotspot)

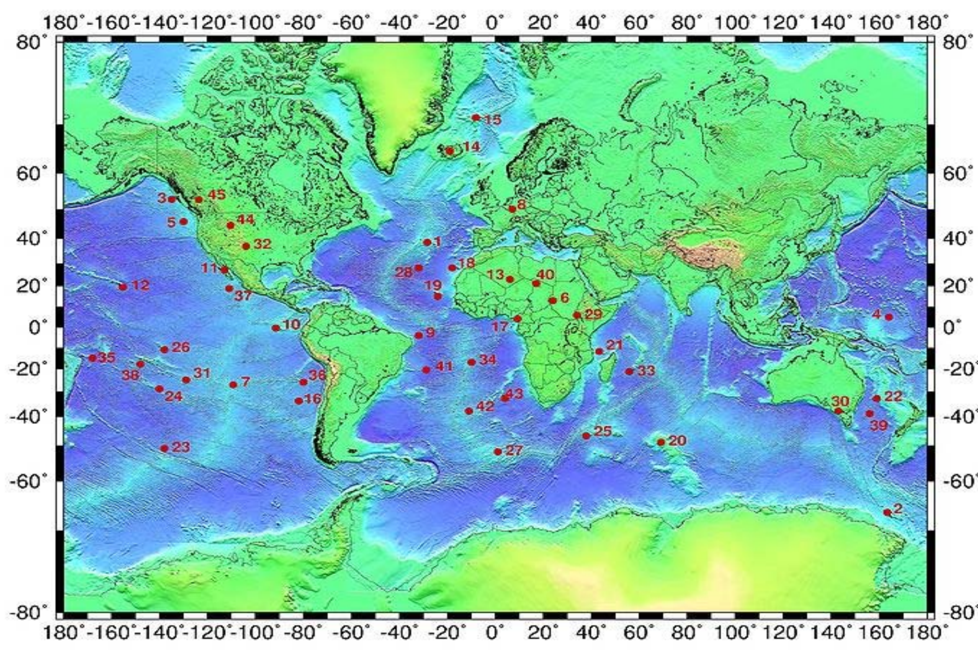
Possible hotspot trails

- Ninety East Ridge (Kerguelen hotspot?)
- Tuamoto-Line Island chain (Crough hotspot, it is probably not a hotspot trail)
- Austral-Gilbert-Marshall chain (Macdonald hotspot)

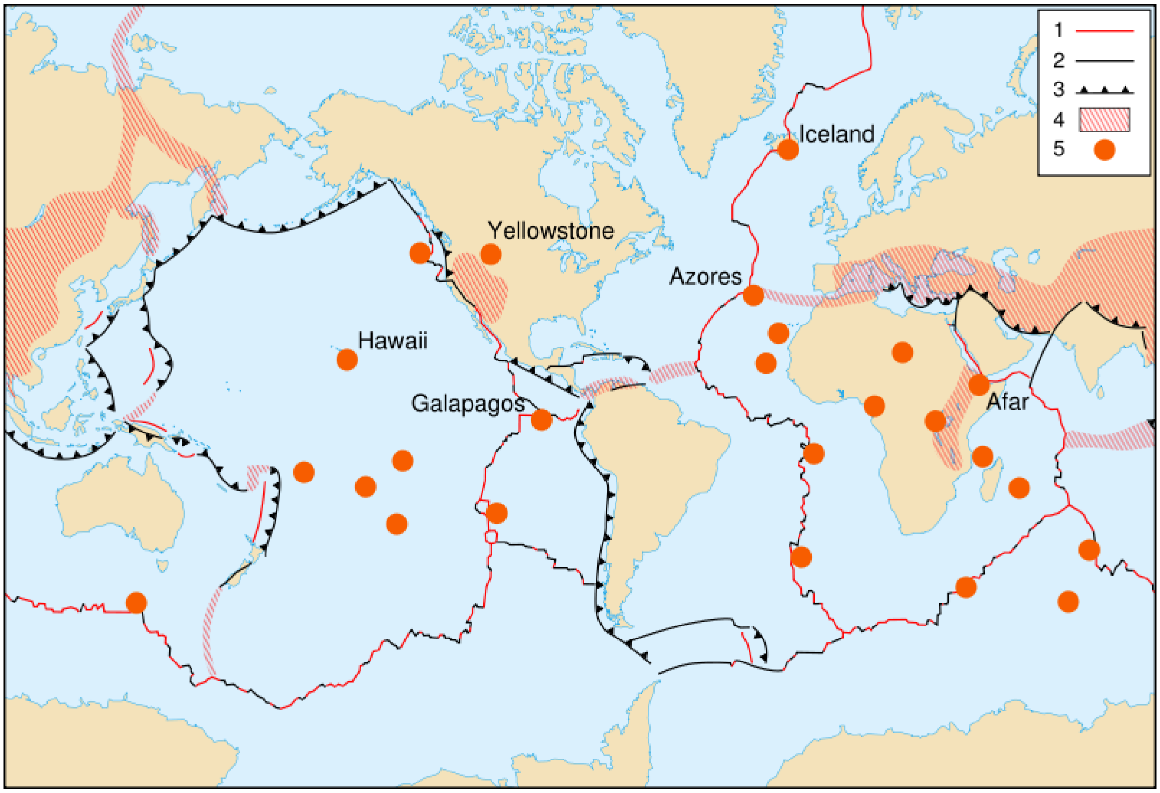
List of hotspots

Abbreviations:

- w: weight is a subjective uncertainty between simulation and determined azimuth;
- az: azimuth (heading of the tectonic plate)
- Weight, explanation:
  - azimuth difference less than 8°: w= 1.0
  - azimuth difference less than 10°: w= 0.8
  - azimuth difference less than 12°: w= 0.5
  - azimuth difference less than 15°: w= 0.3
  - azimuth difference more than 15°: w= 0.2



Distribution of selected hotspots. The numbers in the figure are related to the listed hotspots on the left.



World map showing the locations of selected prominent hotspots. 1) Divergent plate boundaries, 2) Transform plate boundaries, 3) Convergent plate boundaries, 4) Plate boundary zones, 5) Selected prominent hotspots

Eurasian Plate

- Eifel hotspot (8)
  - 50°12′N 6°42′E / 50.2°N 6.7°E, w= 1 az= 082° ±8° rate= 12 ±2 mm/yr
- Iceland hotspot (14)
  - 64°24′N 17°18′W / 64.4°N 17.3°W
    - Eurasian Plate, w= .8 az= 075° ±10° rate= 5 ±3 mm/yr
    - North American Plate, w= .8 az= 287° ±10° rate= 15 ±5 mm/yr
  - Related maybe with the North Atlantic continental rifting (62 Ma), Greenland. Could be a primary hotspot.
- Azores hotspot (1)
  - 37°54′N 26°00′W / 37.9°N 26.0°W
    - Eurasian Plate, w= .5 az= 110° ±12°
    - North American Plate, w= .3 az= 280° ±15°
- Jan Mayen hotspot (15)
  - 71°N 9°W / 71°N 9°W, it is probably not a hotspot
- Hainan hotspot
  - 20°N 110°E / 20°N 110°E, az= 000° ±15°, it is probably a hotspot

African Plate

- Mount Etna
  - 37°45.304′N 14°59.715′E / 37.755067°N 14.99525°E, no trail
- Hoggar hotspot (13)
  - 23°18′N 5°36′E / 23.3°N 5.6°E, w= .3 az= 046° ±12°
- Tibesti hotspot (40)
  - 20°48′N 17°30′E / 20.8°N 17.5°E, w= .2 az= 030° ±15°
- Jebel Marra/Darfur hotspot (6)
  - 13°00′N 24°12′E / 13.0°N 24.2°E, w= .5 az= 045° ±8°
- Afar hotspot
  - 7°00′N 39°30′E / 7.0°N 39.5°E, w= .2 az= 030° ±15° rate= 16 ±8 mm/yr
  - Could be a primary hotspot (Afar Triple Junction, 30 Ma)
- Cameroon hotspot (17)
  - 2°00′N 5°06′E / 2.0°N 5.1°E, w= .3 az= 032° ±3° rate= 15 ±5 mm/yr
- Madeira hotspot
  - 32°36′N 17°18′W / 32.6°N 17.3°W, w= .3 az= 055° ±15° rate= 8 ±3 mm/yr
- Canary hotspot (18)
  - 28°12′N 18°00′W / 28.2°N 18.0°W, w= 1 az= 094° ±8° rate= 20 ±4 mm/yr
- New England/Great Meteor hotspot (28)
  - 29°24′N 29°12′W / 29.4°N 29.2°W, w= .8 az= 040° ±10°
- Cape Verde hotspot (19)
  - 16°00′N 24°00′W / 16.0°N 24.0°W, w= .2 az= 060° ±30°
- St. Helena hotspot (34)
  - 16°30′N 9°30′E / 16.5°N 9.5°E, w= 1 az= 078° ±5° rate= 20 ±3 mm/yr
- Gough hotspot, at 40°19' S 9°56' W.
  - 40°18′S 10°00′E / 40.3°S 10°E, w= .8 az= 079° ±5° rate= 18 ±3 mm/yr
  - Tristan hotspot (42), at 37°07′ S 12°17′ W.
    - 37°12′S 12°18′W / 37.2°S 12.3°W, no trail
  - Vema hotspot (Vema Seamount, 43), at 31°38' S 8°20' E.
    - 32°06′S 6°18′W / 32.1°S 6.3°W, it is perhaps a hotspot
  - Related maybe to the Paraná and Etendeka traps (c. 132 Ma) through the Walvis Ridge.
- Discovery hotspot (Discovery Seamounts)
  - 43°00′S 2°42′W / 43.0°S 2.7°W, w= 1 az= 068° ±3°
- Bouvet hotspot
  - 54°24′S 3°24′E / 54.4°S 3.4°E, it is probably not a hotspot
- Shona/Meteor hotspot (27)
  - 51°24′N 1°00′W / 51.4°N 1.0°W, w= .3 az= 074° ±6°
- Réunion hotspot (33)

- 21°12′S 55°42′E / 21.2°S 55.7°E, w= .8 az= 047° ±10° rate= 40 ±10 mm/yr
- Related maybe to the Deccan Traps (main events: 68.5-65 Ma). Could be a primary hotspot.

- Comoros hotspot (21)
  - 11°30′S 43°18′E / 11.5°S 43.3°E, w= .5 az=118 ±10° rate=35 ±10 mm/yr. It is probably not a hotspot, as the azimuth is wrong. Many other things are probably interacting here.

Antarctic Plate

- Marion hotspot (25)
  - 46°54′S 37°36′E / 46.9°S 37.6°E, w= .5 az= 080° ±12°
- Crozet hotspot
  - 46°06′S 50°12′E / 46.1°S 50.2°E, w= .8 az= 109° ±10° rate= 25 ±13 mm/yr
  - Related maybe to the Karoo-Ferrar geologic province (183 Ma)
- Kerguelen hotspot (20)
  - 49°36′S 69°00′E / 49.6°S 69.0°E, w= .2 az= 050° ±30° rate= 3 ±1 mm/yr
  - Île Saint-Paul and Île Amsterdam could be part of the Kerguelen hotspot trail (St. Paul is probably not another hotspot)
  - Related maybe to the Kerguelen Plateau (130 Ma)
- Heard hotspot
  - 53°06′S 73°30′E / 53.1°S 73.5°E, w= .2 az= 030° ±20°
- Balleny hotspot (2)
  - 67°36′S 164°48′E / 67.6°S 164.8°E, w= .2 az= 325° ±7°
- Erebus hotspot
  - 77°30′S 167°12′E / 77.5°S 167.2°E, no trail

South American Plate

- Trindade/Martin Vaz hotspot (41)
  - 20°30′S 28°48′W / 20.5°S 28.8°W, w= 1 az= 264° ±5°
- Fernando hotspot (9)
  - 3°48′S 32°24′W / 3.8°S 32.4°W, w= 1 az= 266° ±7°
  - Related maybe to the CAMP (c. 200 Ma)
- Ascension hotspot
  - 7°54′S 14°18′W / 7.9°S 14.3°W, it is perhaps a hotspot

North American Plate

- Bermuda hotspot
  - 32°36′N 64°18′W / 32.6°N 64.3°W, w= .3 az= 260° ±15°

- Yellowstone hotspot (44)
    - 44°30′N 110°24′W / 44.5°N 110.4°W, w= .8 az= 235° ±5° rate= 26 ±5 mm/yr
    - Related maybe to the Columbia River Basalt Group (17-14 Ma). Could be a primary hotspot.
- Raton hotspot (32)
    - 36°48′N 104°06′W / 36.8°N 104.1°W, w= 1 az= 240°±4° rate= 30 ±20 mm/yr
- Anahim hotspot (45)
    - 52°54′0″N 123°44′0″W / 52.9°N 123.733333°W (Nazko Cone)

Indo-Australian Plate

- Lord Howe hotspot (22)
    - 34°42′S 159°48′E / 34.7°S 159.8°E, w= .8 az= 351° ±10°
- Tasmanid hotspot (Gascoyne Seamount, 39)
    - 40°24′S 155°30′E / 40.4°S 155.5°E, w= .8 az= 007° ±5° rate= 63 ±5 mm/yr
- East Australia hotspot (30)
    - 40°48′S 146°00′E / 40.8°S 146.0°E, w= .3 az= 000° ±15° rate= 65 ±3 mm/yr

Nazca Plate

- Juan Fernández hotspot (16)
    - 33°54′S 81°48′W / 33.9°S 81.8°W, w= 1 az= 084° ±3° rate= 80 ±20 mm/yr
- San Felix hotspot (36)
    - 26°24′S 80°06′W / 26.4°S 80.1°W, w= .3 az= 083° ±8°
- Easter hotspot (7)
    - 26°24′S 106°30′W / 26.4°S 106.5°W, w= 1 az= 087° ±3° rate= 95 ±5 mm/yr
    - Trail might begin near the Marquesas Islands. Could be a primary hotspot.
- Galápagos hotspot (10)
    - 0°24′S 91°36′W / 0.4°S 91.6°W
        - Nazca Plate, w= 1 az= 096° ±5° rate= 55 ±8 mm/yr
        - Cocos Plate, w= .5 az= 045° ±6°
    - Related maybe to the Caribbean large igneous province (main events: 95-88 Ma). Could be a primary hotspot.

Pacific Plate

- Louisville hotspot (23)

- 53°36′S 140°36′W / 53.6°S 140.6°W, w= 1 az= 316° ±5° rate= 67 ±5 mm/yr
    - Related maybe with the Ontong Java Plateau (125-120 Ma). Could be a primary hotspot.
- Foundation hotspot
    - 37°42′S 111°06′W / 37.7°S 111.1°W, w= 1 az= 292° ±3° rate= 80 ±6 mm/yr
- Macdonald hotspot (24)
    - 29°00′S 140°18′W / 29.0°S 140.3°W, w= 1 az= 289° ±6° rate= 105 ±10 mm/yr
    - Related maybe to the superplume under French Polynesia
- Arago hotspot (Arago Seamount)
    - 23°24′S 150°42′W / 23.4°S 150.7°W, w= 1 azim= 296° ±4° rate= 120 ±20 mm/yr
- North Austral/President Thiers (President Thiers Bank)
    - 25°36′S 143°18′W / 25.6°S 143.3°W, w= (1.0) azim= 293° ± 3° rate= 75 ±15 mm/yr, it is perhaps a hotspot
- Maria/Southern Cook hotspot (Îles Maria)
    - 20°12′S 153°48′W / 20.2°S 153.8°W, w= 0.8 az= 300° ±4°
- Samoa hotspot (35)
    - 14°30′S 168°12′W / 14.5°S 168.2°W, w= .8 az= 285°±5° rate= 95 ±20 mm/yr
    - Could be a primary hotspot.
- Crough hotspot (Crough Seamount)
    - 26°54′S 114°36′W / 26.9°S 114.6°W, w= .8 az= 284° ± 2°
- Pitcairn hotspot (31)
    - 25°24′S 129°18′W / 25.4°S 129.3°W, w= 1 az= 293° ±3° rate= 90 ±15 mm/yr
    - Related maybe to the superplume under French Polynesia
- Society/Tahiti hotspot (38)
    - 18°12′S 148°24′W / 18.2°S 148.4°W, w= .8 az= 295°±5° rate= 109 ±10 mm/yr
    - Related maybe to the superplume under French Polynesia
- Marquesas hotspot (26)
    - 10°30′S 139°00′W / 10.5°S 139.0°W, w= .5 az= 319° ±8° rate= 93 ±7 mm/yr
- Caroline hotspot (4)
    - 4°48′N 164°24′E / 4.8°N 164.4°E, w= 1 az= 289° ±4° rate= 135 ±20 mm/yr
    - Related maybe to the superplume under French Polynesia
- Hawaii hotspot (12)
    - 19°00′N 155°12′W / 19.0°N 155.2°W, w= 1 az= 304° ±3° rate= 92 ±3 mm/yr

    - Related maybe to the Siberian Traps (251-250 Ma). Could be a primary hotspot.
- Socorro/Revillagigedos hotspot (37)
    - 19°00′N 111°00′W / 19.0°N 111°W, it is probably not a hotspot
- Guadalupe hotspot (11)
    - 27°42′N 114°30′W / 27.7°N 114.5°W, w= .8 az= 292° ±5° rate= 80 ±10 mm/yr
- Cobb hotspot (5)
    - 46°00′N 130°06′W / 46.0°N 130.1°W, w= 1 az= 321° ±5° rate= 43 ±3 mm/yr
- Bowie/Pratt-Welker hotspot (3)
    - 53°00′N 134°48′W / 53.0°N 134.8°W, w=.8 az= 306° ±4° rate= 40 ±20 mm/yr

Former hotspots

- Euterpe/Musicians hotspot (Musicians Seamounts)
- Mackenzie hotspot
- Matachewan hotspot

Chapter- 3

Volcanic Features

Conical Mount Fuji in Japan, at sunrise from Lake Kawaguchi (2005)

The most common perception of a volcano is of a conical mountain, spewing lava and poisonous gases from a crater at its summit. This describes just one of many types of volcano, and the features of volcanoes are much more complicated. The structure and behavior of volcanoes depends on a number of factors. Some volcanoes have rugged peaks formed by lava domes rather than a summit crater, whereas others present landscape features such as massive plateaus. Vents that issue volcanic material (lava, which is what magma is called once it has escaped to the surface, and ash) and gases (mainly steam and magmatic gases) can be located anywhere on the landform. Many of these vents give rise to smaller cones such as Puʻu ʻŌʻō on a flank of Hawaii's Kīlauea.

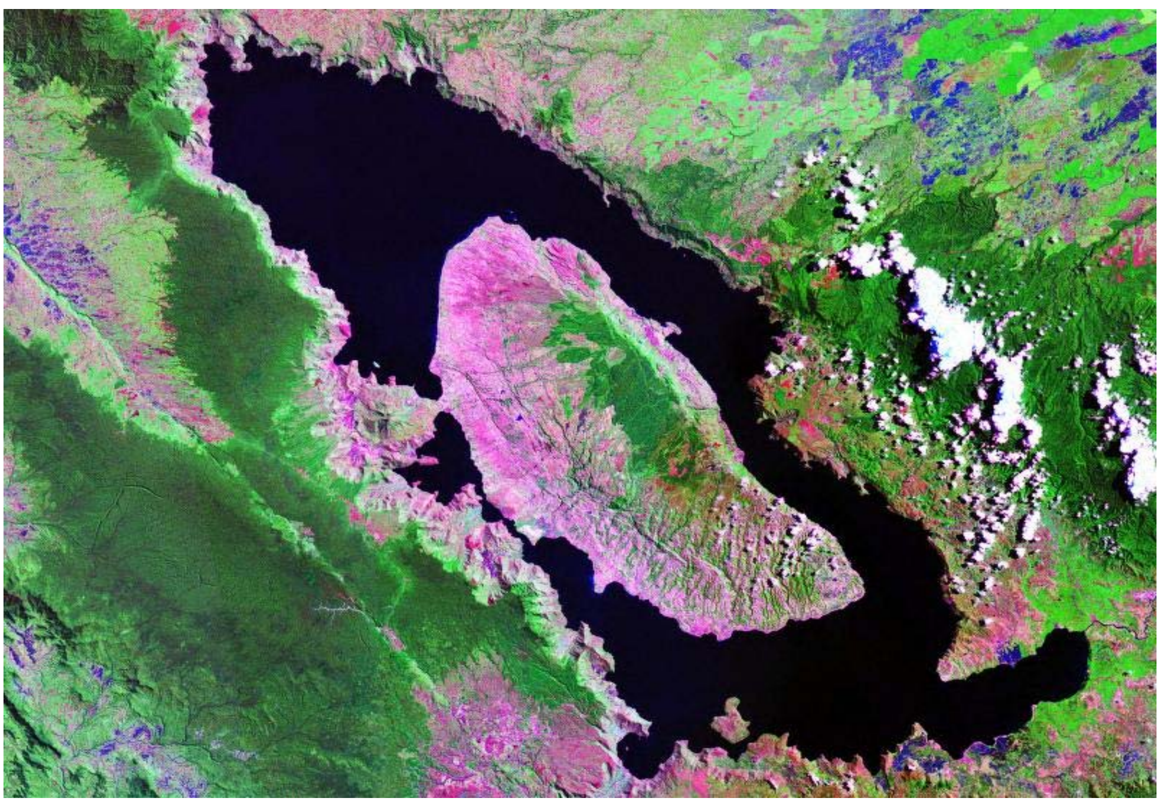
Lakagigar fissure vent in Iceland, source of the major world climate alteration of 1783-84. Volcanic eruptions are experienced somewhere in Iceland on an average of once every five years.

Skjaldbreiður, a shield volcano whose name means "broad shield"

January 2009 image of the rhyolitic lava dome of Chaitén Volcano, southern Chile during its 2008-2009 eruption

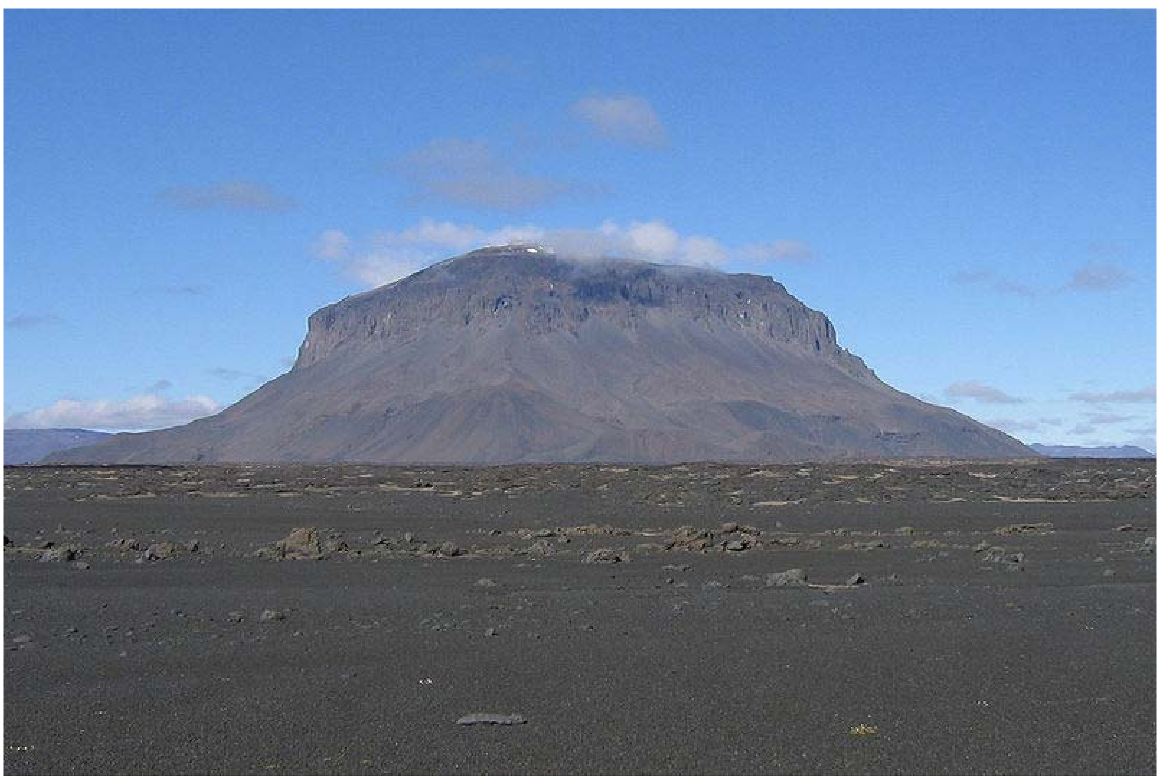
Holocene cinder cone volcano on State Highway 18 near Veyo, Utah

Mayon, near-perfect stratovolcano in the Philippines



The Lake Toba volcano created a caldera 100 km long

Pillow lava (NOAA)



Herðubreið, one of the tuyas in Iceland

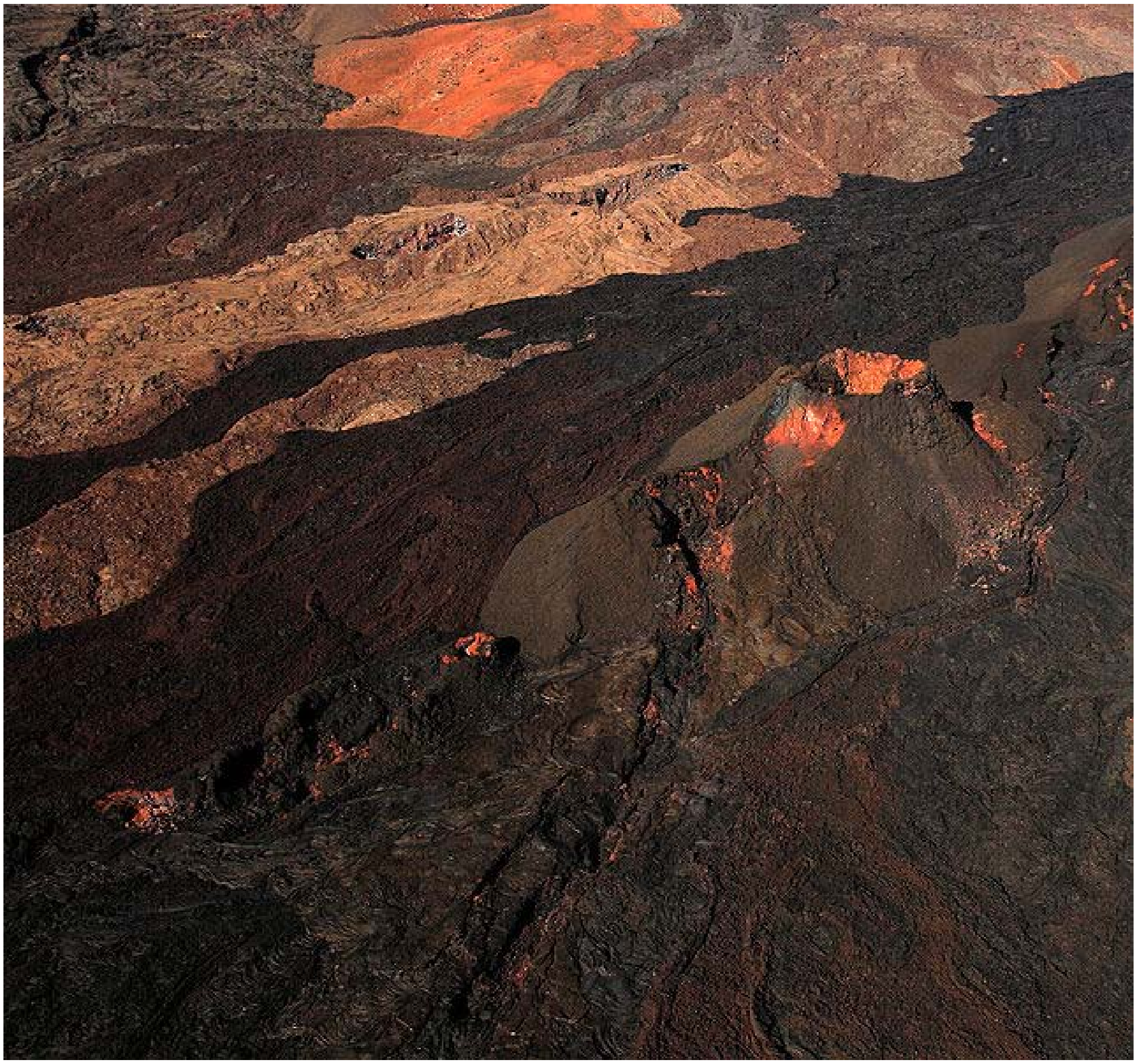
Mud volcano on Taman Peninsula, Russia

Other types of volcano include cryovolcanoes (or ice volcanoes), particularly on some moons of Jupiter, Saturn and Neptune; and mud volcanoes, which are formations often not associated with known magmatic activity. Active mud volcanoes tend to involve temperatures much lower than those of igneous volcanoes, except when a mud volcano is actually a vent of an igneous volcano.

Fissure vent

A volcanic fissure and lava channel

Lava channel on Hawaii



Mauna Loa with different lava flows and fissure vent

A **fissure vent**, also known as a **volcanic fissure** or simply **fissure**, is a linear volcanic vent through which lava erupts, usually without any explosive activity. The vent is usually a few meters wide and may be many kilometers long. Fissure vents can cause large flood basalts and lava channels. This type of volcano is usually hard to recognize from the ground and from outer space because it has no central caldera and the surface is mostly flat. The volcano can usually be seen as a crack in the ground or on the ocean floor. Narrow fissures can be filled in with lava that hardens. As erosion removes its surroundings, the lava mass could stand above the surface as a dyke. The dykes that feed fissures reach the surface from depths of a few kilometers. Fissures are usually found in or along rifts and rift zones, such as Iceland and the Great Rift Valley in Africa. Fissure vents are often found in shield volcanoes.

In Iceland, volcanic vents are often long fissures parallel to the rift zone where lithospheric plates are diverging. Renewed eruptions generally occur from new parallel fractures offset by a few hundred to thousands of metres from the earlier fissures. This distribution of vents and voluminous eruptions of fluid basaltic lava usually build up a thick lava plateau rather than a single volcanic edifice. The Laki fissure system produced the biggest eruption on earth in historical times, in the form of a flood basalt, during the Eldgjá eruption A.D. 934, which released 19.6 km^3 (4.7 mi^3) of lava.

The radial fissure vents of Hawaiian volcanoes produce "curtains of fire" as lava fountains erupt along a portion of a fissure. These vents produce low ramparts of basaltic spatter on both sides of the fissure. More isolated lava fountains along the fissure produce crater rows of small spatter and cinder cones. The fragments that form a spatter cone are hot and plastic enough to weld together, while the fragments that form a cinder cone remain separate because of their lower temperature.

List of fissure vents

Name	Elevation		Location	Last eruption
	metres	feet	Coordinates	
Laki	1725	5659	64°25′N 17°20′W / 64.42°N 17.33°W	1783
Lanzarote	670	2198	29°02′N 13°38′W / 29.03°N 13.63°W	1824
Cordon Caulle	1798	5899	40°28′S 72°15′W / 40.46°S 72.25°W	1960
São Jorge Island	1053	3455	38°39′N 28°05′W / 38.65°N 28.08°W	1907
Vatnafjöll	1235	4052	63°55′N 19°40′W / 63.92°N 19.67°W	1200 BP
Quetena	5730	18799	22°15′S 67°25′W / 22.25°S 67.42°W	Unknown
Nejapa Miraflores	360	1181	12°07′N 86°19′W / 12.12°N 86.32°W	Unknown
Manda-Inakir	600+	1968	12°23′N 42°12′E / 12.38°N 42.20°E	1928
Hertali	900?	2953	9°47′N 40°20′E / 9.78°N 40.33°E	Unknown
Gran Canaria	1950	6350	28°00′N 15°35′W / 28.00°N 15.58°W	less than 1000 BP
Fuerteventura	529	1736	28°21′29″N 14°01′12″W / 28.358°N 14.02°W	Unknown
Estelí	899	2949	13°10′N 86°24′W / 13.17°N 86.40°W	Unknown

Butajiri Silti Field	2281	7484	8°03′N 83°51′E / 8.05°N 83.85°E	Unknown
Bishoftu Volcanic Field	1850+	6069	8°47′N 38°59′E / 8.78°N 38.98°E	Unknown
Alu	429	1407	13°49′N 40°33′E / 13.82°N 40.55°E	Unknown
Singu Plateau	507	1663	22°42′N 95°59′E / 22.70°N 95.98°E	Unknown
Ray Mountain	2050	-	52°14′N 120°07′W / 52.23°N 120.12°W	Pleistocene
Eldgjá	800	2625	63°53′N 18°46′W / 63.88°N 18.77°W	934

Lava dome

Image of the rhyolitic lava dome of Chaitén Volcano during its 2008–2009 eruption

One of the Mono Craters, an example of a rhyolite dome

Lava domes in the crater of Mount St. Helens

In volcanology, a **lava dome** is a roughly circular mound-shaped protrusion resulting from the slow extrusion of viscous lava from a volcano. The geochemistry of lava domes can vary from basalt to rhyolite although most preserved domes tend to have high silica content. The characteristic dome shape is attributed to high viscosity that prevents the lava from flowing very far. This high viscosity can be obtained in two ways: by high levels of silica in the magma, or by degassing of fluid magma. Since viscous basaltic and andesitic domes weather fast and easily break apart by further input of fluid lava, most of the preserved domes have high silica content and consists of rhyolite or dacite.

Dome dynamics

Lava domes are dynamic structures that evolve over time undergoing various processes such as growth, collapse, solidification and erosion.

Lava domes grow by endogenic dome growth or exogenic dome growth. The first one implies dome interior expansion to accommodate new lava and the second one refers to superficial piling up of lava. It is the high viscosity of the lava that prevents it from flowing far from the vent from which it extrudes, creating a dome-like shape of sticky lava that then cools slowly in situ. Domes may reach heights of several hundred meters, and can grow slowly and steadily for months (e.g. Unzen volcano), years (e.g. Soufrière Hills volcano), or even centuries (e.g. Mount Merapi volcano). The sides of these structures are composed of unstable rock debris. Due to the intermittent build up of gas pressure, erupting domes can often experience episodes of explosive eruption over time. If part of a lava dome collapses while it is still molten, it can produce pyroclastic flows, one of the most lethal forms of volcanic event. Other hazards associated with lava domes are the destruction of property, forest fires, and lahars triggered by pyroclastic flows near mud, snow and ice. Lava domes are one of the principal structural features of many stratovolcanoes worldwide.

Characteristics of lava dome eruptions include shallow, long-period and hybrid seismicity, which is attributed to excess fluid pressures in the contributing vent chamber. Other characteristics of lava domes include their hemispherical dome shape, cycles of dome growth over long periods, and sudden onsets of violent explosive activity. The average rate of dome growth may be used as a rough indicator of magma supply, but it shows no systematic relationship to the timing or characteristics of lava dome explosions.

Related landforms

Cryptodomes

Photo showing the bulging cryptodome of Mt. St. Helens on April 27 1980

A cryptodome (from Greek κρυπτός, *kryptos*, "hidden, secret") is a dome-shaped structure created by accumulation of viscous magma at a shallow depth. One example of a cryptodome was in the May 1980 eruption of Mount St. Helens, where the explosive eruption began after a landslide caused the side of the volcano to fail, leading to explosive decompression of the subterranean cryptodome.

Lava coulees

Coulees are lava domes that have experienced some flow away from their original position, thus resembling both lava domes and lava flows.

Examples of lava domes

Lava domes

Dome or volcano name	Country	Volcanic area	Composition	Last dome eruption or growth episode

Chaitén	Chile	Southern Volcanic Zone	Rhyolite	2009
Cordón Caulle	Chile	Southern Volcanic Zone	Rhyodacite to Rhyolite	Holocene
Galeras	Colombia	Northern Volcanic Zone		
Katla	Iceland	Iceland Hotspot	Rhyolite	1999 onwards
Lassen Peak	California, USA	Cascade Volcanic Arc	Basalt	1917
Mount Meager	British Columbia, Canada	Cascade Volcanic Arc	Dacite	2350 BP
Mount Merapi	Indonesia	Sunda Arc		
Nea Kameni	Greece			
Volcán Nuevo	Chile	Southern Volcanic Zone	Dacite	1986
Puy-de-Dôme	France	Chaîne des Puys		ca. 5760 BC
Santiaguito	Guatemala	Central America Volcanic Arc	Dacite	2009
Sollipulli	Chile	Southern Volcanic Zone	Andesite to Dacite	
Soufrière Hills	Montserrat	Lesser Antilles		2009
Mount St. Helens	Washington, USA	Cascade Volcanic Arc	Basalt	2008
Torfajökull	Iceland	Iceland Hotspot	Rhyolite	
Unnamed	Japan	Japan Arc	Dacite	Miocene
Wizard Island	Oregon, USA	Cascade Volcanic Arc	Basalt	2850 BC

Cryptodomes

Cryptodomes are formed when viscous lava forces its way up and causes a bulge. The 1980 eruption of Mount St. Helens was an example. Lava was under great pressure and forced a bulge in the mountain, which was unstable and slid down the north side.

Volcanic cone (cinder cones)

Puʻu ʻŌʻō, a cinder-and-spatter cone on Kīlauea, Hawaiʻi

Volcanic cones are among the simplest volcanic formations in the world. They are built by ejecta from a volcanic vent, piling up around the vent in the shape of a cone with a central crater. Volcanic cones are of different types, depending upon the nature and size of the fragments ejected during the eruption. Types typically differentiated are spatter cones, ash cones, tuff cones, and cinder cones.

Stratocone

Osorno volcano in Chile is an example of a well developed stratocone

Stratocones are large cylindrical structures built up around a main tubular volcanic vent by more than one eruption. Stratocones can form large mountains and possess a distinctive layering of lava flows and tephra.

Spatter cone

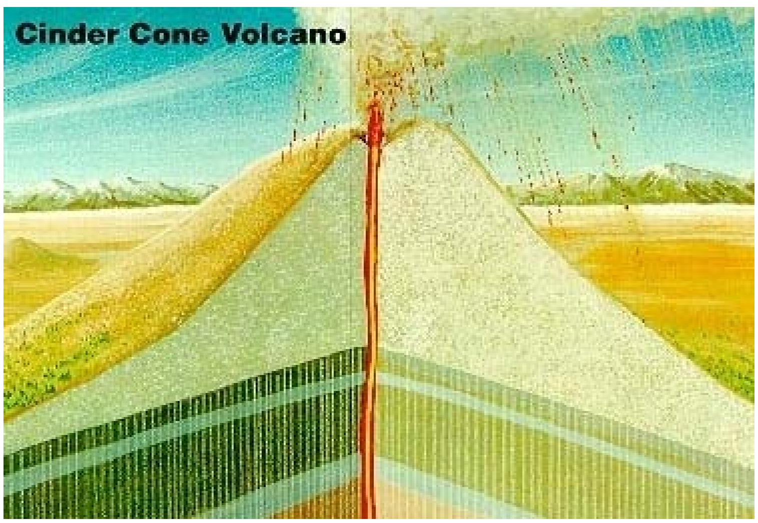
A spatter cone is formed of molten lava ejected from a vent somewhat like taffy. Expanding gases in the lava fountains tear the liquid rock into irregular gobs that fall back to earth, forming a heap around the vent. The still partly liquid rock splashes down and over the sides of the developing mound is called *spatter*. Because spatter is not fully solid when it lands, the individual deposits are very irregular in shape and weld together as they cool, and in this way particularly differ from cinder and ash. Spatter cones are typical of volcanoes with highly fluid magma, such as those found in the Hawaiian Islands. The spatter that builds up the cone can either be agglutinated or welded, the former meaning that the individual spatters pose one above each other with a lesser degree of welding occurring, while welded spatter is almost fluid when it lands and therefore welds easily.

Ash and tuff cones

An ash cone is composed of particles of silt to sand size. Explosive eruptions from a vent where the magma is interacting with groundwater or the sea (as in an eruption off the coast) produce steam and are called *phreatic*. The interaction between the magma, expanding steam, and volcanic gases results in the ejection of mostly small particles called *ash*. Fallen ash has the consistency of flour. The unconsolidated ash forms an *ash cone* which becomes a *tuff cone* or *tuff ring* once the ash consolidates. Flat-floored craters that scientists interpret have formed above diatremes as a result of a violent expansion of magmatic gas or steam; deep erosion of a maar presumably would expose a diatreme.

An example of a tuff cone is Diamond Head at Waikīkī in Hawaiʻi.

Cinder cone



Cinder cone

A cinder cone is a volcanic cone built almost entirely of loose volcanic fragments called cinders (pumice, pyroclastics, or tephra). They are built from particles and blobs of congealed lava ejected from a single vent. As the gas-charged lava is blown violently into the air, it breaks into small fragments that solidify and fall as cinders around the vent to form a circular or oval cone. Most cinder cones have a bowl-shaped crater at the summit.

Cinder cones rarely rise more than 300 to 750 m or so above their surroundings, and, being unconsolidated, tend to erode rapidly unless further eruptions occur. Cinder cones are numerous in western North America as well as throughout other volcanic terrains of the world. Parícutin, the Mexican cinder cone which was born in a cornfield on February 20, 1943, and Sunset Crater in Northern Arizona in the US Southwest are classic examples of cinder cones, as are the ancient volcanoes in New Mexico's Petroglyph National Monument.

Rootless cones

Rootless cones are named because they have no direct magma supply from the interior of the earth but they are instead fed by a lava flow. Rootless cones can also be formed in lava when it flows over wet sediments. Vapor explosions then open up the crust of the lava flow allowing spatter, tuff or cinder to be ejected.

Chapter- 4

Stratovolcano and Supervolcano

Stratovolcano

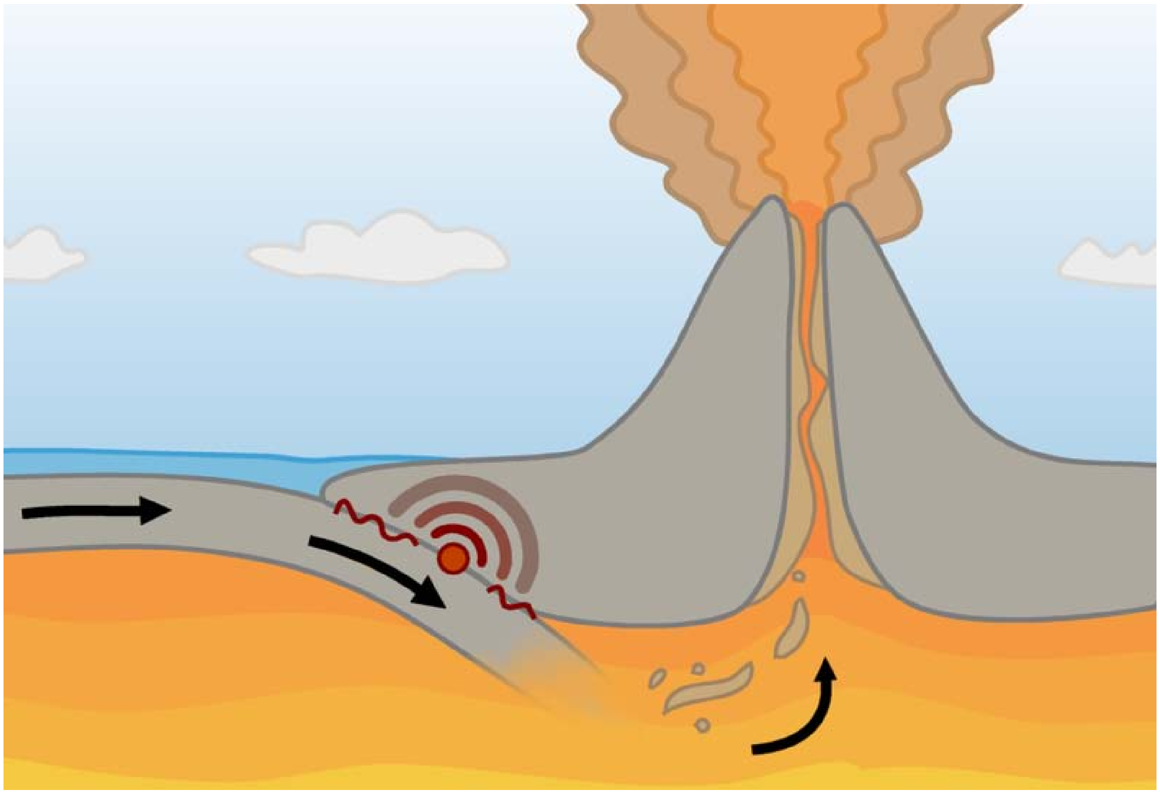
Mount Fuji, an active stratovolcano in Japan that last erupted in 1707–08

Tavurvur, an active stratovolcano near Rabaul in Papua New Guinea

A **stratovolcano**, also known as a **composite volcano**, is a tall, conical volcano built up by many layers (strata) of hardened lava, tephra, pumice, and volcanic ash. Unlike shield volcanoes, stratovolcanoes are characterized by a steep profile and periodic, explosive eruptions. The lava that flows from stratovolcanoes typically cools and hardens before spreading far due to high viscosity. The magma forming this lava is often felsic, having high-to-intermediate levels of silica (as in rhyolite, dacite, or andesite), with lesser amounts of less-viscous mafic magma. Extensive felsic lava flows are uncommon and have traveled as far as 15 km (9.3 mi).

Stratovolcanoes are sometimes called "composite volcanoes" because of their composite layered structure built up from sequential outpourings of eruptive materials. They are among the most common types of volcanoes, in contrast to the less common shield volcanoes. Two famous stratovolcanoes are Krakatoa, best known for its catastrophic eruption in 1883 and Vesuvius, famous for its destruction of the towns Pompeii and Herculaneum in AD79.

Creation



Cutaway diagram of subduction zone and an associated stratovolcano

Stratovolcanoes are common in subduction zones, forming chains along plate tectonic boundaries where oceanic crust is drawn under continental crust (Continental Arc Volcanism, e.g. Cascade Range, central Andes) or another oceanic plate (Island arc Volcanism, e.g. Japan, Aleutian Islands). The magma that forms stratovolcanoes rises when water trapped both in hydrated minerals and in the porous basalt rock of the upper oceanic crust, is released into mantle rock of the asthenosphere above the sinking oceanic slab. The release of water from hydrated minerals is termed "dewatering," and occurs at specific pressures and temperatures for each mineral, as the plate descends to greater depths. The water freed from the rock lowers the melting point of the overlying mantle rock, which then undergoes partial melting and rises due to its lighter density relative to the surrounding mantle rock, and pools temporarily at the base of the lithosphere. The magma then rises through the crust, incorporating silica-rich crustal rock, leading to a final intermediate composition. When the magma nears the top surface, it pools in a magma chamber under the volcano. There, the relatively low pressure allows water and other volatiles (CO_2, S^{2-}, Cl^{-}) dissolved in the magma to escape from solution, as occurs when a bottle of carbonated water is opened. Once a critical volume of magma and gas accumulates, the obstacle provided by the volcanic cone is overcome, leading to a sudden explosive eruption.

Hazards

Cutaway diagram of a stratovolcano

In recorded history, explosive eruptions at subduction zone (convergent-boundary) volcanoes have posed the greatest hazard to civilizations. Subduction-zone stratovolcanoes, like Mount St. Helens and Mount Pinatubo, typically erupt with explosive force: the magma is too stiff to allow easy escape of volcanic gases. As a consequence, tremendous internal pressures mount as the trapped gases expand during ascent, before the pent-up pressure is suddenly released in a violent eruption. Such an explosive process can be compared to putting a thumb over an opened bottle of a carbonated drink, shaking it vigorously, and then quickly removing the thumb. The shaking action separates the gases from the liquid to form bubbles, increasing the internal pressure. Quick release of the thumb allows the gases and liquid to gush out with explosive speed and force.

Two Decade Volcanoes which erupted in 1991 provide examples of stratovolcano hazards. On June 15, Mount Pinatubo spewed ash 40 kilometres (25 mi) into the air and produced huge pyroclastic flows and mudflows that devastated a large area around the volcano. Pinatubo, located 90 km (56 mi) from Manila, had been dormant for 600 years before the 1991 eruption, which ranks as one of the largest eruptions in the 20th Century. Also in 1991, Japan's Unzen Volcano, located on the island of Kyushu about 40 km (25 mi) east of Nagasaki, awakened from its 200-year slumber to produce a new lava dome at its summit. Beginning in June, repeated collapses of this active dome generated destructive ash flows that swept down its slopes at speeds as high as 200 km/h (120 mph). Unzen is one of more than 75 active volcanoes in Japan; its eruption in 1792 killed more than 15,000 people—the worst volcanic disaster in the country's history.

The 79 AD Plinian eruption of Mount Vesuvius, a stratovolcano looming over Naples, completely covered the cities of Pompeii and Herculaneum with pyroclastic surge deposits, with a death toll ranging between 10,000 and 25,000. Mount Vesuvius is one of the most dangerous volcanoes, because of its explosive eruptions and the high population density of the Naples area (around 3 million people).

Climatic effects

While the Unzen eruptions have caused deaths and considerable local damage, the impact of the June 1991 eruption of Mount Pinatubo was global. Slightly cooler than usual temperatures recorded worldwide and the brilliant sunsets and sunrises have been attributed to this eruption that sent fine ash and gases high into the stratosphere, forming a large volcanic cloud that drifted around the world. The sulfur dioxide (SO_2) in this cloud—about 22 million tons—combined with water to form droplets of sulfuric acid, blocking some of the sunlight from reaching the Earth and thereby cooling temperatures in some regions by as much as 0.5 °C. An eruption the size of Mount Pinatubo could affect the weather for a few years; material ejected only into the troposphere will be washed away by rain and winds.

A similar phenomenon occurred in April 1815 with the cataclysmic eruption of Mount Tambora on Sumbawa Island in Indonesia, the most powerful eruption in recorded history. Tambora's volcanic cloud lowered global temperatures by as much as 3 °C. Even a year after the eruption, most of the northern hemisphere experienced sharply cooler temperatures during the summer months. In parts of Europe and in North America, 1816 was known as "The Year Without a Summer".

Ash

Apart from possibly affecting climate, volcanic clouds from explosive eruptions also pose a hazard to aviation safety. For example, during the 1982 eruption of Galunggung in Java; British Airways Flight 9 flew into the ash cloud, suffering temporary engine failure and structural damage. During the past two decades, more than 60 airplanes, mostly commercial jetliners, have been damaged by in-flight encounters with volcanic ash. Some of these encounters have resulted in the power loss of all engines, necessitating emergency landings. Luckily, to date no crashes have happened because of jet aircraft flying into volcanic ash. Ashfall is a threat to health when inhaled, and is also a threat to property with high enough accumulation. Greater than 30 cm (12 in) of accumulation is sufficient to collapse most buildings.

Mudflows

A mudflow from Mount St. Helens in March 1982

Since the year A.D. 1600, nearly 300,000 people have been killed by volcanic eruptions. Most deaths were caused by pyroclastic flows and mudflows, deadly hazards which often accompany explosive eruptions of subduction-zone stratovolcanoes. Pyroclastic flows are fast-moving, avalanche-like, ground-hugging incandescent mixtures of hot volcanic debris, ash, and gases that can travel at speeds in excess of 150 kilometres per hour (93 mph). Approximately 30,000 people were killed by pyroclastic flows during the 1902 eruption of Mont Pelée on the island of Martinique in the Caribbean. In March–April 1982, three explosive eruptions of El Chichón Volcano in the State of Chiapas, southeastern Mexico, caused the worst volcanic disaster in that country's history. Villages within 8 km (5.0 mi) of the volcano were destroyed by pyroclastic flows, killing more than 2,000 people.

Mudflows (also called debris flows or lahars, an Indonesian term for volcanic mudflows) are mixtures of volcanic debris and water. The water usually comes from two sources: rainfall or the melting of snow and ice by hot volcanic debris. Depending on the proportion of water to volcanic material, mudflows can range from soupy floods to thick flows that have the consistency of wet cement. As mudflows sweep down the steep sides of composite volcanoes, they have the strength and speed to flatten or bury everything in their paths. Hot ash and pyroclastic flows from the 1985 eruption of the Nevado del Ruiz Volcano in Colombia, South America, melted snow and ice atop the 5,390-m-high Andean peak; the ensuing mudflows buried the city of Armero, killing 25,000 people.

Volcanic bombs

Volcanic bombs are extrusive igneous rocks that range from the size of a book to the size of a desk or larger, that fly out of Stratovolcanoes when they explode. These rocks can travel over fifteen miles away from the volcano and present a risk of hitting buildings and people while traveling at very high speeds through the air.

Lava

Lava flows are generally not a threat to people because generally lava will move slowly enough to allow people to move away; thus they are more of a property threat. However, Mount Nyiragongo is dangerous because of its lava flows; its magma has extremely low silica content, making it more fluid than normal (even when comparing to Hawaiian lava) and thus less viscous. This is compounded by the extremely steep slope of Nyiragongo leading it to flow at up to 100 km/h (62.14 mph).

Supervolcano

A **supervolcano** is a volcano capable of producing a volcanic eruption with ejecta greater than 1,000 cubic kilometers (240 cubic miles). This is thousands of times larger than most historic volcanic eruptions. Supervolcanoes can occur when magma in the Earth rises into the crust from a hotspot but is unable to break through the crust. Pressure builds in a large and growing magma pool until the crust is unable to contain the pressure. They can also form at convergent plate boundaries (for example, Toba) and continental hotspot locations (for example, Yellowstone).

The Discovery Channel highlighted six known supervolcanoes: the Yellowstone, Long Valley, and Valles Caldera in the United States; Lake Toba, North Sumatra, Indonesia; Taupo Volcano, North Island, New Zealand; and Aira Caldera, Kagoshima Prefecture, Kyūshū, Japan. Although there are only a handful of Quaternary supervolcanoes, supervolcanic eruptions typically cover huge areas with lava and volcanic ash and cause a long-lasting change to weather (such as the triggering of a small ice age) sufficient to threaten the extinction of species.

Terminology

The term "supervolcano" was originally used in the BBC popular science television program *Horizon* in 2000 to refer to these types of eruptions. That program introduced the subject of large-scale volcanic eruptions to the general public.

Volcanologists and geologists do not refer to "supervolcanoes" in their scientific work, since this is a blanket term that can be applied to number of different geothermal conditions. Since 2003, however, the term has been used by professionals when presenting to the public. The term *megacaldera* is sometimes used for calderas with supervolcano characteristics, such as the Blake River Megacaldera Complex in the Abitibi greenstone belt of Ontario and Quebec, Canada. Eruptions that rate VEI 8 are termed "super eruptions."

Though there is no well-defined minimum explosive size for a "supervolcano," there are at least two types of volcanic eruption that have been identified as supervolcanoes: large igneous provinces and massive eruptions.{Read Below}

Large igneous provinces

Large igneous provinces (LIP) such as Iceland, the Siberian Traps, Deccan Traps, and the Ontong Java Plateau are extensive regions of basalts on a continental scale resulting from flood basalt eruptions. When created, these regions often occupy several thousand square kilometres and have volumes on the order of millions of cubic kilometres. In most cases, the lavas are normally laid down over several million years. They do release massive amounts of gases. The Réunion hotspot produced the Deccan Traps about 65 million years ago. Research continues into the effect of the outpourings and whether they contributed to the extinction of the dinosaurs at the end of the Cretaceous.

Such outpourings are not explosive though fire fountains may occur. Many volcanologists consider that Iceland may be a LIP that is currently being formed. The last major outpouring occurred in 1783–84 from the Laki fissure which is ~40 km long. An estimated 14 km^3 of basaltic lava was poured out during the eruption.

The Ontong Java Plateau now has an area of about 2 million km^2, and the province was at least 50% larger before the Manihiki and Hikurangi Plateaus broke away.

Massive explosive eruptions

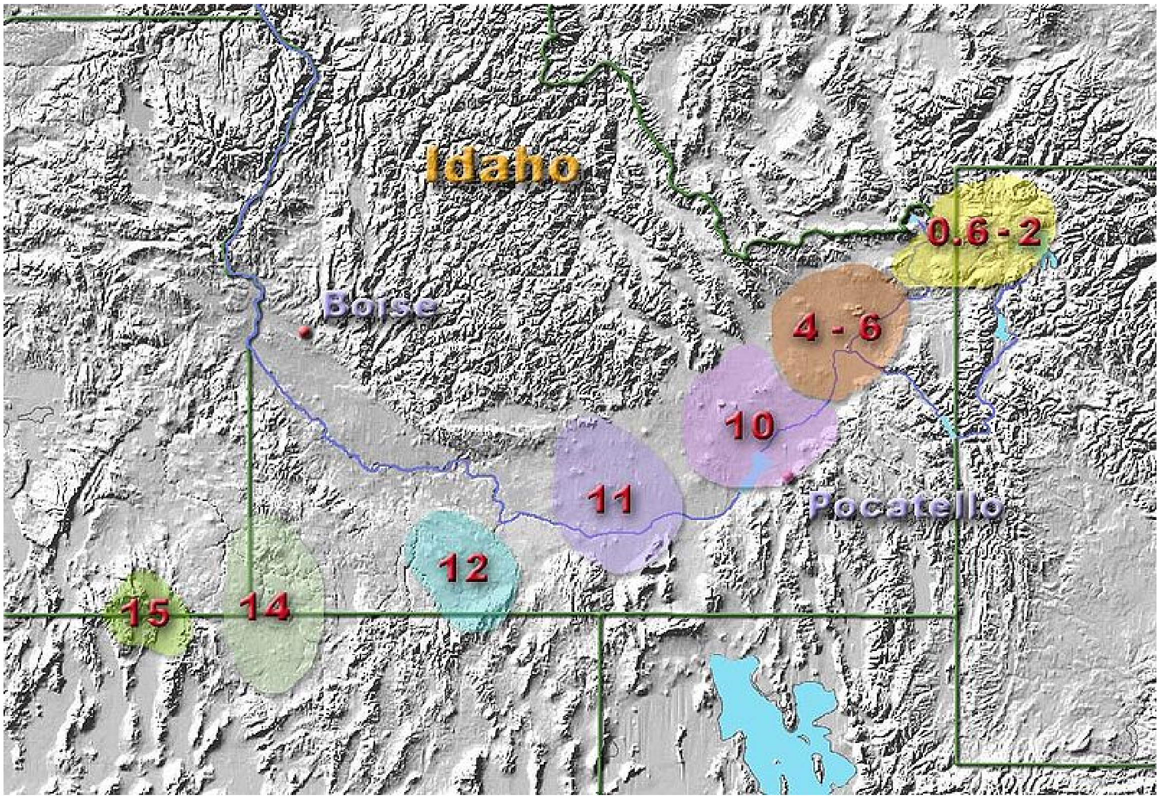
Eruptions with a Volcanic Explosivity Index of 8 (VEI-8) are colossal events that throw out at least 1,000 km^3 Dense Rock Equivalent (DRE) of ejecta; VEI-7 events eject at least 100 km^3 (DRE).

VEI-7 or 8 eruptions are so powerful that they often form circular calderas rather than cones because the downward withdrawal of magma causes the overlying mass to collapse and fill the void magma chamber beneath.

One of the classic calderas is at Glen Coe in the Grampian Mountains of Scotland. First described by Clough et al. (1909) its geology and volcanic succession has recently been re-analysed in the light of new discoveries. There is an accompanying 1:25000 solid geology map.

By way of comparison, the 1980 Mount St. Helens eruption was at the lower end of VEI-5 with 1.2 km^3, and both Mount Pinatubo in 1991 and Krakatoa in 1883 were VEI-6 with 25 km^3.

Known super eruptions



Location of Yellowstone Hotspot in Millions of Years Ago

Estimates of the volume of ejected material are given in parentheses.

VEI 8

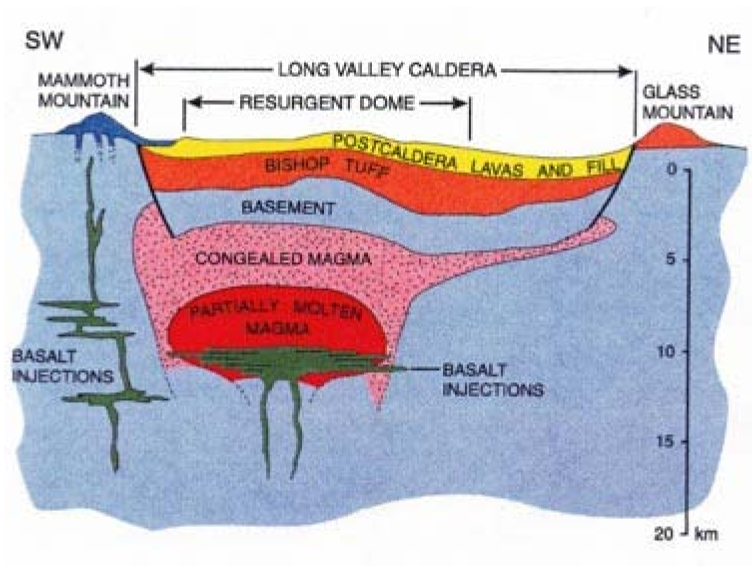
VEI 8 eruptions have happened in the following locations.

- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand - Oruanui eruption ~26,500 years ago (~1,170 km^3)
- Lake Toba, Sumatra, Indonesia - ~74,000 years ago (~2,800 km^3)
- Whakamaru, Taupo Volcanic Zone, North Island, New Zealand - Whakamaru Ignimbrite/Mount Curl Tephra ~254,000 years ago (1,200-2,000 km^3)
- Yellowstone Caldera, Lava Creek Tuff, Wyoming, United States, Yellowstone hotspot - 640,000 years ago (1,000 km^3)
- Island Park Caldera, Huckleberry Ridge Tuff, Idaho/Wyoming, United States, Yellowstone hotspot - 2.1 million years ago (2,500 km^3)
- Cerro Galan, Catamarca Province, Argentina - 2.5 million years ago (1,050 km^3)

- Atana Ignimbrite, Pacana Caldera, northern Chile - 4 million years ago (2,500 km³)
- Heise volcanic field, Kilgore Tuff, Idaho, United States, Yellowstone hotspot - 4.5 million years ago (1,800 km³).
- Heise volcanic field, Blacktail Tuff, Idaho, United States, Yellowstone hotspot - 6.6 million years ago (1,500 km³).
- La Garita Caldera, Colorado, United States - Source of the enormous eruption of the Fish Canyon Tuff ~27.8 million years ago (~5,000 km³)

The Lake Toba eruption plunged the Earth into a volcanic winter, eradicating an estimated 60% of the human population (although humans managed to survive, even in the vicinity of the volcano). However the coincidental agreement in above sources about percentage value of extinction is contrary to differing estimates of human population size at that time.

VEI 7



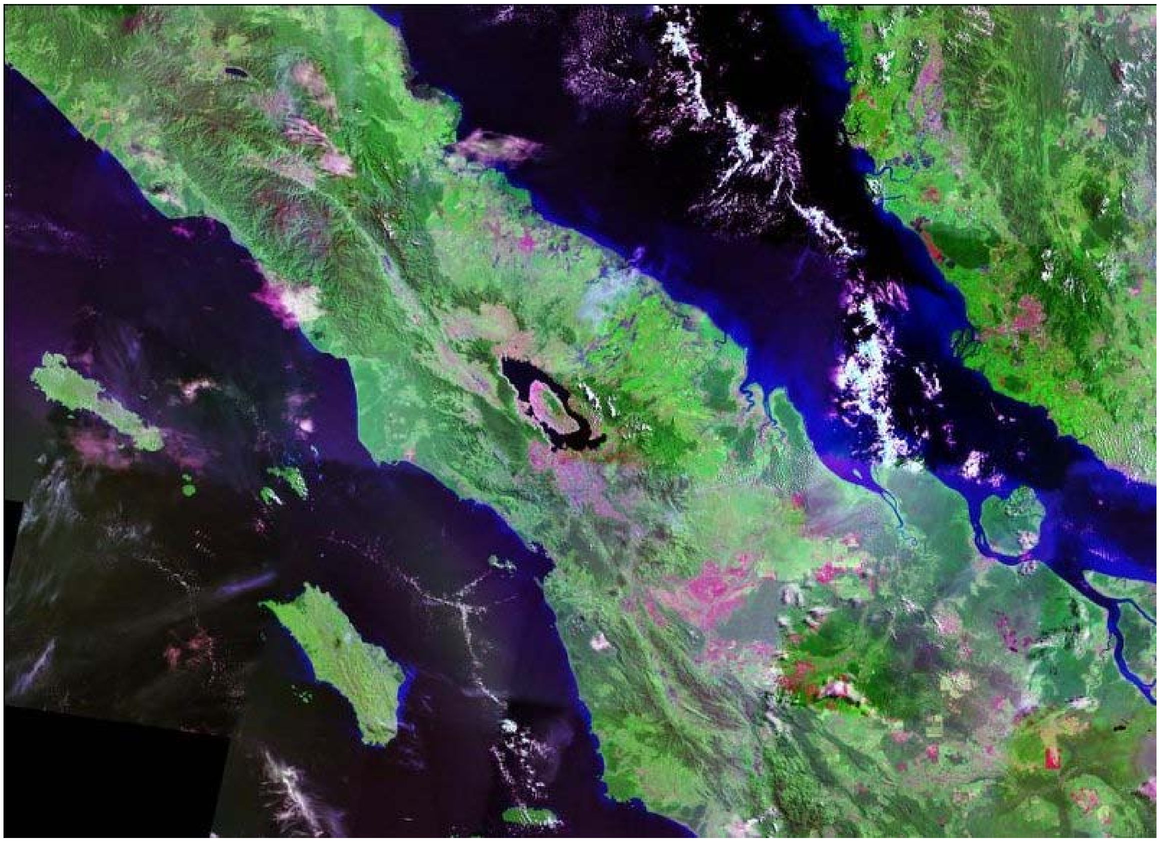
Cross-section through Long Valley Caldera

VEI-7 volcanic events, less colossal but still supermassive, have occurred in the geological past. The only ones in historic times are Tambora, in 1815, Lake Taupo (Hatepe), around 180 CE, and possibly Baekdu Mountain, 969 CE (± 20 years).

- Tambora, Sumbawa Island, West Nusa Tenggara, Indonesia - 1815 (160 km³), the following year 1816 became known as the "Year Without a Summer"
- Baekdu Mountain, China/North Korea - ~969 CE (96±19 km³)
- Lake Taupo, Taupo Volcanic Zone, North Island, New Zealand - Hatepe eruption ~181 CE (120 km³)
- Kikai Caldera, Ryukyu Islands, Japan - ~6,300 years ago (~ 4,300 BCE) (150 km³)

- Macauley Island, Kermadec Islands, New Zealand - ~6,300 years ago (~ 4,300 BCE) (100 km³)
- Aira Caldera, Kyūshū, Japan - ~22,000 years ago (~110 km³)
- Rotoiti Ignimbrite, Taupo Volcanic Zone, North Island, New Zealand - ~50,000 years ago (~240 km³)
- Campi Flegrei, Naples, Italy - 39,280 ± 110 years ago (500 km³)
- Aso, Kyūshū, Japan - four large explosive eruptions between 300,000 to 80,000 years ago (last one > 600 km³)
- Reporoa Caldera, Taupo Volcanic Zone, North Island, New Zealand - 230,000 years ago (~100 km³)* I. A. Nairn; C. P. Wood and R. A. Bailey (December 1994). "The Reporoa Caldera, Taupo Volcanic Zone: source of the Kaingaroa Ignimbrites". *Bulletin of Volcanology* **56** (6): 529–537. doi:10.1007/BF00302833. http://www.springerlink.com/content/mu1970l8163tp006. Retrieved 2010-09-16.
- Mamaku Ignimbrite, Rotorua Caldera,Taupo Volcanic Zone, North Island, New Zealand - 240,000 years ago (>280 km³)
- Matahina Ignimbrite, Haroharo Caldera, Taupo Volcanic Zone, North Island, New Zealand - 280,000 years ago (~120 km³)
- Long Valley Caldera, Bishop Tuff, California, United States - ~760,000 years ago (600 km³)
- Valles Caldera, New Mexico, United States - ~1.15 million years ago (~600 km³)
- Mangakino, Taupo Volcanic Zone, North Island, New Zealand - three eruptions from 0.97 to 1.23 million years ago (each > 300 km³)
- Henry's Fork Caldera, Mesa Falls Tuff, Idaho, United States, Yellowstone hotspot - 1.3 million years ago (280 km³)
- Pastos Grandes Ignimbrite, Pastos Grandes Caldera, 2.9 million years ago (>820 km³)
- Heise volcanic field, Walcott Tuff, Idaho, United States, Yellowstone hotspot - 6.4 million years ago (750 km³).
- Bruneau-Jarbidge, Idaho, United States, Yellowstone hotspot - ~10-12 million years ago (>250 km³) (responsible for the Ashfall Fossil Beds ~1,600 km to the east)
- Bennett Lake Volcanic Complex, British Columbia/Yukon, Canada - ~50 million years ago (850 km³)

Media portrayal



Satellite image of Lake Toba, the site of a VEI-8 eruption ~75,000 years ago

Volcano, lake, and caldera locations in the Taupo Volcanic Zone

- A National Geographic Channel documentary called *Earth Shocks* portrayed the destructive impact of the rapid eruption at Lake Toba approximately 75,000 years ago, which is thought to have caused a phenomenon known as the Millennial Ice Age that lasted for about 1,000 years and killed an estimated 60–75% of the human population of the time. But according to Alan Robock *et al.*, the Toba incident did not initiate an ice age, but rather exacerbated an ice age that had already been underway. Nevertheless, the climate recovered over a few decades.

- In 2005, an eruption of the Yellowstone supervolcano is one of the scenarios depicted in the docudrama *End Day*.

- In 2005, a two-part television docudrama called *Supervolcano* aired on BBC One, the Discovery Channel, and other television networks worldwide. It looked at the events that could take place if the Yellowstone supervolcano erupted. It featured footage of volcano eruptions from around the world and computer-generated imagery depicting the event. According to the program, such an eruption would have devastating effect across the globe and would cover virtually all of the United States with at least 1 cm of volcanic ash, causing mass destruction in the nearby vicinity and killing plants and wildlife across the continent. The dramatic elements in the program were followed by *Supervolcano: The Truth About Yellowstone*, a documentary about the evidence behind the film. The program had originally been scheduled to be transmitted in early 2005, but it was felt that this would be insensitive so soon after the 2004 Indian Ocean tsunami. The program and its accompanying documentaries were released on DVD region 2 simultaneously with its broadcast.

- *Nova* featured an episode "Mystery of the Megavolcano" in September 2006 examining such eruptions in the last 100,000 years.

- In 2006, the Sci Fi Channel aired the documentary *Countdown to Doomsday* which featured a segment called "Supervolcano". The same year, ABC News aired the documentary *Last Days on Earth*, which featured a segment called "Supervolcano". Also in 2006, the TV series *Stargate Atlantis* aired an episode called "Inferno" whose plot revolves around the discovery and subsequent eruption of a supervolcano on another planet.

- In 2008, the Yellowstone supervolcano was featured in the BBC program *10 Things You Didn't Know About Volcanoes*, presented by Dr. Iain Stewart, a volcanologist.

- In 2009, the Toba supervolcano was featured in the episode "Fire and Ice" of Animal Planet series *Animal Armageddon*.

- Also in 2009, the Yellowstone supervolcano erupts during the apocalyptic movie 2012.

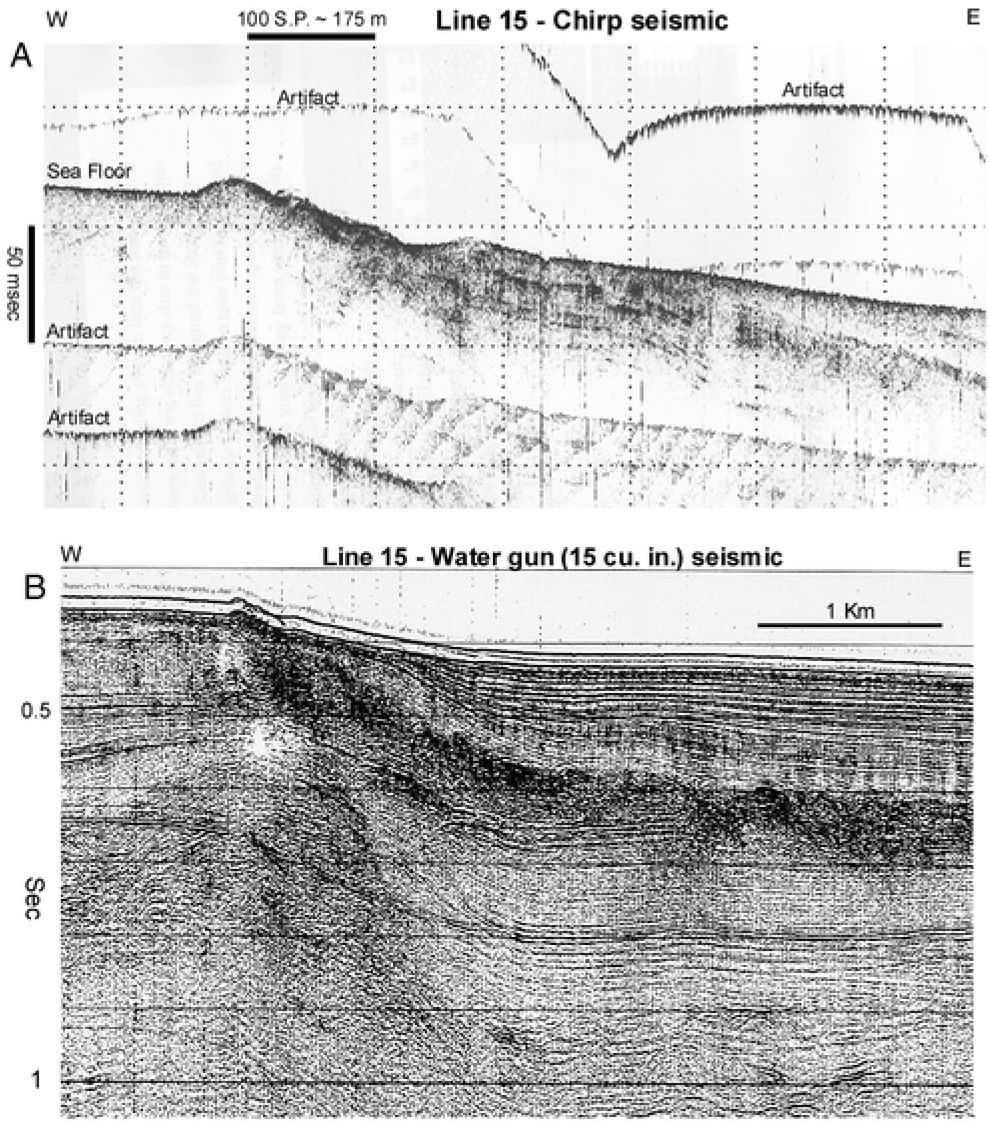
Chapter- 5

Mud Volcano

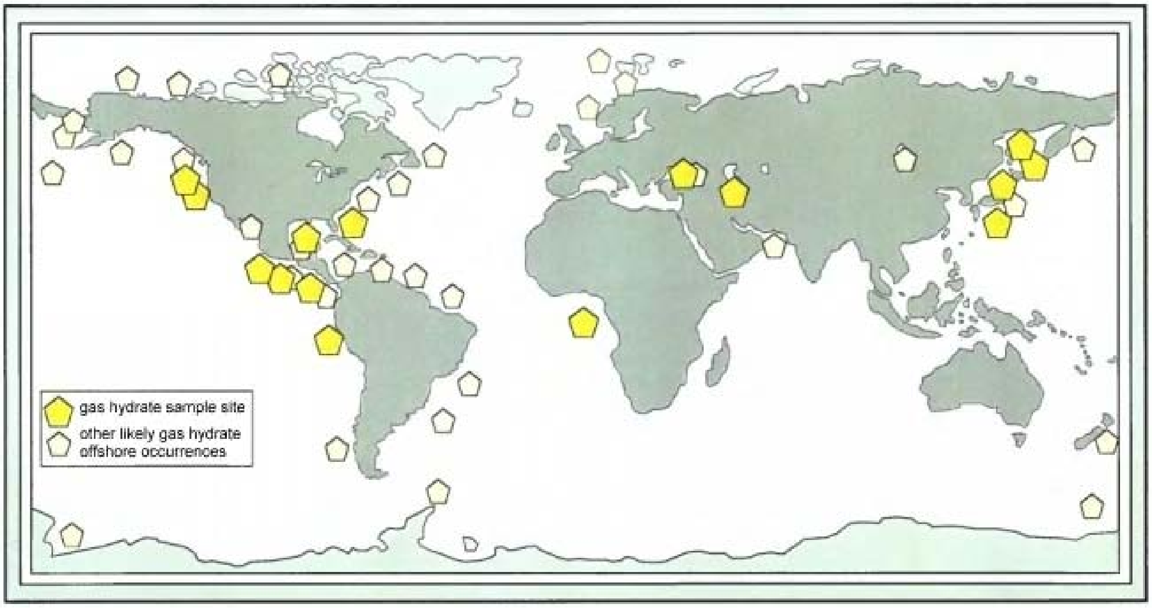
A series of mud volcanoes in Gobustan, Azerbaijan

Mud volcano in Baratang, Andaman Islands. India

Figure 4



Mud volcano in the Gulf of Mexico sea bottom



Hydrate-bearing sediments, which often are associated with mud volcano activity

The geothermal phenomena known as "mud volcanoes" are often not true mud volcanoes.

The terms **mud volcano** or **mud dome** are used to refer to formations created by geo-excreted liquids and gases, although there are several different processes which may cause such activity. Temperatures are much cooler in these processes than found at igneous volcanoes. The largest mud volcano structures are 10 kilometres (6.2 mi) in diameter and reach 700 metres (2,300 ft) in height.

About 20% of the gas released from these structures is methane, with much less carbon dioxide and nitrogen emitted. Ejected materials are often a slurry of fine solids suspended in liquids which may include water, which is frequently acidic or salty, and hydrocarbon fluids.

Recently, possible mud volcanoes have been identified on Mars.

Details

A mud volcano may be the result of a piercement structure created by a pressurized mud diapir which breaches the Earth's surface or ocean bottom. Their temperatures may be as low as the freezing point of the ejected materials, particularly when venting is associated with the creation of hydrocarbon clathrate hydrate deposits. Mud volcanoes are often associated with petroleum deposits and tectonic subduction zones and orogenic belts; hydrocarbon gases are often erupted. They are also often associated with lava volcanoes; in the case of such close proximity, mud volcanoes emit incombustible gases including helium, whereas lone mud volcanoes are more likely to emit methane.

Approximately 1,100 mud volcanoes have been identified on land and in shallow water. It has been estimated that well over 10,000 may exist on continental slopes and abyssal plains.

Features

- **Gryphon**: steep-sided cone shorter than 3 meters that extrudes mud
- Mud cone: high cone shorter than 10 meters that extrudes mud and rock fragments
- Scoria cone: cone formed by heating of mud deposits during fires
- **Salse**: water-dominated pools with gas seeps
- **Spring**: water-dominated outlets smaller than 0.5 meters
- **Mud shield**

Emissions

Most liquid and solid material is released during eruptions, but various seeps occur during dormant periods.

First order estimates of mud volcano emissions have recently been made (1 Tg = 1 million metric tonnes).

- 2002: L.I. Dimitrov estimated that 10.2–12.6 Tg/yr of methane is released from onshore and shallow offshore mud volcanoes.
- 2002: Etiope and Klusman estimated at least 1–2 and as much as 10–20 Tg/yr of methane may be emitted from onshore mud volcanoes.
- 2003: Etiope, in an estimate based on 120 mud volcanoes: "The emission results to be conservatively between 5 and 9 Tg/yr, that is 3–6% of the natural methane sources officially considered in the atmospheric methane budget. The total geologic source, including MVs (this work), seepage from seafloor (Kvenvolden et al., 2001), microseepage in hydrocarbon-prone areas and geothermal sources (Etiope and Klusman, 2002), would amount to 35–45 Tg/yr."
- 2003: analysis by Milkov et al. suggests that the global gas flux may be as high as 33 Tg/yr (15.9 Tg/yr during quiescent periods plus 17.1 Tg/yr during eruptions). Six teragrams per year of greenhouse gases are from onshore and shallow offshore mud volcanoes. Deep-water sources may emit 27 Tg/yr. Total may be 9% of fossil CH_4 missing in the modern atmospheric CH_4 budget, and 12% in the preindustrial budget.
- 2003: Alexei Milkov estimated approximately 30.5 Tg/yr of gases (mainly methane and CO_2) may escape from mud volcanoes to the atmosphere and the ocean.
- 2003: Achim J. Kopf estimated 1.97×10^{11} to 1.23×10^{14} m^3 of methane is released by all mud volcanoes per year, of which 4.66×10^{7} to 3.28×10^{11} m^3 is from surface volcanoes. That converts to 141–88,000 Tg/yr from all mud volcanoes, of which 0.033–235 Tg is from surface volcanoes.

Locations

Two mud volcanoes on the Taman Peninsula near Taman Stanitsa

Satellite image of mud volcanoes in Pakistan

Europe

There are generally few mud volcanoes in Europe, but dozens can be found on the Taman Peninsula of Russia and the Kerch Peninsula of southeastern Ukraine. In Italy, they are common in the northern front of the Apennines and in Sicily. Another relatively accessible place where mud volcanoes can be found in Europe are the Berca Mud Volcanoes near Berca in Buzău County, Romania, close to the Carpathian Mountains.

Asia

Lusi (Indonesia)

Drilling or an earthquake may have resulted in the Sidoarjo mud flow on May 29, 2006, in the Porong subdistrict of East Java province, Indonesia. The mud covered about 440 hectares, or 1,087 acres (4.40 km^2), and inundated four villages, homes, roads, rice fields, and factories, displacing about 24,000 people and killing 14. The gas exploration company involved was operated by PT Lapindo Brantas. In 2008, it was termed the world's largest mud volcano and is beginning to show signs of catastrophic collapse, according to geologists who have been monitoring it and the surrounding area. A catastrophic collapse could sag the vent and surrounding area by up to 150 metres (490 ft) in the next decade. In March 2008, the scientists observed drops of up to 3 metres (9.8 ft) in one night. Most of the subsidence in the area around the volcano is more gradual, at around 0.1 centimetres (0.039 in) per day. Now named Lusi – a contraction of *Lumpur Sidoarjo*, where *lumpur* is the Indonesian word for "mud" – the mud volcano appears to be a hydrocarbon/hydrothermal hybrid.

Central Asia

Many mud volcanoes exist on the shores of the Black Sea and Caspian Sea. Tectonic forces and large sedimentary deposits around the latter have created several fields of mud volcanoes, many of them emitting methane and other hydrocarbons. Features over 200 metres (656 ft) high exist in Azerbaijan, with large eruptions sometimes producing flames of similar scale. Iran and Pakistan also possess mud volcanoes in the Makran range of mountains in the south of the two countries. In fact, the world's largest and highest volcano is located in Balochistan, Pakistan.

Iran

There are many mud volcano in Iran: in Hormozgan province, Sistan & Balouchestan province and Golestan province

Pakistan

In Pakistan there are more than 80 active mud volcanoes, all of them in Baluchistan province; there are about 10 locations having clusters of mud volcanoes. In the west, in Gwadar District, the mud volcanoes are very small and mostly sit in the south of Jabal-e-Mehdi toward Sur Bandar. Many more exist in the north-east of Ormara. The remainder are in Lasbela District and are scattered between south of Gorangatti on Koh Hinglaj to Koh Kuk in the North of Miani Hor in the Hangol Valley. In this region, the heights of mud volcanoes range between 800 to 1,550 feet (243.8 to 472.4 m). The most famous is Chandaragup. The biggest crater found is about 50 feet (15.24 m) in diameter. Most mud volcanoes in this region are situated in out-of-reach areas having very difficult terrain. Dormant mud volcanoes stand like columns of mud in many other areas.

Azerbaijan

Azerbaijan and its Caspian coastline are home to nearly 400 mud volcanoes, more than half the total throughout the continents. In 2001, one mud volcano 15 kilometres (9 mi) from Baku made world headlines when it suddenly started ejecting flames 15 metres (49 ft) high.

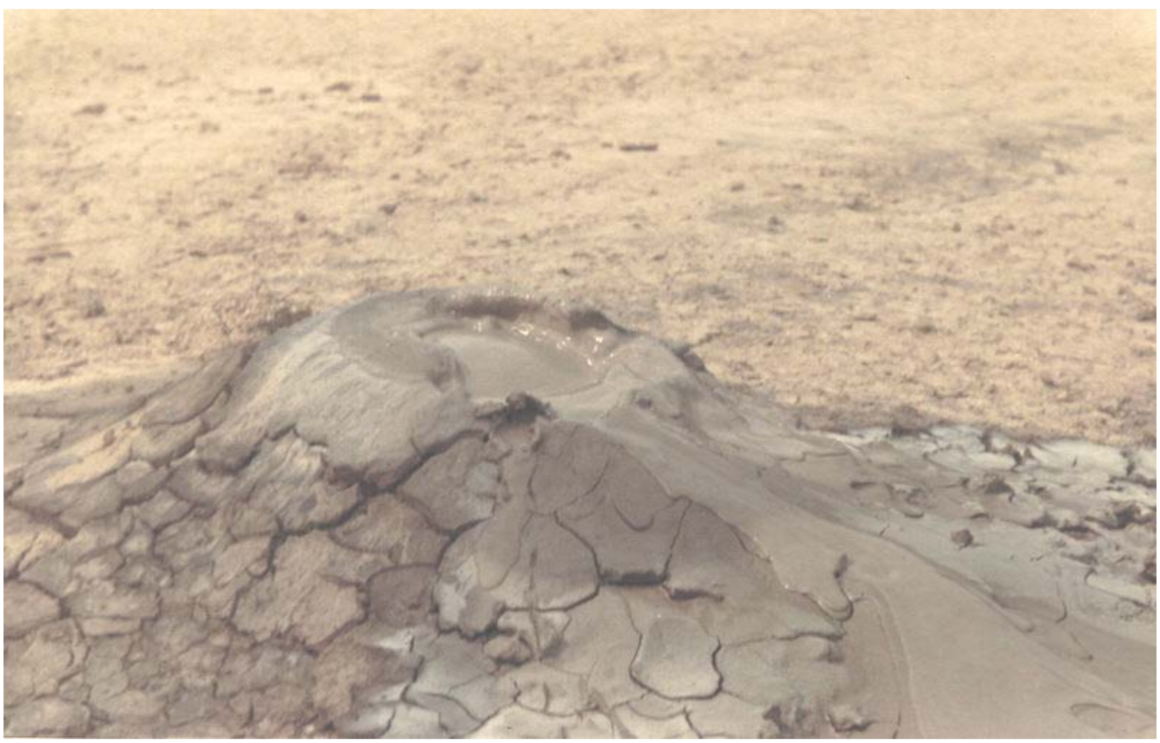
In Azerbaijan, eruptions are driven from a deep mud reservoir which is connected to the surface even during dormant periods, when seeping water still shows a deep origin. Seeps have temperatures up to 2 °C (3.6 °F) - 3 °C (5.4 °F) above the ambient temperature.

Other Asian locations

- China has a number of mud volcanoes in Xinjiang province.
- There are also mud volcanoes at the Arakan Coast in Myanmar (Burma).
- There are two active mud volcanoes in South Taiwan, and several inactive ones.
- The island of Baratang, part of the Great Andaman archipelago in the Andaman Islands, Indian Ocean, has several sites of mud volcanic activity. There was a significant eruption event in 2003.
- There are mud volcanoes on the island of Pulau Tiga, off the western coast of the Malaysian state of Sabah on Borneo.
- A drilling accident offshore of Brunei on Borneo in 1979 caused a mud volcano which took 20 relief wells and nearly 30 years to halt the eruption.

A cold mud pot in Northern California, showing the scale

A cold mud pot in Glenblair, California



Yagrumito Mud Volcano in Monagas, Venezuela (6 km from Maturín)

One of the Devil's Woodyard Volcano (Hindustan, Trinidad & Tobago)

North America

Mud volcanoes of the North American continent include:

- A field of small (<2 metres (6.6 ft) high) fault controlled *cold* mud volcanoes is located on California's Mendocino Coast, near Glenblair and Fort Bragg. The fine grained clay is occasionally harvested by local potters.
- Shrub and Klawasi mud volcanoes in the Copper River basin by the Wrangell Mountains, Alaska. Emissions are mostly CO_2 and nitrogen; the volcanoes are associated with magmatic processes.
- An unnamed mud volcano 30 metres (98 ft) high and with a top about 100 metres (328 ft) wide, 24 kilometres (15 mi) off Redondo Beach, California, and 800 metres (2,620 ft) under the surface of the Pacific Ocean.
- A field of small (<3 metres (9.8 ft)) mud volcanoes in the Salton Sea geothermal area near the town of Niland, California. Emissions are mostly CO_2.
- Smooth Ridge mud volcano in 1,000 metres (3,280 ft) of water near Monterey Canyon, California.
- Kaglulik mud volcano, 43 metres (141 ft) under the surface of the Beaufort Sea, near the northern boundary of Alaska and Canada. Petroleum deposits are believed to exist in the area.

- Maquinna mud volcano, located 16–18 kilometres (9.9–11 mi) west of Vancouver Island, British Columbia, Canada.
- There are many mud volcanoes in Trinidad and Tobago in the Caribbean, near oil reserves in southern parts of the island of Trinidad. As of August 15, 2007, the mud volcano titled the Moruga Bouffle was said to being spitting up methane gas which shows signs that it is definitely active. There are also several other mud volcanoes in the tropical island which include:
    - the Devils Woodyard mud volcano near Hindustan
    - the Moruga Bouffe mud volcano near Moruga
    - the Piparo mud volcano
    - the Chatham mud volcano located underwater in the Columbus Channel; this mud volcano periodically produces a short-lived island.

Yellowstone's "Mud Volcano" feature

Yellowstone's "Mud Volcano"

The name of Yellowstone National Park's "Mud Volcano" feature and the surrounding area is misleading; it consists of hot springs, mud pots and fumaroles, rather than a true mud volcano. Depending upon the precise definition of the term *mud volcano*, the Yellowstone formation could be considered a hydrothermal mud volcano cluster. The feature is much less active than in its first recorded description, although the area is quite dynamic. Yellowstone is an active geothermal area with a magma chamber near the surface, and active gases are chiefly steam, carbon dioxide, and hydrogen sulfide.

The mud volcano in Yellowstone was previously a mound, until suddenly, it tore itself apart into the formation seen today.

South America

Venezuela

The eastern part of Venezuela contains several mud volcanoes, all of them, as in Trinidad, having an origin related to oil deposits. The image shows the *Volcán de lodo de Yagrumito*, about 6 kilometres (3.7 mi) from Maturín, Venezuela. Its mud contains, water, biogenic gas, a certain amount of hydrocarbons and an important quantity of salt. Cows from the savanna often gather around to lick the dried mud for its salt content, which is an integral part of their diet needed to produce milk.

Colombia

Volcan El Totumo, which marks the division between Bolivar and Atlantico in Colombia. This volcano is approximately 50 feet (15 m) high and can accommodate 10 to 15 people on its crater; many tourists and locals visit this volcano due to the medicinal benefits of the mud; the volcano is located next to a *cienaga*, or lake. This volcano is currently under a legal fight between the Bolivar and Atlantico Departamentos because of its tourist value.

Chapter- 6

Shield, Submarine and Subglacial Volcano

Shield Volcano

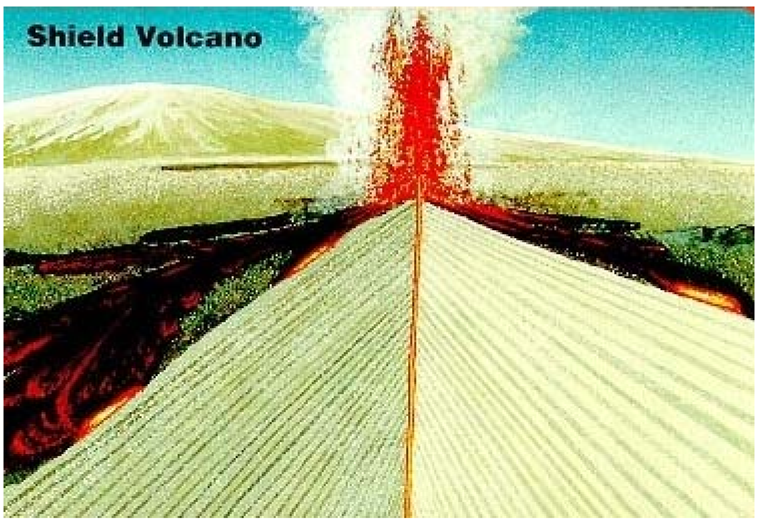


Diagram of a shield volcano, showing the gradual buildup of lava in many layers that eventually constructs them.

A **Shield volcano** is a type of volcano built almost entirely of fluid lava flows. They are named so because of their large size and low profile, resembling a warrior's shield. This is caused by the highly fluid lava they erupt, which travel farther than those erupted from more explosive volcanoes. This results in the steady accumulation of broad sheets of lava, building up the shield volcano's distinctive form.

Geology

Eruptive mechanics

Skjaldbreiður, eponymous for a shield volcano

Shield volcanoes are built almost entirely of highly fluid basaltic lava. They are distinct from the two other major volcanic types, stratovolcanoes, which are driven by the accumulation of more viscous lavas, and cinder cones, which are built up by the consolidation of tephra ejected by explosive eruptions. The types of eruptions that occur at shield volcanoes have been named Hawaiian eruptions, after the Hawaiian chain where they are most prominent. Hawaiian eruptions are characterized by the effusive emission of fluid lavas. The nature of these lavas allows them to travel a longer distance than flows from other volcanic types, resulting in a large, spread-out sheet of lava just 1 m (3 ft) thick. The gradual buildup of thousands of these flows slowly constructs a low-lying, broad, and gently sloping form of a mature shield volcano.

Continuous shield volcanic activity is very common, and will, over time, build up splatter cones at the eruptive sites, despite Hawaiian activity being 90% lava flows.

A hallmark of shield volcanism are lava tubes, cave-like volcanic straights that are formed by the hardening of overlaying lava. These structures further the propagation of lava, as the walls of the tube insulate the flows within. They are an important eruptive element; for example, an estimated 58% of Kilauea is covered by lava tube lava.

Interactions between water and lava at shield volcanoes can cause some eruptions to become hydrovolcanic, which are an explosive eruptive type drastically different from usual shield volcanic activity. These eruptions are especially prevelent at the waterbound volcanoes of the Hawaiian Isles.

Rift zones are another prevalent feature on shield volcanoes that is rare on other volcanic types. The large, decentralized shape of Hawaiian volcanoes versus their small, symmetrical Icelandian cousins can be attributed to these types of eruptions; fissure venting is common in Hawaiʻi, accounting for their asymettrical, non-centralized shapes, and rare in Iceland, where central eruptions from summit calderas dominate and thus the lava distribution is far more even.

In some shield volcano eruptions, basaltic lava pours out of a long fissure instead of a central vent, and shrouds the countryside with a long band of volcanic material in the form of a broud plateau. Plateaus of this type exist in Iceland, Washington, Oregon, and Idaho; the most prominent ones are situated along the Snake River in Idaho and the Columbia River in Washington and Oregon, where they have been measured to be over a 1 mi (2 km) in thickness. Many eruptions start as a so-called "curtain of fire"—a long eruptive chain along a fissure vent on the volcano. Eventually these eruptions die down and start to focus around a few points on the fissure, where activity is concentrated.

Structure

Dark profile of Hualālai, showing typical shape of a shield volcano

Because of their gradual buildup and near continuous eruptive characteristics, shield volcanoes are the largest volcanoes on Earth, usually being at least 3 to 4 mi (5 to 6 km) across and surpassing 1,500 to 2,000 ft (457 to 610 m) in height. The largest shield volcano (and the largest active volcano) in the world is Mauna Loa in Hawaiʻi, which projects 13,677 ft (4,169 m) above sea level.

Shield volcanoes are composed almost exclusively of basalt. Their lower slopes are generally gentle (~2 degrees), but steepen with elevation (reaching ~10 degrees) before flattening near the summit, giving the volcanoes a convex shape.

Over the volcano's lifespan, collapse-driven calderas that form on shield volcanoes are often filled up, and new ones formed elsewhere, in an ongoing cycle of collapse and regeneration.

Distribution

Shield volcanoes are distinctive products of hotspot volcanism, but can form at rift and subduction zones as well.

The largest and most prominent shield volcano chain in the world are the Hawaiian Islands, a chain of hotspot volcanoes in Pacific Ocean. This chain includes the largest volcano on Earth, Mauna Loa. Mauna Kea stands 4,170 m (13,681 ft) above sea level. In addition, its submarine flanks reach a further 5 km (3 mi) below the waterline, and Mauna Loa's massive size depresses the sea floor on which it stands a further 8 km (5 mi), making the volcano's summit about 17 km (56,000 ft) above its base. The volcano is approximately 80,000 km^3 (19,193 cu mi) in total volume.

Kilauea is one of the most active volcanoes on Earth, with the current ongoing eruption having begun in January 1983. The Hawaiian volcanoes are characterized by frequent rift eruptions, their large size (thousands of km3 in volume), and their rough, decentralized shape.

Another major center of shield volcanic activity is Iceland. There, the volcanoes are small (~15 km^3 (4 cu mi)), symmetrical, and are characterized by eruptions from summit calderas.

Olympus Mons on Mars is also a shield volcano.

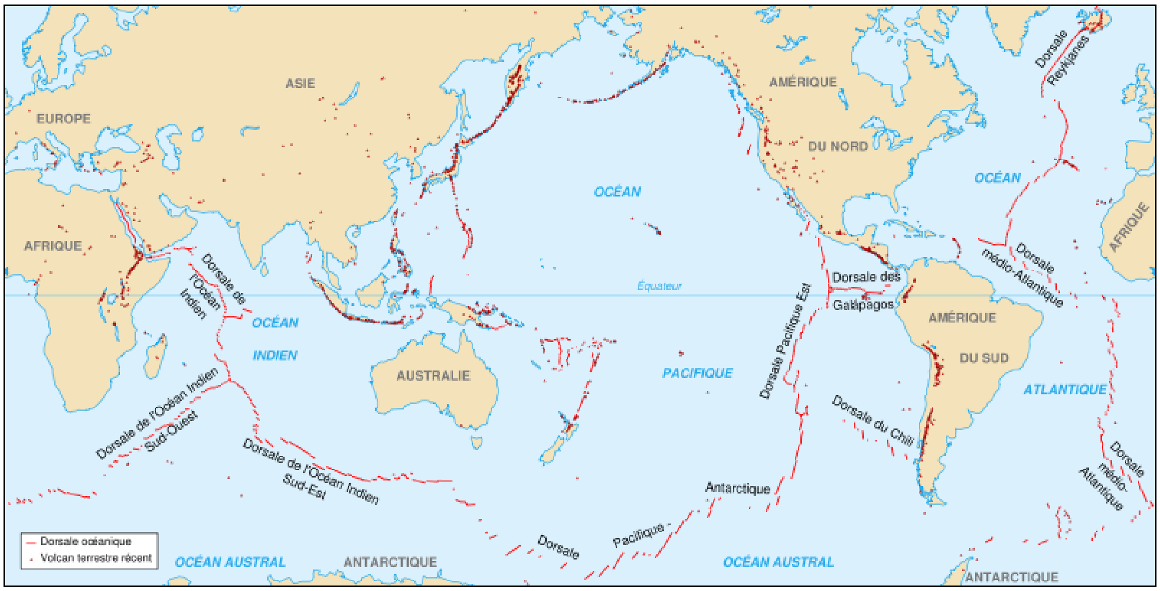
Dangers

The Hawaiian eruptions of shield volcanoes do not pose much threat to humans, as they emit large amounts of slow moving lava over long periods of time. However, they are hazardous to agriculture and infrastructure; the ongoing 1983 eruption of Kīlauea has destroyed over 200 structures and buried kilometers of highways.

Pyroclastic shields

Rarer pyroclastic shield volcanoes are similar to normal mafic shields in shape. But rather than being formed entirely by basalt lavas, pyroclastic shields are mainly formed from explosive eruptions of ignimbrite.

Submarine Volcano

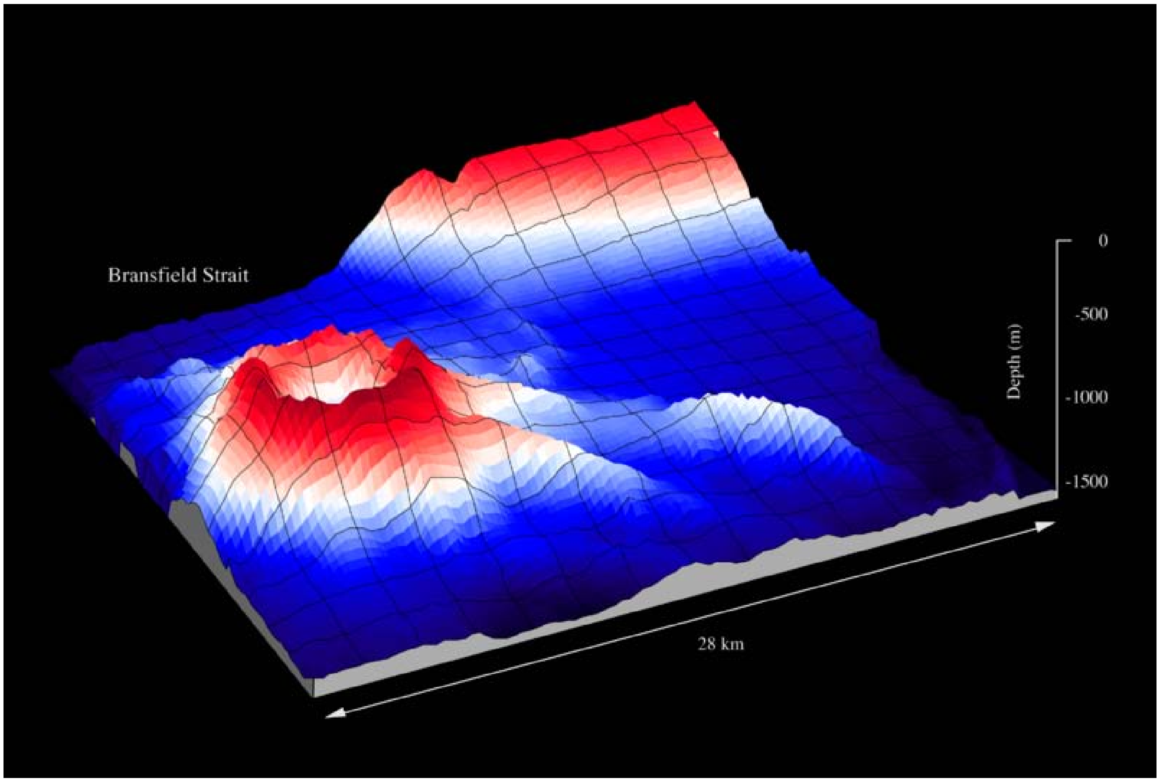


Spreading ridges volcanoes map

Pillow lava formed by a submarine volcano

Submarine volcanoes are underwater fissures in the Earth's surface from which magma can erupt. They are estimated to account for 75% of annual magma output. The vast majority are located near areas of tectonic plate movement, known as ocean ridges. Although most are located in the depths of seas and oceans, some also exist in shallow water, which can spew material into the air during an eruption. Hydrothermal vents, sites of abundant biological activity, are commonly found near submarine volcanoes.

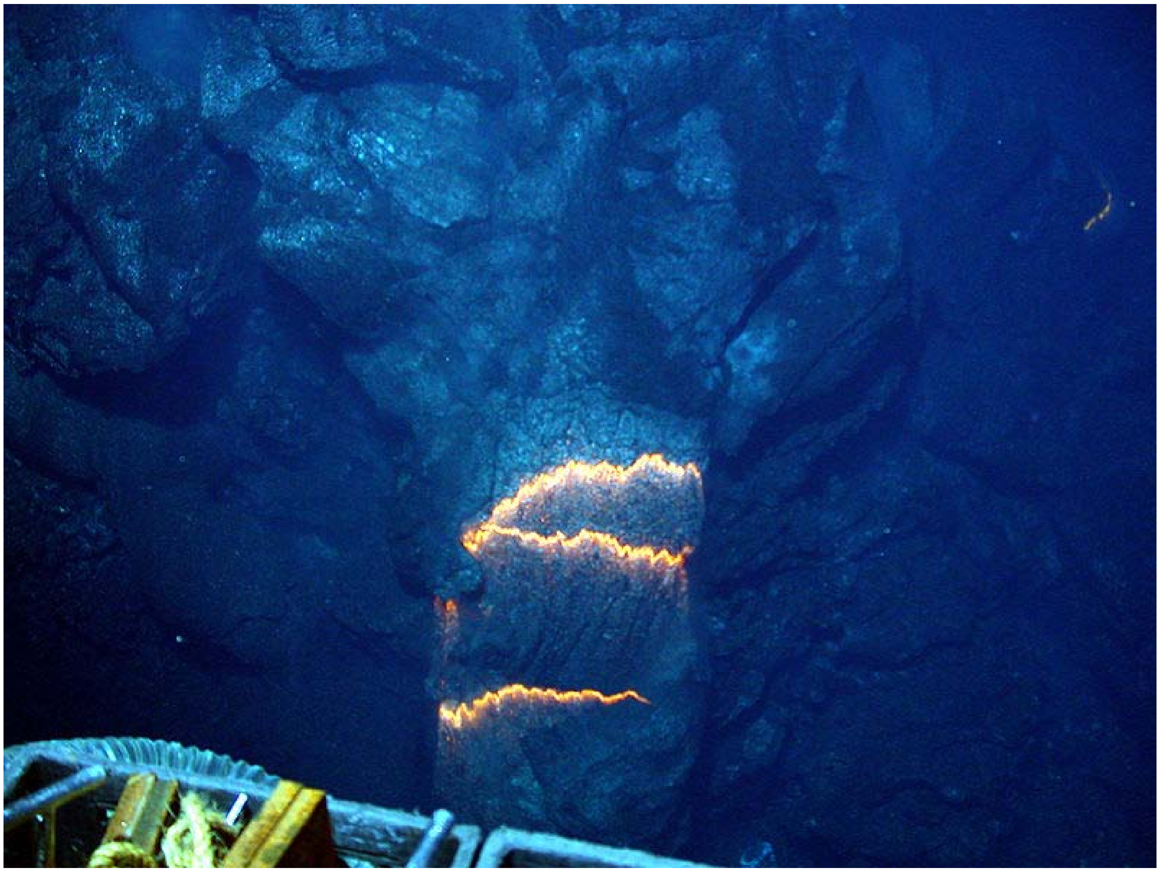
The presence of water can greatly alter the characteristics of a volcanic eruption and the explosions made by these. For instance, the increased thermal conductivity of water causes magma to cool and solidify much more quickly than in a terrestrial eruption, often turning it into a volcanic glass. Below ocean depths of about 2200 meters where the pressure exceeds 218 atmospheres, the critical pressure of water, it can no longer boil; it becomes a supercritical fluid. Without boiling sounds, deep-sea volcanoes are difficult to detect at great distances using hydrophones.



Submarine volcano in the Bransfield Strait, Antarctica

The lava formed by submarine volcanoes is quite different from terrestrial lava. Upon contact with water, a solid crust forms around the lava. Advancing lava flows into this crust, forming what is known as pillow lava.

Scientists still have much to learn about the location and activity of underwater volcanoes. The Kolumbo underwater volcano in the Aegean Sea was discovered in 1650 when it burst from the sea and erupted, killing 70 people on the nearby island of Santorini. More recently, NOAA's Office of Ocean Exploration has funded missions to explore submarine volcanoes. Most notably, these have been the Ring of Fire missions to the Mariana Arc in the Pacific Ocean. Using Remote Operated Vehicles, scientists studied underwater eruptions, ponds of molten sulfur, black smoker chimneys and even marine life adapted to this deep, hot environment.



Submarine volcano, West Mata, May 2009

Many submarine volcanoes are usually found as seamounts. These are typically formed from extinct volcanoes, that rise abruptly and are usually found rising from a seafloor of 1,000 - 4,000 meters depth. They are defined by oceanographers as independent features that rise to at least 1,000 meters above the seafloor. The peaks are often found hundreds to thousands of meters below the surface, and are therefore considered to be within the deep sea. An estimated 30,000 seamounts occur across the globe, with only a few having been studied. However, some seamounts are also unusual. For example, while the summits of seamounts are normally hundreds of meters below sea level, the Bowie Seamount in Canada's Pacific waters rises from a depth of about 3,000 meters to within 24 meters of the sea surface.

Subglacial Volcano

A **subglacial volcano**, also known as a **glaciovolcano**, is a volcanic form produced by subglacial eruptions or eruptions beneath the surface of a glacier or ice sheet which is then melted into a lake by the rising lava. Today they are most common in Iceland and Antarctica; older formations of this type are found also in British Columbia and Yukon Territory, Canada.

During the eruption, the heat of the lava from the subglacial volcano melts the overlying ice. The water quickly cools the lava, resulting in pillow lava shapes similar to those of underwater volcanoes. When the pillow lavas break off and roll down the volcano slopes, pillow breccia, tuff breccia, and hyaloclastite form. The meltwater may be released from below the ice as happened in Iceland in 1996 when the Grímsvötn caldera erupted, melted 3 cubic km ice and gave rise to a large glacial lake outburst flood.

The shape of subglacial volcanoes tends to be quite characteristic and unusual, with a flattened top and steep sides supported against collapse by the pressure of the surrounding ice and meltwater. If the volcano eventually melts completely through the ice layer, then horizontal lava flows are deposited, and the top of the volcano assumes a nearly-level form. However, if significant amounts of lava are later erupted subaerially, then the volcano may assume a more conventional shape. In Canada the volcanos have been known to form both conical and nearly-level shapes. The more distinctly flat-topped, steep-sided subglacial volcanoes are called tuyas, named after Tuya Butte in northern British Columbia by Canadian geologist Bill Mathews in 1947. In Iceland, such volcanoes are also known as table mountains.

Jökulhlaups

Subglacial eruptions often cause jökulhlaups or great floods of water. In November of 1996 the Grímsvötn Volcano beneath the Vatnajökull ice sheet erupted and caused a Jökulhlaup that affected more than 270 mi^2 (750 km^2) and destroyed or severely damaged several bridges. During the ice ages, such floods from Lake Missoula were estimated to have discharges exceeding 17 × 106 m^3/s (4.5 × 10^9 gal/s) and covered a third of eastern Washington state. Sonia Esperanca, program director in the National Science Foundation commented on the danger of subglacial volcanos: "When an ice-covered volcano erupts, the interplay among molten magma, ice and meltwater can have catastrophic results."

Antarctica eruption

In January, 2008, the British Antarctic Survey (Bas) scientists led by Hugh Corr and David Vaughan, reported (in the journal Nature Geoscience) that 2,200 years ago, a volcano erupted under Antarctica ice sheet (based on airborne survey with radar images). The biggest eruption in the last 10,000 years, the volcanic ash was found deposited on the ice surface under the Hudson Mountains, close to Pine Island Glacier.

Subglacial Volcanoes on Mars

Many scientists believe that liquid water exists many kilometers below the surface of mars, but at this point in time it is impossible to drill to those depths with the rovers in existence. Meredith Payne and Jack Farmer of Arizona State University have been studying pictures from the Viking and Mars Orbiter cameras to find several locations where possible subglacial volcanoes may exists that could carry microbes to the surface.

Ice Cores

It is possible to track catastrophic subglacial volcano eruptions in time with the analysis of ice cores such as the Vostok core. Subglacial volcanic eruptions are identified by layers of high concentrations of NO_3^- and SO_4^{2-}.

Chapter- 7

Volcanoes on Other Planetary Bodies

Volcanism on Io

Io, with two plumes erupting from its surface

Volcanism on Io, a moon of Jupiter, produces lava flows, volcanic pits, and plumes of sulfur and sulfur dioxide hundreds of kilometres high. This volcanic activity was discovered in 1979 by *Voyager 1* imaging scientists. Observations of Io by passing spacecraft (the *Voyagers*, *Galileo*, *Cassini*, and *New Horizons*) and Earth-based astronomers have revealed more than 150 active volcanoes. Up to 400 such volcanoes are predicted to exist based on these observations. Io's volcanism makes the satellite one of only four known currently volcanically active worlds in the solar system (the other three being Earth, Saturn's moon Enceladus, and Neptune's moon Triton).

First predicted shortly before the *Voyager 1* flyby, the heat source for Io's volcanism comes from tidal heating produced by its forced orbital eccentricity. This differs from Earth's internal heating, which is derived primarily from radioactive isotope decay. Io's eccentric orbit leads to a slight difference in Jupiter's gravitational pull on the satellite between its closest and farthest points on its orbit, causing a varying tidal bulge. This variation in the shape of Io causes frictional heating in its interior. Without this tidal heating, Io might have been similar to the Earth's moon, a world of similar size and mass, geologically dead and covered with numerous impact craters.

Io's volcanism has led to the formation of hundreds of volcanic centres and extensive lava formations, making the moon the most volcanically active body in the Solar System. Three different types of volcanic eruptions have been identified, differing in duration, intensity, lava effusion rate, and whether the eruption occurs within a volcanic pit (known as a *patera*). Lava flows on Io, tens or hundreds of kilometres long, have primarily basaltic composition, similar to lavas seen on Earth at shield volcanoes such as Kīlauea in Hawaii. While most lavas on Io are made of basalt, a few lava flows consisting of sulfur and sulfur dioxide have been seen. In addition, eruption temperatures as high as 1,600 K (1,300 °C; 2,400 °F) were detected, which can be explained by the eruption of high-temperature ultramafic silicate lavas.

As a result of the presence of significant quantities of sulfurous materials in Io's crust and on its surface, some eruptions propel sulfur, sulfur dioxide gas, and pyroclastic material up to 500 kilometres (310 mi) into space, producing large, umbrella-shaped volcanic plumes. This material paints the surrounding terrain in red, black, and/or white, and provides material for Io's patchy atmosphere and Jupiter's extensive magnetosphere. Spacecraft that have flown by Io since 1979 have observed numerous surface changes as a result of Io's volcanic activity.

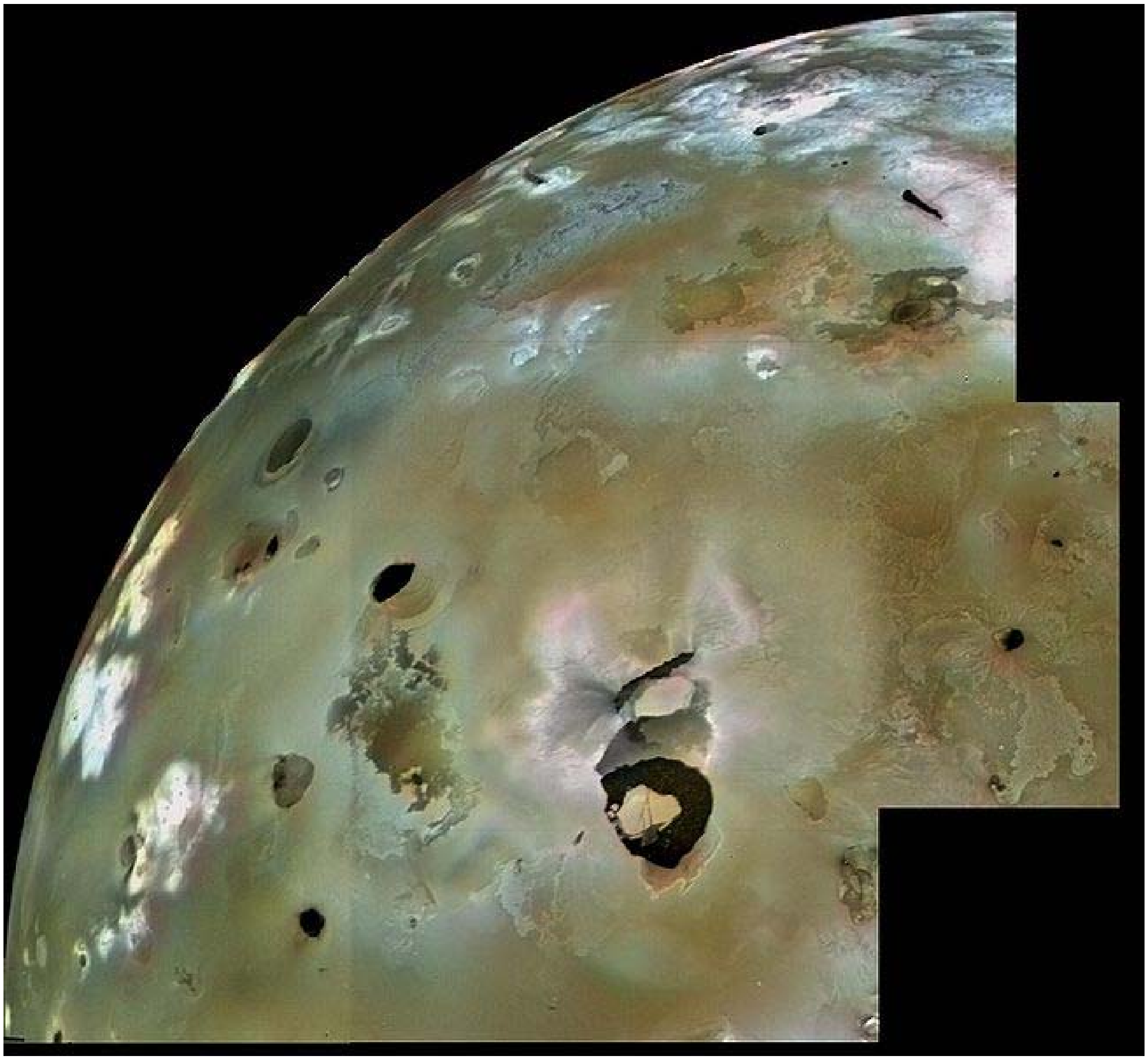
Discovery

Discovery image of active volcanism on Io

Before the *Voyager 1* encounter with Io on March 5, 1979, Io was thought to be a dead world much like the Earth's Moon. The discovery of a cloud of sodium surrounding Io led to theories that the satellite would be covered in evaporites.

Hints of discoveries to come arose from Earth-based infrared observations taken in the 1970s. An anomalously high thermal flux, compared to the other Galilean satellites, was discovered during measurements taken at an infrared wavelength of 10 μm while Io was in Jupiter's shadow. At the time, this heat flux was attributed to the surface having a much higher thermal inertia than Europa and Ganymede. These results were considerably different from measurements taken at wavelengths of 20 μm which suggested that Io had similar surface properties to the other Galilean satellites. It has since been determined that the greater flux at shorter wavelengths was due to the combined flux from Io's volcanoes and solar heating, while solar heating provides a much greater fraction of the flux at longer wavelengths. A sharp increase in Io's thermal emission at 5 μm was observed on February 20, 1978 by Witteborn, *et al.* The group considered volcanic activity at the time, in which case the data was fit into a region on Io 8,000 square kilometres (3,100 sq mi) in size at 600 K (300 °C; 600 °F). However, the authors considered that hypothesis unlikely, and instead focused on emission from Io's interaction with Jupiter's magnetosphere.

Shortly before the *Voyager 1* encounter, Stan Peale, Patrick Cassen, and R. T. Reynolds published a paper in the journal *Science* predicting a volcanically modified surface and a differentiated interior, with distinct rock types rather than a homogeneous blend. They based this prediction on models of Io's interior that took into account the massive amount of heat produced by the varying tidal pull of Jupiter on Io caused by the moon's slightly eccentric orbit. Their calculations suggested that the amount of heat generated for an Io with a homogeneous interior would be three times greater than the amount of heat generated by radioactive isotope decay alone. This effect would be even greater with a differentiated Io.



Voyager 1 observation of Loki Patera and nearby lava flows and volcanic pits

Voyager 1's first images of Io revealed a lack of impact craters, suggesting a very young surface. Craters are used by geologists to estimate the age of a planetary surface; the number of impact structures increase with the age of the planetary surface. Instead, *Voyager 1* observed a multi-coloured surface, pockmarked with irregular-shaped depressions, which lacked the raised rims characteristic of impact craters. *Voyager 1* also observed flow features formed by low-viscosity fluid and tall, isolated mountains that did not resemble terrestrial volcanoes. The surface observed suggested that, just as Peale and colleagues had theorized, Io was heavily modified by volcanism.

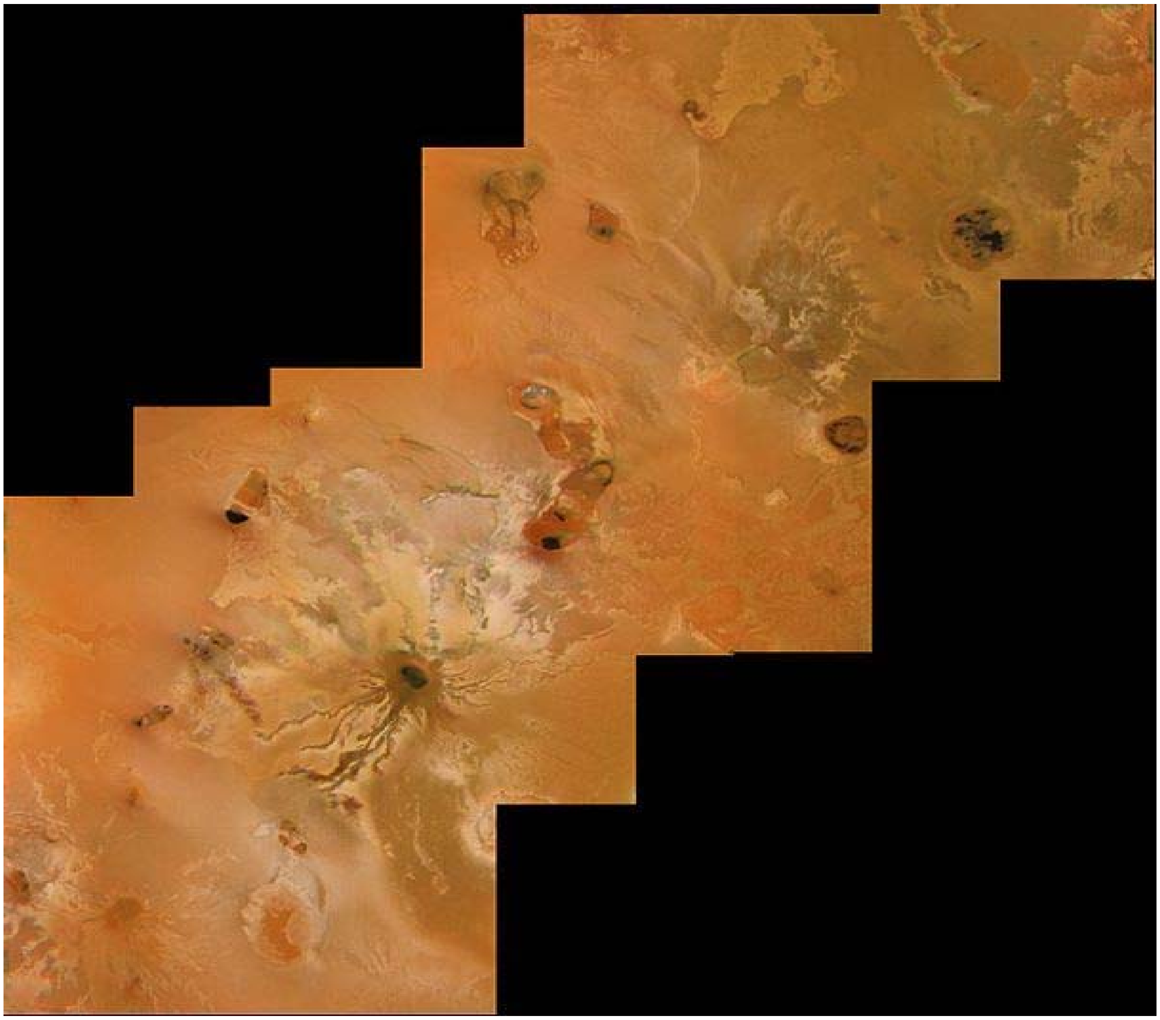
On March 8, 1979, three days after passing Jupiter, *Voyager 1* took images of Jupiter's moons to help mission controllers determine the spacecraft's exact location, a process called optical navigation. While processing images of Io to enhance the visibility of background stars, navigation engineer Linda Morabito found a 300-kilometre (190 mi) tall cloud along the moon's limb. At first, she suspected the cloud to be a moon behind Io, but no suitably sized body would have been in that location. The feature was determined to be a plume generated by active volcanism at a dark depression later named Pele. Following this discovery, seven other plumes were located in earlier *Voyager* images of Io. Thermal emission from multiple sources, indicative of cooling lava, were also found. Surface changes were observed when images acquired by *Voyager 2* were compared to those taken four months previously by *Voyager 1*, including new plume deposits at Aten Patera and Surt.

Heat source

Io's main source of internal heat comes from the dissipation of tidal forces generated by Jupiter's gravitational pull. This external heating differs from the internal heat source for volcanism on Earth, which is a result of radioactive isotope decay and residual heat from accretion. In the Earth, these internal heat sources drive mantle convection, which in turn causes volcanism through plate tectonics.

The tidal heating of Io is dependent on the moon's distance from Jupiter, its orbital eccentricity, the composition of its interior, and its physical state. Its Laplace orbital resonance with Europa and Ganymede maintains Io's eccentricity and prevents tidal dissipation within Io from circularizing its orbit. The eccentricity leads to vertical differences in Io's tidal bulge of as much as 100 metres (330 ft) as Jupiter's gravitational pull varies between the periapsis and apoapsis points in Io's orbit. This varying tidal pull also produces friction in Io's interior, enough to cause significant tidal heating and melting. Unlike Earth, where most of its internal heat is released by conduction through the crust, on Io internal heat is released via volcanic activity and generates the satellite's high heat flow (global total: $0.6–1.6 \times 10^{14}$ W). Models of its orbit suggest that the amount of tidal heating within Io changes with time, and that the current heat flow is not representative of the long-term average. The observed release of heat from Io's interior is greater than estimates for the amount presently generated from tidal heating, suggesting that Io is cooling after a period of greater flexing.

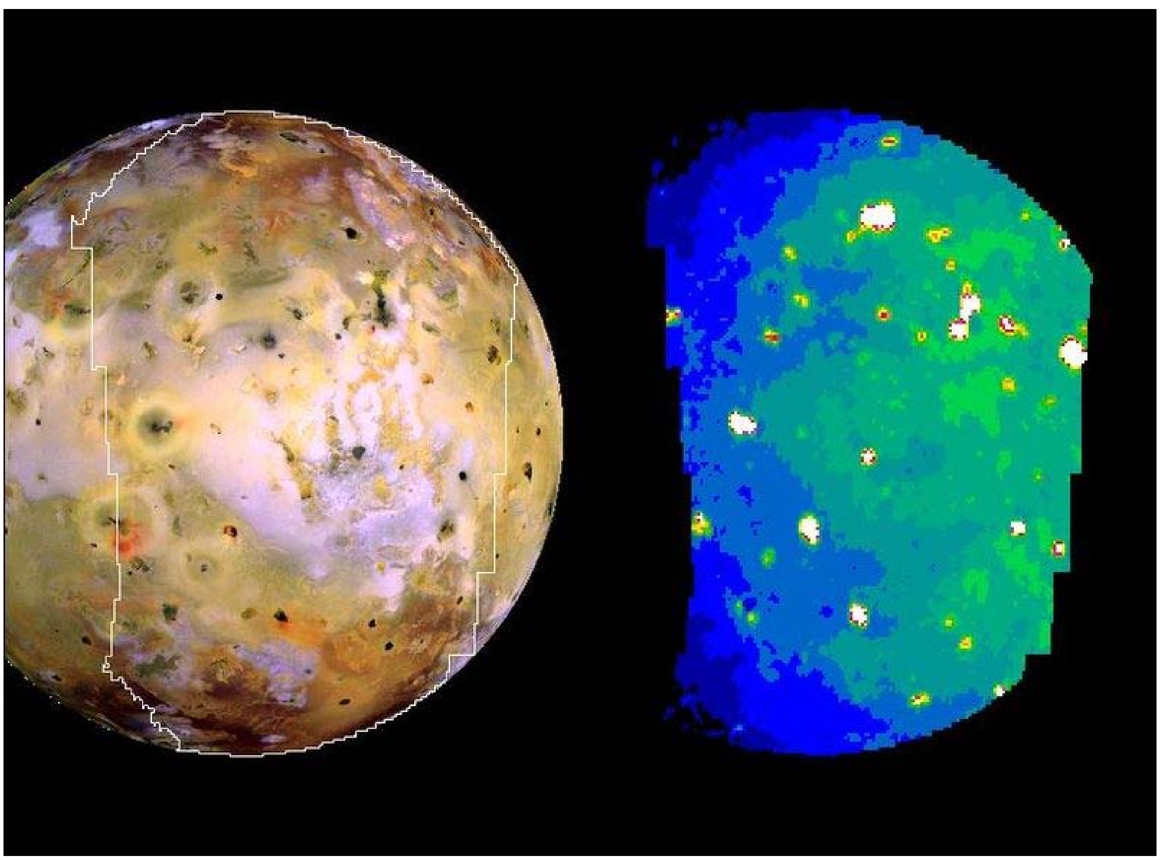
Composition



Voyager 1 image of volcanic pits and lava flows near Ra Patera

Analysis of *Voyager* images led scientists to believe that the lava flows on Io were composed mostly of various forms of molten elemental sulfur. The colouration of the flows was found to be similar to its various allotropes. Differences in the lava colour and brightness are a function of the temperature of polyatomic sulfur and the packing and bonding of its atoms. An analysis of the flows that radiate out from Ra Patera revealed differently colored materials, all associated with liquid sulfur, at different distances from the vent: dark albedo material close to the vent at 525 K (252 °C; 485 °F), red material in the central part of each flow at 450 K (177 °C; 350 °F), and orange material at the farthest ends of each flow at 425 K (152 °C; 305 °F). This colour pattern corresponds to flows radiating out from a central vent, cooling as the lava travels away from it. In addition, temperature measurements of thermal emission at Loki Patera taken by *Voyager 1*'s Infrared Interferometer Spectrometer and Radiometer (IRIS) instrument were consistent with sulfur volcanism. However, the IRIS instrument was not capable of detecting wavelengths that are indicative of higher temperatures. This meant that temperatures consistent with silicate volcanism were not discovered by *Voyager*. Despite this, Voyager scientists deduced that silicates must play a role in Io's youthful appearance, from the moon's high density and the need for silicates to support the steep slopes along patera walls. The contradiction between the structural evidence and the spectral and temperature data following the Voyager flybys led to a debate in the planetary science community regarding the composition of Io's lava flows, whether they were composed of silicate or sulfurous materials.

Earth-based infrared studies in the 1980s and 1990s shifted the paradigm from one of primarily sulfur volcanism to one where silicate volcanism dominates, and sulfur acts in a secondary role. In 1986, measurements of a bright eruption on Io's leading hemisphere revealed temperatures of at least 900 K (600 °C; 1,200 °F). This is higher than the boiling point of sulfur (715 K/442 °C; 827 °F), indicating a silicate composition for at least some of Io's lava flows. Similar temperatures were also observed at the Surt eruption in 1979 between the two *Voyager* encounters, and at the eruption observed by Witteborn and colleagues in 1978. In addition, modeling of silicate lava flows on Io suggested that they cooled rapidly, causing their thermal emission to be dominated by lower temperature components, such as solidified flows, as opposed to the small areas covered by still molten lava near the actual eruption temperature.



Thermal emission map of Io by *Galileo*

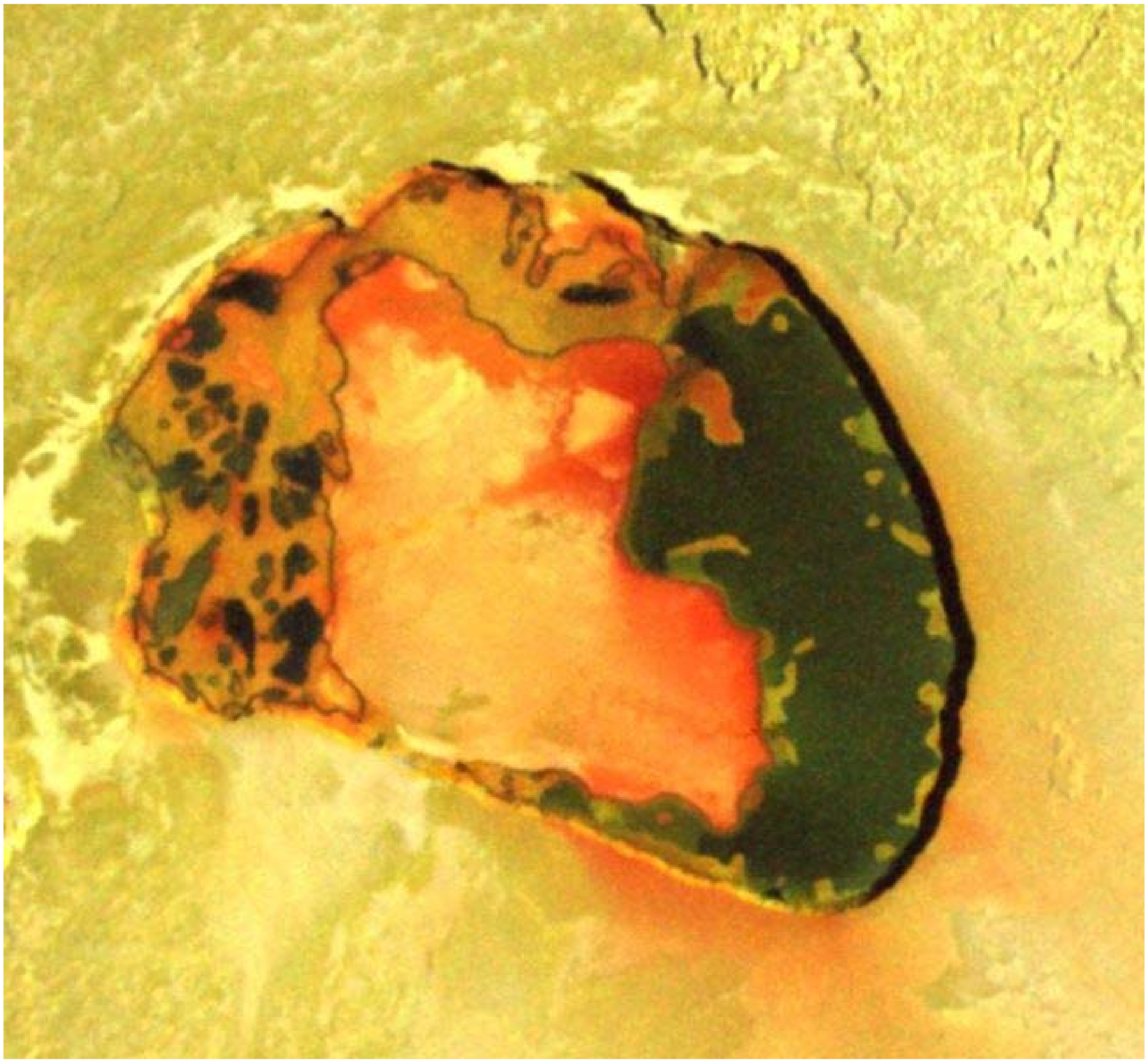
Silicate volcanism, involving basaltic lava with mafic to ultramafic (magnesium-rich) compositions, was confirmed by the *Galileo* spacecraft in the 1990s and 2000s from temperature measurements of Io's numerous hot spots, locations where thermal emission is detected, and from spectral measurements of Io's dark material. Temperature measurements from *Galileo*'s Solid-State Imager (SSI) and Near-Infrared Mapping Spectrometer (NIMS) revealed numerous hot spots with high-temperature components ranging from at least 1,200 K (900 °C; 1,700 °F) to a maximum of 1,600 K (1,300 °C; 2,400 °F), like at the Pillan Patera eruption in 1997. Initial estimates during the course of the *Galileo* mission suggesting eruption temperatures approaching 2,000 K (1,700 °C; 3,100 °F) have since proven to be overestimates since the wrong thermal models were used to calculate the temperatures. Spectral observations of Io's dark material suggested the presence of orthopyroxenes, such as enstatite, magnesium-rich silicate minerals common in mafic and ultramafic basalt. This dark material is seen in volcanic pits, fresh lava flows, and pyroclastic deposits surrounding recent, explosive volcanic eruptions. Based on the measured temperature of the lava and the spectral measurements, some of the lava may be analogous to terrestrial komatiites. Compressional superheating, which could increase the temperature of magma during ascent to the surface during an eruption, may also be a factor in some of the higher temperature eruptions.

While temperature measurements of Io's volcanoes settled the sulfur-versus-silicates debate that persisted between the *Voyager* and *Galileo* missions at Jupiter, sulfur and sulfur dioxide still play a significant role in the phenomena observed on Io. Both materials have been detected in the plumes generated at Io's volcanoes, with sulfur being a primary constituent of Pele-type plumes. Bright flows have been identified on Io, at Tsũi Goab Fluctus, Emakong Patera, and Balder Patera for example, that are suggestive of effusive sulfur or sulfur dioxide volcanism.

Eruption styles

Observations of Io by spacecraft and Earth-based astronomers have led to the identification of differences in the types of eruptions seen on the satellite. The three main types identified include *intra-patera*, *flow-dominated*, and *explosion-dominated* eruptions. They differ in terms of duration, energy released, brightness temperature (determined from infrared imaging), type of lava flow, and whether it is confined within volcanic pits.

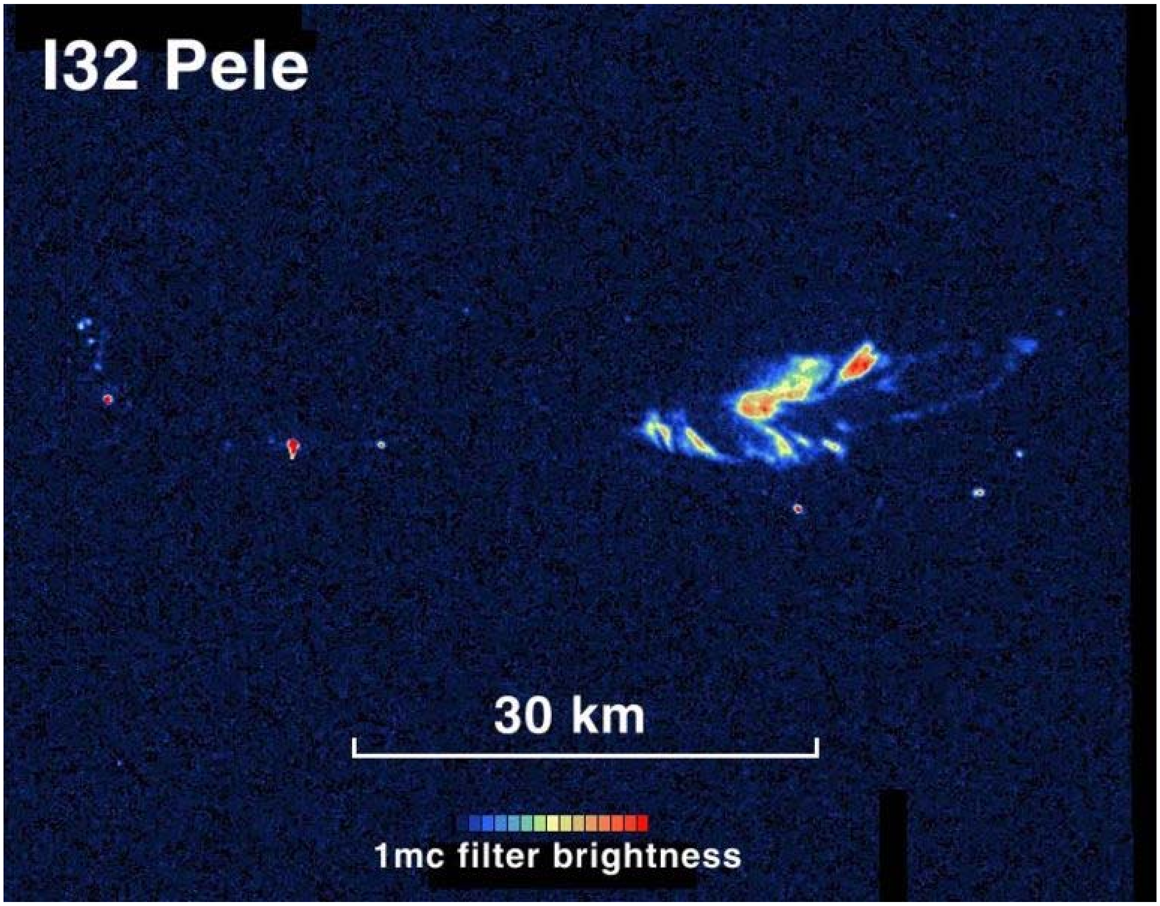
Intra-patera eruptions



Tupan Patera, an example of a volcanic depression

Intra-patera eruptions occur within volcanic depressions known as *paterae*, which generally have flat floors bounded by steep walls. Paterae resemble terrestrial calderas, but it is unknown whether they form when an empty lava chamber collapses, like their terrestrial cousins. One hypothesis suggests that they are produced through the exhumation of volcanic sills, with the overlying material either being blasted out or integrated into the sill. Some paterae display evidence for multiple collapses, similar to the calderas atop Olympus Mons on Mars or Kīlauea on Earth, suggesting that they may occasionally form like volcanic calderas. Since the formation mechanism is still uncertain, the general term for these features uses the Latin descriptor term employed by the International Astronomical Union in naming them, *paterae*. Unlike similar features on Earth and Mars, these depressions generally do not lie at the peak of shield volcanoes and are larger, with an average diameter of 41 kilometres (25 mi) and depth of 1.5 kilometres (0.9 mi). The largest volcanic depression on Io is Loki Patera at

202 kilometres (126 mi) across. Whatever the formation mechanism, the morphology and distribution of many paterae suggest that they are structurally controlled, with at least half bounded by faults or mountains.

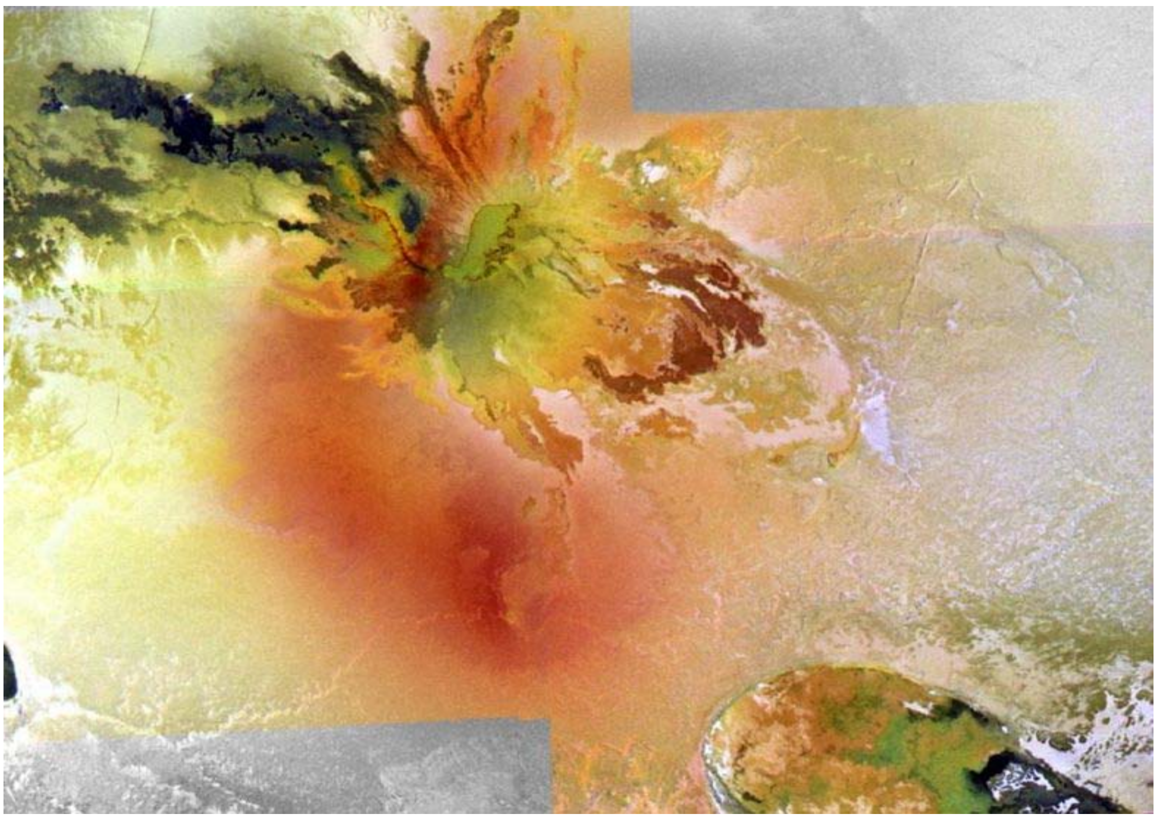


Infrared image showing night-time thermal emission from the lava lake Pele

This eruption style can take the form of either lava flows, spreading across the floor of the paterae, or lava lakes. Except for observations by Galileo during its seven close flybys, it can be difficult to tell the difference between a lava lake and a lava flow eruption on a patera floor, due to inadequate resolution and similar thermal emission characteristics. Intra-patera lava flow eruptions, such as the Gish Bar Patera eruption in 2001, can be just as voluminous as those seen spreading out across the Ionian plains. Flow-like features have also been observed within a number of paterae, like Camaxtli Patera, suggesting that lava flows periodically resurface their floors.

Ionian lava lakes are depressions partially filled with molten lava covered by a thin solidified crust. These lava lakes are directly connected to a magma reservoir lying below. Observations of thermal emission at several Ionian lava lakes reveal glowing molten rock along the patera margin, caused by the lake's crust breaking up along the edge of the patera. Over time, because the solidified lava is denser than the still-molten magma below, this crust can founder, triggering an increase in thermal emission at the volcano. For some lava lakes, like the one at Pele, this occurs continuously, making Pele one of the brightest emitters of heat in the near-infrared spectrum on Io. At other sites, such as at Loki Patera, this can occur episodically. During an overturning episode at these more quiescent lava lakes, a wave of foundering crust spreads out across the patera at the rate of about 1 kilometre (0.6 mi) per day, with new crust forming behind it until the entire lake has been resurfaced. Another eruption would only begin once the new crust has cooled and thickened enough for it to no longer be buoyant over the molten lava. During an overturning episode, Loki can emit up to ten times more heat than when its crust is stable.

Flow-dominated eruptions



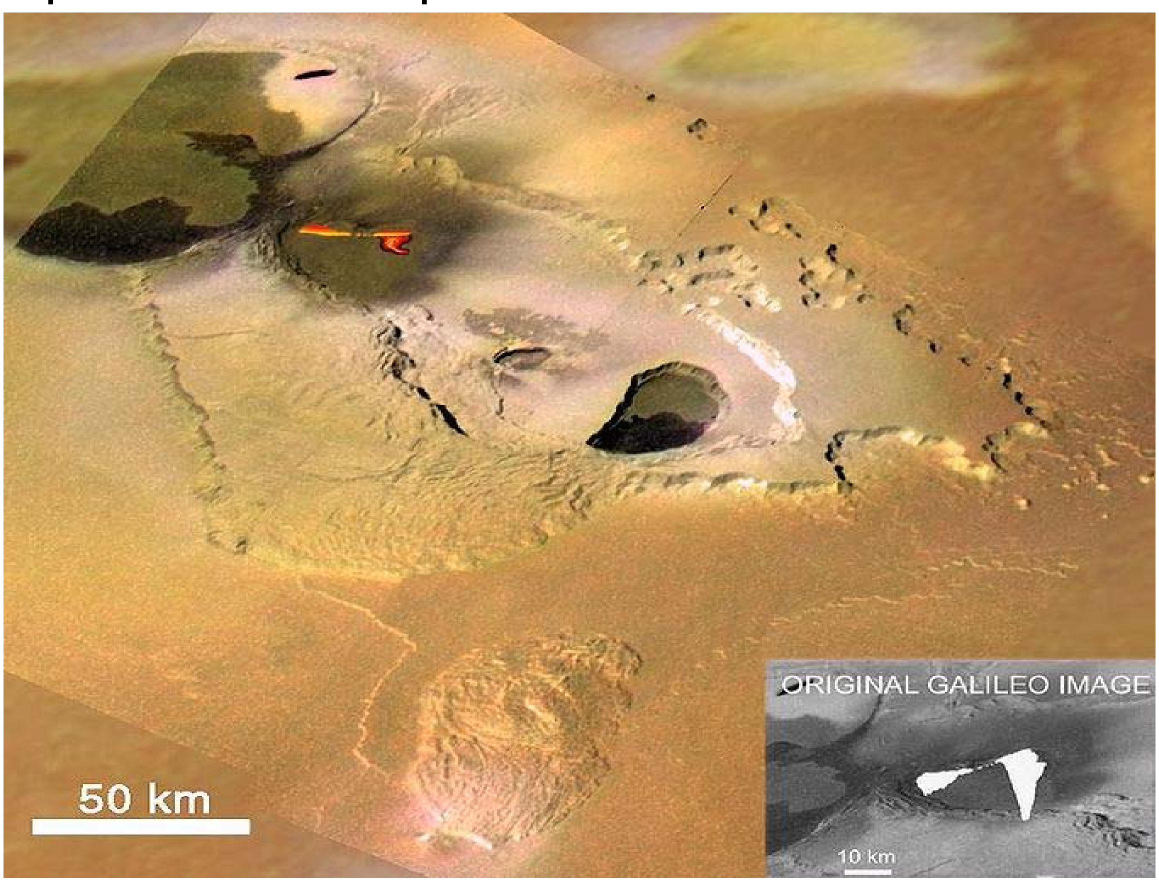
Culann Patera, an example of a flow-dominated eruption

Flow-dominated eruptions are long-lived events that build up extensive, compound lava flows. The extent of these flows makes them a major terrain type on Io. In this style of eruption, magma emerges onto the surface from vents on the floor of paterae, vents surrounding paterae, or from fissures on the plains, producing inflated, compound lava flows similar to those seen at Kīlauea in Hawaii. Images from the *Galileo* spacecraft revealed that many of Io's major flows, like those at Prometheus and Amirani, are produced by the build-up of small breakouts of lava on top of older flows. Flow-dominated eruptions differ from explosion-dominated eruptions by their longevity and their lower energy output per unit of time. Lava erupts at a generally steady rate, and flow-dominated eruptions can last for years or decades.

Active flow fields more than 300 kilometres (190 mi) long have been observed on Io at Amirani and Masubi. A relatively inactive flow field named Lei-Kung Fluctus covers more than 125,000 square kilometres (48,000 sq mi), an area slightly larger than Nicaragua. The thickness of flow fields was not determined by Galileo, but the individual breakouts on their surface are likely to be 1 metre (3 ft 3 in) thick. In many cases, active lava breakouts flow out onto the surface at locations tens to hundreds of kilometres from the source vent, with low amounts of thermal emission observed between it and the breakout. This suggests that lava flows through lava tubes from the source vent to the breakout.

While these eruptions generally have a steady eruption rate, larger outbreaks of lava have been observed at many flow-dominated eruption sites. For example, the leading edge of the Prometheus flow field moved 75 to 95 kilometres (47 to 59 mi) between observations by *Voyager* in 1979 and *Galileo* in 1996. While generally dwarfed by explosion-dominated eruptions, average flow rate at these compound flow fields is much greater than what is observed at similar contemporary lava flows on Earth. Average surface coverage rates of 35–60 square metres (380–650 sq ft) per second were observed at Prometheus and Amirani during the *Galileo* mission, compared to 0.6 square metres (6.5 sq ft) per second at Kīlauea.

Explosion-dominated eruptions

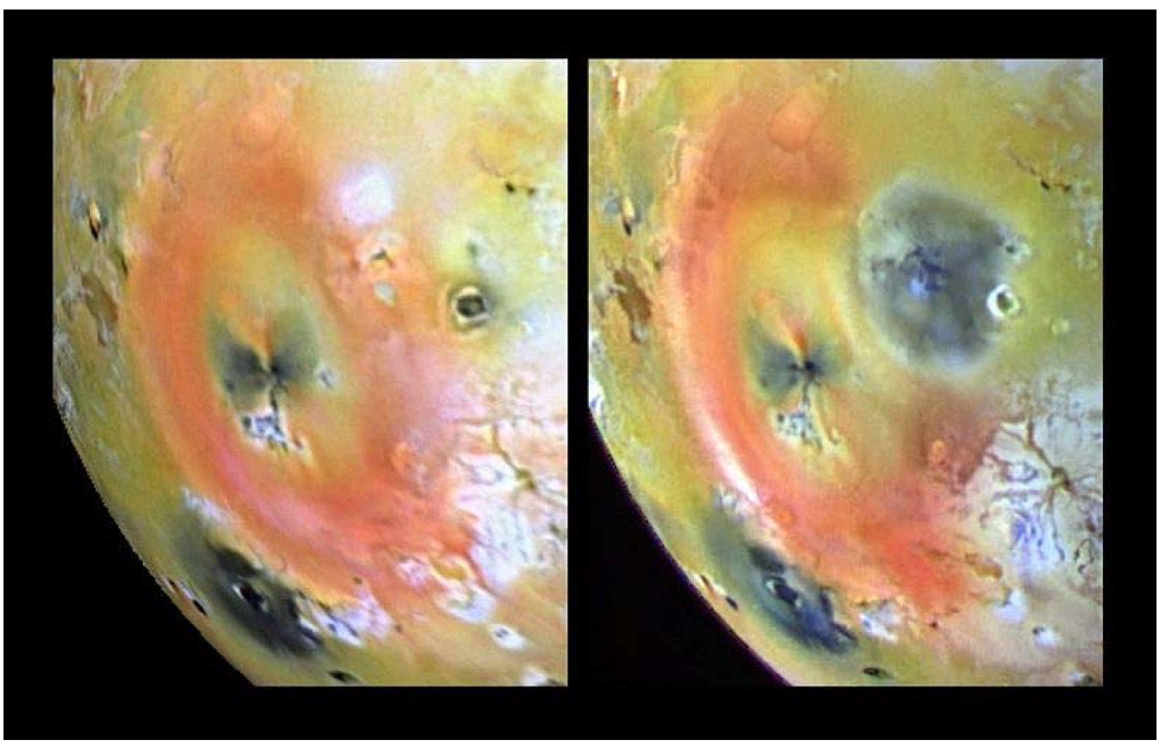


Galileo images of active lava flows and fountains at Tvashtar Paterae in 1999

Explosion-dominated eruptions are the most pronounced of Io's eruption styles. These eruptions, sometimes called "outburst" eruptions from their Earth-based detections, are characterized by their short duration (lasting only weeks or months), rapid onset, large volumetric flow rates, and high thermal emission. They lead to a short-lived, significant increase in Io's overall brightness in the near-infrared. The most powerful volcanic eruption observed in historical times was an "outburst" eruption at Surt, observed by Earth-based astronomers on February 22, 2001.

Explosion-dominated eruptions occur when a body of magma (called a *dike*) from deep within Io's partially molten mantle reaches the surface at a fissure. This results in a spectacular display of lava fountains. During the beginning of the outburst eruption, thermal emission is dominated by strong, 1–3 μm infrared radiation. It is produced by a large amount of exposed, fresh lava within the fountains at the eruption source vent. Outburst eruptions at Tvashtar in November 1999 and February 2007 centred around a 25-kilometre (16 mi) long, 1-kilometre (0.62 mi) tall lava "curtain" produced at a small patera nested within the larger Tvashtar Paterae complex.

The large amount of exposed molten lava at these lava fountains has provided researchers with their best opportunity to measure the actual temperatures of Ionian lavas. Temperatures suggestive of an ultramafic lava composition similar to Pre-Cambrian komatiites (about 1,600 K / 1,300 °C; 2,400 °F) are dominant at such eruptions, though superheating of the magma during ascent to the surface cannot be ruled out as a factor in the high eruption temperatures.

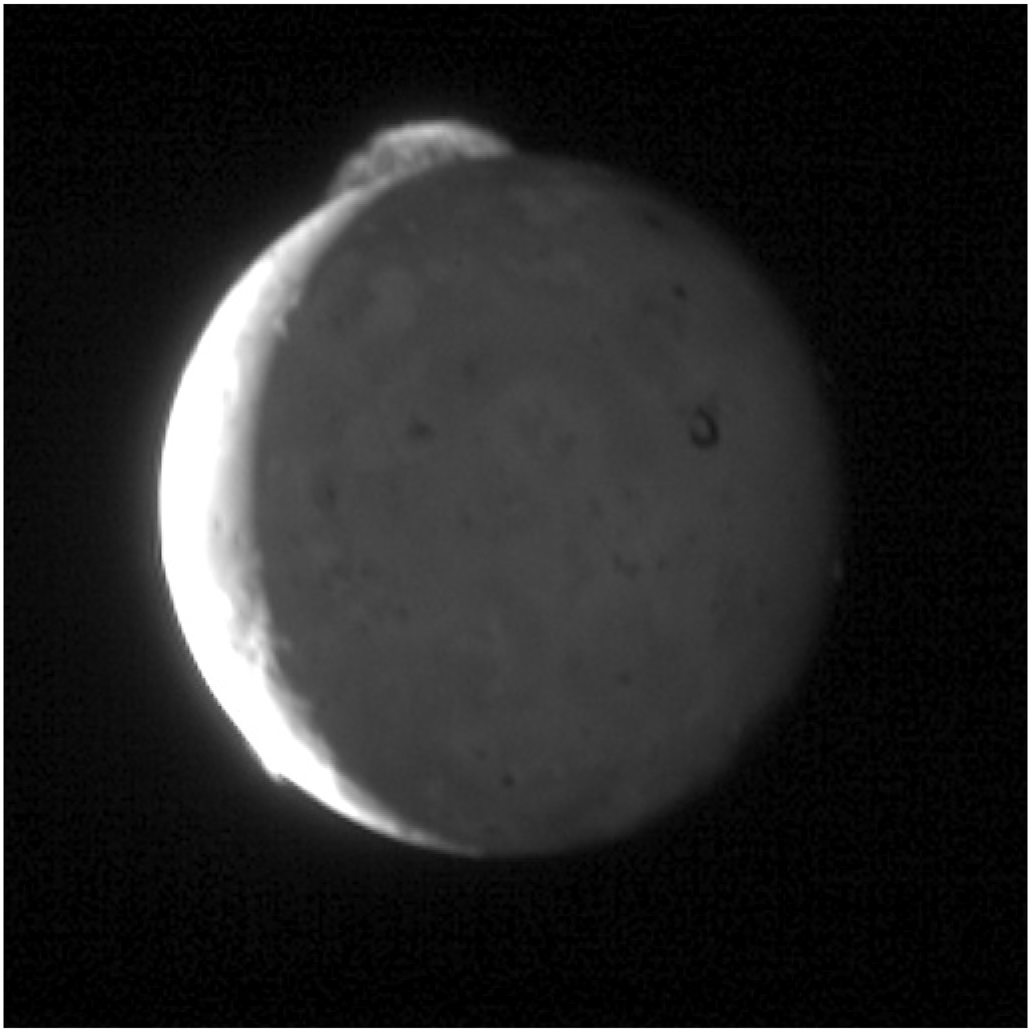


Two *Galileo* images showing the effects of an explosion-dominated eruption at Pillan Patera in 1997

While the more explosive, lava-fountaining stage may last only a few days to a week, explosion-dominated eruptions can continue for weeks to months, producing large, voluminous silicate lava flows. A major eruption in 1997 from a fissure north-west of Pillan Patera produced more than 31 cubic kilometres (7.4 cu mi) of fresh lava over a two and a half to five and a half month period, and later flooded the floor of Pillan Patera. Observations by *Galileo* suggest lava coverage rates at Pillan between 1,000 and 3,000 square metres (11,000 and 32,000 sq ft) per second during the 1997 eruption. The Pillan flow was found to be 10 metres (33 ft) thick, compared to the 1-metre (3 ft 3 in) thick flows observed at the inflated fields at Prometheus and Amirani. Similar, rapidly emplaced lava flows were observed by *Galileo* at Thor in 2001. Such flow rates are similar to those seen at Iceland's Laki eruption in 1783 and in terrestrial flood basalt eruptions.

Explosion-dominated eruptions can produce dramatic (but often short-lived) surface changes around the eruption site, such as large pyroclastic and plume deposits produced as gas exsolves from lava fountains. The 1997 Pillan eruption produced a 400-kilometre (250 mi) wide deposit of dark, silicate material and bright sulfur dioxide. The Tvashtar eruptions of 2000 and 2007 generated a 330-kilometre (210 mi) tall plume that deposited a ring of red sulfur and sulfur dioxide 1,200 kilometres (750 mi) wide. Despite the dramatic appearance of these features, without continuous resupply of material, the vent surroundings often revert back to their pre-eruption appearance over a period of months (in the case of Grian Patera) or years (as at Pillan Patera).

Plumes



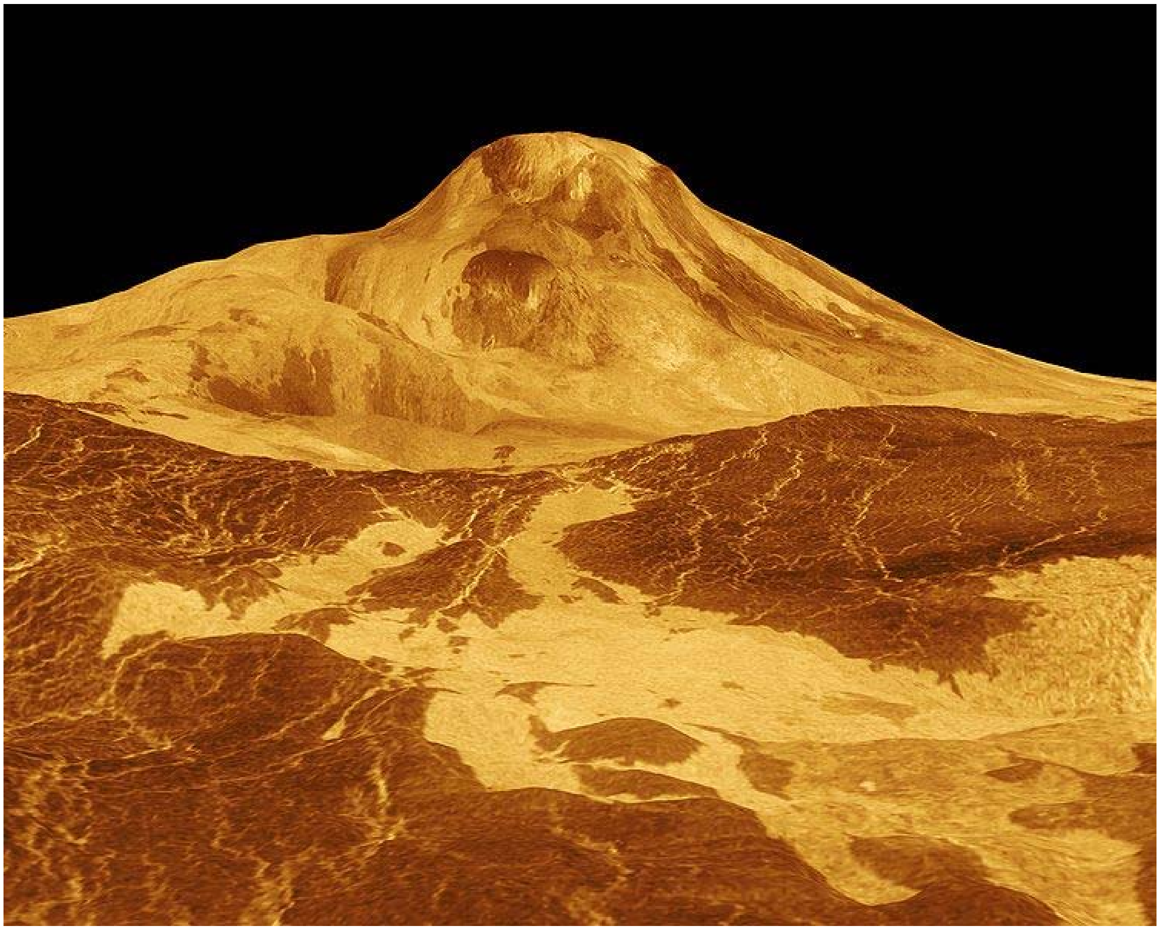
Sequence of *New Horizons* images showing Io's volcano Tvashtar spewing material 330 kilometres (210 mi) above its surface

The discovery of volcanic plumes at Pele and Loki in 1979 provided conclusive evidence that Io was geologically active. Generally, plumes form when volatiles like sulfur and sulfur dioxide are ejected skyward from Io's volcanoes at speeds reaching 1 kilometre per second (0.62 mi/s), creating umbrella-shaped clouds of gas and dust. Additional materials that might be found in the volcanic plumes include sodium, potassium, and chlorine. While striking in appearance, volcanic plumes are relatively uncommon. Of the 150 or so active volcanoes observed on Io, plumes have only been observed at a couple of dozen of them. The limited area of Io's lava flows suggests that much of the resurfacing needed to erase Io's cratering record must come from plume deposits.

The most common type of volcanic plume on Io are dust plumes, or Prometheus-type plumes, produced when encroaching lava flows vaporize underlying sulfur dioxide frost, sending the material skyward. Examples of Prometheus-type plumes include Prometheus, Amirani, Zamama, and Masubi. These plumes are usually less than 100 kilometres (62 mi) tall with eruption velocities around 0.5 kilometres per second (0.31 mi/s). Prometheus-type plumes are dust-rich, with a dense inner core and upper canopy shock zone, giving them an umbrella-like appearance. These plumes often form bright circular deposits, with a radius ranging between 100 and 250 kilometres (62 and 160 mi) and consisting primarily of sulfur dioxide frost. Prometheus-type plumes are frequently seen at flow-dominated eruptions, helping make this plume type quite long-lived. Four out of the six Prometheus-type plumes observed by *Voyager 1* in 1979 were also observed throughout the *Galileo* mission and by *New Horizons* in 2007. While the dust plume can be clearly seen in sunlit visible-light images of Io acquired by passing spacecraft, many Prometheus-type plumes have an outer halo of fainter, more gas-rich material reaching heights approaching that of the larger, Pele-type plumes.

Io's largest plumes, Pele-type plumes, are created when sulfur and sulfur dioxide gas exsolve from erupting magma at volcanic vents or lava lakes, carrying silicate pyroclastic material with them. The few Pele-type plumes that have been observed are usually associated with explosion-dominated eruptions, and are short-lived. The exception to this is Pele, which is associated with a long-lived active lava lake eruption, though the plume is thought to be intermittent. The higher vent temperatures and pressures associated with these plumes generate eruption speeds of up to 1 kilometre per second (0.62 mi/s), allowing them to reach heights of between 300 and 500 kilometres (190 and 310 mi). Pele-type plumes form red (from short-chain sulfur) and black (from silicate pyroclastics) surface deposits, including large 1,000 kilometres (620 mi)-wide red rings, as seen at Pele. They are generally fainter than Prometheus-type plumes as a result of the low dust content, causing some to be called stealth plumes. These plumes are sometimes only seen in images acquired while Io is in the shadow of Jupiter or those taken in the ultraviolet range. The little dust that is visible in sunlit images is generated when sulfur and sulfur dioxide condense as the gases reach the top of their ballistic trajectories. That is why these plumes lack the dense central column seen in Prometheus-type plumes, in which dust is generated at the plume source. Examples of Pele-type plumes have been observed at Pele, Tvashtar, and Grian.

Volcanism on Venus



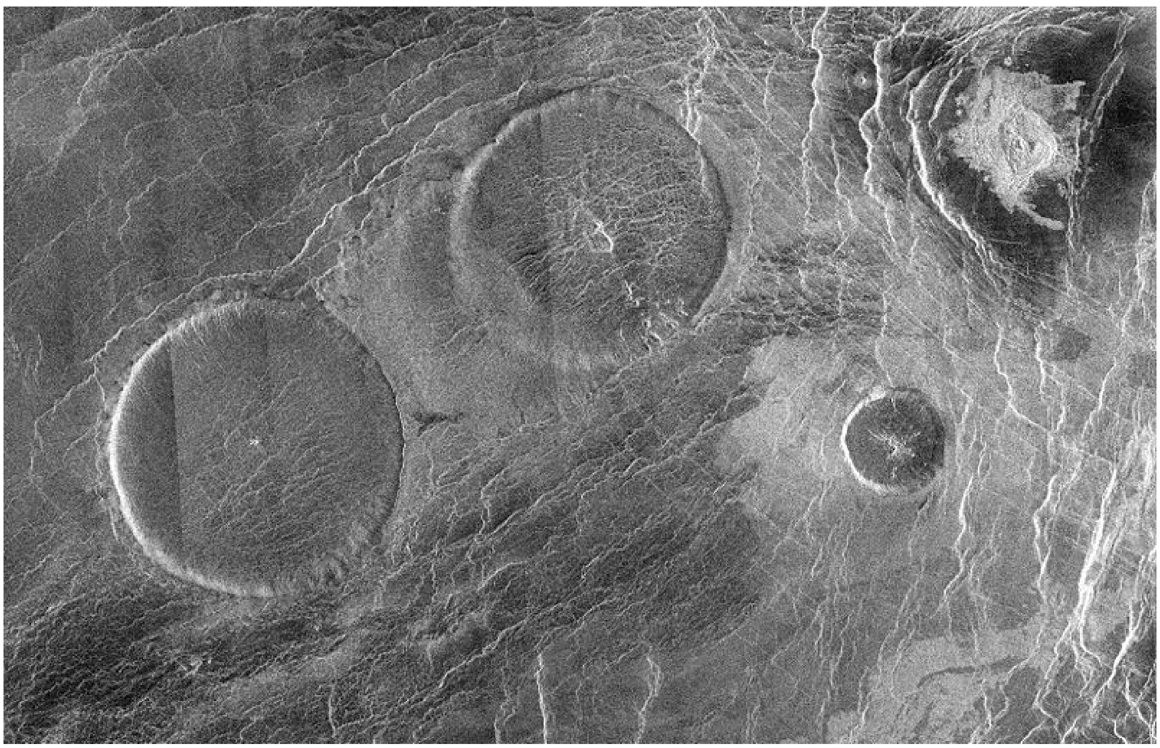
The 8-km-high volcano Maat Mons is displayed in this perspective view of the surface of Venus, with the vertical scale multiplied by 22.5. Based on Magellan probe radar images.

The surface of Venus is dominated by volcanism and has produced more volcanoes than any other planet in the solar system. It has a surface that is 90% basalt, and about 80% of the planet consists of a mosaic of volcanic lava plains, indicating that volcanism played a major role in shaping its surface. The planet may have had a major global resurfacing event about 500 million years ago, from what scientists can tell from the density of impact craters on the surface. Even though there are over 1,600 major volcanoes on Venus, none is known to be erupting at present and most are probably long extinct. However, radar sounding by the Magellan probe revealed evidence for comparatively recent volcanic activity at Venus's highest volcano Maat Mons, in the form of ash flows near the summit and on the northern flank.

Although many lines of evidence suggest that Venus is likely to be volcanically active, present-day eruptions at Maat Mons have not been confirmed. In April 2010, Suzanne E. Smrekar *et al.* announced the discovery of three active volcanoes, which suggests that Venus is periodically resurfaced by lava flows.

Venus contains shield volcanoes, widespread lava flows and some unusual volcanoes called pancake domes and "tick-like" structures which are not present on Earth. Pancake dome volcanoes are up to 15 kilometers (9 mi) in diameter and less than 1 kilometer (0.6 mi) in height and are 100 times larger than those formed on Earth. They are usually associated with coronae and *tesserae* (large regions of highly deformed terrain, folded and fractured in two or three dimensions, believed to be unique to Venus). The pancakes are thought to be formed by highly viscous, silica-rich lava erupting under Venus's high atmospheric pressure.

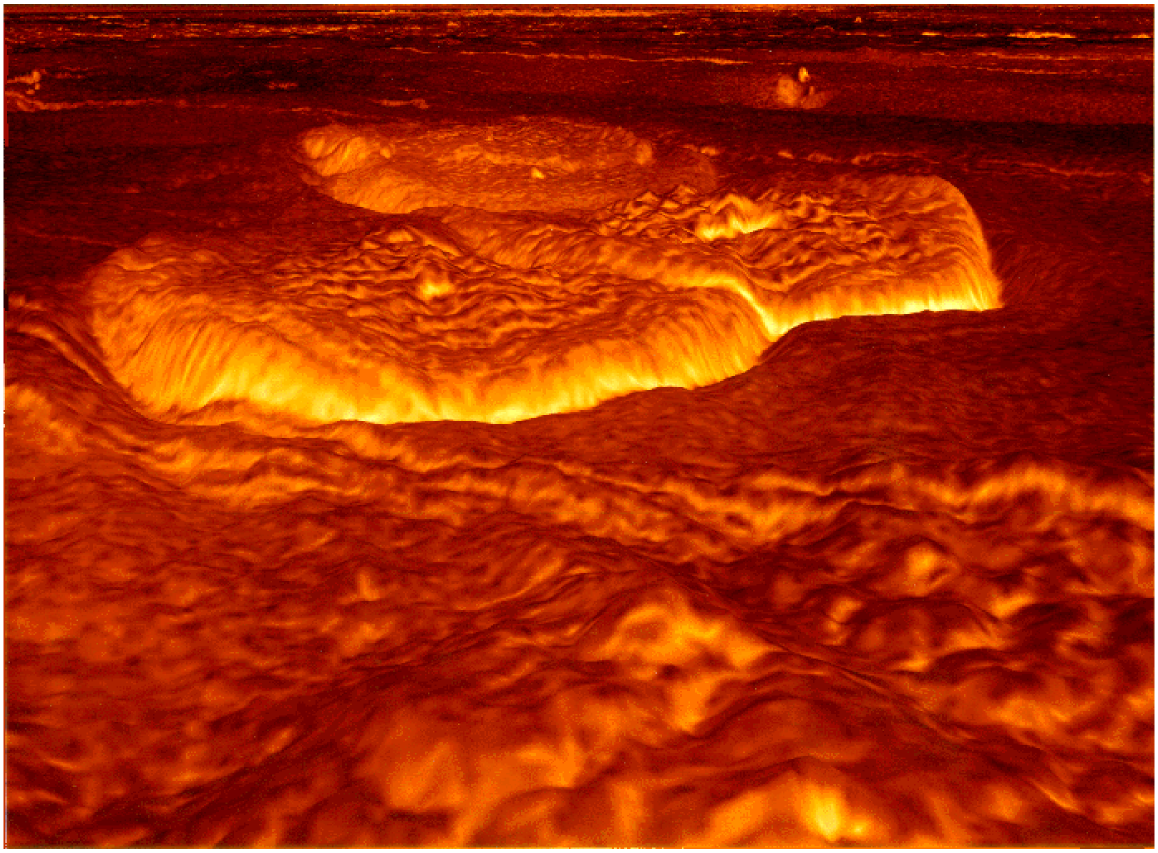
The "tick-like" structures are called scalloped margin domes. They are commonly called *ticks* because they appear as domes with numerous *legs*. They are thought to have undergone mass wasting events such as landslides on their margins. Sometimes deposits of debris can be seen scattered around them.



Radar mosaic of two 65-km-wide (and less than 1-km-high) pancake domes in Venus's Eistla region.

On Earth, volcanoes are mainly of two types: shield volcanoes and composite or stratovolcanoes. The shield volcanoes, for example those in Hawaii, eject magma from the depths of the Earth in zones called *hot spots*. The lava from these volcanos is relatively fluid and permits the escape of gases. Composite volcanos, such as Mount Saint Helens and Mount Pinatubo, are associated with tectonic plates. In this type of volcano, the oceanic crust of one plate is sliding underneath the other in a subduction zone, together with an inflow of seawater, producing a gummier lava that restricts the exit of the gases, and for that reason, composite volcanoes tend to erupt more violently.

On Venus, where there are no tectonic plates or seawater, volcanoes are of the shield type. Nevertheless, the morphology of the volcanos of Venus is different: on the Earth, shield volcanoes can be a few tens of kilometres wide and up to 10 kilometres high (6.2 mi) in the case of Mauna Kea, measured from the sea floor. On Venus, these volcanos can cover hundreds of kilometres in area, but they are relatively flat, with an average height of 1.5 kilometres (0.9 mi).



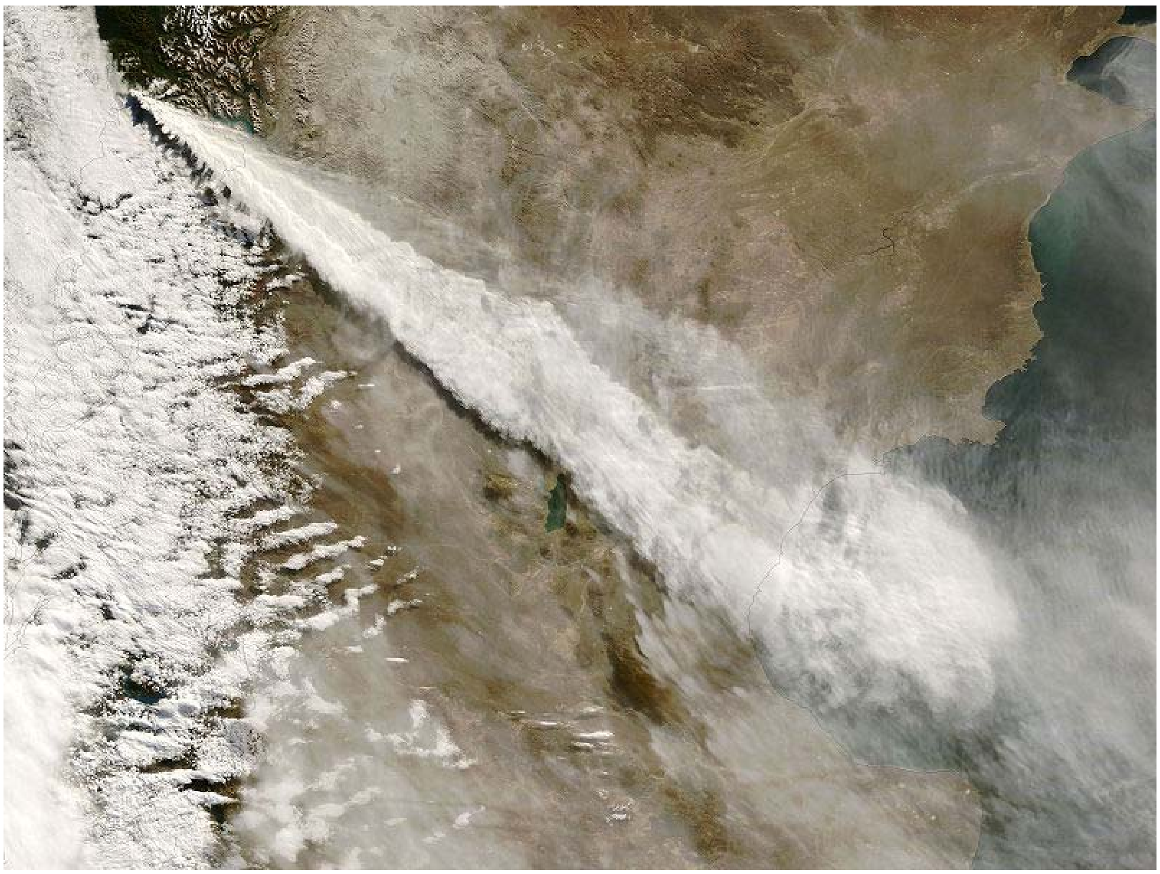
Computer-generated perspective view of pancake domes in Venus's Alpha Regio

Other unique features of Venus's surface are *novae* (radial networks of dikes or grabens) and arachnoids. A nova is formed when large quantities of magma are extruded onto the surface to form radiating ridges and trenches which are highly reflective to radar. These dikes form a symmetrical network around the central point where the lava emerged, where there may also be a depression caused by the collapse of the magma chamber.

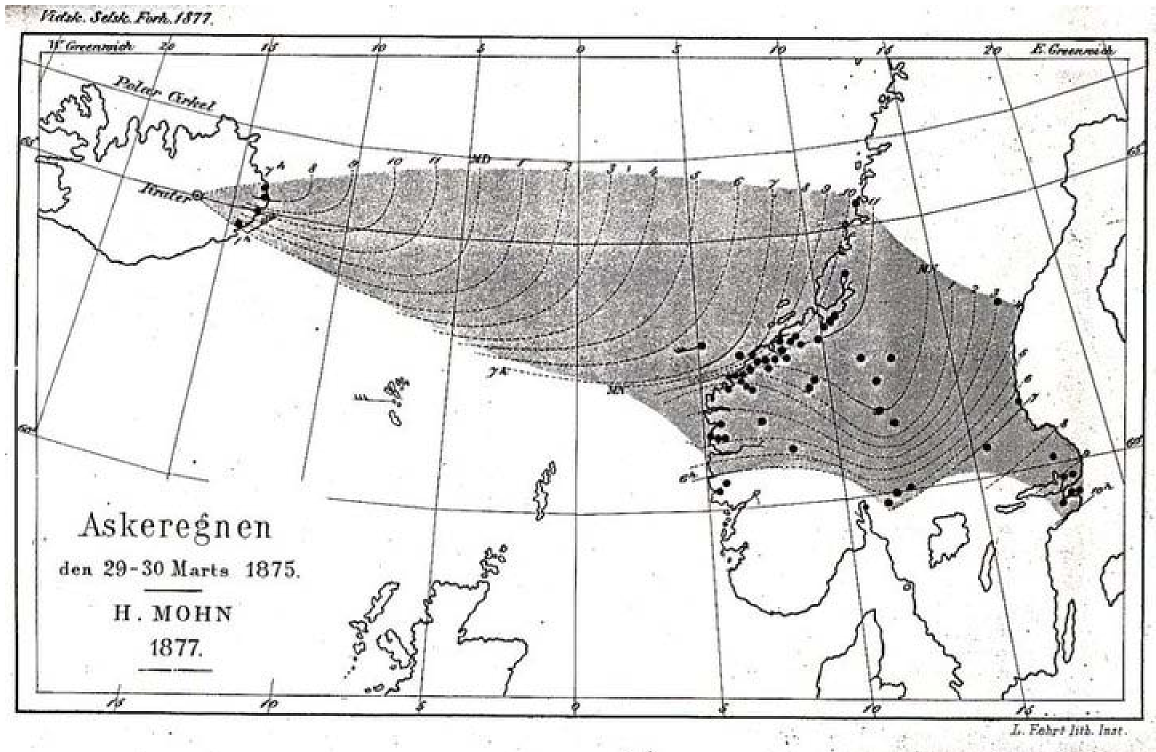
Arachnoids are so named because they resemble a spider's web, featuring several concentric ovals surrounded by a complex network of radial fractures similar to those of a nova. It is not known whether the 250 or so features identified as arachnoids actually share a common origin, or are the result of different geological processes

Chapter- 8

Volcanic Ash



Ash cloud from the 2008 eruption of Chaitén volcano stretching across Patagonia from the Pacific to the Atlantic Ocean.



1875 Icelandic eruption event spreads its ashes to Scandinavia in 48 hours

Volcanic ash consists of small tephra, which are bits of pulverized rock and glass created by volcanic eruptions, less than 2 millimetres (0.1 in) in diameter. There are three mechanisms of volcanic ash formation: gas release under decompression causing magmatic eruptions; thermal contraction from chilling on contact with water causing phreatomagmatic eruptions, and ejection of entrained particles during steam eruptions causing phreatic eruptions. The violent nature of volcanic eruptions involving steam results in the magma and solid rock surrounding the vent being torn into particles of clay to sand size. Volcanic ash can lead to breathing problems and malfunctions in machinery, and clouds of it can threaten aircraft and alter weather patterns.

Ash deposited on the ground after an eruption is known as ashfall deposit. Significant accumulations of ashfall can lead to the immediate destruction of most of the local ecosystem, as well the collapse of roofs on man-made structures. Over time, ashfall can lead to the creation of fertile soils. Ashfall can also become cemented together to form a solid rock called tuff. Over geologic time, the ejection of large quantities of ash can produce an ash cone.

Formation

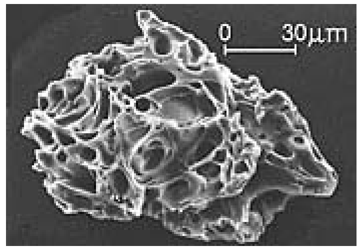
Ash plume from Mt Cleveland, a stratovolcano

There are three mechanisms of volcanic ash formation:

1. Gas release under decompression causing magmatic eruptions;
2. Thermal contraction from chilling on contact with water causing phreatomagmatic eruptions
3. Ejection of entrained particles during steam eruptions causing phreatic eruptions. The violent nature of volcanic eruptions involving steam results in the magma and solid rock surrounding the vent being torn into particles of clay to sand size.

If a volcanic eruption occurs beneath glacial ice, cold water from melted ice chills the lava quickly and fragments it into glass, creating small glass particles that get carried into the eruption plume. This can create a glass-rich plume in the upper atmosphere which is particularly hazardous to aircraft

Composition



Particle of volcanic ash from Mount St. Helens

Light microscope image of ash from the 1980 eruption of Mount St. Helens, Washington

The term for any material explosively thrown out from a vent is tephra or pyroclastic debris. Ash terminology is restricted to very fine rock and mineral particles less than 2 millimetres (0.079 in) in diameter which are ejected from a volcanic vent.

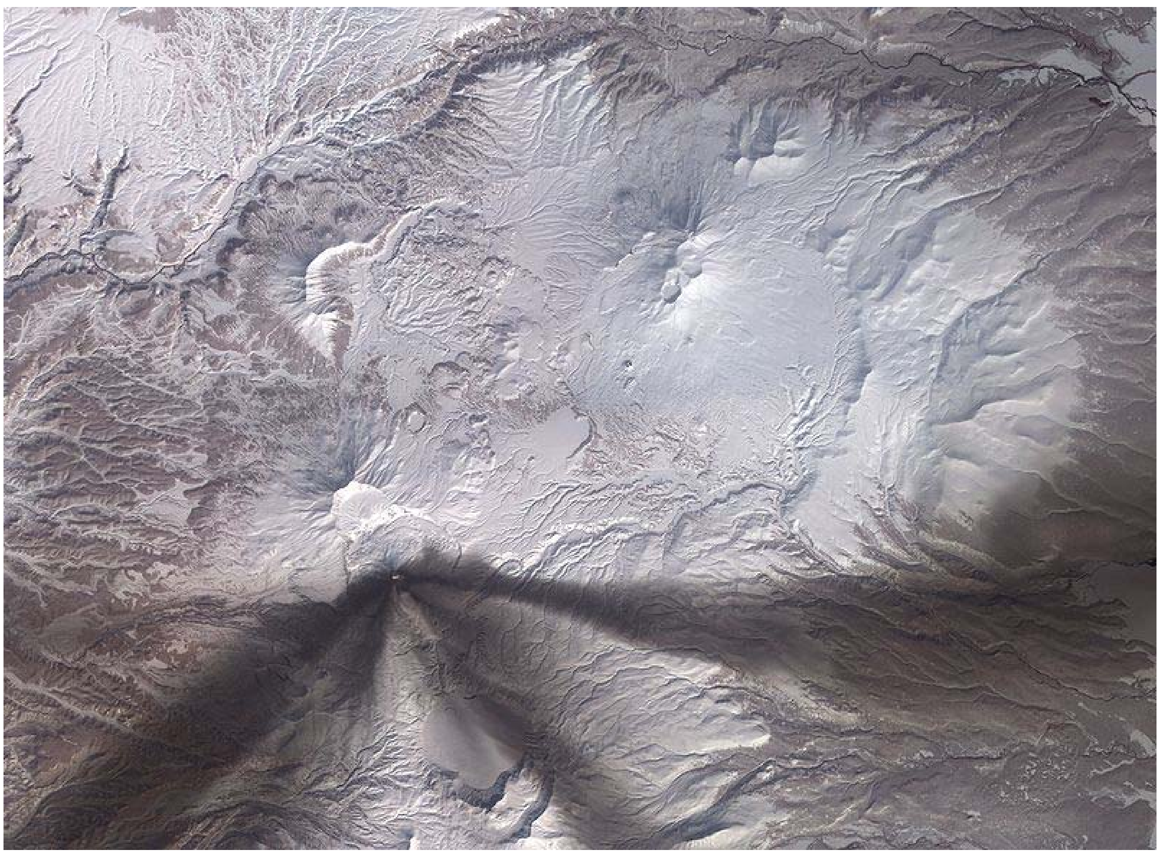
Clast Size	Pyroclast	Mainly Unconsolidated: Tephra	Mainly Consolidated: pyroclastic rock

> 64 mm	Bomb, Block	Agglomerate	Agglomerate, pyroclastic breccia
< 64 mm	Lapillus	Layer, Lapilli Tephra	Lapilli Tuff, Lapillistone
< 2 mm	Coarse Ash	Coarse Ash	Coarse (ash) Tuff
< 0.063 mm	Fine Ash	Fine Ash	Fine (ash) Tuff

Table modified after Heiken and Wohletz, 1985.

Ash is created when solid rock shatters and magma separates into minute particles during explosive volcanic activity. The usually violent nature of an eruption involving steam (*phreatic eruption or phreatomagmatic eruption*) results in the magma and solid rock surrounding the vent being torn into particles of clay to sand size.

Spread



Satellite image of the area around Karymsky. Ash from earlier eruptions has settled onto the snowy landscape, leaving dark grey swaths. The ash stains are confined to the south of the volcano's summit, one large stain fanning out toward the south-west, and another toward the east.

The plume that is often seen above an erupting volcano is composed primarily of ash and steam. The very fine particles may be carried for many miles, settling out as a dust-like layer across the landscape. This is known as an ashfall. If liquid magma is ejected as a spray, the particles will solidify in the air as small fragments of volcanic glass. Unlike the ash that forms from burning wood or other combustible materials, volcanic ash is hard and abrasive. It does not dissolve in water, and it conducts electricity, especially when it is wet.

Ashfall can become cemented together by heat to form a solid rock called tuff. Ashfall breaks down over time, forming highly fertile soil, which has made many volcanic regions densely cultivated and inhabited despite the inherent dangers.

In 1783, the Laki eruption killed about one-fifth of Iceland's population, and sent a huge toxic cloud of ash and sulphurous gases across Western Europe. In Britain alone, it has been estimated that 23,000 died from the poisoning.

Atmospheric effects

When ash begins to fall during daylight hours, the sky turns hazy and a pale yellow color. The ashfall may become so dense that daylight turns the sky gray to pitch black, with the ash severely restricting visibility and deadening sound. A darkened ash sky lowers temperatures during daylight hours from what would otherwise be expected. Loud thunder, lightning, as well as the strong smell of sulfur accompany an ashfall. If rain accompanies an ashfall, the tiny particles turn into a slurry of slippery mud. Rain and lightning combined with ash can lead to power outages, breakdowns of communication, and disorientation.

Volcanic ash particles have a maximum residence time in the troposphere of a few weeks. The finest tephra particles remain in the stratosphere for only a few months, they have only minor climatic effects, and they can be spread around the world by high-altitude winds. This suspended material contributes to spectacular sunsets. The major climate influence from volcanic eruptions is caused by gaseous sulfur compounds, chiefly sulfur dioxide, which reacts with OH and water in the stratosphere to create sulfate aerosols with a residence time of about 2–3 years.

Hazards

Daytime Montserrat image during ash fall (1997)

The most devastating effect of volcanic ash comes from pyroclastic flows. These occur when a volcanic eruption creates an "avalanche" of hot ash, gases, and rocks that flow at high speed down the flanks of the volcano. These flows can be impossible to outrun. They can also be difficult to predict. In many cases prediction is based on the topography of a region, but a valley may fill and overflow. In 1902, the city of St. Pierre in Martinique was destroyed by a pyroclastic flow which killed over 29,000 people.

Fluorine poisoning and death can occur in livestock that graze on ash-covered grass if fluoride is present in high concentrations. Inhaling volcanic ash may cause problems for people whose respiratory system is already compromised by disorders such as asthma or emphysema. The abrasive texture can cause irritation and scratching of the surface of the eyes. People who wear contact lenses should wear glasses during an ashfall, to prevent eye damage. Furthermore, the combination of volcanic ash with moisture in the lungs can create a substance akin to liquid cement.

Therefore, people should take caution to filter the air they breathe with a damp cloth or a face mask when facing an ashfall. Ash is very dense, as only 100 millimetres (3.9 in) of ash leads to the collapse of weaker roofs. A fall of 300 millimetres (12 in) leads to the death of most vegetation, livestock, the wiping out of aquatic life in nearby lakes and rivers, and unusable roads. Accompanied by rain and lightning, ashfall leads to power outages, prevents communication, and disorients people.

Aviation

According to Dr. Dougal Jerram, an earth scientist at the Centre for Research into Earth Energy Systems, University of Durham, UK, "Eruptions which are charged with gas start to froth and expand as they reach the surface. This results in explosive eruptions and this fine ash being sent up into the atmosphere. If it is ejected high enough, the ash can reach the high winds and be dispersed around the globe, for example, from Iceland to Europe. These high winds are exactly where the aeroplanes cruise." Volcanic ash can harm a plane mainly in four ways:

Sandblasting effect

Ash can "blind" pilots by sandblasting the windscreen requiring an instrument landing, damage the fuselage, and coat the plane (KLM Flight 867 and BA Flight 9). In addition, the sandblasting effect can damage the landing lights, making their beams diffuse and unable to be projected in the forward direction (BA Flight 9). Propellor aircraft are also endangered.

Clogging of the plane's sensors

Accumulation of ash can also block an aircraft's pitot tubes. This can lead to failure of the aircraft's air speed indicators.

Electromagnetic wave insulation

Volcanic ash particles are charged and disturb communication by radio.

Combustion power failure

Volcanic ash damages machinery. The effect on jet aircraft engines is particularly severe as large amounts of air are sucked in during combustion operation, posing a great danger to aircraft flying near ash clouds. Very fine volcanic ash particles (particularly glass-rich if from an eruption under ice) sucked into a jet engine melt at about 1,100 °C, fusing onto the blades and other parts of the turbine (which operates at about 1,400 °C).

The effect on the operation of a jet engine is often to cause it to cut out—failure of all a plane's engines is common:

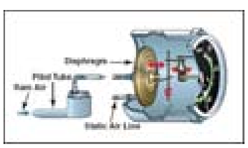
- Volcanic ash particles can erode and destroy parts, drive it out-of-balance, and cause jams in rotating machinery.
- Also simple lack of oxygen is given as a probable cause of engine failure (fooling of the air/fuel control).
- Fooling of the engine temperature sensors (KLM Flight 867).
- And compressor stall and flameout can be other reason.

The standard emergency procedure when jet engines begin to fail had been to increase power, which makes the problem worse. The best procedure is to throttle back the engines, turn on engine and wing anti-ice devices (it helps to avoid compressor and wing stall), and to lose height so as to drop below the ash cloud as quickly as possible. The inrush of cold, clean air is usually enough to cool, solidify, and shatter the glass, unclogging the engines.

Occurrences

There are many instances of damage to jet aircraft as a result of an ash encounter. After the Galunggung, Indonesia volcanic event in 1982, a British Airways Flight 9 flew through an ash cloud; all four engines cut out. The plane descended from 36,000 feet (11,000 m) to 12,000 feet (3,700 m), where the engines could be restarted. On December 15, 1989 a KLM Boeing 747-400 (Flight 867) flying from Amsterdam Schiphol Airport to Anchorage International Airport encountered similar problems near Mount Redoubt (Alaska). The damage was 80 million US$; there was 80 kg ash in each turbine; it took 3 months work to repair the plane.

In April 2010, airspace all over Europe was closed—which was unprecedented—due to the presence of volcanic ash in the upper atmosphere from the eruption of the Icelandic volcano Eyjafjallajökull. On 15 April 2010 the Finnish Air Force halted training flights when damage was found from volcanic dust ingestion by the engines of one of its Boeing F-18 Hornet fighters. On 22 April 2010 UK RAF Typhoon training flights were also temporarily suspended after deposits of volcanic ash were found in a jet's engines.



Volcanic ash mixed with the ram air can block the aircraft's pitot tubes thereby rendering the air speed indicators inoperative.

Large amounts of air enter the engine during normal combustion operation.

Cooling channels in the turbine blades become clogged by ash leading to overheating of the blades and their catastrophic failure.

Aviation risks of flight through downstream ash clouds

A distinction can be made between flight through (or in the immediate vicinity of) an eruption plume, and flight through the so-called affected airspace. Volcanic ash in the immediate vicinity of the eruption plume is of an entirely different particle size range and density to that found in downwind dispersal clouds, which contain only the finest grade of ash. The actual level of ash loading which catastrophically affects normal engine operation has not yet been established, beyond the knowledge that relatively high ash densities must exist for this to happen. Whether this silica-melt risk still remains at the much lower ash densities characteristic of downstream ash clouds is currently unclear.

This is however a serious safety hazard which requires preventive risk-management strategies, in line with other comparable aviation hazards.

Detection and Avoidance

In June 2010, Easyjet airline company has unveiled a system that it says will allow airlines to safely fly around ash clouds. The system is based on 20-year old research by Fred Prata at the Australian research organisation CSIRO and now based at the Norwegian Institute for Air Research.

Marine transportation

Similar to aviation, volcanic ash has detrimental effects on marine transportation machinery. However, it poses much less of a hazard—an aircraft encountering an ash plume has engines sucking in huge amounts of air, and cannot stop them until the plume passes, possibly days later.

Advisories concerning ongoing events

Increasing numbers of airplane incidents from atmospheric ash prompted a 1991 aviation industry meeting to decide how best to distribute information about ash events. One solution was the creation of Volcanic Ash Advisory Centers. There is one VAAC for each of nine regions of the world. VAACs can issue advisories and serve as liaisons between meteorologists, volcanologists, and the aviation industry.

Chapter- 9

Volcanic Gas and Volcanic Field

Volcanic Gas

Volcanic gases are leaving to the atmosphere with dust and tephra during eruption of volcano Augustine, 2006.

Eruption of Mount St. Helens

Image of the rhyolitic lava dome of Chaitén Volcano during its 2008-2010 eruption

Volcanic gases include a variety of substances given off by active (or, at times, by dormant) volcanoes. These include gases trapped in cavities (vesicles) in volcanic rocks, dissolved or dissociated gases in magma and lava, or gases emanating directly from lava or indirectly through ground water heated by volcanic action.

The sources of volcanic gases on Earth include:

- primordial and recycled constituents from the Earth's mantle,
- assimilated constituents from the Earth's crust,
- groundwater and the Earth's atmosphere.

Substances that may become gaseous or give off gases when heated are termed volatile substances.

Magmatic gases and high-temperature volcanic gases

Gases are released from magma through volatile constituents reaching such high concentrations in the base magma that they evaporate. (Technically, this would be described as the exsolution and accumulation of the gases upon reaching excess supersaturation of these constituents in the host solution (magmatic melt), and their subsequent loss from the host by diffusion and phase separation into bubbles). Molten rock (either magma or lava) near the atmosphere releases high-temperature volcanic gas (>400 °C). In explosive volcanic eruptions, sudden release of gases from magma may cause rapid movements of the molten rock. When the magma encounters water, seawater, lake water or groundwater, it can be rapidly fragmented. The rapid expansion of gases is the driving mechanism of most explosive volcanic eruptions. However, a significant portion of volcanic gas release occurs during quasi-continuous quiescent phases of active volcanism.

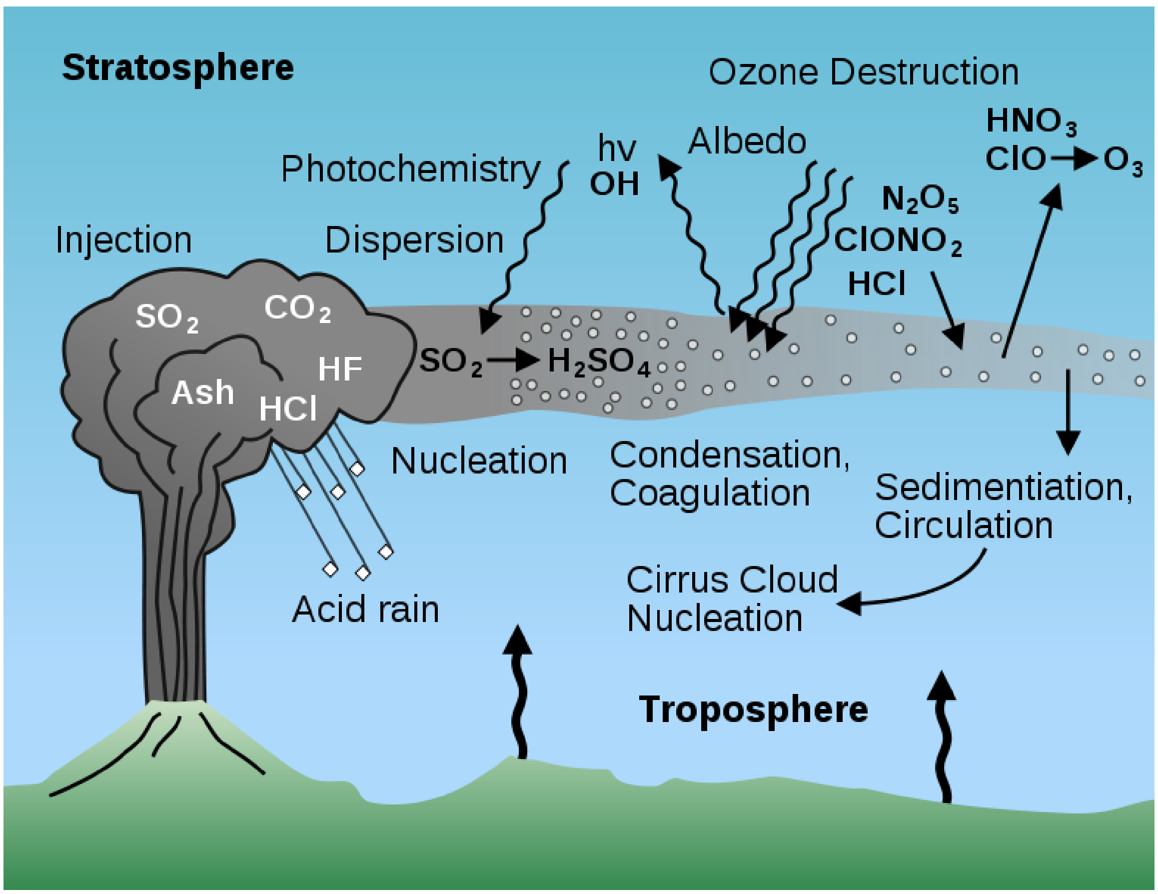
Low-temperature volcanic gases and hydrothermal systems

If the magmatic gas traveling upward encounters meteoric water in an aquifer, steam is produced. Latent magmatic heat can also cause meteoric waters to ascent as a vapour phase. Extended fluid-rock interaction of this hot mixture can leach constituents out of the cooling magmatic rock and also the country rock, causing volume changes and phase transitions, reactions and thus an increase in ionic strength of the upward percolating fluid. This process also decreases the fluid's pH. Cooling can cause phase separation and mineral deposition, accompanied by a shift toward more reducing conditions. At the surface expression of such hydrothermal systems, low-temperature volcanic gases (<400 °C) are either emanating as steam-gas mixtures or in dissolved form in hot springs. At the ocean floor, such hot supersaturated hydrothermal fluids form gigantic chimney structures called black smokers, at the point of emission into the cold seawater.

Non-explosive volcanic gas release

The gas release can occur by advection through fractures, or via diffuse degassing through large areas of permeable ground as Diffuse Degassing Structures (DDS). At sites of advective gas loss, precipitation of sulfur and rare salts forms sulfur deposits and small sulfur chimneys, called fumaroles. Very low-temperature <100 °C) fumarolic structures are also known as solfataras. Sites of cold degassing of predominantly carbon dioxide are called mofettes. Hot springs on volcanoes often show a measurable amount of magmatic gas in dissolved form.

Composition



Schematic draw of volcanic eruption

The principal components of volcanic gases are water vapor (H_2O), carbon dioxide (CO_2), sulfur either as sulfur dioxide (SO_2) (high-temperature volcanic gases) or hydrogen sulfide (H_2S) (low-temperature volcanic gases), nitrogen, argon, helium, neon, methane, carbon monoxide and hydrogen. Other compounds detected in volcanic gases are oxygen (meteoric), hydrogen chloride, hydrogen fluoride, hydrogen bromide, nitrogen oxide (NO_x), sulfur hexafluoride, carbonyl sulfide, and organic compounds.

Exotic trace compounds include methylmercury, halocarbons (including CFCs), and halogen oxide radicals.

The abundance of gases varies considerably from volcano to volcano. However, water vapor is consistently the most common volcanic gas, normally comprising more than 60% of total emissions. Carbon dioxide typically accounts for 10 to 40% of emissions.

Volcanoes located at convergent plate boundaries emit more water vapor and chlorine than volcanoes at hot spots or divergent plate boundaries. This is caused by the addition of seawater into magmas formed at subduction zones. Convergent plate boundary volcanoes also have higher H_2O/H_2, H_2O/CO_2, CO_2/He and N_2/He ratios than hot spot or divergent plate boundary volcanoes.

Sensing, collection and measurement

Volcanic gases were collected and analysed as long ago as 1790 by Scipione Breislak in Italy.

Volcanic gases can be sensed (measured in-situ) or sampled for further analysis. Volcanic gas sensing can be:

- within the gas by means of electrochemical sensors and flow-through infrared-spectroscopic gas cells
- outside the gas by ground-based or airborne remote spectroscopy (e.g., COSPEC, FLYSPEC, DOAS, FTIR)

Volcanic gas sampling is often done by a method involving an evacuated flask with caustic solution, first used by Robert W. Bunsen (1811-1899) and later refined by the German chemist Werner F. Giggenbach (1937-1997), dubbed *Giggenbach-bottle*. Other methods include collection in evacuated empty containers, in flow-through glass tubes, in gas wash bottles (cryogenic scrubbers), on impregnated filter packs and on solid adsorbent tubes.

Analytical techniques for gas samples comprise gas chromatography with thermal conductivity detection (TCD), flame ionization detection (FID) and mass spectrometry (GC-MS) for gases, and various wet chemical techniques for dissolved species (e.g., acidimetric titration for dissolved CO_2, and ion chromatography for sulfate, chloride, fluoride). The trace metal, trace organic and isotopic composition is usually determined by different mass spectrometric methods.

Volcanic gases and volcano monitoring

Certain constituents of volcanic gases may show very early signs of changing conditions at depth, making them a powerful tool to predict imminent unrest. Used in conjunction with monitoring data on seismicity and deformation, correlative monitoring gains great efficiency. Volcanic gas monitoring is a standard tool of any volcano observatory. Unfortunately, the most precise compositional data still require dangerous field sampling campaigns. However, remote sensing techniques have advanced tremendously through the 1990s.

Hazards

Volcanic gases were directly responsible for approximately 3% of all volcano-related deaths of humans between 1900 and 1986. Some volcanic gases kill by acidic corrosion; others kill by asphyxiation. The greenhouse gas, carbon dioxide, is emitted from volcanoes, although volcanic emissions account for less than 1% of the annual global total. Some volcanic gases including sulfur dioxide, hydrogen chloride, hydrogen sulfide and hydrogen fluoride react with other atmospheric particles to form aerosols.

Volcanic Field

The north face of Mount Garibaldi rises above The Table and Garibaldi Lake in the Garibaldi Lake volcanic field

SP Crater in the San Francisco volcanic field is a cinder cone with a basalt lava flow that extends for 4 miles (6 km)

A **volcanic field** is an area of the Earth's crust that is prone to localized volcanic activity. They usually contain 10 to 100 volcanoes, such as cinder cones and are usually in clusters. Lava flows may also occur. They may occur as a monogenetic volcanic field or a polygenetic volcanic field.

Examples

Canada

- Atlin Volcanic Field, British Columbia
- Desolation Lava Field, British Columbia
- Garibaldi Lake volcanic field, British Columbia
- Mount Cayley volcanic field, British Columbia
- Tuya Volcanic Field, British Columbia
- Wells Gray-Clearwater volcanic field, British Columbia
- Wrangell Volcanic Field, Yukon Territory

United States

- Boring Lava Field, Oregon
- Clear Lake Volcanic Field, California
- Coso Volcanic Field, California
- Indian Heaven, Washington

- Marysvale Volcanic Field, Utah
- Raton-Clayton volcanic field, New Mexico
- San Francisco volcanic field, Arizona
- Taos Plateau volcanic field, Taos County, New Mexico
- Wrangell Volcanic Field, Alaska

Chapter- 10

Prediction of Volcanic Activity

Prediction of volcanic eruption (also: *volcanic eruption forecasting*) is an interdisciplinary scientific and engineering approach to natural catastrophic event forecasting. Volcanic activity prediction has not been perfected, but significant progress has been made in recent decades. Significant amounts are spent monitoring and prediction of volcanic activity by the Italian government through the Istituto Nazionale di Geofisica e Vulcanologia INGV, by the United States Geological Survey (USGS), and by the Geological Survey of Japan. These are the largest institutions that invest significant resources monitoring and researching volcanos (as well as other geological phenomena). Many countries operate volcano observatories at a lesser level of funding, all of which are members of the World Organisation of Volcano Observatories (WOVO).

Mount St. Helens erupted explosively on May 18, 1980 at 8:32 a.m. PDT

General Principles

Various methods including the following sections are used to help predict eruptions. In using these methods, five major principles form the basis of eruption forecasting is as follows:

- the *principle of inflection points in trends* states that with unknown rates of change, a point in time is reached at which the volcanic system becomes unstable and likely will erupt;

- the *principle of coinciding change* states that one monitored parameter alone may not yield significant symptoms to diagnose an imminent eruption, but unrelated trends of several monitored parameters may start co-evolving as the system approaches a state of instability;
- the *principle of known behavior* treats a volcano as if it were a medical patient, assuming that responses to changes in the underground may be highly individual to a volcano's particular internal structure and can become better known by understanding its past eruptive characteristics;
- the *principle of unexpected behavior* treats volcanoes, the public, and decision-makers alike as inherently inconsistent systems - leading to unexpected eruptions (e.g., fast magma ascent from unexpected depth), and mitigation failures;
- the *principle of symptom-based short-term forecast* as with all the other principles is similar to an epidemiological diagnosis, whereby forecasts are based on symptoms and *patient history*.

Volcanic eruptions can to date not be predicted by stochastic methods, but only by catching early symptoms before an imminent eruption. Therefore, continuous monitoring even of dormant volcanoes, though costly, is the only way to enable eruptive behavior forecasts. The following sections describe individual groups of methods typically deployed in monitoring volcanoes and the symptomatic evolution of their activity

Methods

The most widely used method is studying the geographical area of the volcano.

Taking seismic readings, measuring poison gasses, and using satellites

Seismicity

General principles of volcano seismology

Seismic activity (earthquakes and tremors) always occurs as volcanoes awaken and prepare to erupt and are a very important link to eruptions. Some volcanoes normally have continuing low-level seismic activity, but an increase may signal a greater likelihood of an eruption. The types of earthquakes that occur and where they start and end are also key signs. Volcanic seismicity has three major forms: **short-period earthquake**, **long-period earthquake**, and **harmonic tremor**.

- Short-period earthquakes are like normal fault-generated earthquakes. They are caused by the fracturing of brittle rock as magma forces its way upward. These short-period earthquakes signify the growth of a magma body near the surface and are known as 'A' waves. These type of seismic events are often also referred to as Volcano-Tectonic (or VT) events or earthquakes.

- Long-period earthquakes are believed to indicate increased gas pressure in a volcano's plumbing system. They are similar to the clanging sometimes heard in a house's plumbing system, which is known as "water hammer". These oscillations are the equivalent of acoustic vibrations in a chamber, in the context of magma chambers within the volcanic dome and are known as 'B' waves. These are also known as resonance waves and long period resonance events.

- Harmonic tremors are often the result of magma pushing against the overlying rock below the surface. They can sometimes be strong enough to be felt as humming or buzzing by people and animals, hence the name.

Patterns of seismicity are complex and often difficult to interpret; however, increasing seismic activity is a good indicator of increasing eruption risk, especially if long-period events become dominant and episodes of harmonic tremor appear.

Using a similar method, researchers can detect volcanic eruptions by monitoring infra-sound—sub-audible sound below 20Hz. The IMS Global Infrasound Network, originally set up to verify compliance with nuclear test ban treaties, has 60 stations around the world that work to detect and locate erupting volcanoes.

Seismic case studies

A relation between long-period events and imminent volcanic eruptions was first observed in the seismic records of the 1985 eruption of Nevado del Ruiz in Colombia. The occurrence of long-period events were then used to predict the 1989 eruption of Mount Redoubt in Alaska and the 1993 eruption of Galeras in Colombia. In December 2000, scientists at the National Center for Prevention of Disasters in Mexico City predicted an eruption within two days at Popocatépetl, on the outskirts of Mexico City. Their prediction used research that had been done by Bernard Chouet, a Swiss volcanologist who was working at the United States Geological Survey and who first observed a relation between long-period events and an imminent eruption. The government evacuated tens of thousands of people; 48 hours later, the volcano erupted as predicted. It was Popocatépetl's largest eruption for a thousand years, yet no one was hurt.

Iceberg tremors

It has recently been published that the striking similarities between iceberg tremors, which occur when they run aground, and volcanic tremors may help experts develop a better method for predicting volcanic eruptions. Although icebergs have much simpler structures than volcanoes, they are physically easier to work with. The similarities between volcanic and iceberg tremors include long durations and amplitudes, as well as common shifts in frequencies. (Source: Canadian Geographic "Singing icebergs")

Gas emissions

Gas and ash plume erupted from Mount Pinatubo, Philippines

As magma nears the surface and its pressure decreases, gases escape. This process is much like what happens when you open a bottle of soda and carbon dioxide escapes. Sulphur dioxide is one of the main components of volcanic gases, and increasing amounts of it herald the arrival of increasing amounts of magma near the surface. For example, on May 13, 1991, an increasing amount of sulphur dioxide was released from Mount Pinatubo in the Philippines. On May 28, just two weeks later, sulphur dioxide emissions had increased to 5,000 tonnes, ten times the earlier amount. Mount Pinatubo later erupted on June 12, 1991. On several occasions, such as before the Mount Pinatubo eruption and the 1993 Galeras, Colombia eruption, sulphur dioxide emissions have dropped to low levels prior to eruptions. Most scientists believe that this drop in gas levels is caused by the sealing of gas passages by hardened magma. Such an event leads to increased pressure in the volcano's plumbing system and an increased chance of an explosive eruption.

Ground deformation

Swelling of the volcano signals that magma has accumulated near the surface. Scientists monitoring an active volcano will often measure the tilt of the slope and track changes in the rate of swelling. An increased rate of swelling, especially if accompanied by an increase in sulfur dioxide emissions and harmonic tremors is a high probability sign of an impending event. The deformation of Mount St. Helens prior to the May 18, 1980 eruption was a classic example of deformation, as the north side of the volcano was bulging upwards as magma was building up underneath. But most cases of ground deformation are usually detectable only by sophisticated equipment used by scientists, but they can still predict future eruptions this way. The Hawaiian Volcanoes show significant ground deformation, there is inflation of the ground prior to an eruption and then an obvious deflation post eruption. This is due to the shallow magma chamber of the Hawaiian Volcanoes, movement of the magma is easily noticed on the ground above.

Thermal monitoring

Both magma movement and changes in gas release and hydrothermal activity can lead to thermal emissivity changes at the volcano's surface. These can be measured using several techniques:

- forward looking infrared radiometry (FLIR) from hand-held devices installed on-site, at a distance, or airborne;
- Infrared band satellite imagery;
- in-situ thermometry (hot springs, fumaroles)
- heat flux maps
- geothermal well enthalpy changes

Hydrology

There are 4 main methods that can be used to predict a volcanic eruption through the use of hydrology:

- Borehole and well hydrologic and hydraulic measurements are increasingly used to monitor changes in a volcanoes subsurface gas pressure and thermal regime. Increased gas pressure will make water levels rise and suddenly drop right before an eruption, and thermal focusing (increased local heat flow) can reduce or dry out acquifers.

- Detection of lahars and other debris flows close to their sources. USGS scientists have developed an inexpensive, durable, portable and easily installed system to detect and continuously monitor the arrival and passage of debris flows and floods in river valleys that drain active volcanoes.

- Pre-eruption sediment may be picked up by a river channel surrounding the volcano that shows that the actual eruption may be imminent. Most sediment is transported from volcanically disturbed watersheds during periods of heavy rainfall. This can be an indication of morphological changes and increased hydrothermal activity in absence of instrumental monitoring techniques.

- Volcanic deposit that may be placed on a river bank can easily be eroded which will dramatically widen or deepen the river channel. Therefore, monitoring of the river channels width and depth can be used to assess the likelihood of a future volcanic eruption.

Remote Sensing

Remote sensing is the detection by a satellite's sensors of electromagnetic energy that is absorbed, reflected, radiated or scattered from the surface of a volcano or from its erupted material in an eruption cloud.

- '*Cloud sensing*: Scientists can monitor the unusually cold eruption clouds from volcanoes using data from two different thermal wavelengths to enhance the visibility of eruption clouds and discriminate them from meteorological clouds
- '*Gas sensing*: Sulphur dioxide can also be measured by remote sensing at some of the same wavelengths as ozone. TOMS (Total Ozone Mapping Spectrometer) can measure the amount of sulphur dioxide gas released by volcanoes in eruptions
- *Thermal sensing*: The presence of new significant thermal signatures or 'hot spots' may indicate new heating of the ground before an eruption, represent an eruption in progress or the presence of a very recent volcanic deposit, including lava flows or pyroclastic flows.
- *Deformation sensing*: Satellite-borne spatial radar data can be used to detect long-term geometric changes in the volcanic edifice, such as uplift and depression. In this method, called InSAR (Interferometric Synthetic Aperture Radar), DEMs generated from radar imagery are subtracted from each other to yield a differential image, displaying rates of topographic change.
- *Forest Monitoring*: In recent period it has been demonstrated the location of eruptive fractures could be predicted, months to years before the eruptions, by the monitoring of forest growth. This tool based on the monitoring of the trees growth has been validated at both Mt. Niyragongo and Mt. Etna during the 2002-2003 volcano eruptive events.

Mass movements and mass failures

Monitoring mass movements and -failures uses techniques lending from seismology (geophones), deformation, and meteorology. Landslides, rock falls, pyroclastic flows, and mud flows (lahars) are example of mass failures of volcanic material before, during, and after eruptions.

The most famous volcanic *landslide* was probably the failure of a bulge that built up from intruding magma before the Mt. St. Helens eruption in 1980, this landslide "uncorked" the shallow magmatic intrusion causing catastrophic failure and an unexpected lateral eruption blast. *Rock falls* often occur during periods of increased deformation and can be a sign of increased activity in absence of instrumental monitoring. *Mud flows* (*lahars*) are remobilized hydrated ash deposits from pyroclastic flows and ash fall deposits, moving downslope even at very shallow angles at high speed. Because of their high density they are capable of moving large objects such as loaded logging trucks, houses, bridges, and boulders. Their deposits usually form a second ring of debris fans around volcanic edifices, the inner fan being primary ash deposits. Downstream of the deposition of their finest load, lahars can still pose a sheet flood hazard from the residual water. Lahar deposits can take many months to dry out, until they can be walked on. The hazards derived from lahar activity can several years after a large explosive eruption.

A team of US scientists developed a method of predicting lahars. Their method was developed by analyzing rocks on Mt. Rainier in Washington. The warning system depends on noting the differences between fresh rocks and older ones. Fresh rocks are poor conductors of electricity and become hydrothermically altered by water and heat. Therefore, if they know the age of the rocks, and therefore the strength of them, they can predict the pathways of a lahar. A system of Acoustic Flow Monitors (AFM) has also been emplaced on Mount Rainier to analyze ground tremors that could result in a *lahar*, providing an earlier warning.

Local case studies

Nyiragongo

The eruption of Mt. Nyiragongo on January 17, 2002 was predicted a week earlier by a local expert who had been watching the volcanoes for years. He informed the local authorities and a UN survey team was dispatched to the area; however, it was declared safe. Unfortunately, when the volcano erupted, 40% of the city of Goma was destroyed along with many people's livelihoods. The expert claimed that he had noticed small changes in the local relief and had monitored the eruption of a much smaller volcano two years earlier. Since he knew that these two volcanoes were connected by a small fissure, he knew that Mt. Nyiragongo would erupt soon.

Mt. Etna

British geologists have developed a method of predicting future eruptions of Mt. Etna. They have discovered that there is a time lag of 25 years between events that happen below the surface and events that happen on the surface, i.e. a volcanic eruption. The careful monitoring of deep crust events can help predict accurately what will happen in the years to come. So far they have predicted that between 2007 and 2015, volcanic activity will be half of what it was in 1972.

Sakurajima, Japan

Sakurajima is possibly one of the most monitored areas on earth. The Sakurajima Volcano lies near Kagoshima City, which has a population of 500,000 people. Both the Japanese Meteorological Agency (JMA) and Kyoto University's Sakurajima Volcanological Observatory (SVO) monitors the volcano's activity. Since 1995, Sakurajima has only erupted from its summit with no release of lava.

Monitoring techniques at Sakurajima:

- Likely activity is signalled by swelling of the land around the volcano as magma below begins to build up. At Sakurajima, this is marked by a rise in the seabed in Kagoshima Bay – tide levels rise as a result.

- As magma begins to flow, melting and splitting base rock can be detected as volcanic earthquakes. At Sakurajima, they occur two to five kilometres beneath the surface. An underground observation tunnel is used to detect volcanic earthquakes more reliably.

- Groundwater levels begin to change, the temperature of hot springs may rise and the chemical composition and amount of gases released may alter. Temperature sensors are placed in bore holes which are used to detect ground water temp. Remotes sensing is used on Sakurajima since the gases are highly toxic – the ratio of HCl gas to SO_2 gas increases significantly shortly before an eruption.

- As an eruption approaches, tiltmetre systems measure minute movements of the mountain. Data is relayed in real-time to monitoring systems at SVO.

- Seismometers detect earthquakes which occur immediately beneath the crater, signaling the onset of the eruption. They occur 1 to 1.5 seconds before the explosion.

- With the passing of an explosion, the tiltmeter system records the settling of the volcano.