APPENDIX I.

VOLCANISM IN A PLATE TECTONIC PERSPECTIVE

By Tom Sisson

Volcanoes and Earth's Interior Structure

(*See* **Surrounded by Volcanoes** *and* **Magma Mash** *for relevant illustrations and activities.*)

To understand how ***volcanoes***[1] form, it is necessary to know something about the inner structure and dynamics of the Earth. The speed at which ***earthquake*** waves travel indicates that Earth contains a dense ***core*** composed chiefly of iron. The inner part of the core is solid metal, but the outer part is melted and can flow. Circulation (movement) of the liquid outer core probably creates Earth's magnetic field that causes compass needles to point north and helps some animals migrate. The outer core is surrounded by hot, dense rock known as the ***mantle***. Although the mantle is nearly everywhere completely solid, the rock is hot enough that it is soft and pliable. It flows very slowly, at speeds of inches-to-feet each year, in much the same way as solid ice flows in a ***glacier***.

Earth's interior is hot both because of heat left over from its formation 4.56 billion years ago by meteorites crashing together (accreting due to gravity), and because of traces of natural radioactivity in rocks. As radioactive ***elements*** break down into other elements, they release heat, which warms the inside of the Earth. The outermost portion of the solid Earth is the ***crust***, which is colder and about ten percent less dense than the mantle, both because it has a different chemical composition and because of lower pressures that favor low-density ***minerals***. Due to its low ***density***, the crust can be thought of as floating on the mantle. The crust underlying the oceans is no more than a few miles thick, whereas that which forms the continents is twenty to forty miles thick. Crustal rocks are relatively cold, so they are stiff and tend to move as rigid plates, bounded along their margins by major ***faults***, belts of ***volcanoes***, or both. Single plates can be thousands of miles across but are only miles to tens of miles thick. The motion of these plates atop the flowing mantle is known

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[1] *Words in **bold italics** are listed at first occurrence in each section and are defined in the* **Glossary**.

as ***Plate Tectonics***. At ***transverse*** (“***transform”) plate boundaries***, plates slide past one another along major fault systems, like the San Andreas in California. At ***divergent plate boundaries***, such as the ***Juan de Fuca Ridge***, plates move away from each other with volcanic activity creating new crust where the plates separate. At a ***convergent plate boundary***, such as where the ***Juan de Fuca plate*** meets the ***North America plate,*** one plate sinks beneath an adjacent plate creating mountain ranges, great earthquakes, and chains of volcanoes.

Principal Types of Magma

The principal types of ***magma*** vary considerably in their chemical and physical properties (composition, temperature, ***density***, ***viscosity***), depending on their origin and subsequent history. Magmas are classified mainly by their chemical compositions. The most abundant ***elements*** in common magmas and rocks are oxygen (chemical symbol O), silicon (Si), and aluminum (Al). For historical reasons having to do with early methods of chemical analysis, the composition of rocks or magmas is usually expressed as oxides (SiO^2, Al^2O^3, etc.) in weight percent units (as opposed to molecular or volume fractions). With increased concentration of SiO_2 (“***silica***”), common magmas or ***volcanic rocks*** are referred to as basalt (up to 52% SiO^2), ***andesite*** (52-62% SiO^2), ***dacite*** (62-72% SiO^2), or ***rhyolite*** (more than 72% SiO^2). ***Basalts*** are widespread in ocean basins and are formed by partial melting of mantle rocks; andesites and dacites predominate along ***subduction zones***, and are accompanied by smaller amounts of basalt and rhyolite. Rhyolites erupt voluminously in continental interiors. Magma temperatures and densities generally decrease, and viscosities increase, from basalt, through andesite and dacite, to rhyolite.

SEAFLOOR SPREADING

(*See* **Surrounded by Volcanoes**, **Soda Bottle Volcano**, *and* **Riding the Magma Elevator**, *and for relevant illustrations and activities.*)

Most of Earth's Volcanoes Are Beneath the Seas

It may be surprising to learn that most of Earth's ***volcanoes*** are under the oceans. These volcanoes are lined up in long, narrow, undersea mountain ranges, known as ***mid-ocean ridges***, which lie along ***divergent plate boundaries***. As the flanking plates move away (diverge) from the mid-ocean ridges, new ***magma*** rises from the ***mantle*** to fill the space that would otherwise be created. Some of these magmas erupt onto the seafloor as ***lavas,*** whereas others solidify short distances underground as ***intrusive igneous*** rocks. Together these rocks attach to the margins of the diverging plates, creating new ***crust***. The combined process of plate growth and divergence is known as ***seafloor spreading***.

Oceanic Crust is Older and Older away from Mid-Ocean Ridges because of Seafloor Spreading

One consequence of seafloor spreading is that volcanic rocks are young at the ***midocean ridges*** and are progressively older (were erupted longer and longer ago) at greater distances away from the ridges. ***Lavas*** recently erupted at the mid-ocean ridges have little or no ***sediment*** covering them. However, fine sediments, including shells of tiny marine organisms, continually rain down onto the seafloor and bury the volcanic rocks. Because ***oceanic crust*** rocks that are progressively farther from the mid-ocean ridges were erupted longer ago (spreading has since carried them from the ridges), more time has elapsed for sediments to bury them, and the thickness of deep ocean sediments therefore increases progressively away from the mid-ocean ridges. Deep-sea drill samples show that as distance from the ridges increases, fossils in the sediments directly atop the lavas are older species, some of which are now extinct.

The ***eruption*** age of ***volcanic rocks*** can be determined by a variety of methods. One technique is to measure the amount of the element argon in the rock (strictly speaking, one measures argon isotopes—types of argon atoms differing in their neutron abundances). Argon is produced by natural radioactive decay of the element potassium, so by measuring the abundances (and isotopic compositions) of argon and potassium, and knowing the radioactive decay rate of potassium, it is possible to calculate the time elapsed since the magma cooled. An indirect dating method utilizes the magnetic character of a volcanic rock. Earth's magnetic field reverses polarity at erratic intervals (about every 1 million to several tens of millions of years), and volcanic rocks record this polarity as they cool. Due to seafloor spreading, the oceanic crust develops a symmetric mirror-image pattern of normal and reversed rock magnetic polarity on either side of the ridges. Wide bands of normal or reversed rock magnetic polarity result from long periods when Earth's magnetic field remained constant. Likewise, narrow bands result from brief magnetic periods. This fingerprint–like magnetic pattern of the seafloor is revealed by towing a sensitive magnet behind a ship. By correlating the magnetic patterns to areas where lava ages have been measured directly, it became possible to estimate the ages of the seafloor, and the rates of seafloor spreading and plate motion, over most of the oceans to a precision not attainable on land.

Among other successes, the theory of seafloor spreading explains matches of old fossils, rock types, and rock ages on opposite sides of the Atlantic Ocean, which had perplexed earth scientists, most of whom had believed that land masses remained fixed in place, only moving up and down during cycles of mountain building and ***erosion***. It is now known that North and South America were once connected to Europe and Africa, but split away during opening of the Atlantic Ocean by spreading along the mid-Atlantic Ridge. This tearing apart of large landmasses by newly forming ***spreading ridges***, sometimes called continental rifting, has also been a major process for isolating plants and animals, assisting the evolution of new species. For example, the native mammals of Australia are chiefly marsupials because rifting and seafloor spreading isolated Australia from other land masses long ago. Ensuing evolution took a different course there than on the other continental landmasses that were co-joined until more recently.

Mid-Ocean Ridges Are Oases of Life

Mid-ocean ridges are also interesting because they support oases of life in the total darkness of the deep oceans, and it is possible that such places are where life first began on Earth. In the late 1970s, scientists using deep-diving research submarines, such as the ALVIN, were surprised to find dense communities of clams, crabs, worms, and other creatures clustered at hot springs along the mid-ocean ridges. Prior to this time, it had been believed that all life depended directly or indirectly on sunlight; however, microorganisms living off the heat, and in some instances using sulfur instead of oxygen for metabolism, are the primary food sources for these deep-sea communities. Early in its history, Earth's atmosphere was poor in oxygen, and thus had little ozone (ozone is a gaseous molecule made of three oxygen atoms) to filter out harmful ultraviolet radiation from the sun. Without ozone, areas exposed to sunlight would be bathed in intense ultraviolet radiation that can break up organic molecules, preventing or killing early life forms by inflicting lethal sunburns. Water filters out ultraviolet radiation, much as it does visible light, so hot springs along early Earth's mid-ocean ridges could have supplied energy for life and would have been shielded from lethal radiation. Once begun, life could have migrated to shallower waters and evolved the ability to photosynthesize, using light and carbon dioxide as fuels, giving off oxygen as a by product. About 2.3 billion years ago photosynthetic organisms made Earth's atmosphere oxygen-rich, creating ozone at high altitudes. With time, the ozone filtered out ultraviolet radiation, allowing life to survive everywhere on Earth's surface.

Magma Results from Reduction of Pressure Beneath the Mid-Ocean Ridges

Magmas form beneath ***mid-ocean ridges*** by an unfamiliar process. Normally we think of things melting because they are heated (ice on a warm day, butter in a hot pan), but melting below mid-ocean ridges results from reduced pressure as hot mantle rocks rise to shallower levels, replacing rocks that moved away from the mid-ocean ridge by seafloor spreading. A rule of thumb is that lower density (larger volume for the same mass) substances are favored at lower pressures (and vice versa). Magma is less dense than solid rock, so if a rock is close to its melting temperature and the pressure is reduced enough, the rock will start to melt. As the hot rock of the mantle wells up beneath mid-ocean ridges, the weight of overlying rocks is less (they move aside at shallow levels), so the pressure drops, and upwelling mantle rock melts by a small amount. Being liquid, the newly created magmas rise faster than the upwelling mantle and escape toward the surface, forming the volcanic and intrusive igneous rocks of the ***oceanic crust***. Conversion of solid (rock) to liquid (magma) absorbs heat, so the rising mantle and the resulting magma actually cool-down slightly as melting progresses. Pressure release melting due to mantle upwelling is the dominant process that creates magma on Earth.

Melting due to reduced pressure is similar to water boiling at cooler temperatures high in the mountains (lower atmospheric pressure). This lower boiling temperature is why pasta and rice take much longer to cook in the mountains (it is not just that you are hungrier and it seems to take longer). Explorers used to estimate the elevations of unknown regions by measuring the boiling temperature of water, using the relation between air pressure (less at higher elevation), altitude, and boiling temperature (the boiling temperature of water is lower by 1° C or 1.8° F for every 1,000 ft above sea level). Ice is anomalous in its melting, since liquid water is denser than ice (ice, after all, floats). Unlike rock, ice can melt if the pressure increases.

SUBDUCTION ZONE VOLCANISM

Subduction zones recycle oceanic crust back into the mantle (*See* **Surrounded by Volcanoes**, **Soda Bottle Volcano**, **Riding the Magma Elevator**, *and for relevant illustrations and activities.*)

If new crust continually forms along ***mid-ocean ridges*** and then spreads away from the ridges, where does it go? One possibility entertained by a few scientists was that the Earth was expanding over time and ***seafloor spreading*** resulted from this expansion. Much evidence weighed against this expansion model, and the correct interpretation is that oceanic crust and the top of the underlying ***mantle*** eventually sink back into Earth's interior along what are known as ***subduction zones***. Subduction zones were first recognized as regions of frequent, powerful ***earthquakes*** arranged in inclined sheets extending far into the mantle from near the surface. The shallow ends of these sheets of earthquakes begin beneath the oceans, commonly near the submarine valleys or "***trenches***" that run parallel to the margins of some continents and volcanic island chains. The earthquakes are deeper in the mantle at greater distances away from the trench in the direction of the continent or island chain. Rocks have to be relatively cold to crack and create earthquakes (if hot, they bend easily and flow, like stiff clay), so the inclined sheets of earthquakes show the locations of cold slabs of rock that penetrate into the mantle, beginning at the deep ocean trenches. Scientists have since gathered much additional evidence that ***oceanic crust*** eventually sinks back down (***subducts***) into the mantle. Because of the relative motion of the plates, subduction zones are sometimes referred to as convergent plate boundaries. The deadly Indian Ocean ***tsunami*** of December 26, 2004, resulted from faulting and a powerful earthquake along the subduction zone adjacent to the island of Sumatra, Indonesia.

Ocean-Floor Rocks Subduct because Cooling Increases Their Density

When ***oceanic crust*** forms by volcanic processes at mid-ocean ridges, it and the underlying mantle are hot, but seawater circulating through cracks cools the crust and eventually the uppermost mantle, too. As rocks cool, they shrink slightly but their weight and mass remain the same, so their ***density*** (mass divided by volume) increases. Hot or cold, the rocks of the oceanic crust are less dense than rocks of the mantle, so the oceanic crust does not sink into the mantle on its own. Cooling penetrates into the upper portion of the underlying mantle, and when cooled, the upper mantle rocks are denser than rocks of the deeper, hotter mantle. Therefore, the cooler upper mantle rocks eventually sink back into the Earth at ***subduction zones***, carrying along the attached oceanic crust. As the oceanic crust is carried deeper and deeper into the mantle, it is squeezed by the increasing weight of overlying rocks. Eventually the pressure reaches the point that ***minerals*** in the subducted oceanic crust convert into denser types, chiefly garnet. Once this metamorphosis takes place, even the subducted oceanic crust is denser than mantle rocks, causing it to sink on its own account. The continents do not subduct because they have much greater thicknesses of low-density rocks, although at times continents have been dragged into subduction zones and locally have been forced under the edges of adjacent continents. This process of continental collision accounts for some of Earth's largest mountain ranges, notably the Himalayas.

Seafloor Spreading and Subduction Control the Age of the Ocean Floor

All oceanic crust remaining on the seafloor is younger than 200 million years, although scraps of older oceanic crust are preserved by having been faulted up onto continents. Two hundred million years may seem old, but the Earth formed 4.56 billion years ago, and there is good evidence for the presence of surface water as far back as 4.0 billion years. Seafloor spreading and subduction were probably active since that time, and perhaps earlier, so the oceanic crust that formed over more than ninety-five percent of Earth's history is gone, having been subducted back into the mantle.

Subduction Zones—Homes for the Second-Most Abundant Volcanoes on Earth

Subduction zones are home for the second most abundant ***volcanoes*** on Earth, and these are the most important for people because of the ***hazards*** they pose and also because they create watersheds, fertile soils, recreation areas, and many ore deposits. At subduction zones, ***active volcanoes*** are lined up along the margin of the non-subducting plate (sometimes referred to as the overriding or upper plate, or in miner's terms the "hanging wall"). The upper plate can be made of either continental or oceanic crust. Subduction-zone volcanoes encircle much of the rim of the Pacific Ocean, forming what is known poetically as the ***Ring of Fire***. The Ring of Fire includes the active volcanoes of the Andes and Central America, the Cascades (northern California to southern British Columbia), the Aleutians (Alaska), Kamchatka and the Kuriles Russia), Japan, the Philippines, the island chains of Tonga and Kermadec extending south to New Zealand, and a branch forming the Izu-Bonin and Marianas island chains (southwest Pacific). Along the Ring of Fire, oceanic crust subducts beneath most of the landmasses surrounding the Pacific Ocean. This contrasts with the Atlantic Ocean where subduction only takes place in small areas along the Lesser Antilles (Caribbean) and the South Sandwich Islands (between South America and Antarctica). Another major area of subduction zone volcanoes is in Java and Sumatra (Indonesia), due to subduction of the Indian Ocean seafloor.

Water Induces the Melting of Rocks Deep below Subduction-Zone Volcanoes

Different subducting plates dive into the mantle at different slopes and sink to increasing depths away from the plate boundary (illustrate this by slowly sliding a sheet of paper off the edge of your desk). The volcanoes usually sit in a line above where the subducting plate passes through about 100 kilometers (60 miles) depth in the Earth. Depending on the subducted plate's steepness, this line of volcanoes can be close to (steeply dipping plate), or far from (gently dipping plate), where the ***oceanic plate*** starts to descend into the mantle. The earliest theory for the origin of subduction-zone volcanoes was that the sinking plate releases water as it warms up in the mantle (think of the plate as sweating). This water causes small amounts of melting in the hotter rocks of the nearby mantle. These low-density ***basaltic magmas*** then rise toward the surface. Some of these basaltic magmas feed volcanoes directly, but most basaltic magmas cool to varying degrees and shed dense ***crystals***, thereby changing in chemical composition to ***andesitic*** and ***dacitic*** magmas. Hot basaltic magmas may also incorporate and melt rocks from the crust, leading to similar or greater changes in composition and thus in density, ***viscosity***, and temperature. An alternate theory is that the subducting plate itself heats up enough to melt by small amounts, creating magmas that rise to the surface. Because it is conceptually easy, this idea of plate melting is commonly presented in introductory science textbooks; however, calculations of the temperatures of sinking plates have long shown that the plates do not generally get hot enough to melt. Notable exceptions are where the subducting plate has only recently formed at a mid-ocean ridge and is still hot when it begins to subduct. Temperatures sufficiently high for melting are also inconsistent with the abundant deep, powerful subduction-zone earthquakes that require rocks to be cold enough to crack.

How Adding Water Melts Hot Rock

The ability of water or steam to induce melting in hot mantle rocks is similar in principle to the ability of salt to melt ice on a road or sidewalk. As a rule, adding a chemical substance that can dissolve in a liquid but not in a solid promotes the conversion of the solid to the liquid. Salt will dissolve in water, but practically none can be incorporated into the structure of ice. Adding salt to ice will melt some of the ice, as long as the ice is already close to its melting temperature. Because melting absorbs heat (the atoms need energy to move quickly and freely in a liquid), adding salt to ice also lowers the temperature below the freezing point of fresh water. This is why salt-ice mixtures are used to lower the temperature in old-fashioned ice cream makers. At the high pressures of subduction zones, much water can dissolve in ***magma***, but very little can be absorbed into hot mantle rocks. The release of water from the subducting plate therefore partly melts the adjacent hot mantle and cools it slightly. The localization of volcanoes to 100 kilometers (60 miles) above the subducting plate may indicate the breakdown of a specific water bearing ***mineral***, either in the subducting plate or in the adjacent mantle, leading to copious melting.

HOTSPOT VOLCANISM

Some Long Chains of Volcanoes Are Evidence of Plate Movement over Hotspots

Other major sites of ***volcanism*** on Earth are isolated ocean island groups and ***seamounts*** (Galapagos, submarine mountains), ocean island or seamount chains (Hawaii), broad submarine plateaus (Kerguelen in the south Indian Ocean), and in continental interiors (Yellowstone). Volcanic island chains like Hawaii form as a tectonic plate moves over a localized site of melting in the underlying ***mantle*** (some call these sites of melting "***hotspots***"). ***Magma*** rises from the site of melting and pierces through the plate, creating a volcanic seamount that may become an island. As the moving tectonic plate gradually carries the seamount or island away from the underlying source of magma, volcanism at that edifice eventually dies out. A new ***volcano*** forms above the melting region at the leading end of the volcanic chain and a new seamount or island is created. The progressive growth of these volcanic chains is somewhat like a sewing machine (the hotspot) stitching through moving fabric (the plate), leaving a line of stitches that is young at one end (the active volcanic island) and gets progressively older away from the needle (the island chain).

Because of plate motion, some chains of volcanoes and seamounts are quite long and vary progressively in age along their length, with young ***active volcanoes*** at one end and volcanoes that systematically increase in age up the chain. The island of Hawaii (the Big

Island) is the young end of the Hawaiian island chain. Along the chain to the northwest, the volcanic islands are so old that most have been eroded away and remain as a line of submarine seamounts extending north to nearly the Aleutian Islands.

Hotspots in Motion

Until recently it was thought that ***hotspot***s did not move relative to each other and to Earth as a whole, thereby providing reference locations against which absolute plate motions could be determined. More careful observations have shown that hotspots are not truly fixed in position. They do move relative to one another but at speeds less than the motion of the tectonic plates. The slow motions of hotspots are taken as evidence that they are rooted deeply in the ***mantle*** and are not shallow features that would be influenced by tectonic plate motion. The most widely accepted explanation of hotspots is that they are narrow plumes of mantle rock that are hotter and less dense than the surrounding mantle and rise through it, much as warm air and smoke rise from a chimney or smokestack. As the plume rises, pressure-release melting creates magmas that rise to the surface, feeding the active end of the volcanic island chain.

Outpourings of Basalt Form Lava Plateaus

Oceanic plateaus form by infrequent, but voluminous outpourings of ***magma*** in restricted locations on the seafloor away from mid-ocean ridges. These plateaus are the oceanic analogs of "***flood basalts***" that form thick blankets of basalt at some continental areas such as central Washington and large areas of India, Brazil, western Africa, and Siberia. A popular but speculative explanation for oceanic plateaus and flood basalts is that they form by partial melting of the large, blob-like top of a mantle plume (a "plume head" or "mantle ***diapir***") that has just risen to depths shallow enough to start melting. It is unlikely that the many small volcanic seamounts and isolated volcanic oceanic islands are each caused by mantle plumes; they are too small and short lived and they are not aligned in order of age. Volcanic seamounts are more abundant in some regions of the oceans than in others, particularly the equatorial-to-southwest Pacific. There is some evidence from ***earthquake*** speeds that the mantle beneath that region is slightly hotter than elsewhere (hotter rocks transmit earthquake waves more slowly). A subtle bulge in the average shape of Earth's surface also coincides with this region, and it may be that the mantle is upwelling slightly over an enormous region, counterbalancing the down-flow of mantle due to ***subduction*** along the ***Ring of Fire*** to the north, west, and east. This very gentle upwelling leads to traces of melting that fuel the numerous small seamounts of the southwest Pacific.

Volcanism in Continental Interiors

Most large volcanic centers in continental interiors, such as at Yellowstone, are fueled from below by hot ***basaltic*** magmas that originate in the mantle, but most of the erupted ***lavas*** and ashes at these centers are unlike those of the mid-ocean ridges and ***hotspots***. Much of the western United States from eastern California to western Utah, and from Mexico north through eastern Oregon has been pulling apart for about 30 million years. This pulling apart thins the crust, reducing the pressure on the underlying mantle, leading to small amounts of melting. Some of these melts rise to the surface directly and erupt as basaltic lava flows. Many, however, engulf and melt blocks of rock from the crust, or grow and shed dense ***crystals*** upon slow cooling at great depth, and through these processes transform into lower temperature and more viscous magmas like ***dacite*** and rhyolite. Yellowstone itself lies at the eastern end of a chain of large, ***extinct*** volcanic centers that are progressively older to the west. The age succession and great volumes of magma produced are similar to ocean island chains like Hawaii. Many scientists have proposed that Yellowstone lies atop a hotspot, perhaps fed by a deep mantle plume. Others disagree, and efforts are underway to produce 3-D images of the upper mantle below Yellowstone, using earthquake speeds to search for a hot mantle plume, but results to date are inconclusive. Whatever their original cause, the mantle-derived ***basalts*** stall in the deep crust, crystallizing to great degrees, and engulfing and melting rocks of the continent, giving rise to the rhyolitic magmas that dominate Yellowstone ***volcanism***.

BIRTH OF A VOLCANO

(*See* **Surrounded by Volcanoes**, **Cascade Volcano Timeline**, **Soda Bottle Volcano**, **Riding the Magma Elevator**, **A String of Volcanoes**, *and* **Volcano Hall of Fame** *for relevant illustrations and activities.*)

The Lifespan of a Volcano is Generally Greater Than the Lifespan of a Human

There are surprisingly few accounts of the births of wholly new ***volcanoes***, probably because volcanoes exist over ***geologic time*** spans that are long compared to human history. For example, the ***active volcanoes*** of the Cascades started to grow several tens of thousands to roughly half a million years ago. Several grew atop the eroded remains of volcanoes that had occupied the same locations, in some cases for as far back as one million years ago. Evidence of human habitation in North and South America does not become widespread until about 13,000 years ago, close to the end of the last Ice Age. In fact, skeletons like those of modern humans have been found as old as about 160,000 years (in Africa and Eurasia), but no older, so it is likely that modern humans had not even evolved at the time that most of the present Cascade and many other ***active volcanoes*** started to grow. Lacking observations, accounts of the inception of volcanoes are necessarily general and center on processes.

Magmas Form by Melting Events—They are Not Tapped from a Long-Lasting Molten Zone in the Earth

Regardless of setting, the events leading to a volcano begin by partial melting of rocks deeper in the Earth. Contrary to popular conception, the tectonic plates ride on hot rock, not liquid, and there is no large region or layer of melt in the Earth other than the outer ***core***. The ***molten*** metal of the outer core is far too distant and dense to rise to the surface and feed volcanoes. In most cases melting begins in the upper ***mantle*** where temperatures are quite high - about 1,300° C (2,400° F). Rocks melt incrementally over a range of temperature or pressure and it is rare for a rock to melt entirely to liquid. Instead, small amounts of melt form, coexisting with abundant ***crystals***. Because the liquid is less dense than the rock, it filters upward initially as thin films between melting crystals, but gradually the liquid accumulates into veins and pods. One might expect this melt would rise to the surface directly and rapidly so that specific ***eruptions*** would represent specific melting events, or that the volcanoes would erupt continuously during the periods of melting; but this does not seem to be so. ***Magmas*** that erupt or reach shallow levels in the crust typically are cooler (down to about 700^{o} C ($1{,}300^{o}$ F)) than melts formed directly from mantle rocks. Their chemical compositions have changed in route to the surface, and these changes strongly influence how the magmas erupt. As magma rises through the ***crust***, it loses heat to its surroundings, and this cooling forces the magma to start to grow crystals. It so happens that the first crystals to grow are rich in some chemical ***elements***, but not in others, so that crystal growth changes the chemical composition of the remaining melt. Typically, crystallization enriches the melt in silicon, sodium, potassium, and dissolved water, and impoverishes it in magnesium, iron, and calcium. Since the new crystals are also denser than the melt, the crystals tend to lag behind the rising melt, and this separation of crystals from melt changes the bulk composition of the magma. Because of differences in chemical composition, many crustal rocks melt at lower temperatures than mantle rocks, so hot magmas produced in the mantle can also incorporate and melt rocks of the crust, which further cools the mantle-derived magma and modifies its composition. Cooling, crystallization, and chemical changes take time and are evidence that magmas reach the surface with some difficulty, stalling at various levels, and in many cases failing to reach the surface at all.

Crustal Conditions Influence Ascent of Magma

Some factors that impede ascent of magma are: (1) The shallow crust is relatively cool and loss of heat to the crust forces magmas to grow crystals, which make the magmas more viscous and dense and slows them down. Many small batches of magma lose so much heat that they solidify completely within the crust and never reach the surface. (2) The magma has to open a pathway to the surface and this requires breaking rock and moving it aside. Breaking and moving rock takes work (try it), and this work is accomplished only if enough magma accumulates so that its buoyant (floating) force breaks and displaces overlying rock. In areas that are spreading apart, like mid-ocean ridges, cracks open easily and there is little resistance to the ascent of magmas. Other regions are squeezing together and uplifting mountains, and in these areas it is more difficult for magmas to move to the surface. Larger masses of magma have to accumulate and ascent rates are slower. In some cases the magma doesn't reach the surface at all, and instead solidifies underground, forming ***granite*** and other similar ***intrusive igneous*** rocks like ***gabbro*** and ***diorite*** (granite is ***rhyolite*** or ***dacite*** magma that crystallized underground; similarly, most gabbros crystallized from ***basalts***, and most diorites crystallized from ***andesites***).

Gases Propel Some Magmas to Earth's Surface

Eventually, enough magma may work its way to shallow levels in the crust that some breaks through to the surface and starts the growth of a new volcano. The final few miles of ascent are very different from everything up to that point because the pressure falls low enough that ***gases*** boil out of the magma, making it much more voluminous and less dense. The abundant gases are steam (H_2O) and carbon dioxide (CO_2 pt), with lesser sulfur compounds (SO_2 pt, H_2S). Deep in the crust and upper mantle, the pressures are high enough that most or all of these gases are dissolved in the melt, like the carbon dioxide in an unopened can of soda or a bottle of champagne. With the sudden reduction in pressure close to the surface, the vigorous boiling-out of gases jets the magma out of the ground at high speed, again like a rapidly opened carbonated drink (think of the champagne opened by the winning team at the end of the World Series). High speeds and sudden expansion of gas bubbles fragment the magma into bubbly molten lumps and bits that either cool and harden into various types of ***tephra***, including ***pumice***, or that fall back to the ground while still molten and feed ***lava flows***.

In some situations the gases escape before the magma reaches the surface, in which case the degassed magma is more likely to feed a lava flow or ***lava dome***. Magmas that come nearly directly from the mantle (basalts) are hot, fluid, and relatively poor in dissolved gases. The fluidity of those magmas allows gas bubbles to escape easily, and their ***eruptions*** tend not to be very explosive. The explosive periods are short (hours) and the lavas generally fountain no more than 500 meters (1,500 feet) into the air (fine-grained ***ash*** particles rise higher). Once a clear conduit has opened to the surface, the gas bubbles can escape readily, and eruptions become effusive, feeding lava flows. Most eruptions in Hawaii are of this type.

Magmas that move through the crust slowly, and that cool and change in chemical composition by growth and separation of ***crystals***, and by melting of crustal rocks (andesites, dacites, rhyolites), are viscous (thick, resisting flow) and can have high concentrations of dissolved gases (especially H_2O). Their eruptions can be extremely explosive because of the large quantity of gases and because the magma's increased ***viscosity*** keeps the bubbles from escaping until very close to the surface. Explosive eruptions of dacites and rhyolites can throw magma to more than 20,000 meters (65,000 feet) into the air. So much magma can erupt in a short time that the ground collapses, forming a caldera, like at Yellowstone, Crater Lake, or Long Valley (eastern California). Other, smaller explosions are created where magma encounters groundwater at shallow depths. The groundwater is heated to steam, thereby expanding significantly, leading to explosions that are usually small. For a new volcano, the early explosions are likely to be small and caused by groundwater heated to steam either directly by shallow magma or by hot gases released by shallow magma. Eventually, the groundwater dries out, and larger explosions caused by direct release of magmatic gases take over.

A New Volcano May be Heralded by Events Weeks to Hundreds of Years before the First Explosions

Releases of magmatic gas and boiling of shallow groundwater shake the ground, and produce small ***earthquakes*** and ***steam vents***. It is likely that a new ***volcano*** would be signaled with subtle rise or fall of the ground surface over a broad area, accompanied by frequent small earthquakes, and the release of volcanic ***gases*** either from new cracks in the ground, or into shallow groundwater or springs. Springs and streams might become warmer and richer in sulfur or chlorine derived from the degassing magma at depth. Steam could issue from the ground, or the water could condense underground, leaving only invisible carbon dioxide to reach the surface. Weeks to hundreds of years might pass before the first explosions, depending on the amount of magma involved. The first explosions would probably be small and caused by boiling of groundwater near the surface, and again, weeks to hundreds of years could pass before the first eruptions of magma. Once eruptions commence, the volcano can remain intermittently active for as little as a few decades, or for as much as a million years, depending on the supply of magma.

PRINCIPAL TYPES OF VOLCANOES

(*See* **Lava Building Blocks of Mount Rainier**, **Volcanic Processes**, *and* **Understanding Volcanic Hazards** *for relevant illustrations and activities.*)

Shield Volcanoes

Particular ***volcanoes*** tend to erupt the same kinds of ***magma*** over their history and this results in the volcanoes developing into characteristic shapes. If a volcano mainly erupts high-temperature, fluid, gas-poor magmas (***basalts***), its ***lavas*** can spread as thin ribbons and sheets for long distances in various directions. More lava accumulates close to the ***vent*** than farther away, so if the volcano is active long enough, it builds up into a very broad, gently rounded hump. Seen from a distance, these volcanoes look like enormous shields resting on the ground, and consequently they are known as ***shield volcanoes***.

Shield volcanoes are typically big and long-lived. They include the largest and most active volcanoes on Earth—Mauna Loa and Kilauea in Hawaii. Many shield volcanoes are capped by a circular depression known as a caldera (a broad pit many times larger than any included ***vents*** or ***craters***), and the surfaces of shield volcanoes can be decorated by many smaller shields, ***cinder cones***, and craters. Some particularly large shield volcanoes have systems of aligned fissures where lava erupts preferentially, leading to growth of raised, ridge-like "rift zones" many tens of kilometers (miles) in length. In some cases shield volcanoes are so broad and gently sloping (typically less than 5 degrees steepness) that they are difficult to recognize as volcanoes. In the Pacific Northwest, the broad raised area south of Bend, Oregon, is the shield of Newberry Volcano. Similarly, a broad, raised area east of Mount Shasta, northern California, is the shield of Medicine Lake volcano. Steeper slopes are typical for the submarine portions of oceanic shield volcanoes because water chills lava, reducing the flow distance. Due to ***density*** of water being greater than the density of air, the water also provides buoyancy, allowing lava and rock debris to accumulate to steeper slopes before failing. Nevertheless, steep submarine slopes sometimes collapse, producing large submarine ***landslides*** whose deposits are spread across the deep ocean floor surrounding the volcano. The Hawaiian Islands and the Galapagos (among others) are areas where large submarine landslides have been discovered. Though infrequent (perhaps a few worldwide every 100,000 years), these events are capable of producing large, ocean-spanning ***tsunamis***.

Stratovolcanoes

Many ***volcanoes*** in ***subduction zones*** erupt pasty, viscous magmas (mostly ***andesite*** and ***dacite***, with some ***rhyolite***). Compared with shield volcanoes, their ***lava flows*** tend to be thick and travel short distances, and commonly the magmas break up into fragments, either during explosive ***eruptions*** or by crumbling of the margins of slowly moving lava. End results are that the volcanoes are tall, steep-sided (25 degrees is common), and are made up of diverse combinations of lava flows, ***lava domes*** (flows that are so pasty they just pile up atop the ***vent***), and fragmental rock debris. Typically the upper surface of each lava flow consists of blocky lava fragments and ***ash***, so that successions of flows appear as alternating layers of dense rock (the slowly cooled flow interiors) and ***rubble*** (each flow's rubbly carapace). This distinctly layered or stratified appearance gives rise to the name ***stratovolcano*** (also known as ***composite*** volcano because they are composites of diverse volcanic materials). Like shield volcanoes, some stratovolcanoes are capped by a caldera or crater, though ***calderas*** on stratovolcanoes are usually products of especially large and explosive eruptions (Crater Lake, Oregon), whereas many calderas on shield volcanoes result from summit collapse during the quiescent eruption of large volumes of fluid magma. Because stratovolcanoes are steep, often tall, and are made of poorly consolidated materials, their flanks can collapse, leading to very destructive ***landslides*** and ***lahars*** (fast moving volcanic mud- or ***debris flows***). In slightly more than 100 years, there have been four large collapses of stratovolcano flanks (Mount Bandai-san, Japan, 1888; Bezymianny, 1956; and Shiveluch, Kamchatka, Russia, 1964; Mount St. Helens, USA, 1980), and countless smaller debris flows. The well-known tall volcanoes of the Cascades are all stratovolcanoes.

Cinder Cones

A cinder cone is a third type of volcanic edifice that forms where gas-bearing but fluid magmas (some basalts) erupt from a single location. Most ***basaltic*** magmas have low concentrations of ***gases***, so the gases only boil out very near the surface and jet the magma up to a few thousand feet in the air. The rapid motion and sudden boiling break up the magma into frothy lumps and particles that cool and harden into dark cinders riddled with holes left from the escaping gas bubbles. Because the magma is jetted only short distances into the air, the cinders fall back to the ground right around the ***vent*** and pile up into a cone. ***Cinder cones*** usually form during only one eruption or ***eruptive period***, though this period may consist of multiple separate eruptions spaced over years or even decades. Cinder cones are small features, typically no more than one kilometer (slightly more than half a mile) across and up to 300 meters (one thousand feet) high. In Hawaii, eruptions frequently begin with many hours of ***lava fountaining***, where magma jets into the air from vents spaced closely along a crack in the volcano's surface. Quickly the eruption narrows to one or a few locations and the height of magma fountaining lowers. Cinders start to accumulate around these vents, piling up as cinder cones. At times, magma will well up within a cinder cone and breach its wall. The magma then pours from a notch or gap in the side of the cone, feeding a lava flow. This can happen several times, but continued low fountaining of magma at the vent can quickly heal the gap by filling it with cinders. When the eruption ends, the lava flow can deceptively appear to have tunneled out the side of the cinder cone.

Large Ash-Flow Calderas

Ash-flow calderas are another major type of ***volcano***. These volcanoes are usually many tens of kilometers (miles) across and develop over hundreds of thousands to more than a million years, during which large volumes of gas-rich, viscous magma erupt suddenly and explosively, one or more times, separated by extended periods of intermittent ***lava*** eruptions. During the explosive events, the magma first jets high into the atmosphere, breaking up into ***pumice*** and ash, but then so much material erupts in a short time that pumice and ash collapse down and sweep across the landscape as a high-velocity sheet of hot ***tephra***. These eruptions bury the landscape in blankets of hot ash tens to locally hundreds of meters thick. In some, the ash and pumice are still so hot when the flows comes to rest that the grains stick together, squeezing out hot ***gases*** and air, and collapsing and cooling into dense rock—a process known as "welding". So much magma can erupt in a short time that the ground surface collapses, creating a circular or oval depression kilometers to tens of kilometers (miles to tens of miles) across, and in some cases swallowing up part or all of the preexisting volcanic edifice. Because large ash flows travel many tens of kilometers (miles), the resulting volcanoes have low, broad forms, much like a shield volcano capped by a large caldera. Subsequent eruptions of pasty lava often partly fill the caldera, and shallow intrusions of magma can bow the caldera floor upward, both obscuring its shape. Yellowstone is probably the premier example of a large ash flow caldera.

VOLCANO AND MOUNTAIN BUILDING IN THE PACIFIC NORTHWEST

(*See* **Cascade Volcano Timeline** *and for relevant illustrations and activities.*)

Current Volcanoes of the Cascade Range Grew upon Older Mountains

Images of the Pacific Northwest center on forested mountains sloping down to the sea. The mountains are snow capped in their highest reaches and formed in two ways. Most are made of rocks that were pushed up by squeezing and sliding forces along the edge of the North American tectonic plate, much like rumpled covers on an unmade bed. The currently ***active volcanoes*** of the Cascades grew atop these mountains by ***eruption*** and accumulation of ***lava***, like gigantic versions of the drip castles children make at the beach. While the two types of mountains formed in different ways, they are not unrelated. Many of the rocks forced up by squeezing and sliding processes were originally lavas and other ***volcanic rocks*** that erupted tens of millions of years ago, or are ***granites*** that crystallized miles underground from ***magma***s that failed to erupt. Active volcanoes are few and small in the North Cascades, the highest part of the Cascade Range. It is likely that strong squeezing and uplift there prevents most magma from penetrating the crust. Instead, magma probably ponds near the base of the ***crust*** and, in part, buoys up the region.

Coastal Mountains Built by Faulting and Squeezing along the Continental Margin

The detailed development of the Pacific Northwest landscape is complicated. In simple terms, two parallel mountain belts, the Coast Ranges (including the Olympics) and the Cascades, are separated by a valley occupied in the south by the Willamette River and in the north by Puget Sound. Offshore, ***oceanic crust*** generated at the ***Juan de Fuca Ridge subducts*** in a northeasterly direction beneath North America. As the oceanic crust subducts, sandstones, mudstones, and volcanic hills are shoved beneath the edge of the continent and warp it upward. Much of the Coast Range, particularly in the Olympics, are built of rocks scraped off the subducting oceanic crust. Since the subducting oceanic crust is moving oblique to the north-trending edge of the continent, the rocks of the Coast Ranges are also being shuffled to the north and are twisting or rotating slowly clockwise. This slight northward shuffling extends into the valleys east of the Coast Range and drives motion on recently discovered ***faults*** that cut beneath the cities of Seattle and Portland. Many of the rocks that are uplifting to form the Coast Range, and that underlie the valley between the Coast Ranges and the Cascades, are lavas that erupted under the sea. These lavas probably erupted as ***seamounts*** near a mid-ocean ridge, as is indicated by the lavas' distinctive chemical compositions. It is likely that the Willamette Valley, Puget Sound, and the eastern margin of the Olympics are floored by a fragment of oceanic crust that formed about 60 to 45 million years ago, as demonstrated by radiometric measurements of the lavas' ***eruption*** ages. In places these lavas are inter layered with sandstones and shales composed of ***sediments*** derived from the land showing that the seamounts grew not far off the margin of the continent. The seamount lavas are overlain by thick accumulations of ***sedimentary rocks***, varying between 50 and 40 million years in age. This indicates that by about 40 million years ago the region had become attached to the edge of North America.

The North Cascades are Built Mainly of Granites and Metamorphic Rocks

The North Cascades, from Snoqualmie Pass (due east of Seattle) into British Columbia to the north, are made chiefly of highly metamorphosed (recrystallized by heat and pressure) volcanic and sedimentary rocks that are intruded by masses of granite. The original volcanic and sedimentary rocks were erupted or deposited from about 100 million to perhaps slightly more then 1 billion years ago, and were assembled by ***fault*** action to form narrow northwest-trending belts of related rocks, each belt about 25 kilometers (15 miles) wide and 160 kilometers (100 miles) long. Where these ***metamorphic*** rocks originated, and how they came together, is not understood well at all. Granites of roughly two ages intrude (cut and displace) the metamorphic rocks and many of the faults. These granites crystallized as the deep underground roots of subduction-zone ***volcanoes*** that have since been eroded away. One group of granites crystallized about 90 million years ago. The other group is younger, having crystallized between about 35 and 15 million years ago, but there are also very small masses of granite as young as about 2 million years. Many of the older granite masses solidified roughly 25 kilometers (15 miles) deep in the ***crust***, while the younger granites crystallized at much shallower levels, perhaps no more than about 8 kilometers (5 miles) deep. The difference in crystallization depths shows that the region was uplifted into mountains and deeply eroded at least once, and possibly several times over the last 90 million years.

South of Snoqualmie Pass, the Cascade Mountains Consist of Volcanic and Sedimentary Rocks

From near Snoqualmie Pass southward, most of the Cascade Range is composed of ***lava,*** sedimentary rocks derived from lava (sandstones and breccias), and some pyroclastic rocks. The earliest of these ***volcanic rocks*** erupted about 40 million years ago and partly bury the older sandstones and shales that cover the seamount lavas flooring the Puget and Willamette basins. The appearance of widespread volcanic rocks at 40 million years ago marks the beginning of the Cascades magmatic arc, a belt of vigorous volcanic activity driven by ***subduction*** off the margin of North America that extends from northern California to southern British Columbia. Many ***volcanoes*** began, grew, and died, and the currently active Cascade volcanoes are only the latest products of this ongoing process. At first, volcanoes spread lava flows and related sediments broadly over a relatively flat region along the edge of the continent, and under part of the ocean. Eventually, taller volcanoes grew and their eruptive products overlapped one another. From time to time, periods of modest squeezing and faulting uplifted, tilted, and folded (bent) the volcanic rocks. ***Erosion*** incised gentle valleys through the volcanic debris, and later eruptions refilled some valleys with volcanic rocks. Gradually, the volcanoes grew high enough to cast a rain shadow east of the Cascades. At the same time, the crust underneath much of the volcanic range was subsiding, allowing the accumulation of perhaps as much as a 15-kilometer (about 10 mile) thickness of volcanic rocks spanning the Cascades from southern Washington through Oregon.

Subsidence of the crust ended in the southern Washington Cascades near or shortly after about 14 million years ago, and was followed by strong uplift. This uplift raised the volcanic rocks, and erosion cut into these, exposing small masses of granite that were the underground feeder systems for long-lived volcanic centers. The youngest granites in southern Washington solidified at about 8 kilometers (5 miles) below the surface from 17 to 14 million years ago. That these granites are now exposed on the surface shows that as much as 8 kilometers (5 miles) of uplift and erosion have taken place since then. A large, nearly flat basin lay to the east of the active Cascades volcanic chain. Over the period of 17.5 to 13.5 million years ago, a great outpouring of hot, fluid lava erupted from near the present Washington – Idaho – Oregon border and flowed westward to the eastern foot of the Cascades. These lava flows, known as the ***Columbia River flood basalts***, form great stacks of flat-lying, dark lavas along the Columbia River and its tributaries east of the Cascades. Some of the flood ***basalts*** even reached the Pacific Ocean through the gap in the Cascades carved by the Columbia River. The flood basalts are uplifted and tilted eastward along the east side of the Cascades in Washington, confirming that much of the uplift of the Cascade Range is younger than about 14 million years ago. Uplift results mainly from regional squeezing and shearing motions along the ***North American plate*** margin and probably continues today.

The Cascade Range in Oregon—Less Complex than in Washington

In Oregon, the Cascade Range has not been squeezed and uplifted to the extent it has in Washington. As a result the volcanic rocks in Oregon are not as steeply or complexly tilted. Instead, the mountain range in Oregon is spreading apart slightly, with the western slope moving to the west and north relative to the eastern slope. Global Positioning System (GPS) measurements show that this sense of motion continues today. The minor extension (spreading) allows fissures to open easily and ***vents*** magmas to the surface over broad areas. Whereas in Washington, the large ***active volcanoes*** are separated by 100 to 160 kilometers (60 to 100 miles) of folded, tilted, and eroded older rocks, the large volcanoes in Oregon are separated by chains of smaller volcanoes whose lava flows were fed by ***basaltic*** magmas that ascended though these fissure systems. Magmas were able to rise quickly along the fissure systems and arrived at the surface hotter and less modified chemically than most lavas erupted in the Washington Cascades.

Pacific Northwest Plate Tectonics Summary

Plate tectonic processes forged the landforms of the Pacific Northwest. In the North Cascades, the dominant mountain-building processes are squeezing and uplifting of older rocks. Few young volcanic deposits remain, and possibly few magmas are able to reach the surface because of tectonic forces holding fissures closed. Granite intrusions are the chief products of magmatism preserved in the North Cascades. It is also possible that some of the ongoing uplift in the North Cascades is due to buoying up of the region by magmas trapped beneath the ***crust***. In Oregon, constructional volcanic features define the landforms of the Cascade crest. Southern Washington represents a complex transition area, where much lava has erupted. However, the region has also been squeezed and uplifted, mainly in the last 14 million years, so that most landforms result from faulting, ***folding***, and ***erosion*** of relatively young volcanic rocks. To human observers, the currently active Cascade ***volcanoes*** are large, impressive, and potentially dangerous, but in the overall history of the Cascades, they are comparatively small volcanic centers.

MOUNT RAINIER AND SOME COMPARISONS WITH NEIGHBORING CASCADE VOLCANOES

(*See* **Fire, Flood, and Fury**, **Nineteenth-Century News**, **A String of Volcanoes**, **Volcano Hall of Fame**, **Lahar in a Jar**, *and* **The Next Eruption of Mount Rainier** *for relevant illustrations and activities.*)

Eruptions Built Cones of Many Cascade Volcanoes during the Ice Ages

All of the large ***active volcanoes*** in the Cascades started to grow during the ***Ice Ages*** (a period from about 2 million to 10,000 years ago) among earlier, older mountains. ***Glaciers*** filled most of the high mountain valleys, and mountain slopes were sheathed with snow and ice fields. It is likely that many Cascade volcanoes began near or beneath snow and ice with early steam ***vents*** melting ice caves and pits. Meltwater from the glaciers would have flooded into the ***steam vents***, leading to small explosions. Eventually, small amounts of ***magma*** reached the surface, melted through and chilled against snow and ice, and formed small ***lava flows*** and ***lava domes***. Explosions would have spread muddy debris onto the glaciers, forming wet, boulder-rich slurries (***lahars***) that traveled far down the glacier systems. Between ***eruptions*** the glaciers would have ground away at the early lava flows, in some cases removing them entirely. As more and more ***magma*** reached the surface, eruptions would have become more frequent and voluminous, building volcanic edifices that were large enough to support their own glacier systems. At the end of the Ice Ages, the glaciers retreated to areas of highest elevation, such as at Mounts Rainier, Adams, St. Helens, Hood, Baker, Shasta, and Glacier Peak – all ***active volcanoes*** today.

Evidence that Mount Rainier is an Active Volcano

Anyone who has climbed to the summit of Mount Rainier will have seen evidence that the ***volcano*** remains active and will erupt again. The summit is capped by two ***craters***, each about 0.4 kilometer (0.25 mile) across. The crater to the west is the older and is overlapped by the east summit crater, which is a nearly perfect circle of outward sloping lava, uninterrupted or breached by the large glaciers that begin near the summit. If this were an old, ***extinct volcano***, the ***glaciers*** would have carved pieces out of the craters. Moreover, steam and warm mist emanate from areas along the inner walls of both craters and have melted a complex of caves into the ice that fills the crater floors. From the first ascent of Mount Rainier in 1870, climbers have sheltered in these caves, steamed on one side, and frozen on the other. The steam is evidence that Mount Rainier is still receiving heat from below. Besides these qualitative observations, age measurements of ***lavas*** and ashes from Mount Rainier show that the last lava erupted close to 2,200 years ago, and that ***pyroclastic flows*** erupted as recently as 1,100 years ago. Small amounts of ***ash*** and ***pumice*** erupted from Mount Rainier as recently as the 19th century. Minor pumice was deposited between A.D. 1820 and 1850 and there are reports of an observed ash eruption in late November and December of 1894. The truth of the 1894 accounts has been questioned, and no physical evidence (ash, pumice) has been found to corroborate an eruption. Nevertheless, many of the descriptions match the behavior of small ***ash clouds*** produced by very minor eruptions of other volcanoes, and it is likely that Mount Rainier did erupt in 1894 as reported. Mount Rainier has been active for the last 500,000 years; so the 2,200-year interval since the last known lava eruption is less than half a percent of the lifespan of the volcano. The style of volcanic activity remains the same, with no evidence of diminution. For these reasons, Mount Rainier is considered to be an ***active volcano***, and another eruption could begin with little warning.

Some Comparisons with Neighboring Volcanoes — Mount Adams and Mount St. Helens

The various Cascade ***volcanoes*** are subtly different in their eruption styles and magma types. Most of the time, Mount St. Helens erupts relatively low temperature, viscous magmas known as ***dacite***. Because these magmas are ***viscous***, gas has difficulty escaping and the eruptions can be very explosive, lofting ***pumice*** and ***ash*** in a great column high into the air. This ***tephra*** from Mount St. Helens has been carried by the wind, predominantly to the east, leaving extensive sheets of ash and pumice. In fact, most of the obvious ash layers visible in road and stream cuts at Mount Rainier were actually erupted from Mount St. Helens. If gas escapes from the dacite before an eruption, as often happens after an early explosive event, the dacite erupts as a slow-moving pasty mass that piles up atop the vent, or creeps slowly down the side of the volcano. Such extrusions are known as lava domes and made up most of Mount St. Helens prior to its catastrophic 1980 eruption. Most of the activity subsequent to the May 18, 1980 blast has been dome-building. Mount St. Helens is unusual in that it also erupted small amounts of high temperature fluid ***basalt*** and more voluminous dacite from the same vent. Obvious mixtures of basalt and dacite, that are intermediate in chemical composition and eruptive style, have also erupted. The present edifice of Mount St. Helens grew quickly, over the last 30,000 years, and the volcano has been, and is likely to continue to be, the most frequently ***active volcano*** in the Cascades. Recently discovered evidence shows that the location of Mount St. Helens has been volcanically active for several hundred thousand years, but it is unclear why no large edifice remains from that earlier activity. Possibly, the volcano collapses so frequently, as in 1980, that older edifices are destroyed; or perhaps there were very long spans of repose between vigorous ***eruptive periods*** so that ***erosion*** was able to strip away the earlier edifices.

Mount Adams is about as different from Mount St. Helens as any major Cascade volcano. Mount Adams has erupted countless flows of ***andesite*** lava, many of which are close to basalt in chemical composition, and hence eruptive style. Dacites are rare, and there are no known eruptions or deposits of pumice from Mount Adams. Its ***lava flows*** are more viscous and short-traveled than basalt, typically with rubbly flow tops, so Mount Adams is a ***stratovolcano*** with a high, rounded shape, unlike a ***shield volcano***. Sulfur-rich volcanic ***gases*** have emanated widely around Mount Adams' summit, condensing as acidic waters. The acidic waters have altered a wide region of the summit rocks into clay-rich, soft, yellowish-brown material that has collapsed as multiple small ***debris flow***s. Fortunately, few people live around Mount Adams. Mount Adams started to build around 500,000 years ago, but most of its growth was in two time intervals of about 25,000 years duration each.

Mount Rainier is intermediate between Mount St. Helens and Mount Adams in eruptive style and magma composition. Most of Mount Rainier is made of andesite and some dacite lava flows, and the volcano has erupted sizeable amounts of pumice throughout its history, though not as voluminously or as frequently as Mount St. Helens. Pyroclastic flows, formed by explosive fragmentation of magma rising through the conduit system and by collapse of lava flows traveling over steep terrain, are a minor but ubiquitous component of Mount Rainier's eruptive products. Lava domes are almost unknown at Mount Rainier, unlike Mount St. Helens, probably due to the overall more fluid andesitic magmas at Mount Rainier. Around 500,000 years ago, Mount Rainier started to grow atop the eroded remains of an earlier ancestral Mount Rainier that was active 1-2 million years ago. The modern edifice grew as a series of four alternating stages of voluminous and modest volcanic activity, averaging a little more than 100,000 years duration. The periods of high output saw the eruption of Mount Rainier's largest and longest reaching lava flows, some of which traveled about 24 kilometers (15 miles) from the summit and had volumes as great as eight cubic kilometers (approximately two cubic miles.) In the periods of modest volcanic output, including today, the lava rarely extends beyond eight kilometers (five miles) from the summit. Glaciers deeply filled the surrounding valleys over most of the volcano's history. Lava flows skirted the margins of the glaciers, and when the Ice Ages ended, the solidified lavas were left high above the newly exposed valley floors.

Like Mount Adams, Mount Rainer had sizeable areas of ***hydrothermally altered rock*** in its upper portions. Most of these rocks collapsed 5,600 years ago as an extremely voluminous lahar, known as the ***Osceola Mudflow***. The Osceola Mudflow swept down the west and main forks of the White River, reaching the then limit of Puget Sound near present-day Puyallup. The Osceola collapse left a horseshoe-shaped crater, open to the eastnortheast, much larger than the crater produced by the 1980 eruption of Mount St. Helens. Most of the Osceola crater has been filled in by subsequent lava eruptions, most recently about 2,200 year ago. The ***Electron Mudflow*** swept hydrothermally altered rock from the west side of the volcano approximately 500 years ago.

Future Eruptions and Lahars at Mount Rainier

New eruptions of Mount Rainier will most likely be small, starting with steam and ash explosions at the summit, and progressing to the effusion of a small lava flow or the explosive release of a pyroclastic flow. Either type of eruption will probably create lahars that can reach heavily populated areas. Weak, hydrothermally altered rocks remain at high elevation on the volcano's west flank, and some of this material could be dislodged by ***earthquakes*** during an ***eruptive period***. We cannot rule out the possibility that altered material could collapse due to its own weakness, without a triggering eruption or earthquake. Many people live in the river valleys downstream from Mount Rainier, so these eruptive and collapse events pose substantial ***hazards*** that are the reason for concerted scientific studies of Mount Rainier.

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