VOLCANOES, A REVIEW

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Introduction:

A volcano (the word is derived from Vulcan, the Roman god of volcanoes) is any place where molten rock, volcanic ash, or volcanic gases are, or have been, erupted onto the surface of a planet. Volcano also refers to the edifice of erupted products. Molten rock below the surface is called magma whereas on the surface it is called lava. Depending mostly on how much gas the magma contains, volcanic eruptions can range from quiet welling of lava out of the ground (little gas) to tremendously violent jets of gas and ash particles (lots of gas) or anything in between. If external water mixes with the erupting magma, the explosiveness of any eruption increases.

Magma is produced 100-150 km below the Earth's surface at very specific locations, most of which are related to the boundaries between tectonic plates. Being hotter and more buoyant than the surrounding solid rocks, magma migrates upward, often collecting in magma chambers that develop either within or below the body of a volcano. When the magma or gas pressure in the chamber become too great, the chamber fractures and magma migrates into the body of the volcano, becoming an eruption if it reaches the surface.

Volcanoes pose hazards to people living nearby and occasionally to people far away. The effects include burial and burns from hot ash, gas, and lava flows, collapsed roofs from ash accumulation, and mudflows (lahars). In the most violent eruptions, volcanic ash and gas may reach the stratosphere where it reflects sunlight, leading to slight cooling of the atmosphere. Ash ingested into jet engines can cause the engines to fail.

Volcanoes are also beneficial. Volcanic materials are rich in nutrients, and in tropical climates these materials break down rapidly into rich soils. Rainfall captured by volcanic slopes provides water in otherwise dry climates. Volcanic gases produced the atmosphere we breathe today. Erupted products provide scientists with samples from within the Earth. And finally, volcanoes provide visual beauty and the inspiration for myths and legends. Volcanology is the study of volcanoes, and it employs many different tools, techniques, and scientific disciplines to understand these exciting natural features, not only to reduce volcanic risks, but also to understand how the Earth works.

Distribution of volcanoes, magma production, and relationships to plate tectonics:

Any map of Earth's volcanoes shows that they do not occur everywhere. In fact, they only occur above the regions where magma is produced in the Earth's mantle (thus, places without volcanoes indicate no magma production). Most volcanoes form linear bands near the margins of continents (e.g. the Andes and Cascades) or ocean basins (e.g. Japan, and Indonesia). A few lines or clusters of volcanoes occur far from continent and ocean margins (e.g. Hawai‘i and the Galápagos Islands).

Plate tectonics states that Earth's lithosphere (crust + uppermost mantle) consists of pieces called plates, and that these plates move relative to each other. Almost all of Earth's volcanoes occur in three locations relative to plates: 1) along subduction zones; 2) along divergent margins; and 3) above hotspots. Subduction zones and divergent margins are types of plate boundaries but hotspots can be anywhere.

A subduction zone is a type of convergent margin where an oceanic plate is pulled under and sinks (subducts) under another oceanic plate or a continental plate. The subducting plate bends downward and heads into the Earth's mantle at an angle. There is water in the pore spaces of the subducting plate and in the ocean sediments it carries. By the time the plate gets to 100-150 km below the surface it is hot enough for this water to boil off. The water migrates upward into the wedge of mantle between the subducting and over-riding plates. Adding this water to these hot (but solid) mantle rocks causes them to partially melt in a process called hydration melting. The magma migrates upward to erupt at the surface. Most subduction zones are arcuate (concave toward the over-riding plate), so the volcanoes associated with them are often called arc volcanoes. Most of the Pacific Ocean is bounded by subduction zones and the volcanoes around it are collectively called the "ring of fire".

The andesite, dacite, and rhyolite magmas produced at subduction zones are relatively cool and high in silicon dioxide (silica), making them viscous. They are also rich in gases (including the water that caused the melting in the first place). These properties cause most arc volcanoes to be steep and their eruptions to be explosive.

Volcanoes also occur at divergent boundaries, where two plates are pulling apart. Most divergent boundaries involve two oceanic plates, such as the oceanic parts of the South American and African plates. When two plates pull apart, mantle material moves upward to fill the space left behind. Moving upward is accompanied by a decrease in pressure and the hot mantle material partially melts by what is called decompression melting. The magma migrates upward and erupts along the fracture between the two plates, actually producing new plate. This basalt magma is hotter, lower in silica, and lower in gas than that produced at subduction zones. Because most divergent margins involve oceanic plates, most divergent volcanism is under water.

The third common location for volcanoes to occur is over what are called "hotspots". Hotspots are hot columns of solid mantle material moving upward very slowly. They move upward because the bottom of the mantle is hotter than the top, the way that soup moves upward from the bottom of a hot pan. Because the movement of the mantle takes place in the solid state, it is very slow. At the top of this column, decompression melting produces hot, low-silica, low-gas basalt magma, which migrates upward to erupt through the overlying plate onto the surface. This is how volcanoes can occur out in the middle of a plate. Famous examples of hotspot volcanism include Hawai'i, the Galápagos, and Iceland.

<u>Products of volcanoes:</u>

The main products of volcanoes are lava, pyroclastics, and gas. Lava is emplaced as molten rock and its appearance varies depending on its composition, temperature, and rate of advance. Fluid lava flows spread easily outward from eruptive vents. Pāhoehoe lava has smooth, glassy surfaces and develops when hot, fluid lava advances slowly. 'A'ā lava flows have rough broken surfaces and a fluid core, and develop from slightly less fluid lava that advances rapidly. Pāhoehoe and 'a'ā are Hawaiian words that have been adopted by most volcanologists, except in Iceland. There, helluhraun ("pavement lava) and apalhraun ("rough lava") are used for pāhoehoe and 'a'ā..

Very viscous lavas are unable to flow easily so they pile up around the vent, forming thick lava domes and/or thick, short, stubby flows with blocky surfaces. These domes and flows advance very slowly but are dangerous because the blocks tumble off their steep margins.

Pyroclastics are the part of the magma that is broken into fragments and thrown into the air by expanding gas. More gas produces stronger explosions and finer pyroclastics. Pyroclastic sizes range from dust and sand (volcanic ash) to pebbles (lapilli) to rocks and boulders (bombs or blocks; Table 1). Tuff refers to any rock made up of pyroclastic particles naturally cemented together.

Table 1: Pyroclastic classification by particle size

Size	Name
<2 mm	ash
2-64 mm	Lapilli
>64 mm	bomb (if still fluid when erupted) block (if already solid when erupted)

Other pyroclastic terms refer to the texture of the particles. Pumice contains a high percentage of frozen gas bubbles (vesicles) in a matrix of volcanic glass. The bubbles are not connected so pumice floats. Pumice is usually associated with dacite and rhyolite compositions. Scoria (cinder) also has many vesicles but because they are connected, scoria doesn't float. Scoria is usually associated with basalt and andesite compositions. Both pumice and scoria are produced by vigorous eruptions and the particles are thrown high into the air. They are solid by the time they land and build up a loose pile of material around the vent (a scoria cone or a pumice cone). Spatter is fluid, bubble-poor pyroclastic material associated with less vigorous eruptions. Spatter blobs do not fly very high and are still molten when they land. Spatter produces steep vent structures (spatter cones and spatter ramparts).

Gases from volcanoes are mostly water vapor (H_2O), carbon dioxide (CO_2) and sulfur dioxide (SO_2). Deep underground these gases exist as individual molecules in the magma rather than bubbles (like the CO_2 in a closed bottle of soda). As magma rises, the surrounding pressure decreases, gas molecules join together into bubbles (like the soda after you open it), and the bubbles expand and start to exert their own outward pressure.

Types of volcanoes:

Volcanoes are classified in a number of ways, and arc, divergent-margin, or hotspot association (i.e., tectonic setting) is one way. Others classification schemes are by chemical composition, how active they are, style of their eruptions, and shape.

There are many chemical compositions but the majority of volcanic rocks fall into four: Basalt, Andesite, Dacite, and Rhyolite (Table 2). Most volcanoes erupt a limited range of compositions but not all do, so this classification doesn't always work.

Defining active vs. extinct can be difficult. Most geologists consider any volcano that has erupted since the last ice age (~10,000 years ago) to be active. Ten thousand years is not specifically significant with regard to volcanism, but it is a convenient geological marker. Using this, there are more than 1500 active volcanoes on Earth today. Some of these have only erupted once in the past 10,000 years whereas others have erupted thousands of times, meaning there is a huge variation in the typical interval between eruptions. This makes the term "dormant" not useful. For a few volcanoes, even 10,000 years is short compared to the typical eruption interval. Yellowstone has had 3 very large eruptions separated by an average interval of ~600,000 years.

Typical eruption styles are described below. At any one volcano there is the potential for even more variation in eruption style than there is for composition so an eruption style classification requires many exceptions.

Table 2: The chemical composition of typical volcanic rocks

	BASALT	**ANDESITE**	**DACITE**	**RHYOLITE**
Approx. eruption temperature	1140-1170º C	1020-1110º C	900-950º C	790-850º C
Silica % by weight	≤ 52	52-63	64-68	>68
Iron and Magnesium by weight %	high	moderate	low	very low
Viscosity	low	moderate	high	Very high
Gas content	low	moderate	high	Very high
Typical eruption explosivity	low	moderate	high	Very high
Ratio of pyroclastic material to lava	low	~equal	high	Very high
Typical color	Black to dark grey	Light grey to dark grey	Light grey to med. grey	Med. grey to almost white
Typical minerals	Olivine, pyroxene, plagioclase feldspar, magnetite	Pyroxene, plagioclase feldspar, amphibole	Plagioclase feldspar, amphibole, quartz	Quartz, potassium feldspar, amphibole
Intrusive equivalent	gabbro	diorite	granodiorite	Granite

Volcanoes are commonly classified by their shape, and the majority of Earth's volcanoes fit into 6 types: 1) shield volcanoes, 2) strato volcanoes; 3) silicic caldera complexes; 4) monogenetic fields; 5) mid-ocean ridges; and 6) flood basalts. There are some volcanoes that don't fit well into any of the 6 types and some that fit into two or more types.

Shield volcanoes are constructed of hundreds of thousands of fluid basalt lava flows. The fluidity and large volume of lava relative to pyroclastic material combine to produce lava flows that extend far down the flanks without piling up steeply. The characteristic slopes of a shield volcano are therefore about 5º. The name derives from the similarity of the profile to that of a warrior's shield. Some of the largest volcanoes on Earth are shield volcanoes. Mauna Loa, if measured from its base on the floor of the ocean, is more than 9000 m tall (taller than Mt. Everest), and its base is nearly 300 km wide.

Most shield volcanoes are associated with hotspots, for example those in Hawai'i the Galápagos islands, Iceland, and the Comoros. There are a few shield volcanoes associated with subduction zones (Masaya in Nicaragua and Westdahl in Alaska), and a few at divergent continental margins (Erta Ale in Ethiopia, Nyamuragira in Congo, and Erebus in Antarctica).

Strato volcanoes are the most common type of individual volcano on Earth, and include the famous volcanoes in human history (Vesuvius, Krakatau, Pinatubo). They usually erupt andesite and dacite, which are typically explosive. These viscous lavas plus lots of pyroclastics produce steep-sided (~30º) volcanoes. The term "strato" (or "composite") refers to the roughly equal amounts of pyroclastics and lava. Most strato volcanoes do not erupt frequently, and they are smaller than shield volcanoes.

Most strato volcanoes occur along subduction zones, although Nyiragongo (Congo) is on a divergent continental boundary. Nyiragongo is also unusual because it is a basalt strato volcano, as is Mt. Fuji. Etna (Italy) has characteristics of both shield and strato volcanoes.

Silicic caldera complexes are often barely recognizable as volcanoes but produce the most explosive eruptions known. At some locations, most of which are continental and associated either with a hotspot or subduction zone, huge volumes of rhyolite magma collects slowly in huge magma chambers. These magmas can erupt in colossally explosive events, throwing ash well into the stratosphere and producing pyroclastic flows (see below) that devastate vast areas. Usually the roof of the magma chamber then collapses, forming a large caldera and the surrounding ground surface may sag inward as well. The result is that silicic caldera complexes are often "inverse" volcanoes - low places rather than high places.

Because it takes a long time for enough rhyolite magma to accumulate, the huge eruptions are fortunately infrequent. One of the 3 large Yellowstone eruptions deposited ash as Louisiana, almost 2500 km away. Most silicic caldera complexes also have more frequent but, smaller, less explosive eruptions as well. Other famous silicic caldera complexes are La Primavera (México), Taupo (Aotearoa), and Toba (Indonesia).

Monogenetic fields are areas of many (sometimes up to a thousand) individual, small, separated volcanic vents. They can be scoria cones tuff cones, maars, small lava shields, and lava domes. The common characteristic is that each individual vent was produced by a single eruption (it was "monogenetic"). Monogenetic fields are associated with subduction zones as well as hotspots but the associations are not well understood. It is almost as if instead of being close and frequent enough to build a single large volcano, the eruptions are spread out over a large area over a long period of time. Often the people living near a monogenetic vent don't realize that "their volcano" is actually part of a much larger monogenetic field.

The most famous monogenetic field is the Michoacan-Guanahuato field in southern México. This is because from 1943 to 1952, Parícutin, the newest member of this field, formed where many people lived and could watch and study its activity. Monogenetic fields also occur in and around the cities of Auckland (Aotearoa), and Flagstaff (Arizona).

Mid-ocean ridges are the places where eruptions create new oceanic plates at divergent boundaries. If the entire ~75,000 km-long mid-ocean ridge system is considered as a single volcano it is by far the largest on Earth. There is debate about this and many geologists consider small segments of the ridge system as individual, and much smaller volcanoes. Tension pulls the plates apart and counters the construction by eruptions. Mid-ocean ridges that spread rapidly (e.g the. East Pacific rise) therefore are broad but not very high. Mid-ocean ridges that spread slowly (e.g. the mid-Atlantic ridge) are narrow but high and steep.

Flood basalts are probably the least familiar type of volcanic feature to most people. These are stacks of very extensive lava flows that cover hundreds of thousands of square km. Individual flows may be a couple hundred km long and/or wide, and 10-50 m thick, and therefore have huge volumes. A few examples of flood basalts are the Columbia River basalts (Washington and Oregon), the Deccan Traps (NW India), and the Paraná basalts (Brazil).

Because of their extreme length it was originally thought that these flows were erupted very rapidly (like "floods" of lava), otherwise they would solidify before flowing very far. Recent work has shown that this is not necessarily the case because lava can flow long distances much more slowly as long as it develops a solid, insulating crust.

<u>Structures and Features of Volcanoes:</u>

Volcanoes are not simple piles of lava and pyroclastics. They have structures relate to, and control, how magma is stored, migrates and erupts. Some of these structures are large and volcano-wide whereas others are small and distributed over a volcano.

A *caldera* is a large depression produced by collapse, and usually located near or at the summit of a volcano. A caldera indicates that at some point in the past, sufficient magma was erupted from the magma chamber that the rocks above collapsed. A caldera is therefore directly related to the magma plumbing system. At the summit the effects of collapse and infilling by eruptions work against each other, and many volcanoes show evidence for multiple generations of caldera.

A *rift zone* is a region on a volcano where eruptions are concentrated. The directions that magma migrates from the magma chamber to the surface are controlled by the stresses within the volcano. If those stresses don't vary through time then the migration directions won't vary and most eruptions will occur in the same areas (the rift zones). In some volcanoes the stresses do vary so these volcanoes don't have rift zones and eruptions take place anywhere.

A *vent* is the opening that lava and/or pyroclastic material erupt out of plus the material that builds up around the opening. Vent size is mainly related to the volume of material that was erupted and the shape is related to the eruption style. *Scoria cones* and *spatter cones* are two examples of vent types. Eruptions that involve passive eruption of fluid lava without explosive activity produce miniature versions of shield volcanoes called satellitic shields. If water is involved in an eruption the explosiveness increases and a high percentage of pyroclastics are thrown sideways as well as upward. This results in vents that are much wider than they are tall, resembling a ring when viewed from the air, and called *tuff rings*. Eruptions involving water may eject little or no new material onto the surface and mainly blast out a hole in the ground. These steep-sided pits, that sometimes contain water, are called *maars* (maar is a German word for lake).

Crater is used for many things. A maar is a type of crater, as is the depression within the ring of a tuff ring or at the summit of a scoria cone. *Pit craters* form purely due to collapse of the surface into an underground fracture or void. Although size differentiates most craters from calderas, it is more useful to consider craters to be any topographic depression whereas calderas are related directly to the magma plumbing system.

Types of eruptions:

Volcanoes erupt in many ways, determined by the amount of gas in the magma, the viscosity of the magma, the rate at which magma is supplied to the vent, and whether or not external water is involved. High gas content means more bubbles form when the magma migrates upward. More bubbles exert more pressure and result in more explosive eruption. Counteracting the expansion of bubbles is the viscosity of the magma. If the viscosity is low (e.g. in basalt), the bubbles can expand at will so that their pressure doesn't build up much and the resulting eruptions are not explosive. If the viscosity is high (e.g. dacite or rhyolite), the magma resists bubble expansion much better meaning that pressure can build up considerably. When the pressure finally overcomes the magma, a very explosive eruption occurs. In either case, if magma is supplied to the vent at a high rate, the eruptions are essentially continuous. If the supply rate is low, the eruption will be episodic because time is required to replenish the magma erupted by the previous explosion.

Volcanic eruptions have been classified by the volume erupted, the energy released, the eruption cloud height, whether they are continuous or episodic, and whether or not external water is mixed in. The first three of these considered together constitute a "scale" of eruptions called the Volcanic Explosivity Index (VEI). Like the Richter scale for earthquakes, the VEI uses powers of 10 so that a VEI 5 eruption is 10 times greater than a VEI 4 eruption. Because such a range of properties are combined into the VEI, the comparison of eruptions is more complicated than that of earthquakes.

A useful way to classify eruptions is based on whether the ejection of material is constant or episodic, and whether the ejected material is able to heat enough surrounding air so that the whole cloud convects upward (Table 3).

Table 3: A classification of explosive volcanic eruptions

	constant	episodic
convective rise	plinian	vulcanian
no convective rise	hawaiian	strombolian

The detailed processes in *plinian* and *hawaiian* eruptions is the same but they differ in how effectively they can heat the surrounding atmosphere and produce convection. This is in turn controlled by how fine the pyroclasts are, which is controlled by the explosion violence, which is controlled by the magma gas content and viscosity. On the other hand, the detailed processes in a hawaiian fountain are different than those in a strombolian explosions but neither is able to entrain sufficient nearby air to produce convection.

These eruption styles are all "dry", meaning that no external water is involved and all the explosive energy comes from gas in the magma itself. When water (ocean, lake, groundwater, etc.) is mixed in to any style of eruption, it converts rapidly to steam and this adds, often significantly, to the explosivity. Such eruptions are called hydromagmatic.

Finally, any or all of these explosive eruption styles may be accompanied by the eruption of lava flows, lava domes, pyroclastic flows, or pyroclastic surges (discussed below). Other eruptions involve almost no pyroclastic explosive at all, such as the quiet effusion of pāhoehoe lava or the slow growth of a lava dome.

Volcanic hazards:

There are 7 main volcanic hazards: 1) lava flows; 2) ash and scoria; 3) pyroclastic flows and surges; 4) lahars (volcanic mudflows); 5) volcanic gases; 6) large volcanic landslides and avalanches; and 7) volcanic tsunami.

Although being buried by lava is a common fear, lava flows pose the least hazard because they almost always advance at rates of <10 km per hour, and this is slow enough for people to escape. Some rare, very fluid lavas do flow fast enough to be hazardous. Although people and animals can almost always get out of the way, this is not true of structures. Lava flows therefore pose considerable hazards to buildings, roads, and harbors. Because lava solidifies to solid rock, areas that have been buried are difficult to reoccupy for a long time.

In an explosive eruption, blocks and bombs fall close to the vent so being hit by them is likely only in a limited area. Ash and lapilli, however, can be carried by the winds for 10s to 100s of km. This finer material is therefore rarely even warm when it lands so it poses little hazard from burns. Instead the hazards contamination of water supplies, damage to crops, and collapse of building roofs. The weight of fallen ash increases to that of cement if it gets rained on, making roof collapse much more likely. Falling ash blocks out sunlight and makes evacuations more dangerous.

Ash is also a hazard to jet aircraft because the high temperatures inside portions of modern jet engines melt ash into little molten droplets. These then solidify on other parts of the engines and combined with their abrasiveness, can cause the engine to fail. Clouds of ash are often invisible from airplanes so air controllers track eruption clouds with satellites and re-route flights if necessary.

Pyroclastic flows and surges are clouds of hot ash and gas that travel mostly along the ground. The combination of high temperature (as high as 600º C), high velocity (10s to 100s of m/s), and high inclusion of debris means that pyroclastic flows and surges are some of the most dangerous volcanic phenomena. They cannot be outrun and they can overtop river banks and ridges so the best thing to do is evacuate areas nearby an active volcano if it has a past history of generating them. In 1902 pyroclastic flows and surges from Mt. Pelee (Martinique) swept through the city of St. Pierre and killed perhaps 28,000 people. Some pyroclastic flows form from collapsing eruption plumes, and because the material in a plume is mostly ash and pumice, these are called pumiceous pyroclastic flows. Other pyroclastic flows form when the margin of a steep-sided lava dome or flow collapses. This releases pressurized gases from within the dome or flow which mixes with the lava fragments to form a block and ash flow, also called a “nuee ardente” (glowing avalanche).

Lahar is an Indonesian word for “flow”, and volcanologists use it for a mudflow on a volcano. Volcanoes are prone to mudflows because they are steep, there are large accumulations of loose ash, they often occur in rainy climates, and earthquakes are common. Lahars consist of water, fine sediment, and any other debris (trees, boulders, etc.) that gets picked along the way. Lahars are usually confined to river and stream valleys but this is also where towns are often located. A lahar leaves behind a thick layer of drying mud that can hardens almost like cement. A lahar from Nevado del Ruiz volcano (Columbia) destroyed the town of Armero in 1985. The death toll may have been as high as 26,000 people. Like pyroclastic flows and surges, lahars can almost never be survived, so evacuation is the best safety measure.

Volcanic gases are a nearly invisible hazard. Of the 3 major volcanic gases, CO_2 is the most hazardous because it causes suffocation in high concentrations. CO_2 is denser than air and if the wind is weak it collects in low places, called mazukus in parts of Africa. Animals or people who wander into these low places can be overcome before they realize the danger. One night in 1986, a volcanic lake (Lake Nyos) in Cameroon produced a large cloud of carbon dioxide, unaccompanied by any magmatic activity. The cloud moved down a valley, hugging the ground as it went, and killed nearly

2000 people (most in their sleep) as it swept through a town below. There is an ongoing effort to prevent carbon dioxide from building up to lethal levels again in the water of Lake Nyos.

Volcanoes are prone to avalanches and landslides because many are steep, constructed of loose ash and fractured lava flows, are weakened by interaction with acidic volcanic gases, and are often shaken by earthquakes. A volcanic avalanche might be associated with an eruption (such at Mt. St. Helens 1980) or it might happen when no eruption is occurring. It is difficult to predict these events, and evacuation during eruptions (because of potential other hazards) is probably the best safety measure.

The entry of a pyroclastic flow or avalanche into the ocean, or catastrophic collapse of a coastal volcano will displace a large volume of water and cause a volcanic tsunami. Tsunami is a Japanese word (for a large wave in a harbor), and tsunami can also be generated by earthquakes. Tsunami spread outward from their source and can be very destructive. Tsunami associated with caldera collapse during the 1883 Krakatau eruption killed more than 30,000 people on nearby coastlines. Evacuation from threatened coastal areas when an eruption is imminent is the best safety measure.

Studying volcanoes:

The three main goals of volcanology are to decrease the risk that volcanoes pose, to gain a better understanding of how the Earth works, and to develop volcanic energy and mineral resources. Reducing the risk from volcanoes involves studying both ongoing eruptions and the deposits of past eruptions to understand how powerful eruptions can be, how far and fast erupted products can travel, and how frequently specific volcanoes erupt. These studies yield information on the potential effects of eruptions at a particular volcano. Deciding whether or when a volcano will erupt requires direct volcano monitoring. Volcanologists monitor seismic activity, deformation of the ground surface, and changes in the compositions and amounts of gases being given off Even the most closely monitored volcanoes do not show pre-eruption signs that are always easy to interpret. On the other hand, few eruptions occur with absolutely no warning signs, although sometimes they aren't recognized in time. At present, eruption forecasting works at two scales. Volcanologists can state pretty confidently the probability of a particular volcano erupting in the next 10, 100, 1000 years. They can also give few-day to few-hour warnings just prior to obviously imminent eruptions. Predictions on the scale of a few years to months are the goal.

Volcanology also provides a variety of information about the Earth's interior, as well as the history of the Earth itself. Most of the samples we have of the mantle are in fragments (called mantle xenoliths) carried to the surface during some eruptions. Because lava flows record the direction of the Earth's magnetic field at the time that they cool, carefully dated flows provide important information about the field through geologic time.

Volcanoes are the source of mineral and energy resources. Geothermal energy involves utilizing the heat within volcanoes to generate electricity, provide hot water, or heat buildings. Although controversial in some parts of the world, geothermal energy can decrease our dependence on fossil fuels. The natural fluids that percolate through volcanoes dissolve precious metals and then concentrate and re-precipitate them in veins. Many of the world's precious mineral resources occur in the roots of old extinct volcanoes now exposed by erosion. Understanding the concentration processes is key to finding new deposits.

Volcanoes on other planets:

Volcanoes, volcanic features, and volcanic rocks have been identified on the Moon, Venus, Mars, and Io (the innermost large moon of Jupiter). Almost all appears to be basalt volcanism. Returned lunar samples were basalt and the chemical compositions (from satellite and rover measurements) of Martian surfaces are basalt. Although much bigger, the volcanoes and their associated lava flows on Mars and Venus have shapes very similar to basaltic shields on Earth. Not all planetary volcanoes look like terrestrial examples and some are actually quite different.

The Voyager I and II spacecraft, which explored the outer solar system in the 1970s and 1980s, collected images of numerous erupting volcanoes on Io. Since then the Galileo spacecraft has upped the total to almost 170 active, and nearly 500 inactive, volcanoes, making Io by far the most volcanically active body in our solar system. Some Io eruptions, although apparently basaltic in composition, have temperatures (measured from satellites and infrared telescopes on Earth) that are 200-300º C higher than the hottest basalt eruptions recorded on Earth. Another remarkable aspect of Io volcanism is the intimate association with sulfur. The sulfur volcanism on Io is not as hot as the basalt but it is no less spectacular. Erupting plumes have been recorded shooting as high as 300 km above Io's surface. Some of the sulfur volcanism seems to emanate from large, moving areas and these have been hypothesized to be where hot basalt flows are flowing over, and vaporizing, surface deposits of sulfur.

For more information, plus some photographs, go to:

http://volcano.und.edu/vwdocs/vwlessons/volcano_types/index.html