Volcanism – Tutorial Script

Volcanoes and volcanic activity are found wherever rocks inside the Earth have melted and rise buoyantly to the surface to erupt. We call molten rock underground a **magma**. Magma is less dense than the solid rock that surrounds it, thus it will migrate upwards towards Earth's surface. Migration happens along cracks between solid rocks. Gradually the cracks intersect and magmas pool together in **magma chambers**, which usually sit a few kilometers below Earth's surface.

When magma erupts and flows on the surface, we call it **lava**. When lava is ejected sky high in an explosive eruption carried by escaping gases, it cools and solidifies quickly as it's thrown through the air. We call these now-solid ejected particles, **tephra**, which come in all sizes. Mud- or flour-sized particles flash freeze to form glass particles called **ash**. We call the larger rounded particles **cinders.** Lavas, tephra, and gas are the primary eruptive products of volcanism. What causes a volcanic eruption? How can we simulate one? Let's start with a simple lava eruption and use a garden hose as an analogy. At any given time when the water is turned off, the hose is filled with the water that was present during its last use but never drained. This is similar to magma sitting in a magma chamber. To remove the water, you open the valve to allow more water to move into the hose. So lavas erupt when new magmas enter the magma chambers at depth and push the existing magmas out. The best simulation of an explosive volcanic eruption is what happens when you shake up a can of soda. Gases dissolved in the soda will migrate out of the liquid and up to the top of the soda can or bottle where they will collect and pressure will build. When magmas rich in gases pool up in chambers in the crust near Earth's surface, gases will escape and pile up at the top. Pressures will build, and eventually cracks will form that allow that pressure to be released, like opening the can of shaken soda. The gas will quickly escape, rising upwards carrying droplets of soda or lava. Small droplets of lava flash freeze to ash, the larger pieces become cinders.

A **volcano** is the landform created through the piling up of lava flows and ash deposits when volcanism happens in a single location over a long period of time – hundreds of thousands to millions of years. We will discuss the various types of volcanoes and other volcanic landforms later in this video tutorial.

Let's descend below the surface to the place below where the magmas first form. We will pass through the crust riddled with plutons across the border between the crust and mantle and into the underlying mantle. Here is where the magmas first form. Why? What is happening here to make the rock melt? The mantle that sits under the crust is very hot (around 1000° Celsius (1832° Fahrenheit)), which is very close to its melting temperature. To melt it partially, we either raise the mantle temperature or we find a way to lower the melting temperature of the rock. When pressure is low, a rock's melting temperature drops and it will melt more easily. Similarly, in the presence of water, a rock's melting temperature also drops. So now we see that there are three ways to melt a hot rock: raise its temperature to its melting point or drop its melting point by dropping its pressure or adding water.

Volcanoes or volcanic activity present on Earth's surface correlate with one of three different geologic settings each of which correlates as well to a different way of melting the mantle: a subduction zone, a divergent plate boundary, or a hotspot. Note: the audience for this video are students of a general geology class who have already learned about Plate Tectonics. If your knowledge of Plate Tectonics is weak, please review the video tutorials on Plate Tectonics before continuing.

Subduction zone magmas are produced by water-rich oceanic crust sinking into the mantle. As the descending oceanic crust moves into areas of higher and higher pressure, it is squeezed, and the water that was soaked up by the seafloor rocks is released, rising upwards into the wedge of mantle rock trapped between the subducting plate and the overriding plate. That water reduces the melting temperature of the rocks, and the mantle will partially melt producing magmas that rise to the surface and form volcanoes. Most of the world's examples of subduction zone volcanoes are found in the Ring of Fire around the Pacific Ocean. These include the Cascade Mountains in the Northwestern United States, The Aleutian Islands of Alaska, the Kamchatka Peninsula in Russia, Japan, the Philippines, Guam and the Marianas Islands, Indonesia, Papua New Guinea, the Solomon Islands, Vanuatu, Tonga, New Zealand's North Island, The Andes mountains of South America, and the volcanoes of Central America and Mexico. We also see some subduction zone volcanoes in Italy, Greece, and the Caribbean.

Divergent plate boundary volcanism is produced by the thinning of the lithospheric plates as they are stretched apart. The subsequent reduction in pressure in the underlying mantle reduces the melting temperature of the rocks. Magmas form and rise to the surface to produce volcanism. Because of coincident spreading, lavas rarely pile up fast enough to produce volcanoes or rise above sea level. Instead, they simply produce more oceanic crust, and spread and make bigger oceans. Thus divergent plate boundary volcanism is found throughout the world's oceans on the mid-ocean ridges that mark the spreading centers.Occasionally we see divergent plate boundaries that are still splitting apart continent and haven't yet developed low-lying ocean basins. An example is in the East African Rift Valley. In such cases the rate of spreading is so slow that lavas can pile up in a single location, and we can see volcanoes forming above the surface, such as the famous Mt. Kilimanjaro.

The third geologic setting for volcanism is known as a **Hotspot** or **Mantle Plume**. In such settings, hot plumes of mantle material rise from as deep as the core-mantle boundary to the surface. As this heat partially melts the mantle, the material rises upwards producing more melts and accumulating in a large mushroom-shaped head that pools and pushes up under the plates and the embedded crust. Eventually these heads produce a series of parallel cracks or fissures and over a million years or more, that molten material in the head will pour out on the Earth's surface in large-scale eruptions that flood the landscape. These eruptions produce what we call **flood basalts.** They mark the intial breakthrough of a hotspot, and the layers of basalt flows that result can be hundreds of meters thick and cover areas as large as 340,000 km^2. Once a hotspot's initial eruption ends, volcanism will continue in a much more localized area until the root fully disappears. The main hotspot root can last a hundred million years or more, producing a chain of volcanoes on the surface that are carried away by plate motion, go extinct, and erode away while new volcanoes form on the plate that sits over the active hotspot. In other words, the hotspot stays relatively fixed, while the plate moves over it. Each volcanic system along the chain accumulated its lavas over about a million years. A great example of a hotspot island chain is the Hawaiian Island-Emperor seamount chain in the center of the Pacific Ocean.

In both subduction zone and divergent plate boundary volcanism, magma supply is low and episodic, so magmas can sit for a while in magma chambers. In these chambers, the magmas can chemically evolve from their original composition, which we refer to as **primitive** or **mafic**, through an **intermediate** composition and then to **felsic** composition magmas. For a more thorough explanations of what's happening in the magma chamber to cause this chemical evolution, refer to the video tutorials on Igneous Rock formation. For purposes of this video tutorial, we need know only that the more primitive mafic magmas are characterized by low water/gas content, low silica content, and low viscosity. Upon eruption, these lavas flow quickly and easily and easily allow gases to escape. Evolved felsic magmas are characterized by high water/gas content, high silica content, and high viscosity. When erupted, these lavas are sticky and produce thick slow flows, often plugging up the vents and trapping gases. Intermediate magmas sit between the two compositionally. For felsic magmas, with high gas content trapped in a highly viscous magma, pressures can build, and the consequent eruptions can be powerful and destructive. The most explosive and dangerous eruptions in the world happen with felsic magmas. In general, the more time magmas spend in the crust, the more likely they will evolve from mafic to intermediate to felsic and thus be associated with explosive eruptions. When magmas move quickly through thin ocean crust, they are more likely to remain mafic in composition. When they rise slowly through thick continental crust, they are more likely to evolve to intermediate or felsic compositions. Therefore, divergent plate boundary and subduction zone volcanism that occurs through continental crust can produce some of the most explosive eruptions on the planet.

Hotpot volcanoes have magma supplies about 10 times larger than divergent plate boundary or subduction zone volcanoes and thus produce some of the largest volcanic landforms on the planet. (That means the initial flood basalt eruptions are about 100 times larger than typical divergent plate boundary or subduction zone volcanoes). Volcanism is accompanied by the eruption of large amounts of gas – primarily carbon dioxide, sulfur dioxide, and water. The Sulfur Dioxide gas can combine with water droplets in the air to produce aerosolized sulfuric acid droplets that block incoming solar radiation and if present in high enough quantities can cool the Earth’s surface substantially. Since flood basalt euptions are so voluminous and can continue over a million years or more, they can produce a lot of this gas and have a major impact on climate. These images show the correlation between flood basalt eruptions from the initiation of a hotspot and major mass extinctions throughout Earth’s history. Much research is underway to explore these connections even further.

When hotspot volcanoes erupt through oceanic or continental crust, because the magma supply is so large (and the transit to the surface so quick), they produce mostly low-viscosity mafic lavas. However, where magma supply is lower (such as on the edges of the plume) and they erupt through thicker crust, they can evolve to produce more felsic magmas. Also if the magma supply is great enough and the chamber underground large enough, the heat from the magma can melt the surrounding crust. This melted crustal material is felsic in composition. In such cases, we can see eruptions of mafic material from the center of the magma chamber, and felsic material from the edges of the chamber. In the former, eruptions are fast-moving lava flows spreading quickly and far from the vents. In the latter, there can be large amounts of gas and pressure and highly explosive large-volume ash eruptions.

In a few oceanic locations, such as Iceland and the Azores, hotspots coincide with divergent plate boundaries. In these cases, because the magma supply is now ten times larger than the rest of the spreading centers north and south, lavas can pile up above sea level faster than spreading can separate them. Thus we get large ocean islands forming atop the spreading center, some of which, such as Iceland, continually widen as seafloor spreading continues.

What do erupting volcanoes look like during and after eruptions? What kind of hazards are associated with them? Are all volcanoes equally hazardous?

As already mentioned, the primary products erupted from volcanoes are lava flows, tephra, and gas. Let's look at each more closely and the hazards and features associated with them.

Lava flows vary considerably in their behavior depending on their composition. Thicker flows mean more viscous evolved lavas. They likely didn't travel far from the vent. Thinner flows were less viscous, more primitive lavas that likely did travel far from the vent. If these now-solid lava flows contain vesicles throughout (holes in the rock, like swiss cheese), it means that gases were freely escaping from the lava as it flowed and cooled around them. Primitive mafic lava flows can be divided into two types, **pahoehoe** and **aa** lavas, which we can recognize from their thickness and surface features. Pahoehoe lavas have a smooth glassy ropy texture on the top and are the thinnest of the two (think of what the top of brownies look like after cooked). Aa lavas are thicker with a rubbly rough but also glassy surface. Aa are slightly higher vicosity than pahoehoe probably because of a slightly higher silica content and/or cooler temperatures. The more evolved intermediate or felsic lavas are even thicker. If vesicles are present at all they will likely be stretched as the lava flows, like what you see when taffy is forming. The most evolved felsic lavas are so sticky viscous that they don't move far from the vent and create domes or plugs atop their vents. The atoms within these lavas can't migrate quickly or easily enough to form crystals during solification, so these domes or plugs can end up 100% glass known as obsidian.

Some lava flows display a cooling feature known as **columnar jointing**, which results when lava flows are cooled a bit slower than normal from their surface and their base simultaneously. While cooling, the lava shrinks, forming cracks that propogate much the same way as mud cracks form. The shrinking cracks produce geometrically shaped often hexagonal columns. Columnar jointing occurs mostly in primitive lavas that cool very close to the surface, but are insulated somehow by their surroundings, so they cool a litle more slowly than normal. These cooling cracks can also form within welded ash deposits that collect within a valley.

Lava flows are rarely hazardous to human life. Even the fastest primitive lavas move at speeds of 4 km/hour and can be easily walked away from. But they can and do destroy human infrastructure that can't be moved, such as buildings, roads, and signs. Low-viscosity primitive lava flows can travel tens of kilometers from the vent. People who live on the flanks of volcanoes with active lava flows must always be prepared to have eruptions in their backyard and potentially cover their property: a major problem for people who live on the active Big Island of Hawaii. This map shows in red the locations of lava flows over the past 150 years and shows the risk associated with continual eruption of the Mauna Loa and Kilauea volcanoes and even the slighly less active but still hazardous Hualalai Volcano to the north.

The volcanic product and hazard that travels furthest from the vent is **ash** ejected from the vent of a volcano in an explosive eruption typically associated with more evolved intermediate or felsic composition lavas because they have more gas. Ash can travel up into the atmosphere many kilometers. If it reaches above the troposphere it will be picked up by the jet stream and carried around the globe. Within the troposphere itself, the zone of weather, it will be picked up by prevailing winds and carried hundreds to thousands of kilometers away. The amount of ash that collects on the surface after an eruption will depend on the size of the eruption and the distance from the vent. Closest to the vent the erupted material can also include large pieces of **tephra**, which we already have called cinders but can also known as **volcanic bombs**. For any person present near the vent during eruption, these volcanic bombs can be deadly if hit by them. Building roofs can collapse under the weight of ash or cinders. Other hazards associated with the ash are asphyxiation if thick enough, clogged machinery – including airplanes that fly through ash clouds, lost crops, and breathing problems increased for asthmatics.

If the ash falls on glacial ice and melts it, or gets picked up by rains, it can migrate down into streams and rivers and lakes and produce fast-moving dangerous **mud flows** or **lahars** that can travel hundreds of kilometers from the eruption site, taking out bridges, structures, and towns anywhere in its path. The safest place to be if a lahar is in progress is along ridge lines above the river valleys. There are many towns near the base of volcanoes that are built on old lahars and thus are susceptible to future inundation. City planners in these zones need to be aware of the past history of eruption of the volcano on which they live. For example, Armero is a town in Columbia that has been rebuilt numerous times in the same place after destructive lahars have destroyed the town in the past. The last lahar in 1985 killed more than 20,000 of the town's 29,000 inhabitants. Ultimately these towns will be safer only if moved to higher ridge lines.

If the amount of ash is voluminous enough and ejected high enough, the column of ash can collapse under its weight and surge down the volcano's flanks in catastrophic flows of ash and debris. These **pyroclastic flows** can be buoyed up on a layer of gas that reduces their friction and allows them to move up to 200 km/hr and travel tens of kilometers from the vent even up and over ridges. They can entrain surrounding rocks as well as larger blobs of lava. This hazard kills the most volcanologists (people who like to stay close to erupting volcanoes). If caught in a pyroclastic flow, there is no chance of survival.

The volcanic hazard that is most stealthy and silent is a **cloud of carbon dioxide gas** that forms above a crack or vent and represents a place where gases are seeping out of the underlying magma chamber. Because carbon dioxide gas is more dense than the surrounding oxygen- and nitrogen-rich air, clouds of carbon dioxide gas will collect on the surface and not necessarily mix with the air. These clouds are invisible and odorless and will roll down hills and settle into the bottoms of valleys, potentially migrating tens of kilometers from the vent. Living organisms trapped within these clouds will die of asphyxiation. In the Long Valley Caldera area of California, carbon dioxide gas clouds have killed the roots of trees in portions of the national forest. In Africa, these gas clouds have descended on villages throughout historical times and suffocated villagers in their sleep or during their daily routines.

Another hazard associated with volcanic gases comes from the Sulphur Dioxide gas that combines with water in the atmosphere and produces **acid rain**. If these droplets reach high into the atmosphere, they can reflect incoming solar radiation and lead to global cooling. At the surface, as they fall to Earth they can lead to increased decay of structures and fabrics, contaminate water, and lead to a temporary lull in growth of vegetation.

Lava flows and ash or pyroclastic flows or lahars, if accumulated in the same location on the surface over hundreds of thousands to millions of years, will produce **volcanoes**. All volcanoes on Earth's surface can be classified as either **shield** or **strato volcanoes**. Shield Volcanoes are built almost exclusively of primitive mafic low-viscosity lava flows that travel large distances and collect over a million years to create a tall broad volcano with gentle slopes. Shield volcanoes can be some of the tallest edifices on Earth's surface. The Hawaiian shield volcano of Mauna Loa is 9,170 m (30,085 ft) when measured from its base on the seafloor. Because of their gentle slopes, shield volcanoes aren't as noticeable in the landscape as the mostly shorter but much steeper strato volcanoes. Stratovolcanoes are built up of alternating ash deposits, lahars, pyroclastic flows, and intermediate or felsic lava flows that don't flow far from the vent. Material accumulates more thickly at the vent, producing steep slopes. A tall stratovolcano, such as Mt. Kilimanjaro, has a height from its surrounding base of 4,900 metres (16,100 ft).

Volcanic landforms also include **plugs or domes** and **cones**. Plugs or domes are highly viscous felsic lavas that rise up through the crust and because they don't flow far away from the vent, act as a plug and trap the rest of the magma under the surface. Many of these domes are so visous they are made exclusively of obsidian (100% glass). Domes or plugs are usually indicators of high volcanic danger, as pressure can build quite high beneath them. Mt. St. Helens has a dome inside its crater, and periodically as pressures build, it cracks and releases small ash and gas eruptions. Cones form through a single small eruption on the flanks of shield or stratovolcanoes accompanied by enough gas that they eject their lavas as tephra in fountains. What remains is a pile of cooling cinders.. Based on the flow rates of these fountains they can be referred to as spatter cones (slopping eruptions) or cinder cones (more consistent ejections that fly through the air and acculumate as perfectly shaped cones of unconsolidated cinder).

Sometimes magmas under volcanoes don't erupt. They remain in cracks or chambers underground and cool and solidify slowly producing rock formations known as **plutons** and discussed further in the Plutons video. If you could dig under the volcanic edifices we see on the surface, you will find numerous plutons injected into the crust below.

Next time you have the good fortune to hike or explore around a volcano, look for the evidence of its past eruption styles. See if you find lahars or pyroclastic flows, high-viscosity or low-viscosity lava flows, and use this information to determine the hazard level of the volcano. City planners should already have hazard maps for all of the volcanoes that could affect their city. Review these maps and be sure that if you buy property you buy it in a place that minimizes your exposure to volcanic hazards.

Volcanoes

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*Mammoth Mountain Tree Deaths (field sites and scientific illustration) – USGS
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*Volcanic structure in Cross-section – USGS
*Cross-section illustrations of Cinder Cones, Domes, Shield Volcanoes, and Stratovolcanoes – USGS
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