3 Volcanism

3.1 Characteristics of magmas

In order to understand the processes of volcanism it is essential to be aware of the nature of the magmas that produce volcanic eruptions. These magmas are derived from two main sources, as follows:

Magma derived from the mantle

The mantle - This includes the lower mantle for mantle-plume (hot-spot) volcanoes, such as those on the Hawaiian Islands; and the upper mantle for rift-related volcanism, including the oceanic ridges, and areas such as the Rift Valley of East Africa. Both types of mantle-derived magma are strongly mafic and generally poor in water and other volatiles (see table below). Mantle-plume and rift-related magmas are not exactly the same. The upper mantle is compositionally different from the lower mantle, and the conditions of magma formation are different. In both cases the process of magma formation is by partial melting of mantle material. In the upper mantle that is largely a result of decreased pressure in rift areas. We don't fully understand how magmas are formed in the lower mantle, but it has a lot to do with the heat of the underlying core.

Magma derived from subduction zones

Melting at subduction zones - The subducting slab includes lithosphere, oceanic crust and some sea-floor sediment. Compared with the surrounding mantle this material is rich in water - both as free water, and as water in hydrated minerals such as clays. This water plays a critical role in lowering the melting point of both the subducting material and the mantle. The resulting melt products rise up to the base of the crust. Some of this material may continue to rise up through the crust, but it is likely that most of the magma generated in this environment is a result of partial melting of the lower crust by the heat of the magma generated on the subduction zone. Magmas in the crust are almost certainly affected by the surrounding crustal rocks. Most magma chambers that supply subduction zone volcanoes have overall intermediate compositions, but various processes that take place near to surface can lead to wide variability in the composition of erupting material. These magmas are relatively rich in volatiles, including water (see table below).

Magma compositions

All magmas are composed predominantly of eight elements, including oxygen, silicon, aluminum, iron, calcium, magnesium, sodium and potassium. Magmas also contain volatile constituents, such as hydrogen, carbon, sulphur, chlorine and nitrogen. Excluding oxygen, the major components of most crustal rocks are positively charged, and in view of the abundance of oxygen, the cations are almost always complexed with oxygen. Geologists commonly express the compositions of igneous rocks in terms of the weight percentages of the oxides, and typical values for the oxides and volatile components in felsic, intermediate and mafic rocks (and magmas) are listed in the table below.

Magma melting temperatures

Apart from the important differences in silica content, there are substantial differences in the contents of iron, calcium, magnesium, potassium and volatiles. The chemical differences are associated with significant differences in melting temperatures - which are around 1200º C for mafic magmas, as opposed to less than 1000º C for felsic magmas. These temperatures are highly dependant on water contents, and are significantly lower for wet magmas.

Another very important difference is the viscosity of the different types of magma. Mafic magmas are generally very runny (a little like ketchup), while felsic magmas are much more viscous (a little like peanut butter). (see figure below) The differences in viscosity are largely related to the silica contents and the tendency for silica tetrahedra to polymerize (form together into chains) even before any minerals begin to crystallize from the magma. Mafic magmas also tend to be hotter than felsic magmas, and this contributes to their low viscosity.

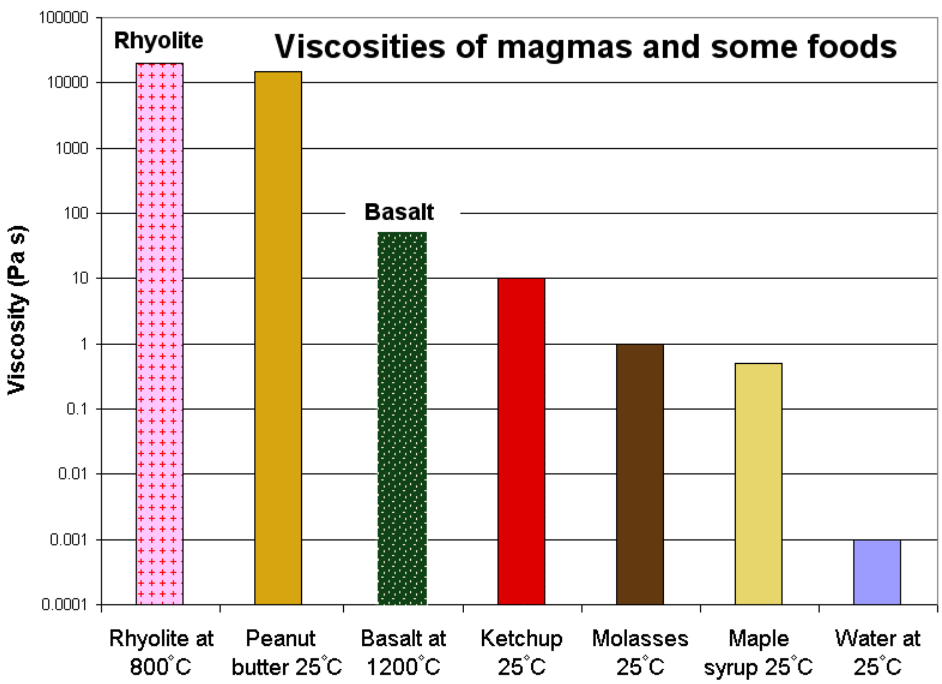
Generalized chemical compositions of felsic, intermediate and mafic magmas

Oxide	Felsic magma (granite/rhyolite)	Intermediate magma	Mafic magma (gabbro/basalt)
SiO_2	65-75%	55-65%	45-55%
Al_2O_3 *	14.0%	16.5%	15.5%
Fe_2O_3	1.5%	2.5%	3.3%
FeO**	1.4%	6.4%	8.1%
CaO	1.7%	6.0%	9.5%
MgO	0.6%	3.0%	7.3%
Na_2O	3.7%	3.6%	2.7%
K_2O	4.2%	2.4%	1.0%
Volatiles	4-6%	3-4%	1-2%

* Ranges are given for SiO_2 only, but the levels of the other oxides are also variable
** Fe_2O_3 represents oxidized (Fe^{3+}) iron, while FeO represents reduced (Fe^{2+}) iron.
(adapted from Best, 1982)

Magma eruption styles

Different magma types erupt in different ways. Eruptions of mafic magmas are normally quite gentle and controlled because the magma flows easily, the volatile content is quite low and the gases that are present can quickly escape through the liquid without causing an explosion. In contrast, eruptions of intermediate, and particularly felsic magmas, can be highly explosive because the magma does not flow easily and gets stuck in conduits, the volatile levels are high and the gases cannot escape easily through the thick magma.



Magma viscosities

Formation of gas bubbles and microlites in magmas

As any magma approaches the surface the pressure drops. Within a few hundred metres of surface the gases start to exsolve (come out of solution), and the gas volume increases dramatically. At the same time a lot of tiny crystals (microlites) start to form. The exsolution of gases and formation of microlites both make the magma even more viscous than it was before. As the magma moves even closer to surface the gas bubbles increase in size and number, and this causes the overall volume of the magma to increase dramatically. In the case of a felsic magma most of the gas is unable to migrate towards the surface (because the magma is too viscous), and thus when the gas expands it caused the magma to expand as well. This expansion puts huge pressures on the conduit and the volcanic dome, and eventually something gives way leading to an eruption. In mafic magmas, (that have relatively low gas contents in the first place), much of the gas is able to migrate to surface and as it expands it only affects the magma close to the surface.

Magma at hot spots

The magmas at volcanoes related to hot-spots and oceanic ridges are derived from the mantle and, in most cases, they move only through mantle material (or oceanic crust) on their way to the surface. Their initial compositions are consistently mafic, and there is little opportunity for modification of the composition through contact with other rocks. The volcanic eruptions in places like Hawaii and Iceland are generally consistent in style, and usually relatively peaceful, although there are some exceptions, as described below.

Magma at subduction zones

In contrast, the magmas at subduction zones are derived from material of varying compositions. They are mostly made up of mantle rock that melts when water from the subducting plate migrates into the mantle, but they may also include some component of oceanic plate and the relatively wet sediments on its upper surface. As they ascend to the base of the crust and then up through the crust these magmas come into contact with various different rock types and they assimilate material from these rocks. That assimilation occurs in two different ways, firstly as a result of the melting of the country rock adjacent to the magma chamber, and secondly as fragments of country-rock break away and mix with the magma - a process known as **stoping**. Another important aspect of subduction-zone magmas is that they are stored in magma chambers at depths of several kilometers below surface. This allows for ongoing interaction with the surrounding rock, and for differentiation within the magma body.

Varying compositions of subduction magmas

The consequence of the assimilation of crustal material and of storage within magma chambers is that the magmas feeding subduction-zone volcanoes can have widely varying compositions, and hence the volcanic eruptions, even at one location, can be very different in style. These magmas are almost always considerably more felsic than the magmas at hot spots and spreading ridges.

Gases in magmas

Numerous gases are released during the eruption of magmas, but the most common is water - which comprises over 90% of the total. Others, in general order of importance, are carbon dioxide (CO_2), sulphur dioxide (SO_2), hydrogen sulphide (H_2S), carbon monoxide (CO), nitrogen (N_2), hydrogen (H_2), hydrochloric acid (HCl) and methane (CH_4). These gases (and liquid water at surface temperatures) contribute to the oceans and the atmosphere, and they also comprise the main elements of life (carbon, hydrogen, oxygen and nitrogen).

3.2 Eruption types and processes

The various terms that are used to describe volcanic eruptions and events are summarized below. Many of these terms come from Italy, where volcanoes were first described in detail - beginning almost 2000 years ago[1].

Plinian eruptions

Plinian eruption
Plinian eruptions are large explosive events that send enormous dark columns of tephra and gas high into the stratosphere (many kilometres). Such eruptions are named for *Pliny the Younger*, who carefully described the disastrous eruption of Vesuvius in 79 A.D. This eruption generated a huge column of tephra into the sky, it also produced pyroclastic flows and surges, and extensive ash fall. Many thousands of people evacuated areas around the volcano, but about 2,000 were killed, including *Pliny the Older* (uncle to the younger). The massive eruption column of Mt. St. Helens in 1980 (following the lateral blast) was a plinian eruption.

The younger Pliny's comments on the Vesuvius eruption are recorded in two letters written to the historian Tacitus. These letters are available on the internet if you are interested: (http://www.mala.bc.ca/~earles/pliny)

Vulcanian eruptions

Vulcanian eruption
Vulcanian eruptions are highly explosive and relatively short-lived. The name is derived from the 1888-90 eruptions of Vulcano, a small volcano in the Eolian Islands north of Sicily. Vulcanian eruptions produce black, ash- and steam-laden columns, and they eject lava fragments that do not take on a rounded shape during their flight

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[1] Much of the material on types of volcanic eruptions comes from the USGS volcano photo-glossary. http://volcanoes.usgs.gov/Products/Pglossary/pglossary.html|

through the air. This may be because the lava is too viscous or because it is already solidified. These moderate-sized explosive eruptions commonly eject a large proportion of volcanic ash and also bread-crust bombs and blocks. Andesitic and dacitic magmas are most often associated with vulcanian eruptions, because their high viscosity makes it difficult for the dissolved volcanic gases to escape except under extreme pressure, which leads to explosive behavior. The explosive eruptions at Montserrat in 1997 were primarily vulcanian in character.

Strombolian eruption

Strombolian eruptions

Strombolian eruptions (named for the Stromboli volcano in Italy) are characterized by the intermittent explosion or fountaining of basaltic lava from a single vent or crater. Each episode is caused by the release of volcanic gases, and they typically occur every few minutes or so, sometimes rhythmically and sometimes irregularly. The lava fragments generally consist of partially molten volcanic bombs that become rounded as they fly through the air.

Effusive eruption

Effusive eruptions

An eruption dominated by the non-explosive outpouring of lava onto the ground is often referred to as an effusive eruption. Most, but not all effusive eruptions involve relatively non-viscous magmas. Lava flows generated by effusive eruptions vary in shape, thickness, length, and width depending on the type of lava erupted, the rate of discharge, the slope of the ground over which the lava travels, and the duration of the eruption.

For example, basaltic lava may form textures such as *aa* or *pahoehoe*, and flow in deep narrow channels or in thin wide sheets. Andesitic lava typically forms thick stubby flows, and dacitic lava often forms steep-sided mounds called lava domes.

Most of the Hawaiian and Icelandic eruptions are effusive in nature.

Phreatic eruption

Phreatic eruptions

Phreatic eruptions are steam-driven explosions that occur when water beneath the ground or on the surface is heated by magma, lava, hot rocks, or new volcanic deposits (for example, tephra and pyroclastic-flow deposits). The intense heat of such material (as high as 1200° C for basaltic lava) may cause water to boil and flash to steam, thereby generating an explosion of steam, water, ash, blocks, and bombs. (Most of the recent (2004) eruptions at Mt. St. Helens were phreatic.)

Small phreatic explosions can occur when pyroclastic deposits flow over a small pond or area of wet ground. The heat causes the water to boil and then explode.

Pyroclastic density current

Pyroclastic density currents

A pyroclastic density current (or nuée ardente) is a ground-hugging avalanche of hot ash, pumice, rock fragments, and volcanic gas that rushes down the side of a volcano at rates as fast as several hundred km/hour. The temperature may be greater than 500° C, sufficient to burn and carbonize wood. Once deposited, the ash, pumice, and rock fragments may deform (flatten) and weld together because of the intense heat and the weight of the overlying material.

Two types of pyroclastic density currents are as follows (after Druitt, 1998):

A **pyroclastic surge** is a dilute and relatively wet suspension of material that flows in a turbulent manner, commonly at a high rate (150 m/s). In most cases they result from the gravitational collapse of an eruption column, or from a phreatic explosion, but they can also result from sudden explosions - such as the *lateral blast* of Mt. St. Helens. The deposits tend to be stratified, and they mantle the landscape rather than filling hollows.

Pyroclastic surges

A **pyroclastic flow** is more dense and poorly sorted and is normally dryer than a pyroclastic surge. The velocities are generally lower (~50 m/s). They commonly result from the destruction of lava domes, but can also be a product the gravitational collapse of an eruption column. Pyroclastic flow deposits tend not to be stratified, and they do fill hollows. They are generally more voluminous and cover wider areas than pyroclastic surge deposits.

Pyroclastic flows

Lahar

Lahars

Lahar is an Indonesian word for a rapidly flowing mixture of rock debris and water that originates on the slopes of a volcano. Lahars are also referred to as volcanic mudflows or debris flows. They form in a variety of ways, chiefly by the rapid melting of snow and ice by pyroclastic flows, intense rainfall on loose volcanic rock deposits, breakout of a lake dammed by volcanic deposits, and as a consequence of debris avalanches.

As described below, lahars are particularly dangerous because they can extend for many tens of kilometres away from the source of the eruption, and because they follow the paths of streams and rivers – places where people live.

Sector collapse

Sector collapse

The catastrophic failure of a major part of a volcano is known as sector collapse. During the 1980 eruption the side of Mt. St. Helens collapsed in the largest landslide event in history – the so-called debris avalanche. The main plinian eruption followed the collapse. That debris avalanche (see description below) was the first observed sector collapse of a volcano. Deposits like those of the debris avalanche at Mt. St. Helens have since been observed at many other volcanoes, and it is now assumed that similar events have taken place elsewhere. As the moving debris rushes down a volcano and into valleys, it incorporates water, snow, trees, bridges, buildings, and anything else in the way. Debris avalanches may travel several kilometers before coming to rest, or they may transform into more water-rich lahars, which travel many tens of kilometers downstream.

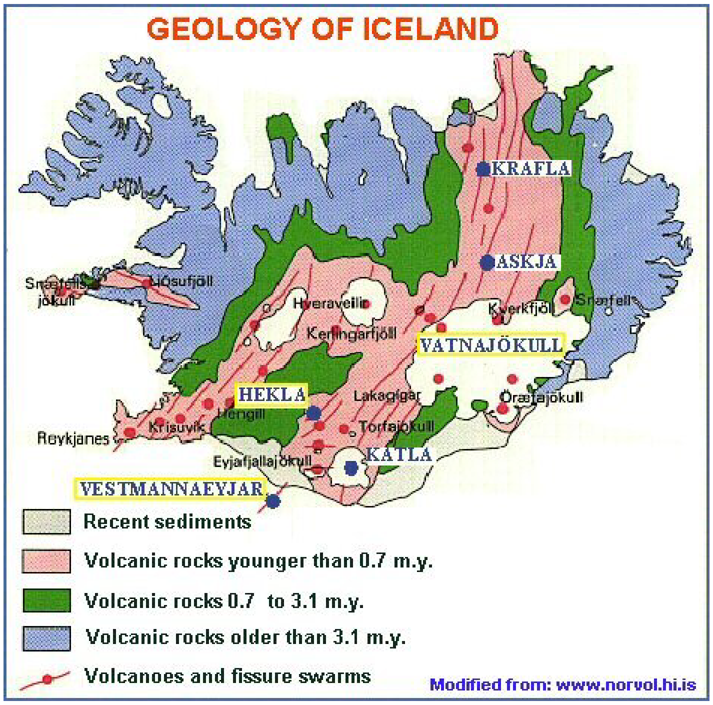
A good part of the lahar associated with the 1980 eruption at Mt. St. Helens flowed out of the bottom of the debris avalanche as it came to rest and lost much of its water.

3.3 Volcanism in Iceland

Iceland is geologically unique in that it represents an exposure of an oceanic spreading ridge. Spreading ridges are normally underwater of course, but Iceland rises above the level of the Atlantic Ocean because it is also the site of a major mantle plume and the underlying mantle is hot and buoyant[2].

Geological map of iceland

Most of Iceland is basaltic in composition and is younger than 4 m.y. (see figure). The oldest rocks are at the western and eastern extremities. Most of the recent volcanic activity has been confined to a strip between 50 and 100 km wide, in the east-central part of the island, on either side of the spreading ridge. The rocks in this area are all younger than 700,000 y. A characteristic feature of volcanism on Iceland is the eruption of lava from long fissures opened up by the tensional forces of the mid-Atlantic spreading system. Some of these fracture systems are shown on the figure above.



1873 eruption at Lika

During 1873 a 25 km long fissure opened up near to Lika (close to Lakagigar at the edge of the main ice cap), and lava poured out a rate of up to 5000 cubic metres per second for 50 days. This is the most voluminous lava flow in recorded history. To put it into perspective, the rate of flow of lava was greater than the average flow of water in the Fraser River. When the eruption ended an area of 565 square kilometres was covered in lava, to an average depth of 23 m (equivalent in height to a 7-story building). The eruption was characterized by a very high discharge of sulphur dioxide (SO_2), which spread out across Europe in a blue haze of sulphuric acid droplets (sulphate aerosols), causing an unusually cold winter. A large amount of fluorine was also released, and this accumulated on vegetation, resulting in the death of more than half of the island's horses and cattle. The ensuing famine took 10,000 lives, some 20% of the Icelandic people.

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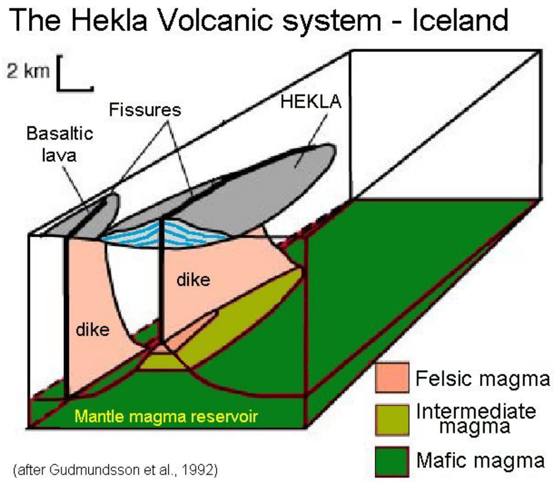
[2] A great deal of information on Icelandic volcanism can be found at http://www.norvol.hi.is

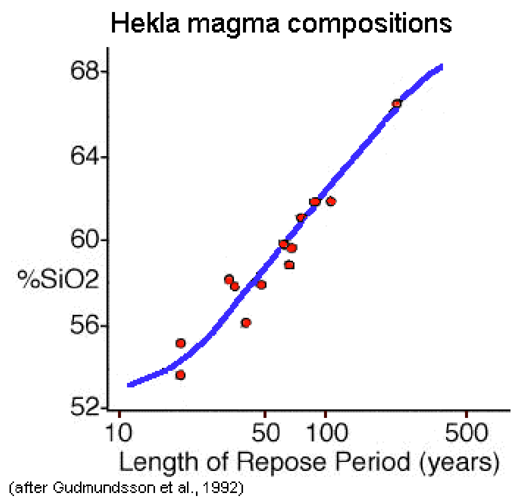
Hekla volcano

While most of Iceland's volcanism is strongly mafic (basaltic) in composition, and the resulting lavas normally spread out across the terrain rather than forming mountains, there are a few volcanoes (ie. volcanic mountains). The most famous (and active) of these is Hekla, a 1500 m peak situated in the south-central part of the country. The magma that formed Hekla is unique for Iceland in having an overall andesitic composition. This is similar to that of the average for a subduction-zone volcano; and like the subduction volcanoes, Hekla is a composite cone - comprised of material with differing compositions (see figure). The magma of Mt. Hekla is not derived directly from the mantle, but passes through a magma chamber that is situated at a depth of approximately 8 km. Considering that crust beneath Iceland is essentially oceanic in character (and therefore quite thin), this means that the chamber is close to or at the interface between the crust and the mantle.



3-dimensional view of the Hekla volcanic system

Studies of magma composition have shown that the longer the time lapse between eruptions, the more felsic the resulting magma at Hekla will be, and the more violent the eruption. The relationship between the magma composition (SiO_2) and the gap time between eruptions is given on the figure to the right. It has been inferred from this that during long periods of non-activity the magma chamber tends to become well zoned and the magma at the top is particularly felsic. It is suggested that a number of different processes taking place with the magma chamber lead to this phenomenon. There may be simple density stratification (settling of the more mafic components to the bottom of the chamber) Crystal settling may also be a factor, if olivine and pyroxene crystallize out in the cooler upper parts of the chamber, and then settle towards the bottom. It is also likely that there is partial melting of some of the surrounding rocks. It could be this partial melting that give the magma its overall andesitic composition, because there is little doubt that the material feeding into the magma chamber - from the mantle - is strongly mafic. The term *partial melting* is the key, because the hot magma will tend to preferentially melt the felsic component of the existing crustal rocks with which it is in contact, and thus the overall composition of the magma in the magma chamber will become more felsic.



Silica composition of Hekla magma as a function of the repose time between eruptions

Eruptions at Mt. Hekla normally produce large volumes of **tephra** (ash and other larger solid particles, a.k.a. **pyroclastic** deposits) that cover a significant part of the country. Following the initial explosive eruption, there are usually many months of relatively quiet flows of more mafic (andesitic or basaltic) lava. Like the Lika fissure eruption, eruptions from Hekla commonly result in the emission of large quantities of fluorine.

There was a significant eruption at Hekla in February and March of 2000. The eruption and its volcanic products are described at http://www.norvol.hi.is/

1973 Heimaey eruption

In January of 1973 there was a volcanic eruption on the tiny island of Heimaey, just off the southern cost of Iceland [Keller - page 217]. This event made the international news because the eruption occurred at the edge of the town of Vestmannaeyjar, which is situated on Iceland's most important fishing harbour. The lava flows destroyed 417 houses, and most of the other buildings were covered with a thick layer of tephra. The lava flow then continued down towards the sea, where it looked as if it might block the entrance to the harbour, and thus destroy the island's economy. In order to save the rest of their houses, and their harbour, the citizens started bulldozing piles of tephra to divert the lava flows. They also poured millions of litres of cold sea-water onto the flow front. This cooled and hardened the flow sufficiently to divert it. The harbour was saved, and in fact it is now even larger and better protected than before.

After the eruption ceased the towns-people started pumping water into the 100 m thick pile of slowly cooling lava. The water is recovered lower down, where, at a temperature of over 90º C, it is used to heat buildings. There is a lot of information on the Vestmannaeyjar eruption at: http://www.norvol.hi.is/

Over the centuries Icelanders have learned to live with volcanism, and as they did on Heimaey, they profit from it. Iceland has one of the oldest and most highly developed geothermal industries in the world. The energy from the earth is used to heat buildings, greenhouses, and swimming pools, and also to generate electricity.

3.4 Volcanism at Mt. St. Helens

Mount St. Helens

Mt. St. Helens, in southern Washington State, is one of a chain of volcanic mountains that are related to the subduction of the Juan de Fuca plate beneath the North American plate. It is a classic composite volcano, made up of lava flows and tephra that have a range of compositions[3].

Older volcanic rocks of the MSH area

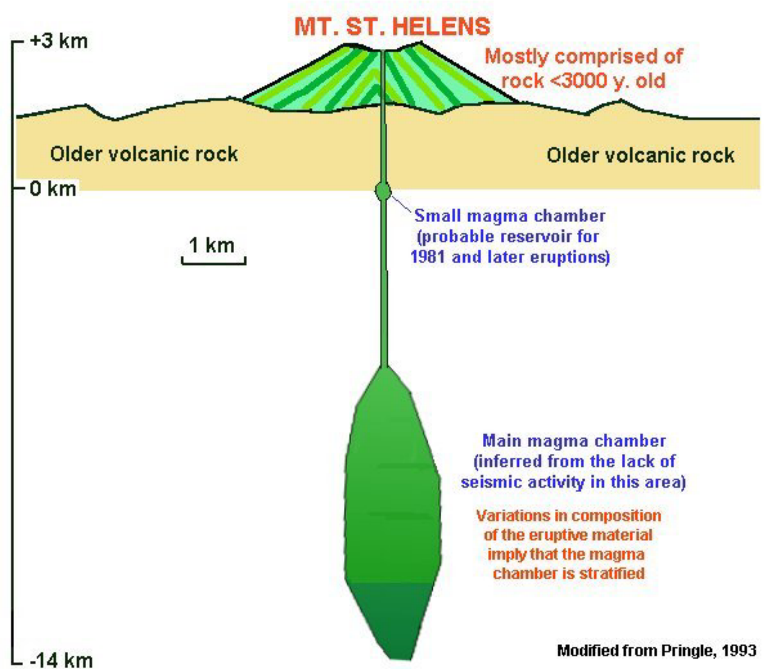
All of the rocks of the area around Mt. St. Helens (MSH) are relatively young in geological terms, and the mountain itself is extremely young. The oldest rocks of the area are parts of the Siletz and Crescent Terranes, oceanic crustal rocks that were accreted onto this part of North America soon after their formation some 50 million years ago. At this time there was subduction of the oceanic plate to the west of the MSH area, and there were subduction-related volcanoes well to the west, in eastern Washington and Idaho. There was extensive sedimentation in what is now western Washington, including the formation of coal deposits.

[3] A comprehensive review of Mt. St. Helens geology, along with hundreds of photographs, is given in: **The 1980 eruption of Mt. St. Helens**, P. Lipman and D. Mullineaux (eds), *U.S. Geological Survey Prof. Paper 1250*. There are also numerous papers of interest in *Geoscience Canada*, V. 17., edited by C. Hickson and D. Peterson.

Around 43 million years ago the subduction zone "jumped" to the west - probably to where it is today off of the coast, and soon after that volcanic activity started along the Cascade Range - extending from southern British Columbia to northern California. Intermittent volcanic activity has continued in this area for the past 40 million years, and most of the solid rocks underneath and surrounding the mountain are the products of this activity. Although there are likely to have been other similar volcanic mountains in this general area during this period, the formation of MSH did not begin until around 40,000 years ago, by which time any previous mountains had been eroded away. In fact, the majority of the rock that makes up MSH was formed long after the end of the last ice age, and most of it was created within the past 3000 years.

Cross-section through Mt. St. Helens and its underlying magma chamber

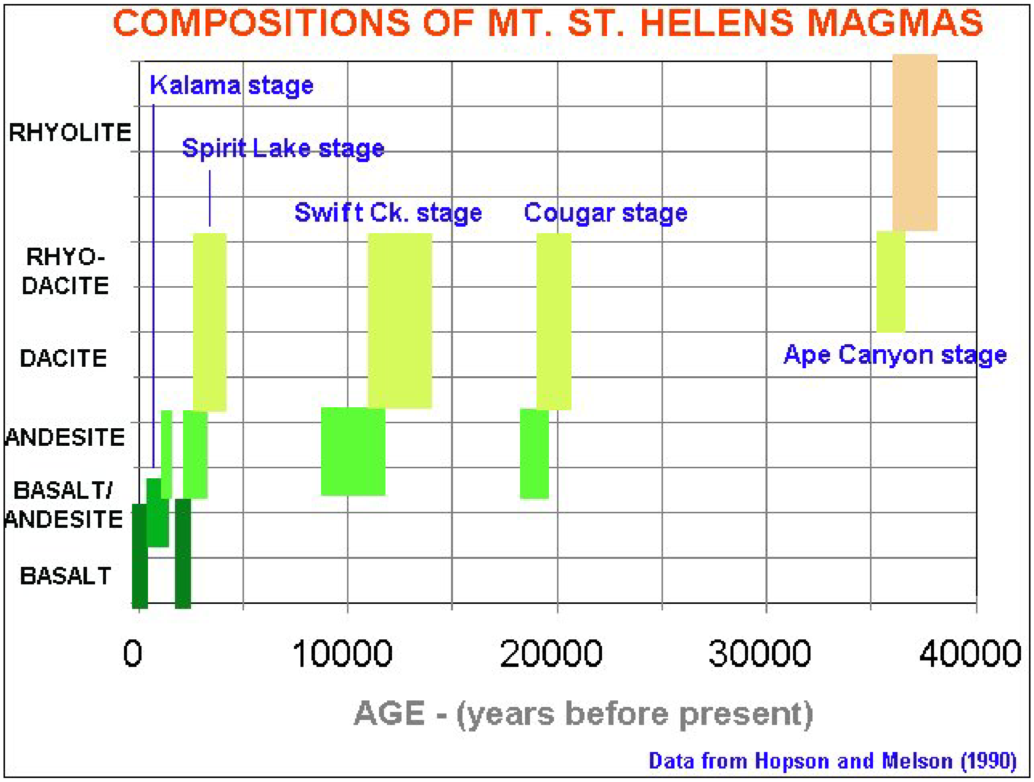
During the 40,000 years of activity at MSH, there has been a broad trend in the composition of the magmas from felsic (rhyodacite - nearly as felsic as rhyolite) to intermediate (andesitic). There have also been some mafic (basaltic) eruptions relatively recently - at 1600 and 1900 years ago.



Zoning in the magma chamber

Seismic studies at MSH have shown that the top of the magma chamber is 6 km below surface and the bottom is 14 km below surface (figure above). The average diameter is 2 to 3 km. The implication of the compositional trends described above is that the magma within this chamber is zoned. Some 40,000 years ago the magma near to the top was probably rhyodacitic in composition while that near to the base was closer to andesitic. At present the magma near to the top of the chamber is andesitic, while that near to the base may be closer to basaltic (Hopson and Melson, 1990).

Superimposed on this long-term variability (at least long-term in the MSH context), are several orders of shorter-term variability with the same general trends. The first-order cycles extend over thousands to tens of thousands of years, the second-order over hundreds to thousands of years, and the third-order over months to tens of years. At each of these time scales there are similar compositional trends (ie. increasing mafic character over the period of an eruptive cycle), and while the ranges of composition are generally smaller than the overall range, there is compositional overlap between the later magma from one cycle and the earlier magma from the next cycle. An example of the variations in the compositions of magma at Mt. St. Helens is given on the figure below.



Variations in the composition of magma erupted at Mt. St. Helens over the past 40,000 years

The implication is that while any specific eruptive event taps increasingly mafic magma, during the periods between eruptions the layering in the magma chamber re-establishes itself to close to what it was before the last eruption. The data suggest that, as at Hekla in Iceland, the longer the repose period, the more completely the zoning will be re-established.

This interpretation of the variability of MSH magma composition is not universally accepted. Some geologists would argue that the cyclic patterns described here are not real - and are merely an artifact of how deposits of various ages are exposed (in other words that we do not understand the history adequately). Others might argue that while there is a cyclic variability, it is not due to stratification within the magma chamber, but to mixing of magmas from different sources.

Other explanations for the variable behaviour

The 1980 Mt. St. Helens eruption

The May 18th 1980 event at MSH was a classic pyroclastic eruption of magma that was primarily of dacitic composition, and hence was relatively viscous, with a high volatile component. The eruption was triggered by a M 5.1 earthquake - which itself was probably related to some movement of magma beneath the mountain. This caused a large part of the side of the mountain (that had been pushed up by pressure from magma during the previous two months), to collapse and slide down the mountain. Like the removal of the cap from a shaken bottle of coke, this release of pressure led to the explosive and violent expulsion of the gas-charged magma in a plinian eruption.

The 1980 eruption at MSH

The amount of magmatic material released on May 18th was relatively small

Small size of

compared to other volcanic eruptions. The volume was around 0.34 km^3, as compared with around 7 km^3 for the 1991 eruption of Mt. Pinatubo in the Philippines, and over 50 km^3 for the 1815 eruption of Mt. Tambora in Indonesia. On the other hand, the collapse and rapid descent of pre-existing material (the debris avalanche) is considered to be the largest landslide in recorded history. Some 2.5 km^3 of rock and debris (over 7 times the volume of the eruption itself) were removed from the upper part of the mountain. Following this catastrophic event the mountain was over 400 m shorter than it had been before the eruption.

the 1980 eruption

The MSH plinian eruption lasted for about 10 hours. During the early stages (first few hours) almost all of the eruption material went straight up. As the intensity decreased, hot ash and gases accumulated near to the vent, and then formed pyroclastic density currents that went racing down the north side of the mountain at speeds of up to 1000 km/h. This material was probably at temperatures of up to about 850^o C. The heat from the exploding material also melted much of the glacier ice on the north side of the mountain, resulting in a massive flow of volcanic debris, mud and water - **lahar** - that roared down the Toutle River, into the Cowlitz River and then into the Columbia River.

Pyroclastic density currents

The distributions of the various deposits and effects associated with the 1980 eruption are shown on Keller's Figure 8.26.

During the main stage of the MSH eruption volcanic material was ejected upward, forming a huge cloud of pumice particles, dust and gases. Most of the larger particles within this cloud settled around the mountain in pumice deposits that are up to 30 m in thickness, but the finer material travelled for hundreds and even thousands of kilometres.

Pumice deposits

The 1980 eruption of MSH did not come as a surprise. From March until May of 1980 there was continual bulging of the dome on the north side of the mountain [Keller, Figure 8.25], there was nearly constant, and increasing, seismic activity around and beneath the mountain, and there was a dramatic increase in the small-scale volcanic activity in the crater near to the summit. A few weeks before the eruption authorities evacuated the area around MSH, and prevented recreational use. Hikers, fishers, loggers, and residents were frustrated by the closures. Some got around the blockades, and most of the 62 people who died were those who came to fish and hike, or stay in their cabins, thinking that the blockade was foolish and unnecessary. Amongst the dead were several geologists, who knew that something was going to happen, and wanted to be as close as they felt safe so that they could witness and record the effects.

Early warning of the 1980 eruption

The environmental effects of the 1980 eruption are numerous, and the environmental impact visible around the mountain is awesome. Fortunately the northern side of MSH is almost entirely a wilderness area, with only a few cabins and logging operations. Otherwise the loss of life would have been much greater.

Environ-mental affects

The debris avalanche, which was triggered by the earthquake and comprised much of the pre-existing side of the mountain, covered the northern side of the mountain and extended over some of the lower hills to the north of the mountain, it also continued for about 10 km down the north fork of the Toutle River, and filled Spirit Lake with mud and debris, raising the water level by about 100 m.

Lahars

The material of the debris avalanche was very wet - mostly because a lot of water had made its way into the side of the mountain during the growth of the bulge. When the debris avalanche came to a stop much of this water was released, and continued on down the valley in the form of a lahar. The rest of the 1980 lahar was derived in the conventional way from melting of ice and snow. Lahar deposits were distributed around all sides of the mountain, but extended the farthest down the Toutle River, where they destroyed numerous bridges and 200 homes. In addition, 35 million cubic metres of sediment reached the Columbia River and disrupted shipping for almost two weeks. Several layers of lahar and pyroclastic flow deposits at one location on Mt. St. Helens are shown on the figure below.

Layers of lahar and pyroclastic flow deposits at Mt. St. Helens (the orange-yellow deposits are pyroclastic)

Blow-down

The explosion of hot gases and tephra that immediately followed the initial landslide affected an area of close to 600 km^2. Within most of this region trees - some of them huge - were immediately blown down, and everything was covered with a thick layer of volcanic ash.

Ash

Fine ash extended across the sate of Washington, turning day into night as far away as Spokane and into Idaho. A yellowish-grey sulphury smelling cloud extended well across the US and into Canada, and very fine material ascended into the stratosphere and traveled all of the way around the earth [Keller, Figure 8.26]. The global environmental effect of this was small, however, because of the relatively small size of the eruption.

For more pictures and description on Mt. St. Helens visit:
http://www.mala.bc.ca/~earles/msh

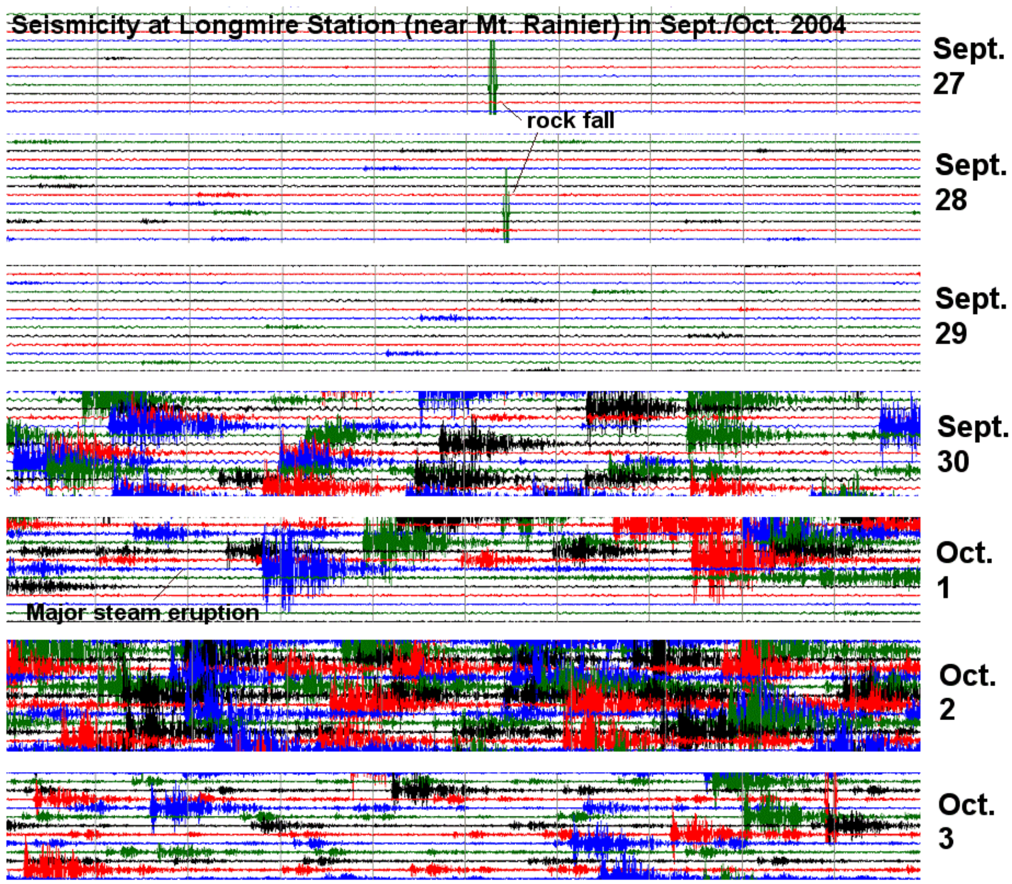
The volcanic activity at Mt. St. Helens in 2004

Following the 1980 eruption MSH continued to be relatively active for almost 10 years. During that time there were several small eruptions, and continued growth of the lava dome within the crater. The mountain quietened down after 1990, but then came back to life in September of 2004.

Recent activity at MSH

As in 1980, the 2004 volcanic activity started with seismicity, although in this case the small earthquakes were relatively close to surface, rather than at the depth of the magma chamber. Some example seismograms from a location about 75 km northeast of MSH are shown on the diagram below. Small earthquakes – mostly less than M1 – occurred at irregular intervals every few minutes for several days.

Seismicity



(From Pacific Northwest Seismic Network: www.pnsn.org)

Partial seismic records from Longmire station for Sept. 27th to Oct. 3rd 2004 (each record represents about 2 hours of data)

During the few days prior to October 1st there were numerous small steam eruptions (phreatic eruptions) from the area of the lava dome, but there was no new magma . At around 12 noon on October 1st a major steam explosion occurred on the south side of the lava dome (see photo below). Seismicity dropped off almost immediately, but then resumed at greater strength on October 2nd. Along with the small earthquakes there was also seismic harmonic tremor - evidence of the movement of magma beneath the mountain.

Phreatic eruptions

Large phreatic eruption at Mt. St. Helens, 12:02 PM, October 1st, 2004

USGS photo (http://vulcan.wr.usgs.gov)

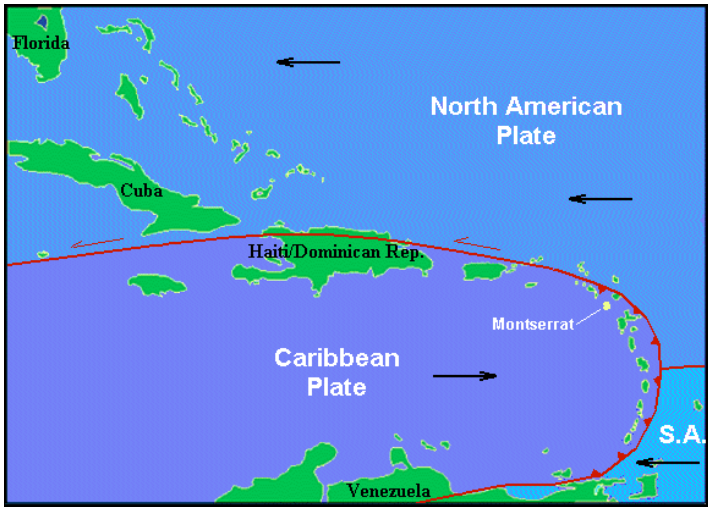
Starting October 3rd and continuing to the present (Jan. 25th, 2005) magma has been extruding on the north side of the old lava dome, creating a new dome that may soon rival the old one in size. (see photo below) There are also ongoing small steam eruptions and continued low-level seismic activity.

Growth of the new lava dome as of January 3rd, 2005

USGS photo (http://vulcan.wr.usgs.gov)

3.5 The 1992 to 1998 eruptions at Montserrat

Tectonic setting of the

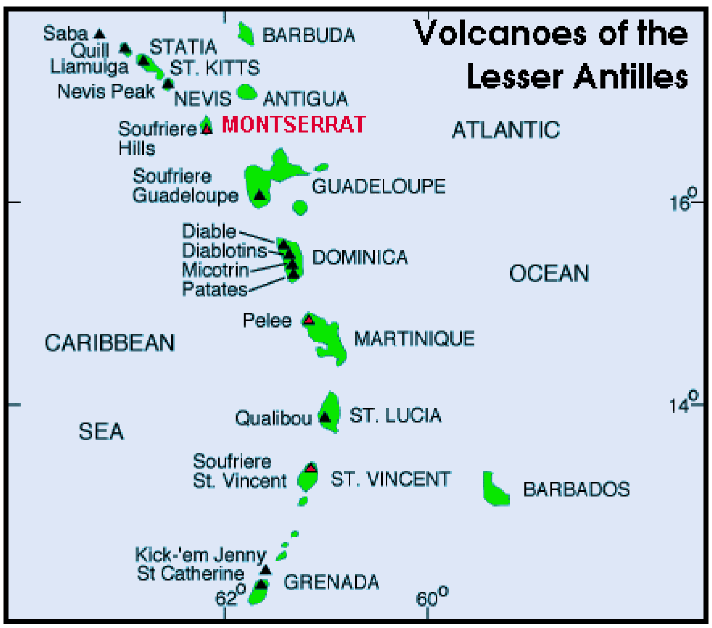


Caribbean

The island of Montserrat is situated in the eastern part of the Caribbean Sea, within the arcuate chain of islands known as the Lesser Antilles. This island arc is the product of the subduction of the North America Plate beneath the Caribbean Plate.

The volcanoes of the Lesser Antilles

Many of the volcanoes of the Caribbean have been active within the past few thousand years. Perhaps the most famous eruption, and the world's deadliest of this century, was on the island of Martinique, when 29,000 died as a result of a pyroclastic flow in 1905. There was also a major eruption at the Soufriere volcano on the island of St. Vincent in 1902 (causing 1600 deaths) and there was more recent activity in the same area in the 1970s. Almost all of the eruptions have been pyroclastic in character. Of 132 recorded Caribbean eruptions, only 4 have been characterized by lava flows[4].



[4] Information and map are from the Univ. of North Dakota's "Volcano World" web site http://volcano.und.nodak.edu

The 1992 to 1998 Montserrat eruptions[5]

The Soufriere[6] Hills volcano on Montserrat has not been particularly active for thousands of years. There were major eruptions around 19,000 years ago, and there were some smaller eruptions around 320 years ago. There was significant seismic activity on Montserrat in the 1930s and 1960s, but no significant eruptions.

The island of Montserrat and the effects of the 1997 and 1998 eruptions

The recent eruption cycle started in January of 1992 with a number of earthquake swarms. Minor earthquakes continued through 1994, and then in July of 1995 there was a phreatic (steam) eruption with small amounts of ash. A phreatic eruption in August 1994 blanketed the capital Plymouth in dust and led to the first of a series of evacuations (Figure 3.9). Dome growth within English's Crater began later that month, and continued relatively quietly over the next two years. There was a significant eruption in September of 1996.

The first pyroclastic event of the recent eruption took place in May of 1997. Pyroclastic activity continued until October 1997. The most significant pyroclastic flow occurred on the 25th of June 1997, causing 19 deaths and the destruction of numerous villages. The flow extended towards the north from the volcano as far as the ocean just south of the airport. During August 1997 pyroclastic material flowed towards the west into the main town of Plymouth.

[5] Much of the information on Montserrat is from the Montserrat Volcano Observatory web page: http://www.geo.mtu.edu/volcanoes/west.indies/soufriere/govt/

[6] The french word *soufriere* refers to a place where sulphur is recovered. Sulphurous deposits are commonly associated with volcanism and it is likely that sulphur has been collected on a relatively small scale from the volcanoes on both Montserrat and St. Vincent.

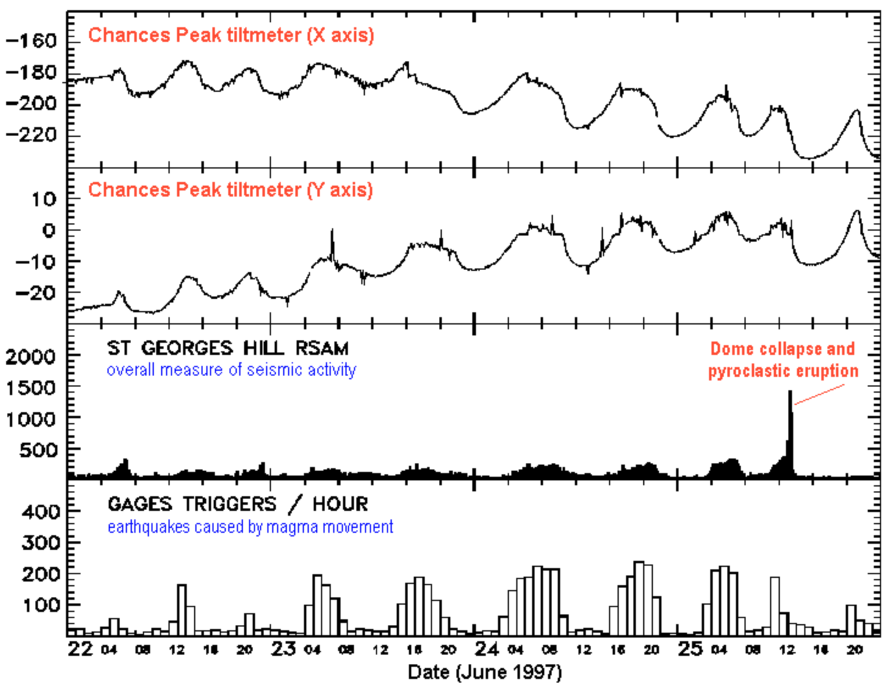
The first of several vulcanian explosions occurred in July of 1997, with other similar eruptions in August, September and October of the same year. Minor activity continued into 1998.

A pyroclastic flow that reached the ocean and created a large fan

Dynamics of the Montserrat eruptions

Monitoring the Soufriere Hills volcano

There was plenty of warning that something was going to happen at Montserrat and that allowed time for geologists to set up a series of seismometers and tilt-meters[7] around the mountain before the main events in 1996 and 1997. Some of the data from these instruments for the period from the 22nd to the 25th of June 1997 are shown on the figure below.



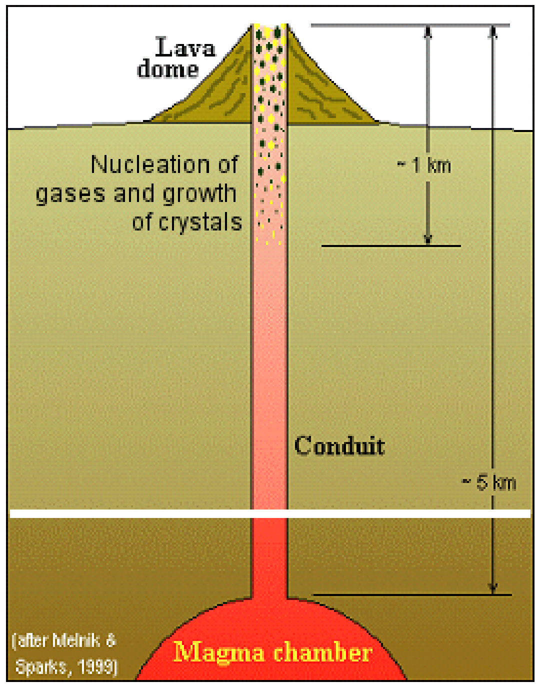
Seismic and tilt meter data gathered from June 22nd to 25th 1997 at the Soufriere Hills volcano

[7] A tilt-meter provides a very sensitive measure of the tilt of the ground at any location. They are commonly used to examine variations in rock deformation around volcanoes. Most are remotely operated and send signals by radio.

The upper two profiles show ground deformation in the Chances Peak area (immediately west of the volcanic centre). The third profile shows the overall level of seismic activity, and the fourth shows the seismic activity related to movement of magma. There is a clear cyclic nature to all of these features, with a period in the order of 10 hours. These features have been discussed in a number of recent papers (Dingwell, 1998, Voight et al., 1999, Wylie et al., 1999, and Melnik and Sparks, 1999), and they are interpreted to be related to the buildup of pressure in the upper part of the volcanic conduit - largely as a result of the exsolution of gases within the uppermost few hundred metres.

Cyclicity in the behaviour of the Soufriere Hills volcano

A model for the eruption behaviour at a typical composite volcano - based on the recent studies at Montserrat - is shown on the diagram to the right. The top of the main magma chamber is at a depth of several kilometres. Exsolution of gases starts as the magma moves to the upper part of the conduit (within about 500 m of surface). At roughly the same time tiny crystals (microlites) start to form. These two processes significantly increase the viscosity of the magma and inhibit it from continuing to move towards surface. The degassing leads to an increase in pressure, which produces both shallow seismicity and deformation of the volcano. (This pressure increase appears to be centred at between 400 and 700 m depth in the case of Montserrat.) As the pressure increases the exsolved gas may gradually be expelled towards surface through the upper part of the conduit, and some magma may be extruded. In some cases, however, the overlying magma may have insufficient permeability to allow the gases to escape, and may be too viscous to be extruded. In such cases an explosive eruption is likely.



Model of the physical conditions and processes at a typical composite volcano (based on data acquired from Montserrat)

On the 23rd and 24th of June 1997 there were several expansions and deflations of the volcano. Late on the 24th and in the morning of the 25th the rate of these events began to speed up, and then just after noon on the 25th the volcanic dome collapsed (ie. it was blown apart) and there was a major explosion, which produced the deadly pyroclastic flow.

The careful monitoring at Montserrat and other volcanoes has provided us with a better understanding of the processes of volcanism in a composite-volcano setting. It has also provided a valuable tool for the prediction of explosive eruptive behaviour, a tool that could save many lives in the future.

3.6 Volcanism in British Columbia

There are three different types of volcanic environments in British Columbia as outlined on the map below:

Types of volcanism in B.C.

- The Garibaldi Volcanic Belt - volcanism related to subduction of the Juan de Fuca Plate
- The Anahim Volcanic Belt – volcanism related to a hot-spot (mantle plume)
- The Stikine Volcanic Belt and the Wells Gray - Clearwater Volcanic Field – volcanism related to crustal rifting.

Distribution of and types of volcanoes in British Columbia

(from a map prepared by Cathy Hickson, Geological Survey of Canada)

Subduction volcanism

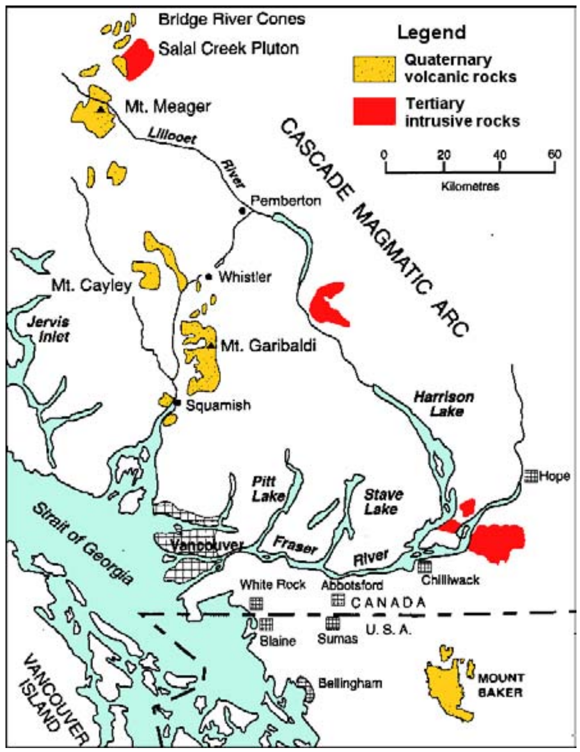
Subduction volcanism in B.C.

Southwestern British Columbia is at the northern end of the Juan de Fuca subduction zone (Cascadia Volcanic belt), but there has been a much lower volume of volcanism here than in the United States. Part of the reason for this may be that there is now here than in the United States. Part of the reason for this may be that there is now some doubt that the northern part of the Juan de Fuca Plate (ie. the Explorer Plate) is still actually subducting (Hickson, 1994). Over the past 2 million years the volume of erupted material northern segment of the Cascadia volcanic arc has been less than 10% of that within the two southern segments (Oregon and California) and about 20% of that within the Washington segment.

As shown of on the map below, there are three main Quaternary (within the last 2 m.y.) volcanic centres in the Canadian segment of the Cascadia Magmatic Arc (Hickson, 1994), as follows:

- Mt. Garibaldi, including Mt. Garibaldi itself, Dalton Dome, Atwell Peak and the Garibaldi Lake area (including Mt. Price and Black Tusk)
- Mt. Cayley and associated lava flows
- Mt. Meager and the Bridge River cones

These three centres are aligned along a north-northwesterly trend that also passes through Mt. Baker and Glacier Peak in Washington.

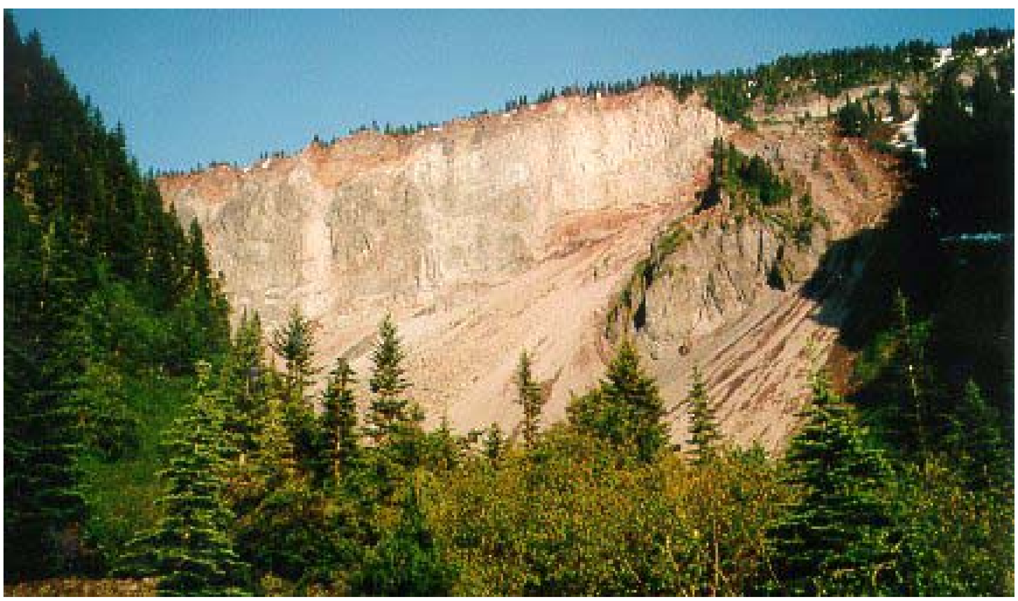


Quaternary volcanic centres (in yellow) of the northern segment of the Cascadia Magmatic Arc

The most recent volcanic activity in this area was some 2400 years ago at Mount Meager, but there was also significant activity in the area during the last glaciation (at approx. 12,000 and 10,000 years ago). Some views of the volcanoes and their deposits are given on the figures below.

Mt Garibaldi from the north

Garibaldi Lake is in the foreground. Mt. Garibaldi on the right with The Table in front of it. This lake and two smaller lakes nearby were created when the drainage system was dammed by a lava flow from Mt. Price that is out of the picture to the right.

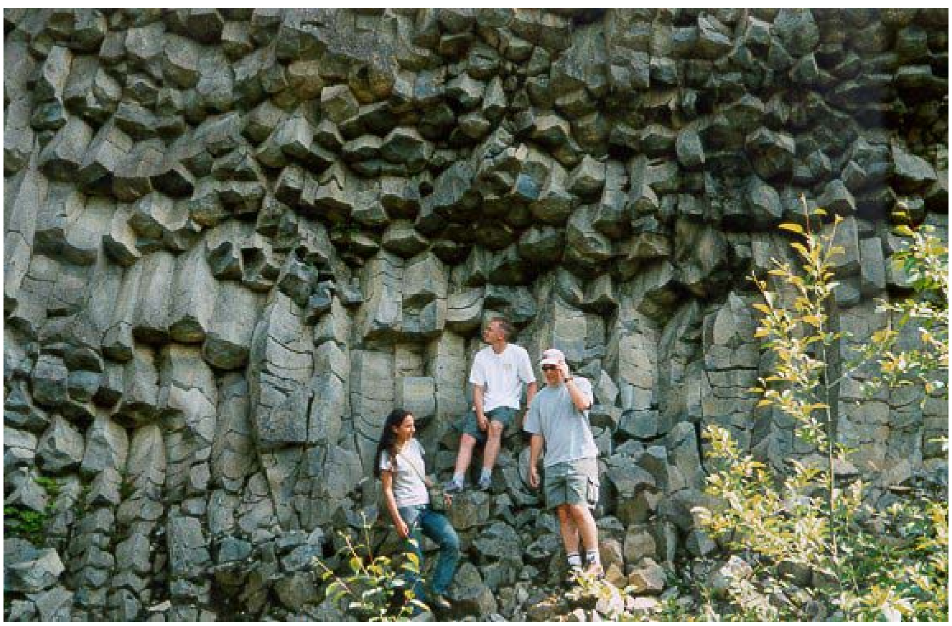


The Barrier

The Barrier is a cliff formed from collapse of the andesite that flowed from Clinker Peak approximately 10,000 years ago. The flow extended as far as the valley of the Cheakamus River, which was filled with glacial ice at the time. When the ice melted, the volcanic material was left as an unstable escarpment.

Satellite image of the Garibaldi area showing lava flows extending from Mt. Price

The northern flow (the Barrier Flow) is the one that dammed up the lakes, and the one that is exposed on the Barrier escarpment. There are well-defined ridges along the edges of the flows because the magma at the margins cooled more quickly than the magma in the middle of the flows, and hence accumulated as thicker solid deposits.



Columnar basalts south of Whistler (probably derived from Mt. Cayley)

Some of the eruptions from the Garibaldi area were quite mafic in composition. The columns in the basalts in this area trend in various directions, suggesting that they cooled in various directions (as opposed to cooling from only above and below, which is typical of most columnar basalts). Some of the flows took place when there was ice in the Cheakamus River Valley, and some of the lava actually flowed within or under the ice.

Stability issues at Mt. Cayley

Mount Cayley is known to have erupted around 200,000 years ago. Although it appears to have been quiet since that time, there is an active hydrothermal system in the area (hot springs etc.), and there have been numerous recent landslides. The landslide potential of the Mt. Cayley area is discussed by Evans and Savigny (1994), who state that there are still "major geomorphic hazards to public safety and economic development" related to futher collapse of the volcanic rocks of Mt. Cayley. The greatest danger is that a future slide at Mt. Cayley could dam up the Squamish River, and then the subsequent collapse of the dam could threaten settlements downstream.

Mt. Meager

Mount Meagher is the largest of all of the BC composite volcanoes, and the most recently active (Hickson, 1994). There is a clearly defined crater at Mt. Meagher and a lava dome within the crater (as there is at Mt. St. Helens). The last known eruption was 2400 years ago. The magma was dacitic in composition, and part of the eruption was plinian in nature. Tephra (volcanic ash) from this eruption reached as far away as Alberta). There is abundant hot-spring activity around Mt. Meagher, and the area has been considered as a potential site for geothermal energy.

Hot-spot volcanism

Nazko cone

The chain of volcanic complexes and cones extending from the coast at Milbanke Sound to Nazko Cone (just west of Quesnel) is interpreted as being related to a mantle plume that is situated beneath the Nazko Cone. The North American Plate is moving in a westerly direction at about 2 cm per year with respect to this plume, and the series of cinder cones and other volcanic deposits get progressively older towards the coast. The volcanism in these areas is generally mafic in composition.

Rift-related volcanism

Rift volcanism

While British Columbia is not about to split into pieces, there are two areas of volcanism that are related to rifting - or at least to extension-produced fractures, some of which extend through the crust. These include the Well Gray - Clearwater field southeast of Quesnel, and the Stikine Volcanic Belt, which extends across the northwestern corner of the province.

Tseax River cone and Mt. Edziza area

The Stikine area includes Canada's most recent volcanic eruption, which took place 200 years ago at Tseax River Cone in the Khutzeymateen River area northeast of Prince Rupert. The Mount Edziza Volcanic field near to the Stikine River, is a huge area of lava flows, shield volcanoes, sulphurous ridges and cinder cones that date from about 1000 years ago.

In all of these areas the volcanism is primarily mafic in composition.

3.7 Other volcanic hazards

Volcanic gases

Volcanic gas hazards

Not all of the environmental effects of volcanism are related to eruptions of magma. The craters of dormant volcanoes are commonly filled with water (such as Crater Lake in Oregon), and within such a lake in west central Cameroun (Africa), gases emanating from the underlying magma chamber continually percolate upward into the muddy lake sediment. One August night in 1986 a landslide, an earthquake or a minor eruption disturbed the lake sediment and released approximately 100 million cubic metres of CO_2 into the lake water. The CO_2 quickly bubbled up through the water and out into the air above the lake. The gas spilled over the lip of the crater, and descended in a white cloud down into the valleys surrounding the crater. 1700 people and 3000 cattle were killed in their sleep [see Keller, p. 216 and 218].

Lahars

Lahars

There is little doubt that the most dangerous effects of many volcanic eruptions are the lahars, largely because they have the potential to affect such a wide area. Pyroclastic flows from the 1985 eruption of the Nevado del Ruiz volcano in Columbia led to melting of glacial ice that produced massive mud-flows extending down stream valleys towards the west, northeast and east of the mountain. A major part of the flow was channeled along the Lagunillas River and then it spilled out over its banks within the town of Armero, situated 45 km away from the mountain. A total of 23,000 people were killed in the 1985 eruption, 21,000 in Armero alone [see Keller p. 219 to 222].

Volcanoes are unstable

Part of the reason for the severe effects of lahars is that composite volcanoes are comprised of material that is not well stuck together. The pyroclastic deposits, ash and previous lahar deposits typical of many volcanoes are largely comprised of materials that cooled in the air, and were not hot enough to be fused together when they hit the ground. Under flood conditions these materials simply wash away. A example of this problem was seen when Hurricane Mitch struck Nicaragua and Guatemala in 1998. The torrential rains washed way part of the side of the volcano just outside of Managua, and hundreds were killed in the ensuing mud flows.

Potential for lahars in the Seattle area

Following the 1980 Mt. St. Helens eruption authorities in Washington State have become acutely aware of the danger of lahars to many other areas, particularly to the suburbs of southern Seattle situated near to Mt. Rainier. There is clear evidence that lahars have been generated by Mt. Ranier in the past, and that they have extended well into populated areas south of Seattle. Mt. Baker, which has more glacial ice than any of the other Cascade volcanoes, has the potential to produce devastating lahars, some of which could have an impact within British Columbia.

Potential for lahars in the Garibaldi area

While the Garibaldi area volcanoes - Garibaldi, Mt. Price, Mt. Cayley, Mt. Meagher - are considered to be dormant, they may not be extinct, and they could come back to life at some time in the future. Because of its very large ice cap, an eruption in the Garibaldi area could produce very significant lahars, which would have devastating consequences for settlements in the Cheakamus and Squamish River valleys (eg. Brakendale or Squamish).

Global effects of volcanic eruptions

Global effects

It is clear that volcanic eruptions do not just affect the environment immediately surrounding the volcano. Most of the wider-spread effects are related to the release of dust and gases high into the atmosphere, where they can be spread around the globe. Experience has shown that each different eruption can affect the climate in a different way. The size of the eruption, and the heights of the eruptions columns are obviously important, but the other significant factors are the type of gas released and the amount of very fine particles.

Acidic gases

The release of volcanic CO_2 contributes to the greenhouse effect, and contributes to warming, while the chlorine gases contribute to the destruction of the ozone layer, and thus reduce the level of protection from ultraviolet radiation. Several gases, including Cl_2, H_2S, CO_2 and SO_2, can also react to form acids in the atmosphere, leading to increases in acid precipitation.

Sulphate aerosols and global cooling

Although volcanic CO_2 contributes to the greenhouse effect, the overall effects of volcanic emissions are cooling rather than warming – at least on the short term. A large amount of volcanic ash will invariably result in the reflection of much of the incoming sunlight, and lead to cooler temperatures. Sulphur dioxide also increases the rate of reflection, as the SO_2 gas reacts to form sulphuric acid droplets or aerosols. Most of the cooling related to volcanism is attributed to sulphate aerosols. Relatively small eruptions like Mt. St. Helens do not have much impact on global climate, but some historic large eruptions have had a significant impact. The ash and pyroclastic material produced by the 1815 eruption of Mt. Tambora in Indonesia led to the cooling of the world's climate by an average of 0.3º C. 1816 was called "the year without a summer". The eruption caused 10,000 direct deaths, but over 70,000 indirect deaths in other parts of the world. As noted above the 1873 Lika eruption in Iceland contributed to serious cooling in Europe over the following year.

1991 Mt. Pinatubo eruption

The 1991 eruption of Mt. Pinatubo resulted in the release of 20 million tonnes of SO_2, over 300 times the amount released by Mt. St. Helens. This caused a 20 to 30% decline in solar radiation reaching the ground in the affected areas, and a mean drop in global temperatures of 0.5º C. The drop in temperatures was almost double that at mid-latitudes of the northern hemisphere.

Very large eruptions

In spite of the major impacts of these eruptions, their effects usually don't continue for more than a couple of years, after which the climate returns to its normal pattern. A more sustained series of very large eruptions would have to take place to change the climate over a longer time period. The massive eruption of the Deccan Traps in India approximately 65 m.y. ago may have caused such a more significant and long-lasting change.

Another important consideration, however, is that there has been a generally consistent rate of volcanism over the past few hundreds of millions of years, and the climate that we have now is partly a result of that. That volcanism has contributed huge amounts of water plus CO_2, SO_2 and other gases to the atmosphere. If the level of volcanic activity was to decrease significantly over a long period, then we could expect some major and long-term impacts on the climate. On the other hand, while volcanic activity does result in the emission of large volumes of volatiles into the atmosphere, there is an overall balance between this output and the consumption of volatiles at subduction zones.

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