PDHonline Course G346 (4 PDH)

Volcanoes: Origin, Types and Eruptions

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2020

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Course Content

Historical Background

The word volcano is derived from the name "*Vulcano*", a small volcanic island located in the Mediterranean: Tyrrhenian Sea, about 25 km north of Sicily. It is the southernmost of the eight Aeolian Islands, has an area of 21 square kilometers, rises to about 500 meters above sea level, and contains several active volcanic centers. The island itself was named after Vulcan, the Roman god of fire. People living at that time believed that Vulcano was the chimney of the forge of Vulcan, the blacksmith of the Roman gods. They thought that the hot lava, rock fragments and clouds of dust erupting from Vulcano came from Vulcan's forge as he beat out thunderbolts for Jupiter, king of the gods, and fabricated weapons for Mars, the god of war. Figure 1, below, is a location map of Vulcano in the Tyrrhenian Sea, within the Mediterranean.

Figure 1: Location Map for the Island Vulcano in the Tyrrhenian Sea, within the Mediterranean.

Also, many ancient accounts ascribe volcanic eruptions to the actions of gods or devils. To the ancient Greeks, the apparently capricious powers of volcanoes could only be attributed to the acts of angry gods determined to punish the sinners and warn the unrepentant. During the middle Ages, the German astronomer Johannes Kepler (1571-1630) believed that volcanoes were ducts for the Earth's tears. Another contrasting early idea was proposed by the Jesuit Athanasius Kircher (1602–1680), who witnessed eruptions of Mount Etna, Stromboli and Vesuvius. He proposed and published his view of an Earth with a central interconnected fire stoked by the burning of sulfur, bitumen and coal.

All the way up to the first part of the twentieth century various propositions continued to be advanced to explain why a volcano would erupt unpredictably. Even following the awareness that compression and radioactive materials may be the sources of heat and elevated temperatures deep within the earth, their contributions were specifically discounted in the explanation of volcanic eruptions. The favored explanation at that time was that strong chemical reactions and a small amount of molten rocks contributed to the spewing of fluid materials onto the surface of the earth.

The following section describes our present understanding of the internal structure of the earth based on information that has been developed since the second half of the twentieth century.

Internal Structure of the Earth

The cores of mountain ranges expose rocks that have in the past been buried at depths of several miles. A few underground mines extend over a mile in depth, and a few oil wells have been drilled to depths that are greater than five miles. These distances are miniscule when compared to the radius of the earth. Our present day knowledge about the deep interior of the earth is mostly derived from indirect derivations and deductions based on:

- Gravity measurements on its surface,
- The earth's rotation and motions from which its moments of inertia can be deduced,
- The period of its free oscillation,
- From the propagation of seismic (earthquake) waves through it, and
- From volcanic eruptions that bring melted rocks and gases from the lower crust and upper mantle up to its surface.

Today we know that the earth has a dense core with a radius of about 3,400 km, a lighter mantle that is about 2,900 km thick, and a still lighter crust that is mostly rigid and up to 60 km in thickness. Figure 2, below, is a cross section of the earth that is consistent with modern data and our present state of knowledge.

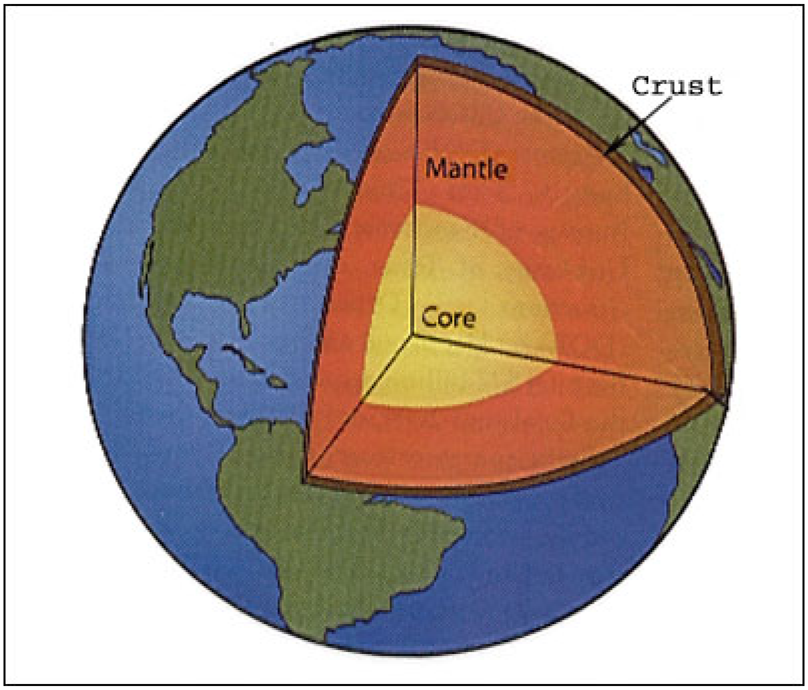

Figure 2: The Earth is composed of concentric spherical shells: crust, mantle and core (not to scale).

The Crust

Overlying the mantle, and separated from it by a sharp discontinuity (the Mohorovicic, known also as Moho, discontinuity), is the lighter solid crust that consist mostly of relatively low density silicates (density less than 3.0 g/cm^3). The crust is the rock base on which we live and from which we derive all our resources, plants, minerals, metals and fuels. The continental crust ranges in thickness from about 35 km to as much as 60 km under mountain ranges and has a density of 2.7 g/cm^3. On the other hand, the oceanic crust, which underlies the oceanic basins, is only about 5-10 km thick and has a density of 3.0 g/cm^3.

The Mantle

The mantle is a major and distinct region that extends into the interior of the earth from the base of the crust to a depth of about 1,800 miles. Our knowledge of the mantle was developed in part on evidence provided by the behavior of P (compression) and S (shear) seismic waves recorded between 700 and 7,000 miles from the origin of earthquakes. At the Moho, the boundary between the crust and mantle, the velocity of the P and S waves increase sharply. For P waves from about 4.5 miles per second to about 5.5 miles per second, and for S waves from about 2.7 to 3.0 miles per second. This sharp increase is an indication that the composition of the material at this boundary changes suddenly. Although we have no direct evidence of the exact composition of the mantle, the change suggests an appreciable increase in overall density.

We know that the mantle is mostly solid because it transmits S waves, which do not propagate in liquids or fluids. Furthermore, the speed of S waves increases with depth within the mantle. These observations were used to conclude that the rigidity of the mantle increases with depth. The mantle is composed of dense mafic minerals (with an upper mantle density of about 3.3 g/cm^3 and a lower mantle density of about 5.8 g/cm^3).

The Core

The core is a distinct region that extends from the base of the mantle, 1,800 miles beneath the crust, to about 4,000 miles, which is at the center of the earth. The analysis of seismographic records from earthquakes at distances greater than 7,000 miles reveal that the core has two parts:

- Outer region about 1,400 miles thick, and
- Inner region with a radius of about 800 miles.

Observations indicate that both P and S waves penetrate through 1,800 miles into the earth. However, below that depth they enter a material that delay the P waves and eliminate the S waves altogether. Since S waves can travel through solids only, the outer region of the core must not be a solid. It is believed to be a liquefied high-density fluid. Additional support of this conclusion is provided by the P waves which travel at a retarded speed through the outer core region. Then, at a depth of about 3,200 miles, they suddenly speed up again. This increase in velocity is indicative that the inner core is solid. By analogy with meteorites the core is thought to be very dense and composed of an iron-nickel alloy.

Of all the natural elements that make up the earth, only iron and nickel are heavy enough to account for the density of the core at the prevailing high temperatures and pressures at the center of the earth. Density jumps abruptly from 5.5 grams per cubic centimeter at the bottom of the lower mantle to 9.5 grams per cubic centimeter in the outer core and 13.5 grams per cubic centimeter in the inner core. For this reason it is believed that the core is composed predominantly of an iron-nickel alloy, which is molten in the outer core and solid in the inner core.

Now that we have defined the internal structure of the earth, the next sections will address our present understanding of the processes that are taking place within it and how these will lead to the development and the eruption of volcanoes.

Heat Sources within the Earth

Everywhere, in boreholes and in mines, the temperature of the ground is found to increase downward. On land, the rate of increase with depth is about one degree centigrade per 100 feet. Temperatures increase even somewhat faster in deep-sea sediments. Therefore, heat must be flowing upward from the interior of the earth. Some of the possible sources of that heat are listed below:

- The current consensus is that the earth formed by the accretion of small, cold particles. This process would release a very large amount of gravitational energy. Most of that heat must have been radiated away during the early stages of the earth's evolution. Still, some of it may have been retained within the interior of the earth.

- The difference in gravitational energy of a uniform earth and a layered earth, with a heavy core and lighter mantle (see Figure 2), is quite large. Release of this energy may have occurred at the time of the formation of the earth, or shortly thereafter. Alternatively, the core may have grown gradually by the slow sinking of the denser components towards the center of the earth and some of that heat may have been retained.

- Radioactive nuclides decay by emitting particles or electrons at very high speed. These sub-atomic particles are stopped by collision with surrounding atoms, and their kinetic energy is transformed into heat. Given the amount of radioactive elements in a rock, it is possible to calculate the rate of heat generation in it. For instance, a crust of granitic composition about 30 km thick would generate more than the normal (measured) heat flow. Radiogenic heat evidently is an important source of internal heat in the earth.

- The gravitational potential of the moon at any point in the earth varies with time as the position of the moon relative to that point changes because of the rotation of the earth and the orbital motion of the moon. The effect of the sun is about one half that of the moon. Thus, equipotential surfaces, such as the surface of the oceans, are periodically deformed, leading to the familiar rise and fall of the tide. The body of the earth also deforms, and points on its surface move away from or toward its center. Although this deformation is essentially elastic, imperfections of elasticity (internal friction) and viscosity leads to the dissipation of the earth's kinetic energy of rotation as heat which amounts to about 10 percent of the observed heat flow

Heat Transfer and Convection

The heat transfer through the earth is not instantaneous. Heat generated now at great depth may not reach the surface until a much later time. The earth is quite large, and its thermal diffusivity quite small. In other words, rocks are good insulators and conduction alone could not cause appreciable cooling of its deeper parts. The slowness with which heat is transferred through rocks is of great interest and has geological consequences, because it influences the rate at which geological processes, such as igneous activity and mountain building, can occur. In other words, geologic events, insofar as they reflect thermal disturbances in the crust and underlying mantle, must have characteristic time scales. Geologic investigations into this issue suggest that this characteristic time is on the order of several hundred million years.

A way by which the rate of heat transfer in the mantle may be increased significantly is by convection. When a fluid in a tank is heated from below the bottom layer will be heated first and, becoming lighter, will rise by buoyancy, while the cold and denser fluid at the top sinks. As a result, a pattern of rising and sinking currents will be established as shown on Figure 3, below.

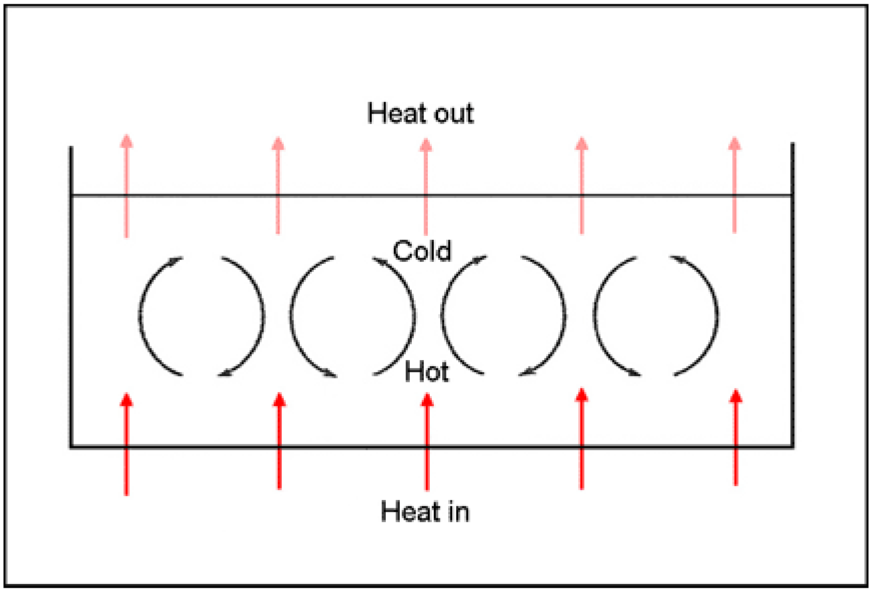

Figure 3: Convection of a fluid in response to a vertical temperature gradient

In a spherical earth, the pattern of motion within the upper mantle consists of localized upward currents of hot material and localized descending currents of colder material. Currents diverge at the top of the rising columns, and converge at the bottom of the sinking ones as shown on Figure 4, below.

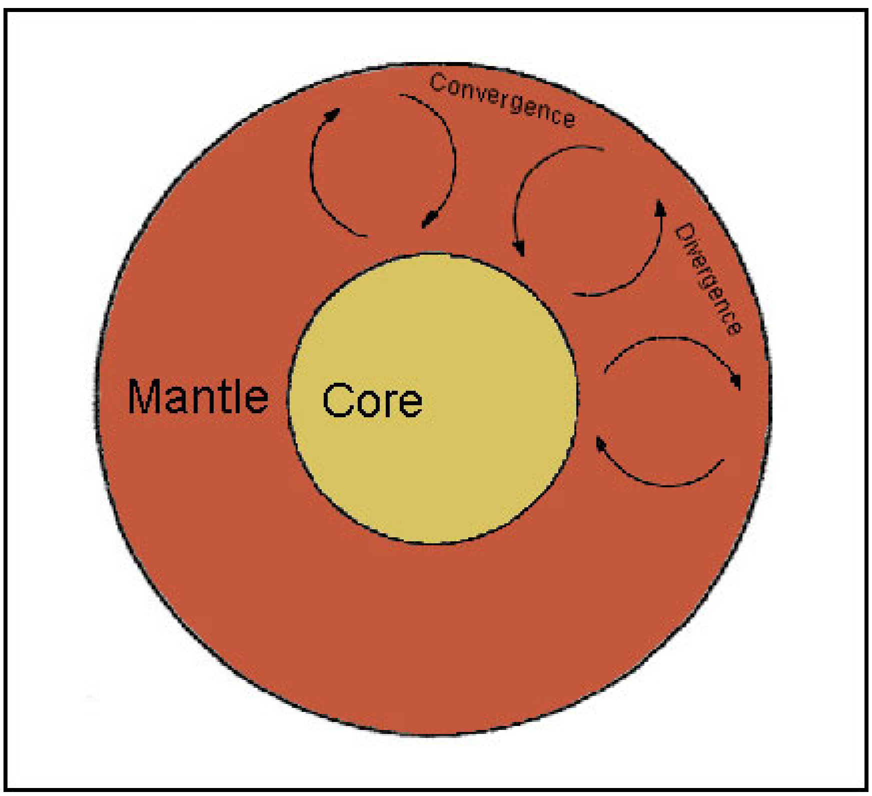

Figure 4: Convection in a layered spherical shell showing convergence and divergence patterns.

It is evident, however, that the mantle does not behave like an ideal fluid with Newtonian viscosity. The pattern of convection in the mantle is most likely dependent on its rheological properties, such as its plasticity under the prevailing state of stress or strain rate. The convection pattern in the mantle is also bound to reflect conditions at the surface as they affect the rate at which the heat from the mantle is discharged. Heat is removed at the top by the relatively slow process of conduction through the crust. Mantle motion will therefore presumably be quite different under continents (slower, thicker crust, more insulation) and oceans (faster, thinner crust, less insulation). Also, heat may be removed by the transfer of molten magma to the surface, such as by volcanic activity.

In experiments on thin layers of fluid heated from below, the distance between rising and sinking columns is proportional with the thickness of the convective shell. On the other hand, when the heat sources are within the fluid itself, as would be the case for radiogenic heat sources within the mantle, the pattern becomes elongated and stretched in the horizontal direction. As a result, significant horizontal motion occurs, as explained below.

Geological Effects of Convection

Convective motion in the upper mantle would affect the crust in the following ways:

1. The heat flow through the crust should be higher above an area of rising motion in the mantle than above an area of downward motion.

2. For the same reason, the crust would be uplifted over an area of the mantle that is particularly hot. Conversely, a down warp would develop over areas where the mantle cools and contracts, as over an area of descending currents.

3. In areas where the top of the mantle is moving horizontally, the crust would be dragged along with it. As a result, either tension or compression stresses would develop the former over diverging currents and the latter over regions of converging currents as shown on Figure 5, below.

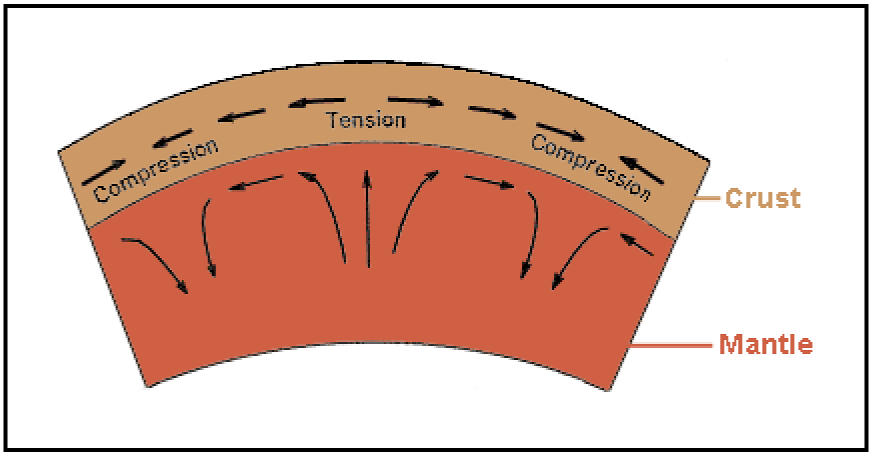

Figure 5: Stresses in rigid crust overlying convection cells in the upper mantle (not to scale)

4. In sections of the upper mantle where convection sets in, magma (molten rock material) is generated. This molten material will then have the tendency to move up by buoyancy to form upon cooling either intrusive igneous rocks such as granite (by slow cooling when injected deep within the crust) or extrusive volcanic rocks such as lava and eruptive byproducts (by fast cooling when ejected all the way to the earth's surface).

Patterns of Crustal Motion

Another way by which significant amounts of molten rock and magma could be formed is by the downward motion of relatively low-melting point material (such as oceanic crust) into the deeper and hotter regions of the upper mantle. This process takes place within the subduction zones that occur along the boundaries of the earth's tectonic plates. Figure 6, below, shows the outline of the major tectonic plates of the earth.

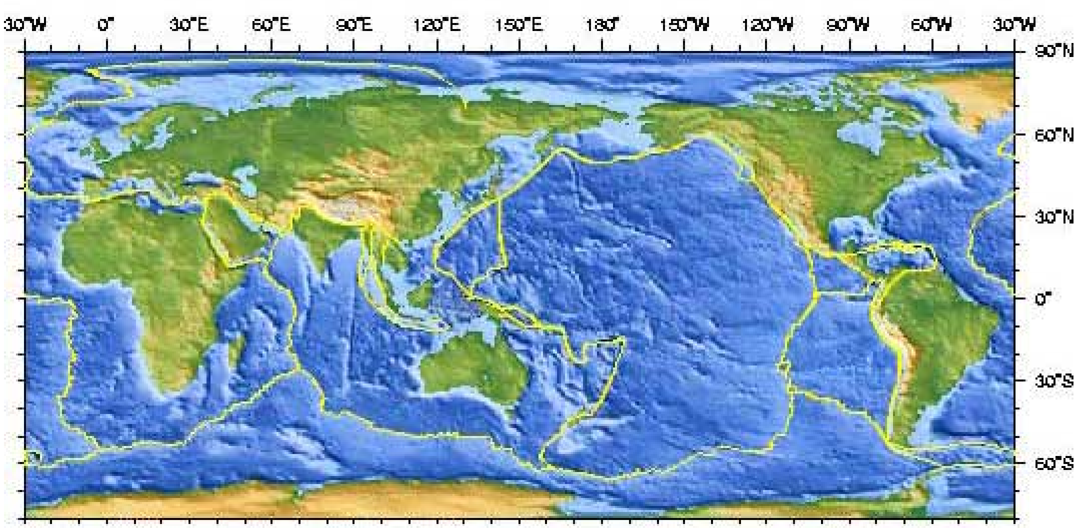

Figure 6: Map showing the boundaries of the earth's major tectonic plates highlighted in yellow.

The process that takes place along the subduction zones, whereas the oceanic crust is driven down into the upper mantle beneath the edge of a continent or an island arc, is diagrammatically illustrated in Figure 7, below.

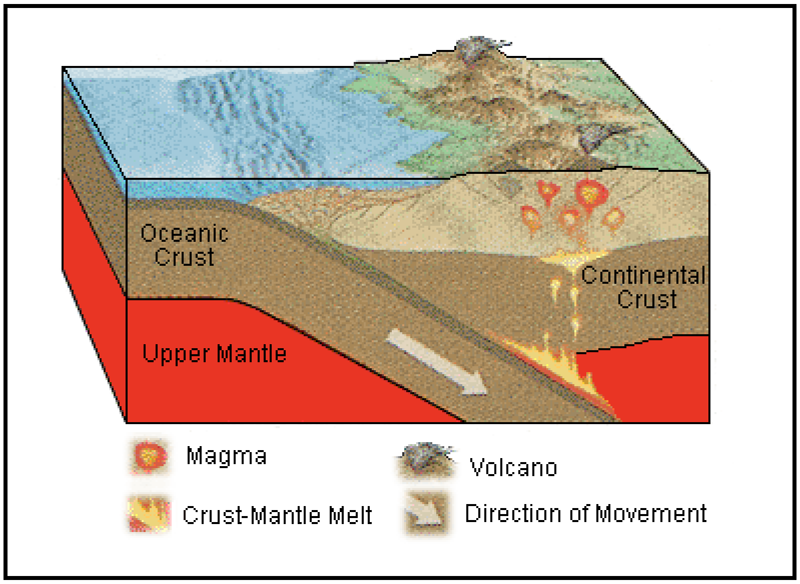

Figure 7: Diagram of the subduction process whereas an oceanic plate (oceanic crust) is pushed under the leading edge of a continental plate (continental crust). As a consequence, a line of volcanoes tend to develop along the edge of the continental plate (Source: modified from a diagram published in 2008 in Special Paper 440, The Geological Society of America).

Notice that upon reaching the upper mantle the leading edge of the oceanic plate begins to melt. The resulting fluid mixture of upper mantle and oceanic crust melt rises into the lower continental crust and begins to fill the magma chambers within the continental crust that will eventually stoke the violent types of volcanic eruptions that are observed at the surface of the earth. All magma that reaches the surface contains dissolved gas. If the magma is thick and pasty, the gas escapes with spectacularly explosive violence throwing out great masses of solid rock as well as lava, ash and dust onto the surface of the earth and into the air. On the other hand, if the magma is a thin fluid, the gas escapes easily and the resulting eruption is subdued and relatively quiet.

The violent types of volcanic eruptions are caused by the heterogeneous nature of their magmatic melts (composed of a mixture of crustal and upper mantle material), their relatively lower temperature and higher viscosity (less fluid). By contrast, the subdued and relatively quiet volcanic eruptions, in which the magma flows out as a uniform outpour onto the surface of the earth, are caused by the homogeneous nature of their magmatic melts (composed predominantly of upper mantle material), their relatively higher temperature and lower viscosity (more fluid). Examples of these two contrasting types of eruptions are described in later parts of this course.

Where Are Most of the Active Volcanoes Located?

It is particularly interesting to note at this point that the majority of all known active volcanoes (and earthquakes for that matter) are actually located along well defined bands that circle the earth parallel to the boundaries of the major tectonic plates that are shown on Figure 6, above. Figure 8, below, highlights the locations where the majority of active volcanoes and earthquakes occur (thick red bands).

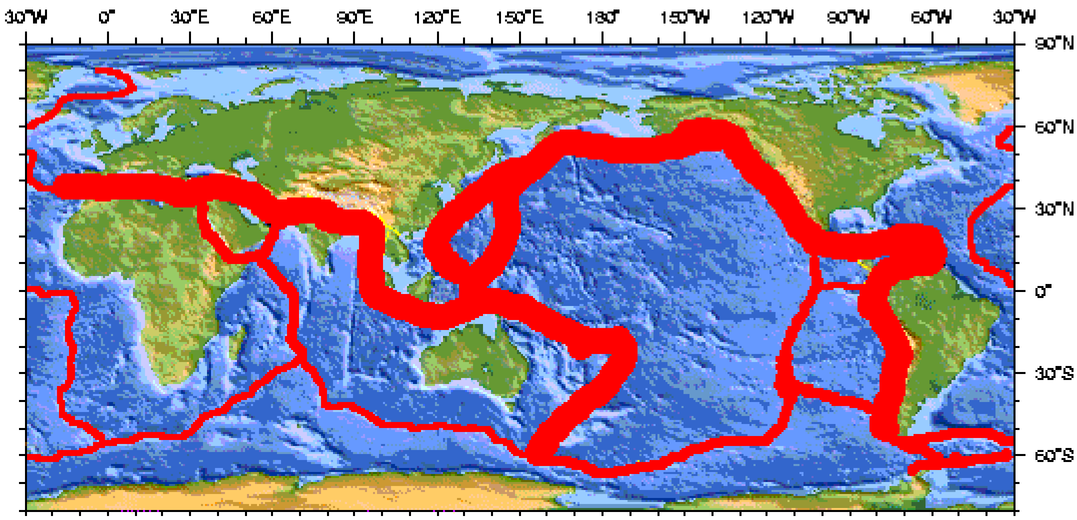

Figure 8: Volcanoes and Earthquakes occur most frequently within the red belts, known as the ring of fire, that circle the earth.

The thick red bands form a continuous belt that rings the Pacific Ocean from New Zealand to the southernmost tip of South America (Tierra del Fuego). It is known as the circum-Pacific belt, also known as the ring of fire. Another stem, known as the Mediterranean belt, branches out from the circum-Pacific belt around Indonesia and the Andaman Islands and extends essentially east-west thereafter through the Himalayas and onto the western Mediterranean. The thin red bands within the oceans coincide with the mid-ocean ridges and highlight the locations where relatively weaker volcanic (and seismic) activity occurs.

Types of Volcanoes

Although volcanoes are sometimes called mountains, they are very different in morphology from the massive ranges that are formed by folding, crumpling, uplift and erosion as regular mountains generally are. Volcanoes are built to their ultimate size and height by the accumulation of their own eruptive products, such as lava, rock fragments, ash and dust. Volcanoes are most commonly conical in form and built around a vent (or vents) located within zones of weakness in the crust. These vents act as conduits connecting the surface to reservoirs of molten rock (magma chambers) deep within the earth. Forced upward in part by contained gas pressure, the molten rock (magma) forces its way to the surface and either pours out from the vent as lava flows or shoots up into the air as dense clouds of gas, ash, lava and rock fragments.

Based mostly on their morphology, geologists recognize four main types of volcanoes which are:

- Cinder Cones
- Composite Cones
- Shield Volcanoes, and
- Lava Domes

These four types are briefly described below.

Cinder Cones

Cinder cones are the simplest types of volcanic structures that form when gases escaping rapidly from the molten magma form ash and cinders that are ejected high into the air and fall back around the volcanic vent and build a cone-shaped edifice. This process was observed from beginning to end in 1943 on a farm near the village of Paricutin, in west-central Mexico. On February 20, 1943, a Mexican farmer was plowing his field when he noticed a cloud of steam starting to rise from the ground. Within a day frequent small explosions were taking place in that same part of the field. Clouds of smoke and dust were boiling up from a hole in the ground. By the end of that week a volcano about 425 feet high had been built of pyroclastics, ash and cinders. A flow of basalt lava began also to flow from a fissure located near the cone. By the end of the year the cone had risen to a height of 1,000 feet. Activity continued intermittently until 1952 when the last explosive eruption left a funnel-shaped depression, called a crater, at the top of the cone. By then volcano Paricutin became inactive and joined a family of many other inactive volcanoes in west-central Mexico. It had reached a total elevation of about 1,200 feet above the ground surface and the lava flows covered a surface of 10 square miles and had a volume of 0.3 cubic mile. Eruption, formation of a cone, lava flow and crater is the normal sequence of events in the formation of cinder cones. There are numerous cinder cones of the Paricutin type in western North America.

Figure 9: 1997 Photo of Paricutin Cinder Cone with lava in the foreground (Source: Smithsonian Institution photo).

Composite Cones

The composite cones are some of the most grandiose types of volcanoes and the most common types located along the ring of fire (see Figure 8). They are built of alternating layers of lava flows, ash and cinders and because of this clearly defined stratification they are sometimes called stratovolcanoes. Figure 10, below is a diagrammatic cross-section through a composite cone showing the nature of its internal stratification.

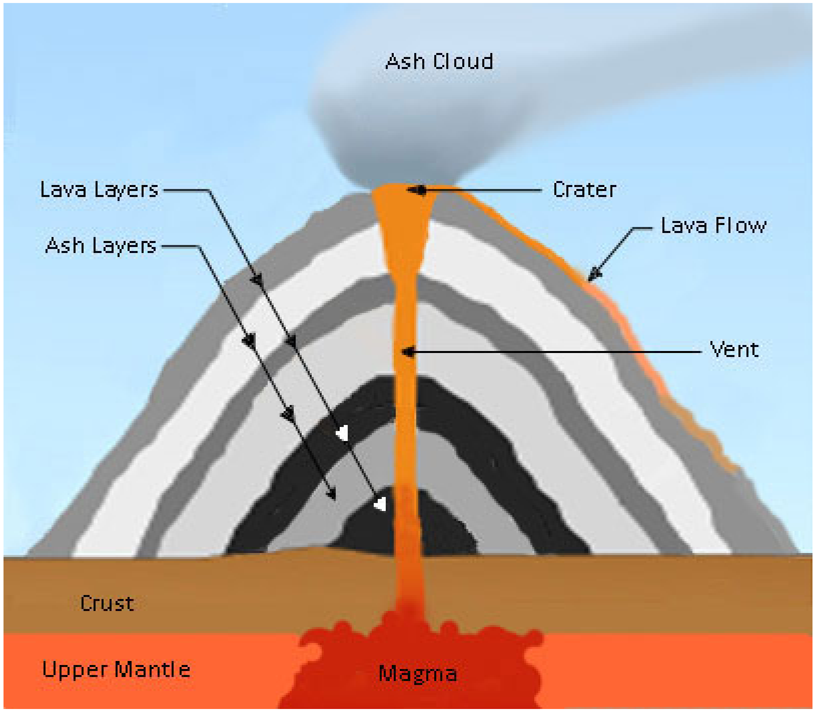

Figure 10: Diagrammatic cross-section (not to scale) through a composite cone (Source: modified from a sketch published on Wikipedia)

Famous examples of these imposing and beautiful structures are: Mt. Fuji in Japan, the Cascade Ranges in Washington, Oregon and northern California. Well known examples within the Cascade Ranges are: Mt. Rainier and Mt. St. Helens in Washington, Mt. Hood and Crater Lake in Oregon, and Mt. Shasta and Lassen Peak in northern California. Composite cones rise generally between 8,000 to 10,000 feet above their bases. Most of the volcanoes around the Circum Pacific belt, the ring of fire, are composite cones.

Some composite cones experience such terrific explosions that they literally blow their top off. Enormous volumes of volcanic ash and dust are expelled and swept down the slopes as avalanches. These phenomenal explosions tend to rapidly drain the lava beneath the volcano and weaken its upper parts which in turn collapse forming a large depression known as a caldera. Sometimes these calderas fill-up with water and form lakes. A beautiful example of the end product of this sequence of events can be seen at Crater Lake in southern Oregon. The parent composite cone at this location, Mt. Mazama, exploded its top about 7,700 years ago forming a caldera that filled with water. During a last gasp of eruption, a small cinder cone was produced which now rises from the lake as Wizard Island. Figures 10, 11 and 12 below are photographs of Mt. Hood (a composite volcano), Crater Lake and the Wizard Island cinder cone within Crater Lake.

Figure 11: Panoramic view of Mt. Hood, a Composite Cone, as seen traveling east from Portland

Figure 12: Panoramic view of Crater Lake, a water filled caldera, Southern Oregon

Figure 13: View of Wizard Island cinder cone rising from Crater Lake, Southern Oregon

Figure 13 is the left hand side extension of figure 12 and completes the picture of the entire perimeter of the lake which is five miles wide and ringed by cliffs almost 2,000 feet high. The lake has a maximum depth of 1,943 feet and is the deepest lake in the U.S. and one of the deepest in the world.

Shield Volcanoes

Shield volcanoes are built almost entirely of lava flows. Repeated flows pour out in all directions from a central vent, or a group of vents, building broad gently sloping cones. Some of the largest volcanoes in the world are shield volcanoes. The Hawaiian Islands, which are composed of clusters of these volcanoes, are the most famous example of this type and can be seen erupting almost continually. The floor of the ocean is more than 15,000 feet deep at the base of the islands. Mauna Loa, on the big island of Hawaii, is the highest of the shield volcanoes in this chain and is about 13,700 feet above sea level. Therefore, the distance from the sea floor to the top of Mauna Loa is over 28,000 feet. Mauna Loa is the largest volcano in the world. Kilauea, also on the big island of Hawaii, is one of the most active. During an eruption in 1959-1960, great fountains of lava, some as high as 1,900 feet, were observed near the volcano summit. The eruptions of Kilauea are of special interest because they are frequent and relatively mild and the material is thought to be coming from great depth which provides clues to the geochemical constitution of the upper mantle. Figure 14, below, is a map of the Hawaiian Islands showing the location of the principal volcanoes in the chain.

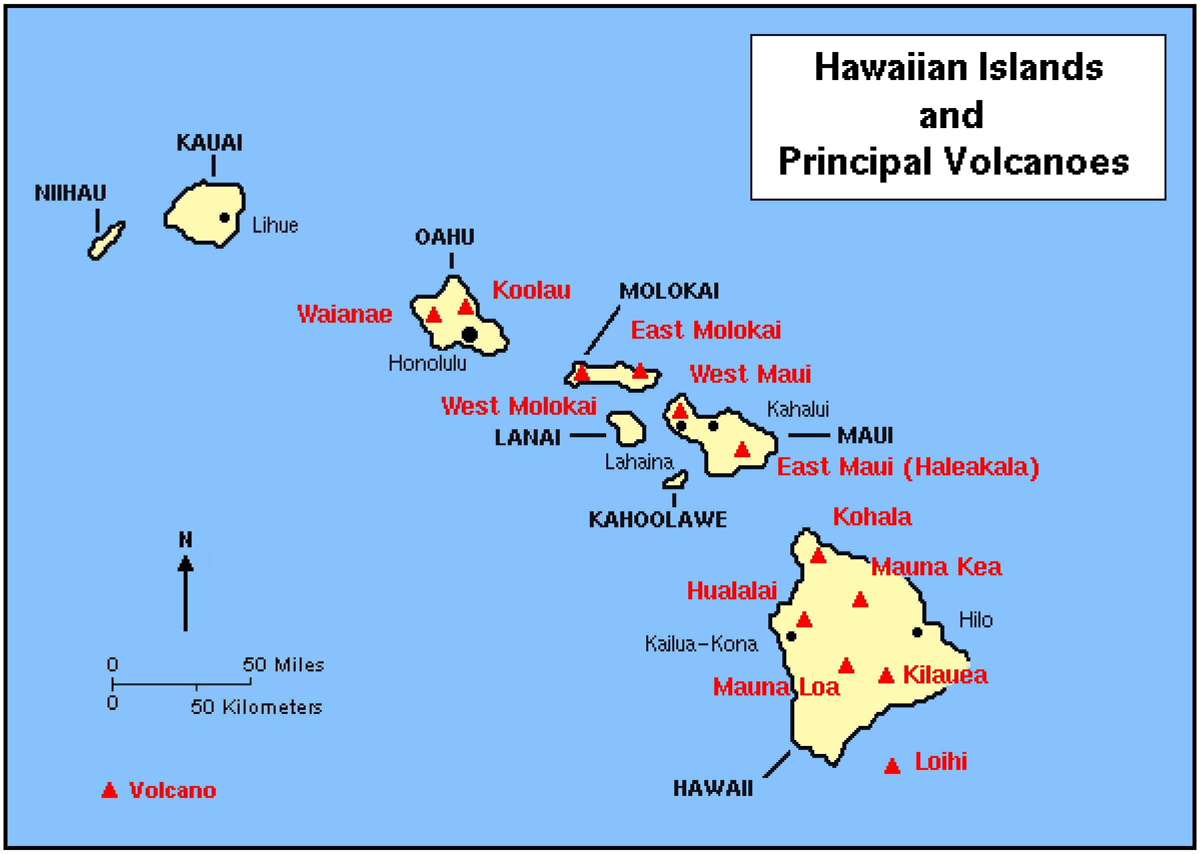

Figure 14: Map of the Hawaiian Islands and Principal Volcanoes in the chain (Source: U S Geological Survey map)

The U.S. Geological Survey maintains the Hawaiian Volcano Observatory on the summit of Kilauea in Hawaii Volcanoes National Park. At the Observatory a team of scientists studies every aspect of volcanic activity. Seismographs record constantly all tremors and earthquakes within and below the volcano, tilt meters measure the expansion and contraction of the volcano (an indicator of the magma movement beneath the volcano), and pyrometers and thermocouples are used to measure the temperatures of erupting lava fountains and flows. Laboratory studies are also conducted to determine the chemical composition of the lavas and the gases that emanate and the minerals that crystallize from the lavas.

The geologic evolution of the Hawaiian volcanoes is particularly interesting to study because their ages are known to decrease systematically from north to south. In fact Volcano Loihi, the youngest in the chain, has not yet risen above ocean level. In addition, as mentioned earlier, their extruding melts have a uniform composition, are relatively fluid and have high extrusion temperatures which together with a relatively uniform chemical and mineral composition point to an upper mantle provenance. Geologists believe that the volcanoes formed over a relatively stationary upper mantle plume of the type shown at the center of Figure 5, above a diverging zone. The plume was able to punch its way through this portion of the Pacific oceanic crust and reach the surface through the vents of the volcanic chain. The ages of the volcanoes decrease from north to south because this portion of the Pacific plate is itself moving northward on its way to the Aleutian subduction zone. It is also interesting to note at this point that the volcanoes of the Aleutian Island Arc are of the Composite type (stratovolcanoes) which are located within the circumpacific belt, also known as the ring of fire.

Repeatedly throughout geologic time very fluid basaltic lava has erupted from swarms of fissures to form vast lava plateaus. The Columbia River Plateau of Washington and Oregon and the Snake River Plains of Idaho are among the best known examples of this type of geologic volcanism. The area of the Columbia River Plateau is about 100,000 square miles and contains approximately 35,000 cubic miles of basaltic lava. Individual lava flows can be traced for distances greater than 100 miles. These lavas must have been extremely fluid to have covered such large areas uniformly.

Of smaller overall dimension are the basaltic lavas of the Craters of the Moon National Monument, at the northern edge of the Snake River Plains, Idaho. The vents from which the lavas poured out are grouped along a northwest trending rift zone, an alignment of fractures in the earth's crust that has repeatedly opened up and spewed molten lava of varying viscosity. Two types of lavas are well represented in these fields:

- Pahoehoe: solidified from very fluid lava. The surface of these flows is characterized by a smooth to ropy texture which can be shown to have traveled long distances, and

- Aa: solidified from more viscous lava that forms steep sided flows composed of craggy blocks on the outside. These masses may have contained a more fluid interior.

These two words "Pahoehoe" and "Aa" are Hawaiian terms adopted the world over to describe two basic types of basaltic lavas that are shown and explained on Figures 15 and 16, below.

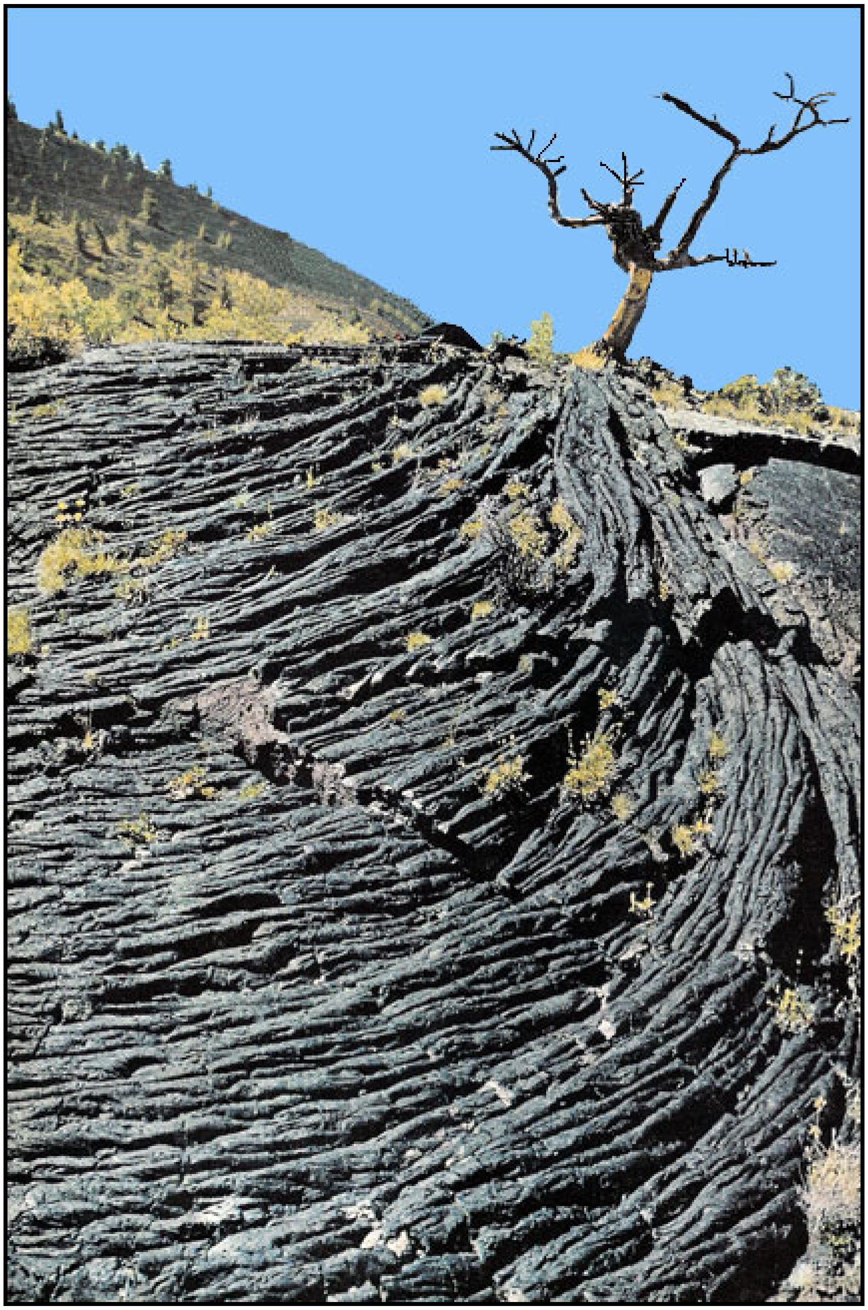

Figure 15: The wrinkled and ropy surface of the pahoehoe results from the hardening of a thin crust on the lava while it is being pushed forward by the still fluid and flowing lava from below (Source: National Park Service photo, Craters of the Moon, Idaho).

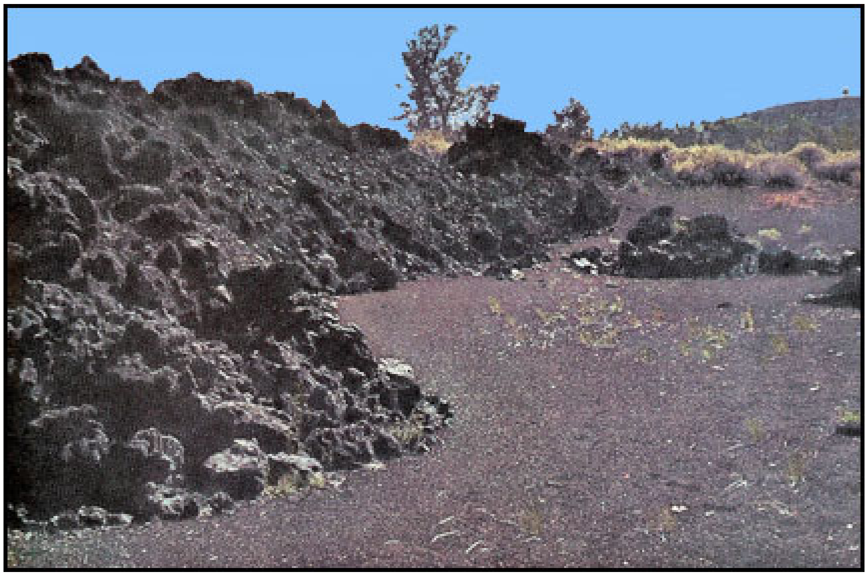

Figure 16: Margin of an “aa” lava flow within the Craters of the Moon National Monument site (Source: National Park Service photo, Craters of the Moon, Idaho).

Sometimes the surface and sides of the lava flows solidify to form a thick outer crust while the hot lava inside continues to move forward and eventually drains out of its own crust leaving behind lava tubes or tunnels. Water entering these tunnels may freeze in the winter and because of the excellent insulation provided by the basalt crust will remain frozen through the summer. Some of the ice in the lava tunnels at the Craters of the Moon National Monument site is known to be several thousand years old.

Lava Domes

Lava domes, which are the products of the fourth type of volcanic eruptions, are built-up of very viscous lava that has the consistency of a paste. The lava is forcibly extruded from the volcanic vent much like toothpaste is squeezed out from its tube. The resulting domes are steep sided and craggy cones that build and mound over the volcanic vent. Notable examples of lava domes are Mount Pelée, on the island of Martinique in the Caribbean, and Lassen Peak and the Mono Domes, in Northern California.

Lassen Peak is the largest of a group of more than 30 volcanic domes that erupted over the past 300,000 years in the Lassen Volcanic National Park area. On May 22, 1915, an explosive eruption at Lassen Peak devastated nearby areas and rained volcanic ash as far away as 200 miles to the east. This explosion was the most powerful in a 1914-17 series of eruptions. Figure 17, below depicts the Lassen Peak Dome as photographed in 1982.

Figure 17: Lassen Peak lava dome as seen from Kings Creek Meadows, Lassen Volcanic National Park (Source: United States Geological Survey).

Mount Pelee, a volcanic dome on the Caribbean island of Martinique, experienced a most destructive eruption in 1902. The town of St. Pierre was completely demolished and 38,000 of its inhabitants were killed by the hot gases and the searing volcanic dust. Only one man survived because he was underground in a poorly ventilated jail cell.

Size of Volcanic Eruptions

The volcanic Explosivity Index (VEI), a scale to estimate the size of volcanic eruptions, was developed in 1982 by Chris Newhall of the United States Geological Survey and Stephen Self, of the University of Hawaii. This scale was initially developed in order to estimate the climatic impact of eruptions. However, it soon became apparent that the amount of sulfur dioxide that is jetted out high into the atmosphere (a variable that is not necessarily related to the size of the eruption) was also a critical factor in the atmospheric disturbances that accompanied volcanic eruptions. Nonetheless, since its inception the VEI scale has been widely adopted by volcanologists to compare quantitatively the magnitude of volcanic eruptions worldwide.

The VEI scale has a range of 0 to 8 with the index of explosivity increasing by a factor of ten for each increase in numerical value. In that respect, it is somewhat similar to the Richter magnitude scale used to measure the size of earthquakes (refer to course G175: Earthquakes: Basic Principles). The VEI uses several factors to assign an index number, including total volume of erupted material (tephra), height of the eruption column, duration of the eruption in hours and other qualitative descriptive terms. The VEI scale is presented in Figure 18, below.

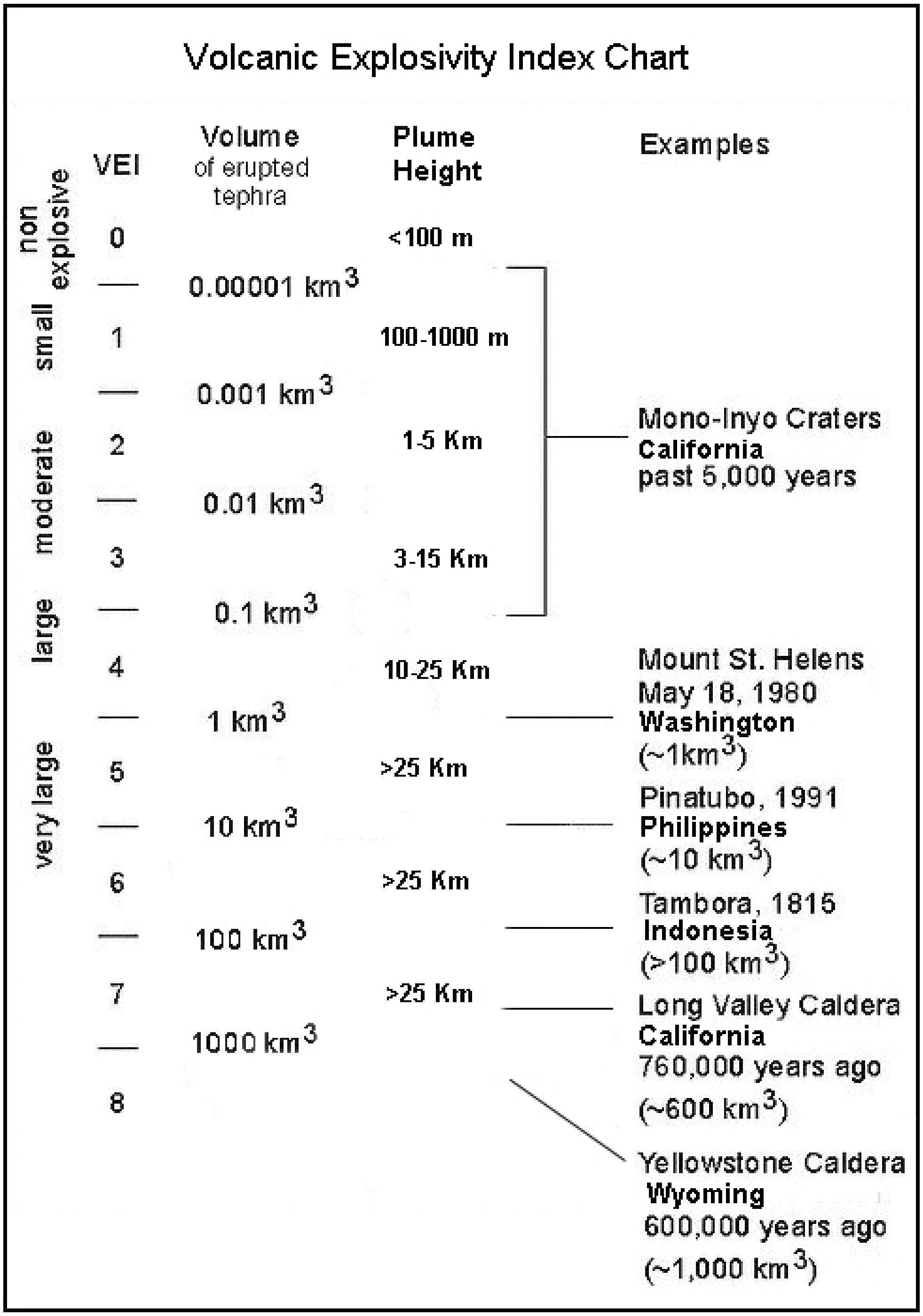

Figure 18: Volcanic Explosivity Index Chart (Source: Modified from a US Geological Survey Table).

It is interesting to note that there are no known explosive events with a VEI larger than 8. Also, like in the case of earthquakes, large explosive volcanic eruptions occur much less frequently than small ones. The records maintained by the Global Volcanism Program of the Smithsonian Institution shows that over the past 10,000 years there were: 3,477 eruptions of VEI 2, 868 eruptions of VEI 3, 421 eruptions of VEI 4, 166 eruptions of VEI 5, 51 eruptions of VEI 6, and 5 (plus 2 suspected) of VEI 7, and 0 of VEI 8. As will be explained in a later section, supervolcanoes have erupted in prehistoric times (older than 10,000 years) with a VEI of 8.

Historically Famous Volcanic Eruptions

Several hundred volcanoes have erupted during the period of recorded human history. In addition, the cones of several thousand others show such slight signs of erosion that they can be considered to be geologically speaking quite young. As explained in earlier sections, the activities of volcanoes differ by the amount and type of materials that are ejected. The composition and temperature of the ejected materials determine the ultimate size and shape of the volcano and the form that the extrusions take. This section describes some of the historically famous eruptions of composite volcanoes to illustrate their behavior and cyclic nature of activity.

Santorini

Santorini, also known as Thera or Thira, is the most active volcanic centre in the South Aegean Volcanic Arc. The volcanic arc is approximately 500 km long and 20–40 km wide, and the region first became volcanically active around 3 to 4 million years ago. The Santorini volcanic center is located about 200 km (120 mi) southeast of the mainland of Greece and volcanism from that center began about 2 million years ago. The remains of this volcanic center today is a water-filled caldera that has been repeatedly reconfigured following enormous explosions that have reshaped what was formerly one large single volcanic island. Figure 19, below shows the volcanic arc and the position of Santorini within it.

Figure 19: location map of the South Aegean Volcanic Arc, including Santorini

There have been at least twelve large explosive eruptions from the volcanic center at Santorini, of which at least four were caldera forming events. The earliest eruptions, many of which were submarine, have been dated between 650,000 and 550,000 years ago. Over the past 360,000 years there have been two major cycles of eruptions each culminating with a caldera forming event. In between the caldera-forming eruptions there were series of smaller explosions that culminated with the formation of lava cones. These cones are believed to impede the flow of magma to the surface which leads to the formation of large magma chambers, in which the magma can evolve to more silicic (silica-rich) compositions. Once this happens, and once the built-up pressure can no longer be contained, a large explosive eruption would destroy the cones. The devastating explosive Minoan eruption of Santorini that has been carbon dated at 1650 to 1600 BC and archeologically dated at about 1500 BC is one such example. The Minoan volcanic eruption of Santorini has become the most famous single event in the history of the Aegean region before the fall of Troy. In fact, it may have been one of the largest volcanic eruptions on Earth in the last few thousand years, with an estimated 6-7 on the VEI (Volcanic Explosivity Index). Figure 20, below, is a satellite image of present day Santorini showing the shape of the caldera that formed as a consequence of the violent Minoan eruption.

Figure 20: Satellite Image of present day Santorini showing the geometry of the caldera that resulted from the Minoan Eruption (Source: NASA photo taken in November 2,000).

Figure 20, above, shows the characteristic central rectangular lagoon (water filled caldera) of Santorini that measures about 12 by 7 km (7.5 by 4.3 mi). The water in the centre of the lagoon is nearly 400 m (1,300 ft) deep. The Kameni islands in the centre of the lagoon are the most recent example of lava cones built by this volcano, with many others hidden beneath the water.

On Santorini, overlying the soil that marks the ground level before the Minoan eruption is a 60 meters thick white tephra deposit thrown out during the eruption. Close-up investigation of this deposit indicates that it can be subdivided into three fairly distinct bands indicating different phases of the eruption. New archaeological discoveries by a team of international scientists, in 2006, have revealed that the Minoan event was much more massive than previously thought; it expelled 61 km^3 of magma and rock into the Earth's atmosphere, compared to the previous estimates of only 39 km^3. The total volume of the tephra ejected is estimated to be 100 km^3. Only the volcanic eruptions of Mount Tambora, Indonesia, in 1815 and Lake Taupo, New Zealand, in 181 released more material into the atmosphere during the past 5,000 years.

The final stage of the Minoan eruption was marked by the violent explosion of the volcano and its near total collapse into the Mediterranean Sea, leaving behind the caldera shown on Figure 20, above. This final explosion and collapse of the volcano triggered the generation of a very powerful tsunami that devastated the northern coast of Crete, 110 km (68 mi) away and destroyed the palace at Knossos (for more information about tsunamis triggered by the collapse of volcanoes refer to Course G207: Tsunamis: Basic Principles). Also, the Mycenaeans conquered the Minoans a few years after the Santorini eruption, and many archaeologists speculate that this volcanic eruption induced a crisis in the Minoan civilization, which allowed the Mycenaeans to conquer them easily. In addition, this very eruption seems to have provided the basis or otherwise inspired Plato to write the story of Atlantis. In Plato's account, Atlantis was a naval power that conquered many parts of Western Europe and Africa approximately 9600 BC. After a failed attempt to invade Athens, Atlantis sank into the sea "in a single day and night of misfortune" believed to coincide with the Minoan eruption of Santorini.

From a geologic standpoint, volcanic activity on Santorini is driven by the subduction zone located south-west of Crete. Along that subduction zone the oceanic crust of the northern margin of the African Plate is being subducted under the thinned continental crust of Greece and the Aegean Sea. As shown on Figure 7 of this course, this type of geologic setting leads to the formation of a volcanic arc (South Aegean or Hellenic volcanic arc), which includes Santorini along with other volcanic centers such as Methana, Milos and Kos (Figure 19).

Vesuvius

The sudden destruction of the cities of Pompeii and Herculaneum in Italy is one of the classic tragedies of ancient Roman history. In the year 79 A.D. Pompeii was buried to a depth of 50 ft by a hot and thick mixture of dust and ash mixed with steam that emanated from the eruption of Vesuvius.

It is well known and documented that the Vesuvius volcano has been periodically active in modern times. Indeed, it has been active frequently since the explosion that destroyed Pompeii. The usual pattern of activity consists of a period of violent eruption and explosion followed by the collapse of the unstable or over-steepened parts of the volcano’s composite cone. The crater ends up catching much of the debris of the eruption. Within a few years lava begins to flow again into the crater and fills it. Weight of the material in the crater allows pressure to build up within the vent. Lava may break through the sides of the cone, and some may also flow over the rim of the crater. These extrusions are normally accompanied by minor explosions. Eventually pressures within the volcano become too great to be contained, and a major eruption begins all over again. These renewed major eruptions may take the form of brilliant firework displays with incandescent ash, bombs, and dust blown out into the air. Alternatively, the activity may also be in the form of a quiet extrusion of red-hot lava. On steep slopes the lava-rivers flow rapidly downhill, carrying partially cooled blocks along with them. At the foot of the volcano, where the slopes break, the motion is slowed and the lava begins to consolidate. A crust forms on top of the flow, but internal heat keeps the center fluid and mobile, and it continues to flow, breaking and cracking the crust as it moves. The front margin of the flow looks like a pile of smoldering broken blocks. As the margin continues to move forward the top blocks keep breaking off and falling into the flowing mass.

At the present time Vesuvius stands about 4,000 feet high in the center of the collapsed crater of an older and larger volcano, known as Mount Somma. All that is left of Mount Somma is a ridge that makes a half-circle around Vesuvius. The dating of a pumice layer at the base of the volcano (Pomici di Base) assigns an age of 18,300 years to the eruption, with an estimated VEI of 6, which resulted in the original formation of the Somma caldera. The last major eruption of Vesuvius occurred in 1944, toward the end of the Second World War.

Figure 21: Vesuvius Volcano within the Somma Caldera as seen from across the Bay of Naples.

Mount Tamboro

This most violent volcanic explosion in recorded history occurred on Sumbawa Island, Indonesia. Volcanic activity at Mount Tamboro started in 1812, and reached its climax with the catastrophic explosive event of April 1815. During this paroxysmal event the Mount Tamboro (also known as Mount Tambora) volcano blew about 40 cubic miles of the earth's crust up into the air. The eruption column reached the stratosphere, an altitude of more than 43 km (140,000 ft), and the debris created by this powerful explosion covered islands for hundreds of miles around. The location of this volcano is shown on Figure 22, below.

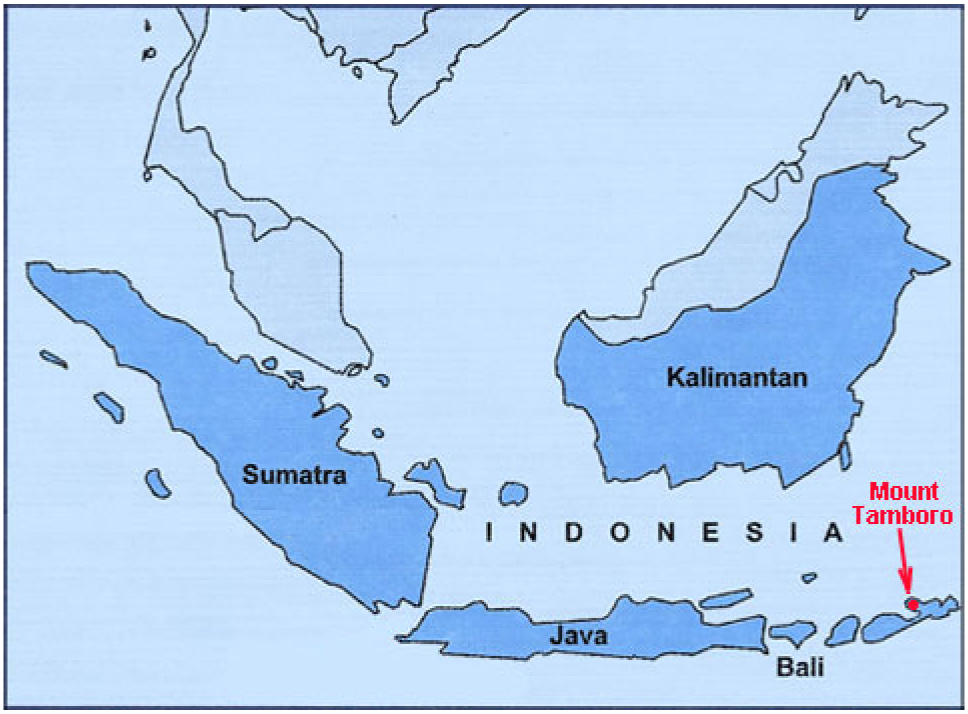

Figure 22: Location Map of Mount Tamboro.

Explosions of this magnitude are relatively rare and most often occur in volcanoes that have been dormant for long periods of time. Because the magma beneath composite cones (stratovolcanoes) may contain large quantities of gases, the explosion that finally occurs relieves the high pressures that have been building up over time beneath the volcano's vent and pipe, the connection between the volcano and the magma, or within the magma chamber itself. Because gases are compressible, pressure will continue to build up until it exceeds the strength of the plug or frozen lava in the vent and pipe that have kept the gases confined. At that point the explosion occurs rather abruptly and with great force.

The Mount Tamboro 1815 eruption is rated at 7 on the Volcanic Explosivity Index (VEI, see Figure 18). The explosion was heard on Sumatra Island, 1,200 miles away and heavy volcanic ash falls were recorded as far away as Borneo, Maluku, Sulawesi and Java. The explosion has left a caldera measuring 6–7 km (3.7–4.3 mi) across and 600–700 m (2,000–2,300 ft) deep. Before the explosion, Mount Tamboro was approximately 4,300 meters (14,100 ft) high, one of the tallest peaks in the Indonesian archipelago. After the explosion, it now measures only 2,851 meters (9,354 ft).

The death toll from this event was estimated to be at least 71,000 people, of whom 11,000–12,000 were killed directly by the eruption. However, most deaths were caused from starvation and disease because the eruptive fallout ruined agricultural productivity in the region. Also, the eruption created unique global climate anomalies and the year of 1816 became known as "the year without summer" because of the widespread weather effects on North America and Europe. The cause of these disturbances is attributed to the finer ash particles that stayed in the atmosphere at an altitude of 10–30 km (about 33,000–98,000 ft) for several months and up to a few years after the eruption. Longitudinal winds spread these fine particles around the globe, creating strange optical phenomena. Prolonged and brilliantly colored sunsets and twilights were frequently seen in the northern hemisphere. The glow of the twilight sky typically appeared orange or red near the horizon and purple or pink above it. Also, in the spring and summer of 1816, a persistent dry fog was observed in the northeastern US. The fog reddened and dimmed the sunlight, such that sunspots were visible to the naked eye. Neither wind nor rainfall dispersed the "fog". It was identified as a “stratospheric sulfate aerosol” veil. Because of the associated temperature drop during the spring and early summer of 1816, agricultural crops failed and livestock died in much of the Northern Hemisphere, resulting in the worst famine of the 19th century.

The phase of intensive volcanic activity ceased on 15 July 1815. Follow-up activity was recorded in August 1819 consisting of a small eruption (VEI = 2) which was considered an extension of the 1815 eruption. Around 1880, Mount Tamboro erupted again, entirely within the caldera. It created small lava flows and lava dome extrusions. This eruption (VEI = 2) created the “Doro Api Toi” small cone considered to be a plug entirely within the caldera. Mount Tamboro is considered to be still active. Minor lava domes and flows have been extruded on the caldera floor during the 19th and 20th centuries. The last small non-explosive eruption was recorded in 1967 (VEI = 0).

Krakatau

Krakatau (also known as Krakatoa) was an island 9 km (5.6 mi) long by 5 km (3.1 mi) wide located in the Sunda Strait, between Sumatra and Java. It contained three volcanic centers named from north to south: Perhoewatan, Danan and Rakata. Collectively the three volcanic centers were known as Krakatau (or Krakatoa). Figure 23, below, is a location map of Krakatau, or what is left of it.

Figure 23: Location Map of the Island of Krakatau, also known as Krakatoa.

On Sunday afternoon, August 26, 1883, a few mild explosions rocked the Island of Krakatau and during the evening and night that followed the explosions increased steadily in number and intensity and vast amounts of ash and pumice began to fall on Southern Sumatra and Northern Java. Early in the morning of Monday, August 27, the first of the gigantic explosions occurred at 5:30 am. The Sumatran town of Ketimbang was destroyed at 6:15 am, and the Java port of Anjer was inundated and wrecked shortly after. A second and third mighty explosion came at 6:44 am and 8:20 am. Finally, the fourth and final terrifying cataclysmic explosion came at 10:02 am, and its detonation that was heard thousands of miles away. Following that last explosion the entire volcano which had stood at 2,667 feet (813 m) above sea level was torn asunder sending more than a cubic mile of rock into the air. A cloud of dust, gases, and debris rose nearly 17 miles (>25 km) into the air. Heavier debris fell back to earth, but the smaller particles of dust that were caught in the upper air currents were blown several times around the earth. For the next two years, before this large quantity of dust settled, it colored sunsets around the world. Later on, when a sounding was made over the original peak of the volcano, the water was 1,000 feet deep, meaning that over 3,600 feet of rock had been instantly obliterated during that last cataclysmic explosion.

As a consequence of the 1883 volcanic eruption, which lasted only for a period of about 21 hours, the island of Krakatoa had in essence disappeared. Six cubic miles of rock had been turned instantly into pumice, ash and clouds of dust. Then, the eruptions and explosions decreased gradually in intensity and became fainter by Monday evening. By Tuesday morning, August 28, 1883, all volcanic activity stopped entirely. In the aftermath, 165 villages were devastated and when the casualties from these events were tallied, it was found that over 36,000 people had lost their lives. Most were victims not of the eruption itself but of the immense tsunami that was triggered by the final and ultimate collapse of Krakatoa and the formation of a caldera. The tsunami devastated the southern coast of Sumatra and the northern and western shores of Java. Figure 24, below, is a satellite image of present day Krakatau.

Figure 24: Satellite Image of present day Krakatau showing what is left of the Island after the 1883 Eruption (Source: NASA photo taken in 18 May, 1992).

The island of Krakatoa resembled most other volcanic islands in the Pacific, which are essentially composite cones that were built in the course of many eruptions. The site on which Krakatoa was built was one previously occupied by older volcanoes. A fringe of islands marks the caldera rim of a former volcano which exploded and collapsed before recorded history. Within the section of the island that vanished during the 1883 eruption, a new volcanic cone began to rise from the sea in June 1927 in the midst of random eruptions of bubbles and clouds of steam. It finally emerged in January 1928 and the new volcanic cone was named Anak Krakatau (son of Krakatau). It has been highly eruptive ever since and within several months had reached a height of 70 feet above the sea. The permanence of this fledging new island above sea level was established in 1930. In the following twenty years it grew from a few feet and half a mile long to a 500 feet tall peak, a mile long and half a mile wide. Today it is a double cratered large cone that is over 1,500 ft high. Figure 25, below, shows a map prepared by the United States Geological Survey showing the outline of the portion of the Island that was obliterated during the 1883 eruption and the new location of Anak Krakatau.

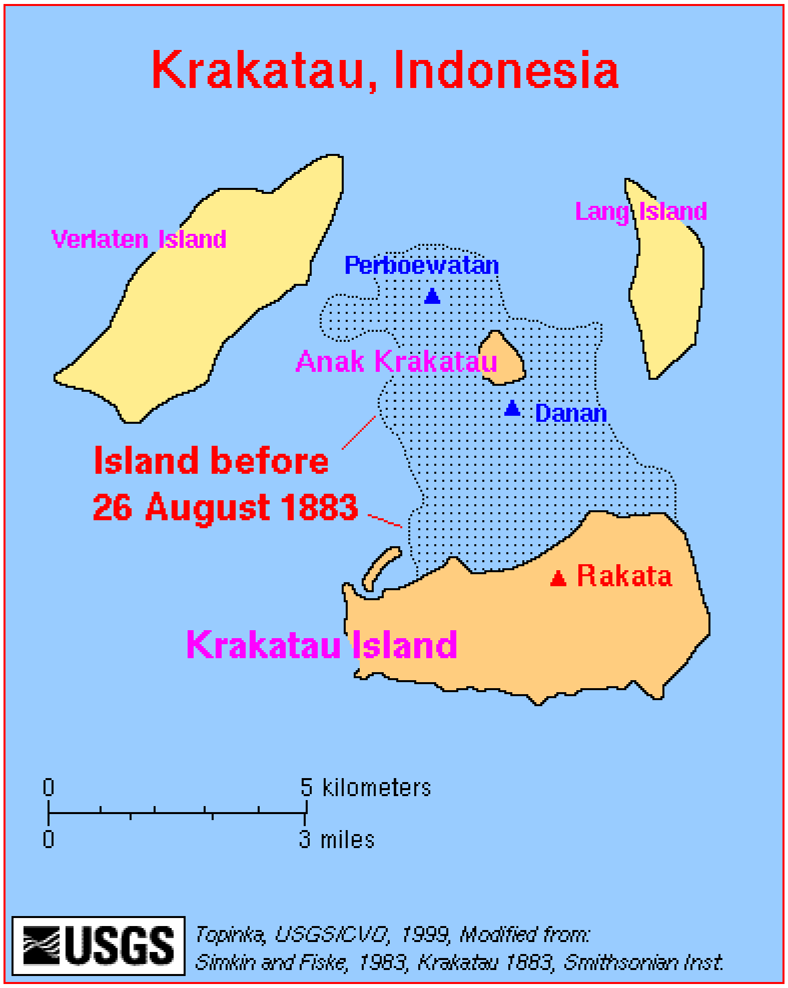

Figure 25: Map of Krakatau after the 1883 eruption showing the portion of the island that was obliterated and the new volcanic cone Anak Krakatau.

From a tectonic standpoint, Krakatau is directly above the leading edge of the Indo-Australian Plate that is subducting beneath the Eurasian Plate. It is located at the point where the plate boundaries make a sharp change of direction between Sumatra and Java, possibly resulting in an unusually weak crust in this region.

Mount St. Helens

Mount St. Helens is located in southwestern Washington about 75 miles southeast of Seattle and about 50 miles northeast of Portland, Oregon. It is one of the imposing volcanoes in the Cascade Range of the Pacific Northwest. The volcanoes of the Cascade Range in the US (from Mount Baker in the north to Lassen Peak in the south) and the other potentially active volcanoes in the western Unites States are shown on Figure 26, below.

Figure 26: Map of the active and potentially active volcanoes in the Western United States (Source: modified from a map published by the US Geological Survey).

Before 1980, the snow-capped and symmetrical Mount St. Helens was known as the “Mount Fuji of America.” At the base of the volcano’s northern flank, Spirit Lake, with its clear water and wooded shores, was especially popular as a recreational area for camping, fishing, swimming and boating. Although Mount St. Helens was intermittently active for a span of 26 years between 1831 and 1857 and minor steam explosions occurred in 1898, 1903 and 1921, the volcano gave no indication of being a real hazard during most of the 20th century. Figure 27, below, is a view of the volcano before its 1980 eruption.

Figure 27: Panoramic view from the north of Mount St. Helens before the 1980 eruption (Source: US Geological Survey, photo by Harry Glicken).

However, this serenity and tranquility was shattered abruptly in the spring of 1980, when the volcano swelled, started to shake and exploded in a fiery display reminding everyone that the volcano was still active and dangerous. Indeed, the volcanoes of the Cascade Range in the US and British Columbia together with those of Alaska comprise the North American segment of the circum-Pacific "Ring of Fire," a well-defined continuous zone that produces frequent, and often destructive, earthquakes and volcanic eruptions (see Figure 8).

As early as March 16, 1980, several small earthquakes began to shake the area and on March 20, 1980, a magnitude 4.2 earthquake was the first real indication that Mount St. Helens was awakening after being dormant for over 123 years. By March 25 earthquake activity continued to increase gradually and over 170 earthquakes of magnitude greater than 2.6 were recorded over a period of two days. Several hundred earthquakes of lesser magnitude were also recorded during that same time period and many were felt by the local population. With one, or possibly two simultaneous explosions, the volcano began to eject ash and steam at 12:36 pm Pacific Time on March 27, 1980. The crown of the ash column rose about 6,000 ft. above the volcano. These initial explosions formed a fresh new crater 250-foot wide within the much larger existing snow and ice filled crater and new fractures opened up across the summit of the volcano.

As reported by the US Geological Survey:

"As early as March 31, seismographs also began recording occasional spasms of *harmonic tremor*, a type of continuous, rhythmic ground shaking different from the discrete sharp jolts characteristic of (regular) earthquakes. Such continuous ground vibrations, commonly associated with eruptions of volcanoes in Hawaii, Iceland, Japan, and elsewhere, are interpreted to reflect subsurface movement of fluids, either gas or magma. The combination of sustained strong earthquake activity and harmonic tremor at Mount St. Helens suggested to scientists that magma and associated gases were on the move within the volcano, thereby increasing the probability of magma eruption."

During late March to mid-May 1980, the volcano was shaken by hundreds of earthquakes, intermittent eruptions of ash and debris derived from steam blasts. The edifice also experienced extremely large and rapid deformation caused by magma intrusion. For two months the volcano was literally being wedged apart, creating a highly unstable and dangerous situation. The eventual collapse of the bulge on the north flank triggered the chain of catastrophic events that took place on May 18, 1980.

Shortly after 8:32 a.m. Pacific Time a magnitude 5.1 earthquake originating one mile beneath the volcano initiated a tragic chain of events that triggered the collapse of the bulged, unstable north flank of Mount St. Helens resulting in widespread devastation that killed 60 people, including a volcanologist, David A. Johnston, who was on duty at an observation post about 6 miles north of the volcano. The collapse of the north flank produced the largest landslide-debris avalanche recorded in history up to that time. At one location, about 4 miles north of the summit, the advancing front of the avalanche had sufficient momentum to flow over a ridge more than 1,150 feet high. The resulting hummocky avalanche deposit consisted of volcanic debris and glacial ice covering an area of about 24 square miles. The total volume of the deposit was about 0.7 cubic mile. The dumping of the avalanche debris into Spirit Lake, at the northern foot of the volcano, raised its bottom by about 295 feet and its water level by about 200 feet. The sudden unloading of much of the volcano's north flank abruptly released the confined pressure of the volcanic system as a whole and unleashed a tremendous, northward directed lateral blast of rock, ash, hot gases, and magmatic material that devastated an area about 230 square miles in a fan-shaped sector north of the volcano. Very shortly after the lateral blast a strong, vertically directed explosion of ash and steam rose up very quickly. In less than 10 minutes the ash column had reached 12 miles and began to expand and drift downwind in an east-northeasterly direction. During the 9 hours of vigorous eruptive activity, about 540 million tons of ash fell over an area of more than 22,000 square miles. The ash plume crossed the United States in three days and circled the earth in 15 days. Lahars filled nearby rivers with mud and debris destroying 27 bridges and 200 homes.

The eruption of ash further enlarged the depression formed initially by the debris avalanche and the lateral blast, and helped to create an amphitheater-shaped crater open to the north. This new crater is about 1 mile by 2 miles wide and about 2,100 feet deep. The area of this crater is roughly that occupied by the former bulge on the north flank of the volcano. The 1980 violent eruption and the ensuing intermittent unrests of Mount St. Helens stopped in October 1986, after 6 years of on-again off-again lava dome growth within the enlarged crater. Between 1989 and 1991, at least six unexpected explosions from the cooling dome produced ash plumes and minor fallout of volcanic material. Between 2004 and 2008 additional dome emplacement took place involving the continuous extrusion of degassed magma spines. The triggering mechanism for such eruptions is believed to be controlled by forces driving and resisting the dome and spine extrusion, implying that a delicate balance between magma pressure and friction determines the character of the eruptions which can last for years, affecting areas both close and distant from the volcano. Figure 28, below, is a 1982 panoramic view of Mount St. Helens with a lava dome growing within its new crater which is open to the north.

Figure 28: Steam plume rising from lava dome growing within the amphitheater-like crater formed by the violent eruption of Mount St. Helens on May 18, 1980. Spirit Lake is in the foreground (Source: US Geological Survey, photo by Lyn Topinka).

After the 1980 violent eruption, the highest point of the volcano was 8,364 feet, or 1,313 feet lower than the former summit elevation. Most of Mount St. Helens visible cone is less than 3,000 years old and is believed to have been entirely built within several hundred years. So far the volcano has rebuilt only 7% of the volume it lost to the landslide of May 18, 1980 eruption. The volcano will surely continue its reconstruction in the coming years.

In response to the 1980 eruption of Mount St. Helens, the US Geological Survey established the Cascades Volcano Observatory not only to monitor the ongoing flare-ups but also to monitor volcanoes throughout the Cascades Range. In addition, the US Geological Survey and the US Agency for International Development jointly developed the Volcano Disaster Assistance Program (VDAP) for the purpose of rapid response to volcanic crises in developing countries around the world. Thus, by 1991, when Mount Pinatubo, in the Philippine, began to exhibit signs of unrest, VDAP and other scientists were prepared to respond on short notice. The response brought state-of-the-art equipment and experience that were crucial to helping the Philippine to respond successfully to Pinatubo's convulsive eruption of 12-15 June 1991 that was ten times stronger than the eruption of Mount St. Helens. The VEI rating of the Mount St. Helens and Pinatubo eruptions is shown on Figure 18.

Supervolcanoes

The term "Supervolcano" is applied to those volcanic centers that have generated eruptions estimated to be of magnitude 8 on the Volcano Explosivity Index (VEI) scale. No eruption of this magnitude has happened since the dawn of civilization, about 10,000 years ago. This reality is of great importance to humanity and is, in one sense, a very lucky coincidence that enabled the unimpeded development of the human race and our civilization. However, the geologic record contains clear evidence that magnitude 8 eruptions have occurred repeatedly and have caused major extinctions.

Recall that a VEI magnitude 8 eruption implies that more than 1,000 cubic kilometers (240 cubic miles) of magma (partially molten rock) has erupted. The most notable such event on Earth occurred 74,000 years ago at the site of the Toba Caldera in Sumatra, Indonesia. Other known eruptions that fall within this category include: the Yellowstone (Huckleberry event) which occurred 2.2 million years ago, the Yellowstone (Lava Creek event) which occurred 640,000 years ago, and the Taupo (Oruanui event) which occurred 26,500 years ago in New Zealand.

As explained earlier in this course, calderas, a word derived from cauldrons after which they were named, are broad, sunken areas often filled with lakes, ringed with hot springs and landscaped with domes of lava. The size of a caldera, which tends to form towards the end of an explosive volcanic eruption, can be used to estimate the force and violence of that eruption and can be used to differentiate whether the eruption emanated from a volcano or a supervolcano. For example, the explosive crater left after the 1980 Mount St. Helens eruption is about 2 square miles. The surface area of Crater Lake, the caldera left after the explosive eruption of Mount Mazama 7,700 years ago, is about 21 square miles. On the other hand, the Toba caldera, on the island of Sumatra, which formed following the 74,000 years old eruption, is 1,080-square-miles.

Toba Eruption

The last major VEI 8 eruption that emanated from the location of the Toba Caldera, Indonesia, 74,000 years ago, caused such global cooling that some scientists think it nearly drove humans to near extinction. In fact, some researchers suspect that the Toba super eruption and the global cold spell it triggered might explain a mystery in the human genome. Our genes suggest that all humans descended from a few thousand people just tens of thousands of years ago, instead of from a much older and bigger lineage — as the fossil evidence seem to support. However, both interpretations could be true if only a few small groups of humans survived the cold years following the Mount Toba super eruption. The location of the Toba caldera is shown below on Figure 29.

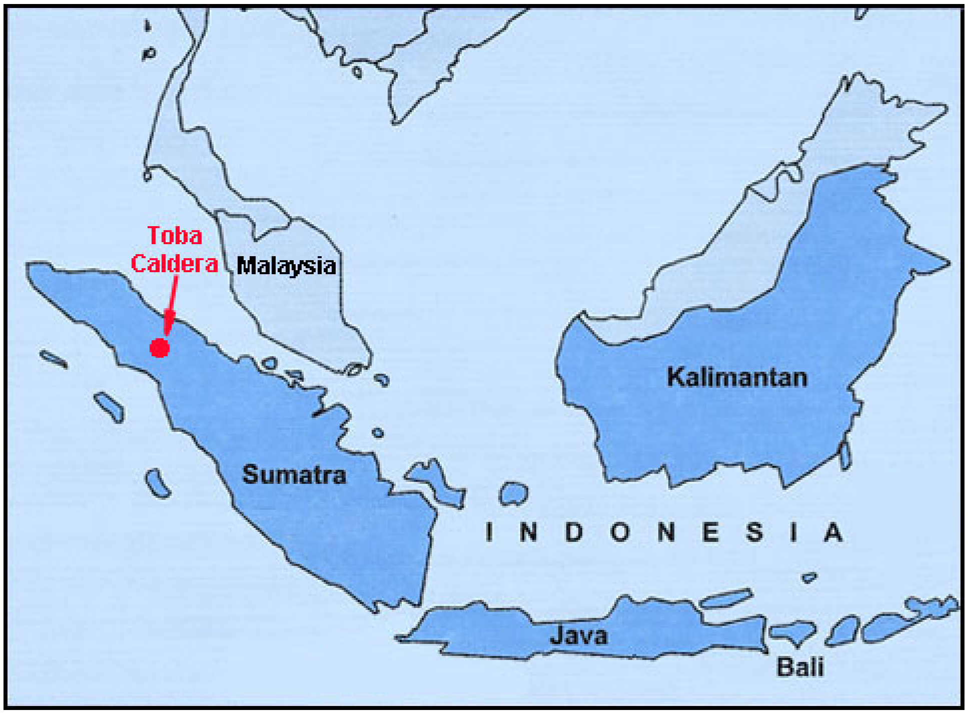

Figure 29: Location of the Toba Caldera, on the Island of Sumatra, Indonesia.

The Toba eruption that occurred 74,000 years ago was the third and latest of a series of at least three caldera forming eruptions which have originated from this volcanic center. The earlier two calderas formed around 700,000 and 840,000 years ago. The last eruption, at an estimated VEI 8, was possibly the largest explosive volcanic eruption on the planet within the last twenty-five million years.

Volcanologists have estimated that the total amount of erupted material during this third event was about 2,800 km^3 (670 cu mi). About 2,000 km^3 (480 cu mi) which flowed overland consisted of lava and hard rock blown out of the volcano, and around 800 km^3 (190 cu mi) was blown as a plume that reached the stratosphere and fell back to earth as ash. Today, the ash deposits from this event are as thick as 600 meters (1,969 ft) by the site of the eruption. In central India, the Toba ash layer today is up to 6 m (20 ft) thick, and parts of Malaysia are covered with 9 m (30 ft) of Toba ash. For further comparison, the Mount Tambora, Indonesia, 1815 event, the largest volcanic eruption in historic times, ejected the equivalent of around 100 km^3 (24 cu mi) of dense rock and made 1816 the “Year Without a Summer” in the whole northern hemisphere, and the 1980 Mount St. Helens eruption in Washington State ejected a mere total of around 1.2 km^3 (0.29 cu mi) of dense material.

Although the eruption may have lasted only a few weeks, the pyroclastic flows of the Toba eruption destroyed an area of 20,000 square kilometers (7,722 sq mi). In addition, volcanologists estimated that 6,000 to 10,000 million metric tons of sulfuric acid and sulfur dioxide were ejected into the atmosphere by the event, causing acid rain fallout and a "volcanic winter" that lasted for several years. As a result, the average global temperature dropped suddenly and it appears that very few plants or animals in Southeast Asia survived these abrupt changes. It is also possible that the eruption itself caused a planet-wide die-off of plants and animals. There is some DNA evidence that the human race may have been reduced at that time to only a few tens of thousands of individuals.

Smaller eruptions have occurred at Toba since its major eruption 74,000 years ago, and the small cone of *Pusukbukit* has formed since then on the southwestern margin of the caldera. The most recent eruption may have been at the northwestern edge of the caldera, since the present lack of vegetation at that location could be due to an eruption within the last few hundred years. Some parts of the caldera have also experienced uplift due to partial refilling of the magma chamber, pushing *Samosir Island* and the *Uluan Peninsula* above the surface of the water filled caldera (Toba Lake). The lake sediments on *Samosir Island* show that it has been uplifted by at least 450 meters (1,476 ft) since the cataclysmic eruption that occurred 74,000 years ago. Such uplifts are usually attributed to the upward pressure of un-erupted magma.

More recently, large earthquakes have occurred in the vicinity of the Toba Volcanic Center, notably in 1987 along the southern shore of the Lake at a depth of 11 km (6.8 mi). Other earthquakes have occurred in the area in 1892, 1916, and 1920-1922. Lake Toba lies near the Great Sumatran Fault which runs along the centre of Sumatra, and the volcanoes of Sumatra and Java are part of a continuous arc resulting from the northeasterly movement of the Indo-Australian tectonic plate which is sliding under the Eurasian Plate. The subduction zone in this area is very active and has produced several major earthquakes recently, including the magnitude 9.3 2004 Indian Ocean earthquake and tsunami that killed well over 200,000 people and left 5 million homeless and the magnitude 8.7 2005 Sumatra earthquake, the epicenters of which were around 300 km (190 mi) from Toba. Also, on 12 September 2007, a magnitude 8.5 earthquake shook the ground in Sumatra and was felt in Jakarta, the Indonesian capital on the island of Java. The epicenter for this earthquake was not as close as the previous two earthquakes, but it was in the same vicinity. All of these various signs and warnings indicate that Toba is still potentially active.

Yellowstone Eruptions

Today we know that Yellowstone National Park sits on top of a magma chamber that is relatively close to the surface, about 5 miles underground in some places. It is this magma chamber that fuels thousands of geysers, steam vents, mud pots and hot springs and makes Yellowstone a very popular tourist attraction. However, few people may realize that this subterranean chamber of molten rock and gas is so vast, about 40 by 80 kilometers across, that the region can be considered one of the largest active volcanic regions in the world. The continual feeding of the magma chamber below Yellowstone is believed to be fueled by a “hot spot” that geologists believe is the surface expression of a persistent plume of hot material rising up from the mantle.

Like other calderas worldwide, the Yellowstone landscape of calderas was created by the "roof collapse" of a magma chamber after the molten rocks were ejected in massive prehistoric eruptions. Today, three distinct massive eruptions can be identified in the geologic record at the present location of the hot spot under Yellowstone. These events occurred 2.1 million, 1.3 million and 640,000 years ago. The respective sizes of these eruptions can be estimated from the dimensions of the calderas they left behind. Figure 30, below, shows the locations of the three calderas.

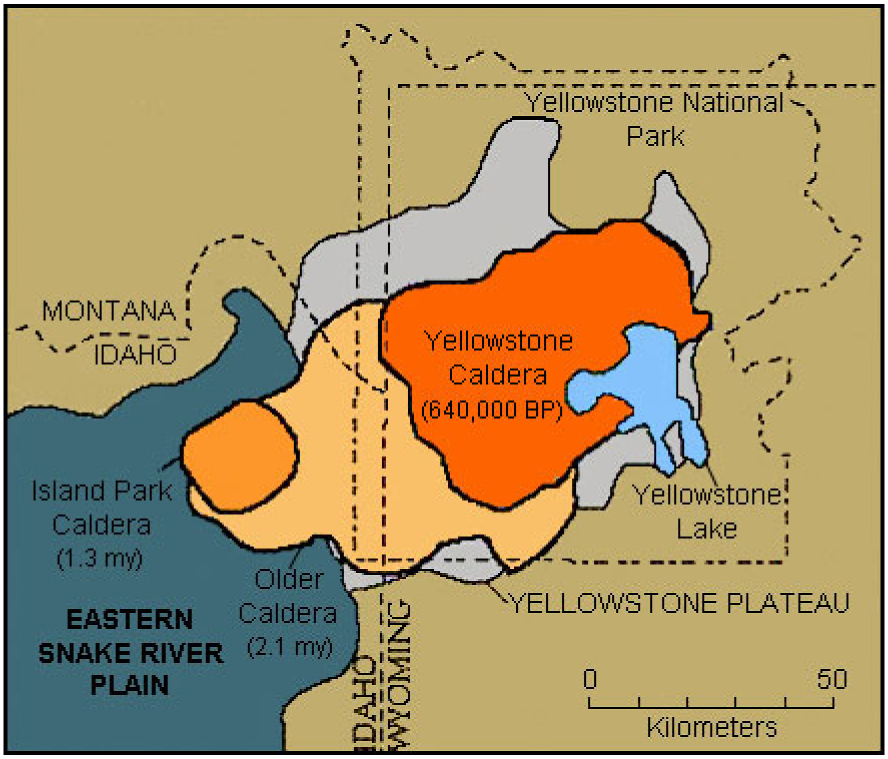

Figure 30: Locations of the three Yellowstone Calderas that erupted 2.1 million, 1.3 million and 640,000 years before present (Source: modified from a map published by the US Geological Survey).

The Yellowstone Caldera, a depression in the Earth equivalent to a crater top, has a surface area of some 1,500 square miles. For comparison, remember that the crater atop Mount St. Helens, following the 1980 eruption, was only about 2 square miles. Consequently, the last major eruption at Yellowstone, some 640,000 years ago, is estimated to have ejected 8,000 times the ash and lava that erupted at Mount St. Helens. And that was not even the largest eruption in Yellowstone's prehistoric past, since the 2.1 million years event resulted in the formation of an Older Caldera (Huckleberry Ridge) that is distinctly larger than the Yellowstone Caldera (see Figure 30, above). A modern full-force Yellowstone eruption of the Huckleberry Ridge type could kill millions, directly and indirectly, and would make every volcano in recorded human history look minor by comparison. Fortunately, the geologic record indicates that "super-eruptions" from “super-volcanoes” have occurred somewhere on the planet only once every million years or longer. Volcanologists also believe that super-volcanoes are likely to give decades, or even centuries, of warning signs before they erupt. Those signs would include the occurrence of numerous earthquakes, massive bulging of the land, an increase in small eruptions, clusters of earthquakes in specific areas, changes in the chemical composition of lavas from smaller eruptions, changes in gasses escaping the ground and, possibly, large-scale cracking of the land.

In the case of Yellowstone, there is evidence that over time the North American continent moved to the southwest over the hot spot. This continuous movement over time has left a 350-mile trail marked by several generations of ever-older calderas. Marching away to the southwest of Yellowstone the calderas that are encountered are now considered extinct. The oldest is a 16.5-million-year-old extinct caldera straddling the Oregon-Nevada state line near McDermitt, Nevada. The trail of extinct calderas is evidence that the hot spot has remained in place while the North American continent has moved southwest over it. The average rate of movement of the North American continent for the last 16.5 million years has been about 4.6 centimeters per year. When analyzed in segments, however, the continent can be inferred to have moved about 6.1 centimeters per year from 16.5 to about 8 million years ago, and then slowed down to about 3.3 centimeters per year for the past 8 million years. Figure 31, below, shows the track of the scars in the earth's crust left by the Yellowstone hot spot.

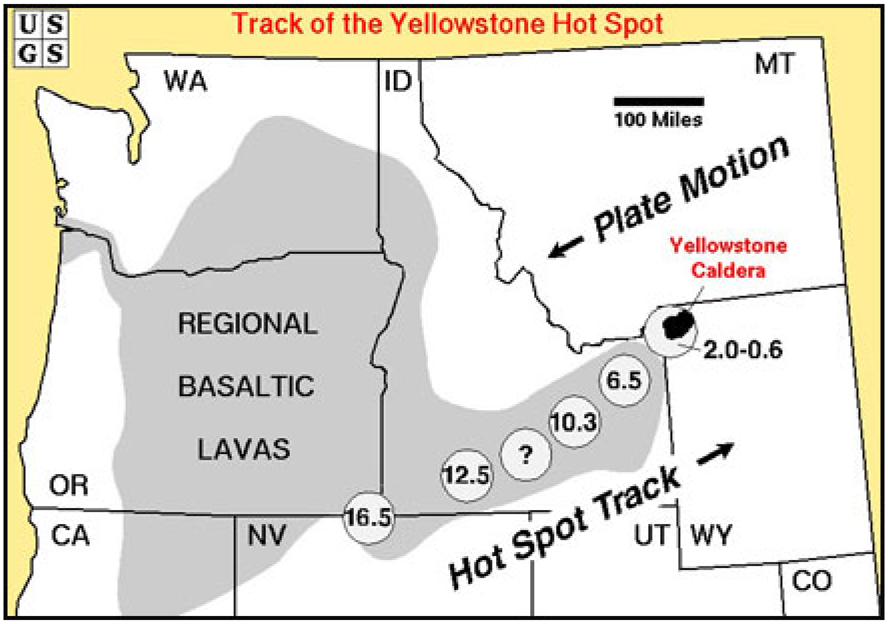

Figure 31: The track of extinct calderas left by the Yellowstone hot spot over the past 16 million years. Numbers in circles are in millions of years (Source: modified from a map published by the US Geological Survey).

Taupo (Lake Oruanui) Eruption

The Oruanui eruption of New Zealand's Taupo Volcano, which occurred 26,500 years ago, was one of the world's largest known eruptions in the not too distant geologic past, with an estimated Volcanic Explosivity Index (VEI) of 8. Volcanologists have estimated that the total amount of erupted material during this event exceeded 300 cubic miles. It generated approximately 430 km^3 (100 cu mi) of pyroclastic fall deposits, 320 km^3 (77 cu mi) of pyroclastic density current (PDC) deposits (mostly ignimbrite) and about 530 km^3 (130 cu mi) of magma. The eruption is divided into 10 phases on the basis of distinct fall units that were mapped in the field.

Modern Lake Taupo partly fills the caldera generated during this eruption. The maximum length of the Lake is 46 km (29 mi), and the maximum width 33 km (21 mi). The lake has a surface area of 616 km^2 (238 sq mi). Most of the structural collapse area is concealed beneath the lake, and the lake outline reflects coeval volcanic and tectonic collapse. Early eruption phases came from shifting vent positions and the development of the caldera to its maximum extent occurred during phase 10. The location of the Lake Taupo Caldera is shown on Figure 32, below.

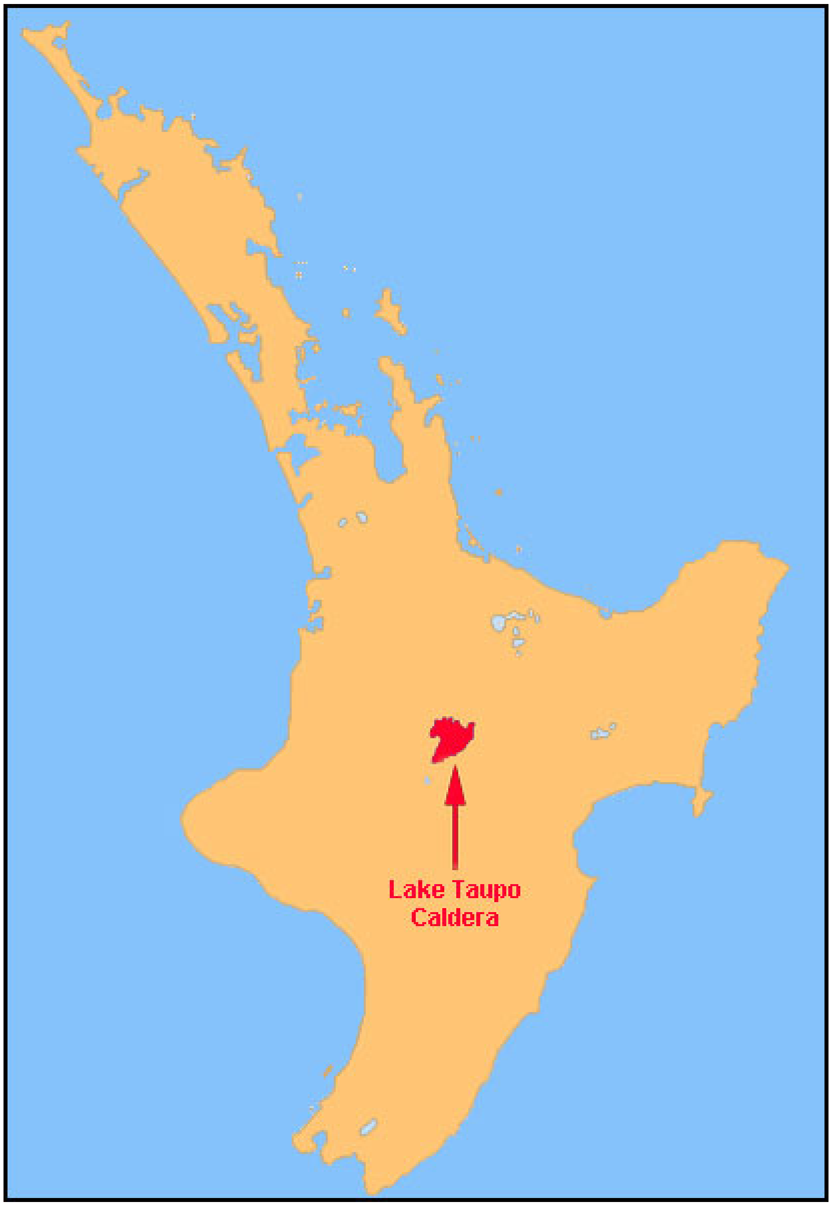

Figure 32: Location of the Lake Taupo Caldera at the center of North Island, New Zealand.

The Oruanui event has many unique characteristics: an episodic eruption lasting over 10 distinct phases, a wide dispersal of fall deposits under a wide range of depositional conditions, and a complex interplay of falls and pyroclastic flows. Tephra from the eruption covered much of the central North Island of New Zealand with ignimbrite up to 200 meters (660 ft) deep. Most of New Zealand was affected by ash fall, with even an 18 cm (7 in) ash layer left on the Chatham Islands, 1,000 km (620 mi) away. Also, later erosion and sedimentation had long-lasting effects on the landscape, and caused the *Waikato River* to shift from the *Hauraki Plains* to its current course through the *Waikato* and into the Tasman Sea.

Related Links

Examples of Volcanic Eruptions

The table below contains examples of volcanic eruptions classified by their Volcanic Explosivity Index (VEI), as published in Wikipedia. In the Year column "BC" stands for "Before Christ", "BP" stands for "Before Present", "Ma" stands for "Million annum", and "Ordovician" stands for a geologic period that covered the span between 500 and 440 million years ago. This period lasted for 60 million years. By pointing and clicking on the name of the volcano or eruption you will get to a Wikipedia page that contains additional information on the listed volcanic eruption or the region in which the now extinct volcanic region is located.

VEI	Volcano (eruption)	Year
0	Hoodoo Mountain	7050 BC?
0	Mauna Loa	1984
0	Lake Nyos	1986
0	Piton de la Fournaise	2004
1	Wells Gray-Clearwater volcanic field	1500?
1	Kilauea	1983 - present
1	Nyiragongo	2002
2	Mount Hood	1865-1866
2	Kilauea	1924
2	Tristan da Cunha	1961
2	Mount Usu	2000-2001
2	Whakaari/White Island	2001
3	Mount Garibaldi	9,300 BP
3	Nazko Cone	7,200 BP
3	Mount Edziza	950 AD ± 1000 years
3	Mount Vesuvius	1913-1944
3	Surtsey	1963-1967
3	Eldfell	1973
3	Nevado del Ruiz	1985
3	Mount Etna	2002-2003

4	Mount Pelée	1902
4	Parícutin	1943-1952
4	Hekla	1947
4	Galunggung	1982
4	Mount Spurr	1992
4	Mount Okmok	2008
4	Eyjafjallajökull	2010
4	2010 eruptions of Mount Merapi.	2010
5	Laacher See	12,900 BP?
5	Hekla (Hekla 3 eruption)	1021 + 130/-100 BC
5	Mount Meager	≈400 BC (2350 BP)
5	Mount Vesuvius (Pompeian eruption)	79
5	Mount Edgecumbe/Pūtauaki	c. 300
5	Mount Tarumae	1739
5	Mount Mayon	1814
5	Mount Tarawera	1886
5	Katla	1918
5	Mount Agung	1963
5	Mount St. Helens	1980
5	El Chichón	1982
5	Mount Hudson	1991
5	Chaiten	2008
6	Morne Diablotins	30,000 BP
6	Nevado de Toluca	10,500 BP
6	Mount Okmok	8300 BP
6	Mount Etna	8000 BP?
6	Mount Veniaminof	1750 BC
6	Mount Vesuvius (Avellino eruption)	1660 BC ± 43 years
6	Grímsvötn	8230 BC ± 50 years
6	Mount Aniakchak	≈1645 BC
6	Mount Okmok	c. 400 BC
6	Ambrym	c. AD 100
6	Ilopango	450 ± 30 years
6	Mount Churchill (White River Ash)	≈750 (1200 BP)
6	Katla (Eldgjá)	934

6	Baekdu Mountain (Tianchi eruption)	969 ± 20 years
6	Kuwae	1452 or 1453
6	Bárðarbunga	1477
6	Huaynaputina	1600
6	Laki	1783
6	Krakatoa	1883
6	Santa María	1902
6	Novarupta	1912
6	Mount Pinatubo	1991
7	Bennett Lake Volcanic Complex	50 Ma
7	Valles (Lower Bandelier eruption)	1.47 Ma
7	Yellowstone (Mesa Falls eruption)	1.3 Ma
7	Valles (Upper Bandelier eruption)	1.15 Ma
7	Long Valley Caldera (Bishop eruption)	759,000 BP
7	Maninjau	280,000 BP
7	Atitlán (Los Chocovos eruption)	84,000 BP
7	Kurile (Golygin eruption)	41,500 BP
7	Campi Flegrei	37,000 BP
7	Aira Caldera	22,000 BP
7	Kurile (Ilinski eruption)	≈6400 BC
7	Crater Lake, Oregon (Mount Mazama eruption)	≈5700 BC
7	Kikai (Akahoya eruption)	≈5300 BC
7	Thera (Minoan eruption)	1620s BC
7	Taupo (Hatepe eruption)	186
7	Mount Tambora (1816 a year without a summer)	1815
8	Scafells	Ordovician
8	Glen Coe	420 Ma
8	La Garita Caldera	27 Ma
8	Yellowstone (Huckleberry Ridge eruption)	2.2 Ma
8	Galán	2.2 Ma
8	Yellowstone (Lava Creek eruption)	640,000 BP
8	Whakamaru (Whakamaru Ignimbrite/Mount Curl Tephra)	254,000 BP
8	Toba	69,000-77,000 BP
8	Taupo (Oruanui eruption)	26,500 BP

Summary

Following a brief introduction to the myths and fanciful speculations that surrounded the subject of volcanic eruptions the course embarked on explaining the scientific principles that undergird our present day understanding of why, where and how do volcanoes erupt. The course started by considering the internal structure of the earth, which we now know is composed of a dense core, a lighter mantle, and a still lighter crust. The processes that are active within the deep reaches of our planet were elucidated and the processes that lead to the development and the eruption of volcanoes were explained.

The concept of mantle convection was introduced and its consequence on the development of a clearly defined pattern of crustal segmentation (crustal plates) and crustal motion (plate tectonics) was clarified. Also, the process of subduction, whereas an oceanic plate is pushed under the leading edge of a continental plate, was illustrated. The ultimate outcome of this process is that volcanic chains develop parallel to the margin of continental plates. The jetting of plumes from the mantle into the crust also results in the development of volcanic centers within continents and oceans.

The course pointed out that the majority of all known active volcanoes, and earthquakes for that matter, are actually located, or occur, along well defined narrow bands that circle the earth parallel to the boundaries of the major tectonic plates. Other thinner bands that circle the earth within the oceans coincide with the mid-ocean ridges and highlight the locations where relatively weaker volcanic and seismic activity occurs. These features were all formed by the active and ongoing interaction between the tectonic plates that form the crust of the earth.

Based on their mode of origin and distinctive internal morphology, four main types of volcanoes can be recognized namely: Cinder Cones, Composite Cones, Shield Volcanoes, and Lava Domes. The four types were presented, illustrated and described in sufficient detail to characterize and classify the products of their eruptions. Next, the volcanic Explosivity Index (VEI), a scale to estimate the size of volcanic eruptions, was presented and its use by volcanologists to compare quantitatively the magnitude of volcanic eruptions worldwide was explained.

The next section of the course described some of the historically famous volcanic eruptions. Included were descriptions of the eruptions of Santorini (Thera), Vesuvius, Mount Tamboro, Krakatoa, and Mount St. Helens. This part of the course was followed by a section on Supervolcanoes that explained how these oversized features were identified from their geologic record and the size of their eruptions estimated. The cataclysmic eruptions of Toba, Yellowstone and Taupo (Lake Oruanui) were presented as examples and contrasted to the largest known volcanic eruptions in the historical record. Finally, the course concluded with a table that listed 89 notable eruptions sequenced in the order of their estimated Volcanic Explosivity Index (VEI). Students can access a Wikipedia description of each listed eruption by clicking with their mouse on the name of the volcano or eruption.

Glossary of Terms and Acronyms used in this Course

Active Volcano: A volcano that is currently erupting has recently erupted or is likely to erupt again.

Ash: The term usually refers to unconsolidated fine volcanic particles (less than 2.0 mm diameter; or 0.06 mm for fine ash) ejected from a volcano. The consolidated counterpart is referred to as *tuff*.

Ash Fall: Coat of volcanic ash which covers the ground following a volcanic eruption.

Basaltic Lava: A term used to describe fine grained dark-colored volcanic rocks containing more iron and magnesium than silica.

Bomb: A spherical mass of congealed magma that is blown out during an eruption.

Breccia: Rock formed by angular blocks of hardened lava embedded in volcanic ash.

Caldera: A large, basin shaped volcanic depression of roughly circular shape, the diameter of which is several times greater than the volcanic crater or vent. It tends to form as the result of an explosion of the volcanic edifice during the last stages of its eruption.

Cinder: A fragment of lava with entrapped bubbles that falls to the ground in an essentially solid condition.

Cinder Cone: An unstable volcanic cone formed of loose pyroclastic material.

Core: The central zone or nucleus of the Earth's interior. It is divided into an *outer core* and an *inner core*, with a transition zone in between. The outer core is a fluid and the inner core is a solid. The magnetic field originates within the core, which is of nickel-iron composition.

Crater: A circular depression formed by the explosion or the collapse of a volcanic vent.

Crust: The outermost layer or shell of the Earth, defined on the basis of seismic velocities that reflect the density and composition of that outer layer. It represents less than 0.1% of the Earth's total volume and is subdivided into *continental crust* and *oceanic crust*.

Crust, Continental: The portion of the Earth's crust that underlies the continents and the continental shelves. It ranges in thickness from about 35 km to about 60 km under mountain ranges. The density of the upper layer is about 2.7 g/cm^3, and the velocities of compression seismic waves (P waves) through it are less than 7.0 km/sec.

Crust, Oceanic: The portion of the Earth's crust that underlies the ocean basins. The oceanic crust is about 5 to 10 Km thick. It has a density of 3.0 g/cm3, and the velocities of compression seismic waves (P waves) through it exceed 7.0 km/sec.

Earthquake Epicenter: The point on the earth's surface that is directly above the focus, or point of origin of the earthquake.

Earthquake Hypocenter: The initial rupture point of an earthquake, where strain energy is first converted to elastic wave energy, the center point of an earthquake within the Earth.

Earthquake P-wave: A seismic elastic wave that travels through the interior of the earth with a compression propagation mode.

Earthquake S-wave: A seismic elastic wave that travels through the interior of the earth with a shearing propagation mode.

Eruption: The release of solids, liquids, and gases from a volcano by either slow emissions or explosive outbursts.

Extinct Volcano: A volcano that has been cut-off from its magma chamber and shows no signs of ever erupting again.

Extrusion: The discharge of viscous magma onto the Earth's surface by effusive volcanic and eruptive processes. The resulting extrusive rocks include lava flows and pyroclastic material such as volcanic ash. The igneous rock mass so formed by fast cooling has an extremely finely crystalline to glassy texture.

Fissures: Elongated cracks, or fractures along the sides of a volcano.

Flank Eruption: An eruption occurring on the side of the volcano as opposed to its peak.

Hot Spot: A large volcanic center that is persistent over tens of millions of years and is thought to be the surface expression of a rising *plume* of hot mantle material.

Intrusion: The emplacement and crystallization of magma deep within the earth's crust. The igneous rock mass so formed by slow cooling is characterized by a well developed crystalline texture. Granite is one example of an intrusive rock mass.

Island Arc: Also known as volcanic arc is a generally curved belt of volcanoes above a subduction zone. Examples include the Aleutian, Japan-Philippines and Indonesian Islands.

Lahar: A mudflow composed chiefly of volcanic materials on the flank of a volcano. The debris carried in the flow includes fragments from the primary lava extruded from the volcano.

Lava: A general term used to describe the rock that is solidified from a molten magma upon its extrusion from a vent or fissure onto the Earth's surface. Upon fast cooling the resulting rock develops a very finely crystalline to glassy texture.

Lava Dome: A dome-shaped mass of congealed lava that forms over a vent when the lava is so viscous that it cannot flow easily.

Lava Tube: A pipe-like tunnel formed to drain the molten lava trapped within a cooling lava flow.

Mafic: Dark colored rocks composed chiefly of ferromagnesian minerals (rich in iron and magnesium.

Magma: Naturally plastic and mobile rock material generated deep within the earth and capable of *intrusion* and *extrusion*. Upon slow cooling deep within the crust *intrusive* igneous rocks, such as granite, are formed. Upon fast cooling when reaching the surface *extrusive* igneous rocks, such as lava and basalt, are formed.

Magma Chamber: The underground cavity which contains the magma which erupts from a volcano.

Mantle: The zone in the interior of the earth that is below the crust and above the core. It is divided into the *upper mantle* and the *lower mantle*, with a transition zone in between.

Mohorovicic Discontinuity (Moho): A sharp seismic velocity discontinuity that separates the earth's crust from the underlying upper mantle. It marks the level in the earth at which the compression seismic wave velocities (P waves) change abruptly from 6.7 to 7.2 km/sec in the lower crust to 7.6 to 8.6 km/sec at the top of the upper mantle.

Nuées Ardentes: A French term used to describe an extremely hot mass of gas-charged cinders which is expelled at high velocity down a volcano.

Plate Tectonics: A theory that considers the crust and a portion of the upper mantle of the earth (top 100 kilometers) to be divided into a number of rigid plates that interact with one another at their boundaries, causing earthquakes, volcanic eruptions and other types of geologic deformation.

Plume: A localized body of volcanic rock rising into the crust from the mantle and thought to be the cause of a *hot spot* in the crust.

Pumice: A very light-weight rock which is actually a froth of volcanic material that has been chilled with intact gas bubbles still entrained within it. Pumice is sometimes so light that it floats in water.

Pyroclastic: Rock fragments of volcanic origin.

Pyroclastic Flow: A turbulent flow of pyroclastic material and hot gases.

Rheology: The study of the deformation and flow of matter.

Ring of Fire: A zone of frequent earthquakes and volcanic eruptions extending around the rim of the Pacific Ocean.

Subduction: The process of one crustal plate descending beneath another into the upper mantle. For example, this process takes place along the Peru-Chile trench (which parallels the coast of South America) or along the volcanic arc belts of the northern and western Pacific Ocean (Aleutians, Japan and the Philippines).

Tephra: A general term used to describe all pyroclastic emanations from a volcano.

Tuff: Type of volcanic ash that has been consolidated. In some cases tuff is deposited from a very hot and glowing cloud of erupted material from a volcano which upon cooling is welded into an even more coherent mass (*welded tuff*) than ordinary volcanic tuff.

USGS: United States Geological Survey

Vent: A volcanic conduit, which is usually cylindrical or pipe-like, that connects the volcano to its magma chamber.

Vesicle: A small cavity in volcanic rock resulting from the entrapment of a gas bubble during solidification.

Viscosity: The property of a substance that offers internal resistance to flow.

Volcano: The cone shaped edifice of volcanic material built around a vent or opening in the earth's crust through which magma, gases and ash erupt.

Vulcan: The name of the Roman God of fire from which the word volcano is derived.