Chapter 11. Volcanism

Introduction

Learning Objectives

After carefully reading this chapter, completing the exercises within it, and answering the questions at the end, you should be able to:

- Explain the relationships between plate tectonics, the formation of magma, and volcanism
- Describe the range of magma compositions formed in differing tectonic environments, and discuss the relationship between magma composition, including gas content, and eruption style
- Explain the geological and eruption-style differences between different types of volcanoes, especially shield volcanoes, composite volcanoes, and cinder cones
- Understand the types of hazards posed to people and infrastructure by the different types of volcanic eruptions
- Describe the behaviours that indicate a volcano is ready to erupt, and how we monitor those behaviours and predict eruptions
- Summarize the types of volcanoes that have erupted in British Columbia over the past 2.6 Ma, and the characteristics of some of those eruptions

What Is A Volcano?

A volcano is any location where magma comes to the surface, or has done so within the past several million years. This may or may not be a mountain. Some volcanic eruptions happen on land, in which case they are called subaerial eruptions. However, volcanic eruptions can also happen underwater, such as on the ocean floor or under a lake. These kinds of eruptions are called subaqueous eruptions.

Canada has a lot of volcanic rock, but most of it is old—some of it billions of years old. Only in B.C. and the Yukon are there volcanoes that have been active within the past 2.6 Ma (Pleistocene or younger), and the vast majority of these are in B.C. We’ll look at those in some detail toward the end of this chapter, but a few of them are shown on Figures 11.1 and 11.2.

Studying volcanoes helps us understand the geological evolution of Earth, and significant changes in climate. A key reason, however, is that understanding volcanoes helps us to save lives and property. Over the past few decades, volcanologists have made great strides in their ability to forecast volcanic eruptions and predict the consequences. This has already saved thousands of lives, but the knowledge was not cheaply bought. Some of this understanding cost the lives of the very people trying to learn about volcanoes in order to save others.
11.1 Plate Tectonics and Volcanism

The relationships between plate tectonics and volcanism are shown on Figure 11.3. Magma is formed at three main plate-tectonic settings:

- divergent boundaries where melting happens by decompression
- convergent boundaries where flux melting occurs as a result of water being released from slabs of subducting ocean crust
- mantle plumes where hot mantle material is decompressed as it rises up from deep within the mantle, and can cause eruptions away from plate boundaries both on land and in the ocean

Mantle and crustal volcanic processes are illustrated in more detail in Figure 11.4.
Figure 11.3 Plate tectonic settings of volcanism. Composite volcanoes form at subduction zones, either on ocean-ocean convergent boundaries (left) or ocean-continent convergent boundaries (right). Shield volcanoes and cinder cones form in areas of continental rifting (far right). Shield volcanoes also form above mantle plumes, and in other tectonic settings. Sea-floor volcanism can take place at divergent boundaries, mantle plumes and ocean-ocean-convergent boundaries. [Steven Earle CC-BY 4.0, after USGS (http://pubs.usgs.gov/gip/dynamic/Vigil.html)]

**Decompression Causes Volcanism at Spreading Centres**

At an ocean spreading ridge (Figure 11.4a), hot mantle rock moves slowly upward by convection at rates of cm per year. At approximately 60 km below the surface, the mantle rocks have decompressed is enough to permit partial melting. Over the triangular area shown in Figure 11.4a, about 10% of the ultramafic mantle rock melts, producing mafic magma that moves upward toward the axis of spreading (where the two plates are moving away from each other). The magma fills vertical fractures produced by the spreading and spills out onto the sea floor to form basaltic **pillows** (more on that later) and lava flows. There is spreading-ridge volcanism taking place about 200 km offshore from the west coast of Vancouver Island.

Figure 11.4 Processes that lead to volcanism in the three main volcanic settings on Earth: (a) volcanism related to plate divergence, (b) volcanism at an ocean-continent boundary (similar processes occur at ocean-ocean convergent boundaries), and (c) volcanism related to a mantle plume. [Steven Earle CC-BY 4.0, after USGS (http://pubs.usgs.gov/gip/dynamic/Vigil.html)]
Volcanism in northwestern BC (Figures 11.5 and 11.6) is related to continental rifting. This area is not yet a divergent boundary, but over time it might develop into a continental rift zone and spreading centre such as that found in eastern Africa. The crust of northwestern BC is being stressed by the northward movement of the Pacific Plate against the North America Plate, and the resulting crustal fracturing provides a conduit for the flow of magma from the mantle.


Below: Figure 11.6 Volcanic rock at the Tseax River area, northwestern BC. [Steven Earle CC-BY 4.0]
Water Causes Partial Melting Along Subduction Zones

At an ocean-continent or ocean-ocean convergent boundary, oceanic crust is pushed far down into the mantle (Figure 11.4b). It is heated up, and while there isn’t enough heat to melt the subducting crust, there is enough to force the water out of some of its minerals. This water rises into the overlying mantle where it contributes to flux melting of the mantle rock. The mafic magma produced rises through the mantle to the base of the crust. There it contributes to partial melting of crustal rock, and thus it assimilates much more felsic material. That magma, now intermediate in composition, continues to rise and assimilate crustal material; in the upper part of the crust, it accumulates into plutons. From time to time, the magma from the plutons rises toward surface, leading to volcanic eruptions. Mt. Garibaldi (Figures 11.1 and 11.2) is an example of subduction-related volcanism.

Decompression of Mantle Plumes Can Cause Volcanism Away from Plate Boundaries

Hot spot volcanoes (Figure 11.4c) can occur within plates, far from where plate boundary processes are taking place. They occur above mantle plumes, which are rising columns of hot solid rock. The rising column may be kilometres to 10s of kilometres across, but near the surface it spreads out to create a mushroom-like head that is 10s to over 100 kilometres across. Mantle plumes are different from the convection that normally occurs beneath ocean spreading centres: plumes rise approximately 10 times as fast as regular mantle convection occurs, and may originate deep in the mantle, possibly just above the core-mantle boundary.

Near the base of the lithosphere (the rigid part of the mantle), pressure on the mantle plume is low enough to permit partial melting of the plume material, producing mafic magma. Heat carried by the mantle plume may also melt rock adjacent to the plume. The magma rises and feeds volcanoes. Most mantle plumes are beneath the oceans, so the early stages of volcanism typically take place on the sea floor. Over time, islands may form like those in Hawaii.

Exercise 11.1 How Thick Is Ocean Crust?

Figure 11.4a shows a triangular zone about 60 km thick. Within this zone approximately 10% of the mantle rock melts to form oceanic crust. Based on this information, approximately how thick do you think the resulting oceanic crust should be?

11.2 Magma Composition and Eruption Style

Magma Composition Depends on Tectonic Setting

The types of magma produced in different volcanic settings can vary significantly. At divergent boundaries and oceanic mantle plumes, magma is consistently mafic. This is because little interaction with crustal materials occurs, and magma fractionation to create felsic melts does not take place.

At subduction zones, where the magma ascends through a significant thickness of crust, a variety of processes can occur that make magma stored within a magma chamber more felsic (Figure 11.7):
1. As the magma begins to cool, higher-temperature minerals such as olivine and pyroxene begin to crystallize. The minerals are denser than the surrounding magma, so they sink to the bottom of the magma chamber. The magma at the top of the chamber is more felsic because of the loss of these minerals.

2. Heat from the magma can trigger partial melting of the country rock around the magma chamber. Lower-temperature felsic minerals will be the first to melt, causing the magma to become more felsic.

3. If fragments of felsic country rock have broken from the walls of the magma chamber, and begin melting within the chamber, this will cause the magma to become more felsic.

4. If mafic minerals have settled to the bottom of the magma chamber, and are heated again, it is possible that they could melt and mix back in with the magma. This would make the magma at the base of the chamber more mafic.

### Magma Composition Affects How Lava Erupts

From the perspective of what happens during a volcanic eruption, there are two important differences between felsic and mafic magmas: **viscosity** (how easily the magma flows), and volatile (or gas) content.
Felsic magmas are more viscous than mafic magmas because they have more silica, and hence more polymerization. Felsic magmas also contain more volatile compounds. Volatile compounds behave as gases when volcanoes erupt. The most common volatile compound in magma is water, followed by carbon dioxide (CO₂), then sulphur dioxide (SO₂). A general relationship between the SiO₂ content of magma and the amount of volatiles is shown in Figure 11.8. Although there are exceptions to the trend show in in Figure 11.8, mafic magmas typically have 1% to 3% volatiles, intermediate magmas have 3% to 4% volatiles, and felsic magmas have 4% to 7% volatiles.

Differences in viscosity and volatile level have significant implications for the nature of volcanic eruptions. When magma is deep beneath the surface and under high pressure from the surrounding rocks, the volatile compounds within it remain dissolved. As magma approaches the surface, the pressure exerted on it decreases. Volatile compounds come out of solution, and accumulate as gas bubbles. The more volatile compounds in the magma, the more bubbles form.

If the gas content is low or the magma is runny enough for gases to rise up through it and escape to surface, the pressure will not become excessive. Assuming that it can break through to the surface, the magma will flow out relatively gently. An eruption that involves a steady non-violent flow of magma is called effusive.

If the magma is felsic, and therefore too viscous for gases to escape easily, or if it has a particularly high gas content, it is likely to be under high pressure. Viscous magma doesn’t flow easily, so even if there is a way for it to move out, it may not flow. Under these circumstances pressure will continue to build as more magma moves up from beneath and more gas bubbles form. Eventually some part of the volcano will break, releasing the pent-up pressure in an explosive eruption.

Because the composition of magma depends on tectonic setting, the behaviour of volcanoes does too. Mantle plume and spreading-ridge magmas tend to be consistently mafic, so effusive eruptions are the norm. At subduction zones, the average magma composition is likely to be close to intermediate, but as we’ve seen, magma chambers can become zoned and so compositions ranging from felsic to mafic are possible. Eruption styles can be correspondingly variable.
Exercise 11.2 Gas Under Pressure

A good analogy for a magma chamber in the upper crust is a plastic bottle of pop on the supermarket shelf. Go to a supermarket and pick one up off the shelf. You’ll find that the bottle is hard because it was bottled under pressure. You should be able to see that there are few gas bubbles inside.

Buy a small bottle of pop and open it. The bottle will become soft because the pressure is released, and small bubbles will start forming. If you put the lid back on and shake the bottle (best to do this outside!), you’ll enhance the processes of bubble formation. When you open the lid, the pop will come gushing out, just like an explosive volcanic eruption.

A pop bottle is a better analogue for a volcano than the old baking soda and vinegar experiment that you did in elementary school, because pop bottles, like volcanoes, come pre-charged with gas pressure. All we need to do is release the confining pressure (remove the cap) and the gases come bubbling out.

11.3 Types of Volcanoes

There are numerous types of volcanoes or volcanic sources. Some of the more common ones are summarized in Table 11.1.

The sizes and shapes of typical shield, composite, and cinder-cone volcanoes are compared in Figure 11.9. To be fair, Mauna Loa is the largest shield volcano on Earth, so all others are smaller. Mauna Loa rises from the surrounding flat sea floor, and its diameter is in the order of 200 km. Its elevation is 4,169 m above sea level. Mt. St. Helens, a composite volcano, rises above the surrounding hills of the Cascade Range. Its diameter is about 6 km, and its height is 2,550 m above sea level. Cinder cones are much smaller. On this drawing, even a large cinder cone is just a dot.

Figure 11.9 Profiles of Mauna Loa shield volcano, Mt. St. Helens composite volcano, and a large cinder cone [Steven Earle CC-BY 4.0]
Table 11.1 A summary of types of volcanoes and volcanism

### Types of Volcanoes

#### Cinder Cones

Cinder cones (also called spatter cones), like Eve Cone in northern BC (Figure 11.10), are typically only a few hundred metres in diameter, and few are more than 200 m high. Most are made up of fragments of vesicular mafic rock (scoria) that were expelled as the magma boiled when it approached the surface, creating fire fountains. In many cases, these later became effusive (lava flows) when the gases were depleted. Most cinder cones form during a single eruptive phase that might have lasted weeks or months. Because cinder cones are made up almost exclusively of loose fragments, they have very little strength. They can be easily, and relatively quickly, eroded away.

Figure 11.10 Eve Cone, situated near to Mt. Edziza in northern B.C., formed approximately 700 years ago [Wikipedia, http://en.wikipedia.org/wiki/Eve_Cone#mediaviewer/File:Symmetrical_Eve_Cone.jpg]
Composite Volcanoes

Composite volcanoes (also called stratovolcanoes), like Mt. St. Helens in Washington State (Figure 11.11), are almost all associated with subduction at convergent plate boundaries — either ocean-continent or ocean-ocean boundaries (Figure 11.4b). They can extend up to several thousand metres from the surrounding terrain, have slopes ranging up to 30°, and are typically up to 10 km across. At many such volcanoes, magma is stored in a magma chamber in the upper part of the crust. For example, at Mt. St. Helens, there is evidence of a magma chamber that is approximately 1 km wide and extends from about 6 km to 14 km below the surface (Figure 11.12). Systematic variations in the composition of volcanism over the past several thousand years at Mt. St. Helens imply that the magma chamber is zoned, from more felsic at the top to more mafic at the bottom.

The rock that makes up Mt. St. Helens ranges in composition from rhyolite (Figure 11.13a) to basalt (Figure 11.13b). This implies that the types of past eruptions have varied widely in character. As already noted, felsic magma doesn’t flow easily and doesn’t allow gases to escape easily. Under these circumstances, pressure builds up until a conduit opens, and then an explosive eruption results from the gas-rich upper part of the magma chamber, producing pyroclastic debris (labelled P in Figure 11.13a). The pyroclastic layers alternate with lahar deposits (labelled L in Figure 11.13a). Lahars are large mud flows triggered when a volcanic eruption leads to rapid melting of ice and snow on a volcano.

Mafic eruptions (and some intermediate eruptions), on the other hand, produce lava flows. The one shown in Figure 11.13b is thick enough (about 10 m in total) to have cooled in a columnar jointing pattern (Figure 11.14). Lava flows both flatten the profile of the volcano (because the lava typically flows farther than pyroclastic debris falls) and protect the fragmental deposits from erosion. Even so, composite volcanoes tend to erode quickly. Patrick Pringle, a volcanologist with the Washington State Department of Natural Resources, describes Mt. St. Helens as a “pile of junk.”
In a geological context, composite volcanoes tend to form relatively quickly and do not last very long. Mt. St. Helens, for example, is made up of rock that is all younger than 40,000 years; most of it is younger than 3,000 years. If its volcanic activity ceases, it might erode away within a few tens of thousands of years. This is largely because of the presence of pyroclastic eruptive material, which is not strong.

**Shield Volcanoes**

Most **shield volcanoes** are associated with mantle plumes, although some form at divergent boundaries, either on land or on the sea floor. Because of their non-viscous mafic magma they tend to have relatively gentle slopes (2° to 10°) and the larger ones can be over 100 km in diameter.

The best-known shield volcanoes are those that make up the Hawaiian Islands, and of these, the only active ones are on the big island of Hawaii. Mauna Loa, the world’s largest volcano and the world’s largest mountain (by volume) last erupted in 1984. Kilauea, arguably the world’s most active volcano, has been erupting, virtually without interruption, since 1983. Loihi is an underwater volcano on the southeastern side of Hawaii. It is last known to have erupted in 1996, but may have erupted since then without being detected.

All of the Hawaiian volcanoes are related to the mantle plume that currently lies beneath Mauna Loa, Kilauea, and Loihi (Figure 11.15). In this area, the Pacific Plate is moving northwest at a rate of about 7 cm/year. This means that the earlier formed — and now extinct — volcanoes have now moved well away from
the mantle plume. As shown on Figure 11.15, there is evidence of crustal magma chambers beneath all three active Hawaiian volcanoes. At Kilauea, the magma chamber appears to be several kilometres in diameter, and is situated between 8 km and 11 km below surface.1

![Figure 11.15 Mauna Kea from near to the summit of Mauna Loa, Hawaii](http://upload.wikimedia.org/wikipedia/commons/f/f1/Hawaii_hotspot_cross-sectional_diagram.jpg)

Kilauea, although not a prominent mountain (Figure 11.9), has a large caldera in its summit area (Figure 11.16). A caldera is a volcanic collapse structure formed when the magma chamber beneath the volcano is emptied, removing support for the rocks above. Calderas are much larger than craters; this one is 4 km long and 3 km wide. It contains a smaller feature called Halema’uma’u crater, which has a total depth of over 200 m below the surrounding area.

![Figure 11.16 Aerial view of the Kilauea caldera. The caldera is about 4 km across, and up to 120 m deep. It encloses a smaller and deeper crater known as Halema’uma’u.](https://physicalgeology.pressbooks.com)

1 Lin, G, Amelung, F, Lavallee, Y, and Okubo, P, 2014, Seismic evidence for a crustal magma reservoir beneath the upper east rift zone of Kilauea volcano, Hawaii. Geology. V.
The level of a caldera or crater floor is influenced by the amount of pressure exerted by the magma body. During historical times, the floors of both Kilauea caldera and Halema’uma’u crater have moved up during expansion of the magma chamber and down during deflation of the chamber.

One of the conspicuous features of Kilauea caldera is rising water vapour (the white cloud in Figure 11.16) and a strong smell of sulphur (Figure 11.17). As is typical in magmatic regions, water is the main volatile component, followed by carbon dioxide and sulphur dioxide. These, and some minor gases, originate from the magma chamber at depth and rise up through cracks in the overlying rock. This degassing of the magma is critical to the style of eruption at Kilauea, which, for most of the past 30 years, has been effusive, not explosive.

The Kilauea eruption that began in 1983 started with the formation of a cinder cone at Pu’u ’O’o, approximately 15 km east of the caldera (Figure 11.18). The magma feeding this eruption flowed along a major conduit system known as the East Rift, which extends for about 20 km from the caldera, first southeast and then east.

Figure 11.17 A gas-composition monitoring station (left) within the Kilauea caldera and at the edge of Halema’uma’u crater. The rising clouds are mostly composed of water vapour, but also include carbon dioxide and sulphur dioxide. Sulphur crystals (right) have formed around a gas vent in the caldera. [Steven Earle CC-BY 4.0]

Figure 11.18 Satellite image of Kilauea volcano showing the East rift and Pu’u ’O’o, the site of the eruption that started in 1983. The puffy white blobs are clouds. [Steven Earle after, http://en.wikipedia.org/wiki/Hawaii_(island)#mediaviewer/File:Island_of_Hawai%27i_-_Landsat_mosaic.jpg]
Lava fountaining and construction of the Pu‘u ‘O’o cinder cone (Figure 11.19a) continued until 1986 at which time the flow became effusive. From 1986 to 2014, lava flowed from a gap in the southern flank of Pu‘u ‘O’o down the slope of Kilauea through a lava tube (Figure 11.19d), emerging at or near the ocean. Since June 2014, the lava has flowed northeast (see Exercise 11.4).

Figure 11.19 Images of Kilauea volcano taken in 2002 (b & c) and 2007 (a & d). a) Pu‘u ‘O’o cinder cone in the background with tephra in the foreground and aa lava in the middle. b) Formation of pahoehoe on the southern edge of Kilauea. c) Formation of aa on a steep slope near the southern edge of Kilauea. d) Skylight into lava tube. [Steven Earle CC-BY 4.0]

The two main types of textures created during effusive subaerial eruptions are pahoehoe and aa. Pahoehoe, ropy lava that forms as non-viscous lava, flows gently, forming a skin that gels and then wrinkles because of ongoing flow of the lava below the surface (Figure 11.19b). Aa, or blocky lava, forms when magma is forced to flow faster than it is able to (down a slope for example) (Figure 11.19c). Tephra (lava fragments) is produced during explosive eruptions, and accumulates in the vicinity of cinder cones.

Figure 11.19d is a view into an active lava tube on the southern edge of Kilauea. The red glow is from a stream of very hot lava (~1200°C) that has flowed underground for most of the 8 km from the Pu‘u ‘O’o vent. Lava tubes form naturally and readily on both shield and composite volcanoes because flowing mafic lava preferentially cools near its margins, forming solid lava levées that eventually close over the top of the flow. The magma within a lava tube is not exposed to the air, so it remains hot and fluid and can flow for tens of kilometres, thus contributing to the large size and low slopes of shield volcanoes. The Hawaiian volcanoes are riddled with thousands of old lava tubes, some as long as 50 km.

Kilauea is approximately 300 ka old, while neighbouring Mauna Loa is over 700 ka and Mauna Kea is over 1 Ma. If volcanism continues above the Hawaii mantle plume in the same manner that it has for the past 85 Ma, it is likely that Kilauea will continue to erupt for at least another 500,000 years. By that time, its neighbour,
Loihi, will have emerged from the sea floor, and its other neighbours, Mauna Loa and Mauna Kea, will have become significantly eroded, like their cousins, the islands to the northwest (Figure 11.15).

**Exercise 11.4 Kilauea’s June 27th Lava Flow**

The U.S. Geological Survey Hawaii Volcano Observatory (HVO) map shown here, dated January 29, 2015, shows the outline of lava that started flowing northeast from Pu‘u ‘O’o on June 27, 2004 (the “June 27th Lava flow,” a.k.a. the “East Rift Lava Flow”). The flow reached the nearest settlement, Pahoa, on October 29, after covering a distance of 20 km in 124 days. After damaging some infrastructure west of Pahoa, the flow stopped advancing. A new outbreak occurred November 1, branching out to the north from the main flow about 6 km southwest of Pahoa.

1. What is the average rate of advance of the flow front from June 27 to October 29, 2014, in m/day and m/hour?

2. Go to the Kilauea page of the HVO website at: http://hvo.wr.usgs.gov/activity/kilaueastatus.php to compare the current status of the June 27th (or East Rift) lava flow with that shown on the map below.

![Lava flow map](image-url)

**Large Igneous Provinces**

While the Hawaii mantle plume has produced a relatively low volume of magma for a very long time (~85 Ma), other mantle plumes are less consistent, and some generate massive volumes of magma over relatively short time periods. Although their origin is still controversial, it is thought that the volcanism leading to large igneous provinces (LIP) is related to very high volume but relatively short duration bursts of magma from
mantle plumes. An example of an LIP is the Columbia River Basalt Group (CRGB), which extends across Washington, Oregon, and Idaho (Figure 11.20). This volcanism, which covered an area of about 160,000 km² with basaltic rock up to several hundred metres thick, took place between 17 and 14 Ma.

Most other LIP eruptions are much bigger. The Siberian Traps (also basalt), which erupted at the end of the Permian period at 250 Ma, are estimated to have produced approximately 40 times as much lava as the CRBG.

The mantle plume that is assumed to be responsible for the CRBG is now situated beneath the Yellowstone area, where it leads to felsic volcanism. Over the past 2 Ma three very large explosive eruptions at Yellowstone have yielded approximately 900 km³ of felsic magma, about 900 times the volume of the 1980 eruption of Mt. St. Helens, but only 5% of the volume of mafic magma in the CRBG.

Figure 11.20 Part of the Columbia River Basalt Group at Frenchman Coulee, eastern Washington. All of the flows visible here have formed large (up to two metres in diameter) columnar basalts, a result of relatively slow cooling of flows that are tens of m thick. The inset map shows the approximate extent of the 17 to 14 Ma Columbia River Basalts, with the location of the photo shown as a star. [Steven Earle CC-BY 4.0]

Sea-Floor Volcanism

Some LIP eruptions occur on the sea floor, the largest being the one that created the Ontong Java plateau in the western Pacific Ocean at around 122 Ma. But most sea-floor volcanism originates at divergent boundaries and involves relatively low-volume eruptions. Under these conditions, hot lava that oozes out into the cold
seawater quickly cools on the outside and then behaves a little like toothpaste. The resulting blobs of lava are known as pillows, and they tend to form piles around a sea-floor lava vent (Figure 11.21). In terms of area, there is very likely more pillow basalt on the sea floor than any other type of rock on Earth.

![Figure 4.21 Modern and ancient sea-floor pillow basalts (left) Modern sea-floor pillows in the south Pacific [NOAA, from http://en.wikipedia.org/wiki/Basalt#mediaviewer/File:Pillow_basalt_crop_l.jpg] (right) Eroded 40 to 50 Ma pillows on the shore of Vancouver Island, near to Sooke. The pillows are 30 to 40 cm in diameter. [Steven Earle CC-BY 4.0]](image1)

**Kimberlites**

While all of the volcanism discussed so far is thought to originate from partial melting in the upper mantle or within the crust, there is a special class of volcanoes called *kimberlites* that have their origins much deeper in the mantle, at depths of 150 km to 450 km. During a kimberlite eruption, material from this depth may make its way to surface quickly (hours to days) with little interaction with the surrounding rocks. As a result, kimberlite eruptive material is representative of mantle compositions: it is ultramafic.

Kimberlite eruptions that originate at depths greater than 200 km, within areas beneath old thick crust (shields), traverse the region of stability of diamond in the mantle, and in some cases, bring diamond-bearing material to the surface. All of the diamond deposits on Earth are assumed to have formed in this way; an example is the Ekati Mine in the Northwest Territories (Figure 11.22).

![Figure 11.22 Ekati diamond mine, Northwest Territories, part of the Lac de Gras kimberlite field [http://upload.wikimedia.org/wikipedia/commons/8/88/Ekati_mine_640px.jpg]](image2)
The kimberlites at Ekati erupted between 45 and 60 Ma. Many kimberlites are older, some much older. There have been no kimberlite eruptions in historic times. The youngest known kimberlites are in the Igwisi Hills in Tanzania and are only about 10,000 years old. The next youngest known are around 30 Ma old.

### 11.4 Volcanic Hazards

There are two classes of volcanic hazards: direct and indirect. Direct hazards are forces that directly kill or injure people, or destroy property or wildlife habitat. Indirect hazards are volcanism-induced environmental changes that lead to distress, famine, or habitat destruction. Indirect effects of volcanism have accounted for approximately 8 million deaths during historical times, while direct effects have accounted for fewer than 200,000, or 2.5% of the total. Some of the more important types of volcanic hazards are summarized in Table 11.2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
<th>Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tephra emissions</td>
<td>Small particles of volcanic rock emitted into the atmosphere</td>
<td>Respiration problems for some individuals</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Significant climate cooling and famine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Damage to aircraft</td>
</tr>
<tr>
<td>Gas emissions</td>
<td>The emission of gases before, during, and after an eruption</td>
<td>Climate cooling leading to crop failure and famine</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In some cases, widespread poisoning</td>
</tr>
<tr>
<td>Pyroclastic density current</td>
<td>A very hot (several 100°C) mixture of gases and volcanic tephra that flows rapidly (up to 100s of km/h) down the side of a volcano</td>
<td>Extreme hazard — destroys anything in the way</td>
</tr>
<tr>
<td>Pyroclastic fall</td>
<td>Vertical fall of tephra in the area surrounding an eruption</td>
<td>Thick tephra coverage of areas close to the eruption (km to 10s of km)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collapsed roofs</td>
</tr>
<tr>
<td>Lahar</td>
<td>A flow of mud and debris down a channel leading away from a volcano, triggered either by an eruption or a severe rain event</td>
<td>Severe risk of destruction for anything within the channel — lahars can move at 10s of km/h</td>
</tr>
<tr>
<td>Sector collapse/debris avalanche</td>
<td>The failure of part of a volcano, either due to an eruption or for some other reason, leading to the failure of a large portion of the volcano</td>
<td>Severe risk of destruction for anything in the path of the debris avalanche</td>
</tr>
<tr>
<td>Lava flow</td>
<td>The flow of lava away from a volcanic vent</td>
<td>People and infrastructure at risk, but lava flows tend to be slow (km/h) and are relatively easy to avoid</td>
</tr>
</tbody>
</table>

Table 11.2 Summary of volcanic hazards [Stephen Earle CC-BY 4.0]
Volcanic Gas and Tephra Emissions

Large volumes of tephra (rock fragments, mostly pumice) and gases are emitted during major plinian eruptions (large explosive eruptions with hot gas a tephra columns extending into the stratosphere) at composite volcanoes, and a large volume of gas is released during some very high-volume effusive eruptions. One of the major effects is cooling of the climate by 1° to 2°C for several months to a few years because the dust particles and tiny droplets and particles of sulphur compounds block the sun. The last significant event of this type was in 1991 and 1992 following the large eruption of Mt. Pinatubo in the Philippines. A drop of 1° to 2°C may not seem like very much, but that is the global average amount of cooling, and cooling was much more severe in some regions and at some times.

Over an eight-month period in 1783 and 1784, a massive effusive eruption took place at the Laki volcano in Iceland. Although there was relatively little volcanic ash involved, a massive amount of sulphur dioxide was released into the atmosphere, along with a significant volume of hydrofluoric acid (HF). The sulphate aerosols that formed in the atmosphere led to dramatic cooling in the northern hemisphere. There were serious crop failures in Europe and North America, and a total of 6 million people are estimated to have died from famine and respiratory complications. In Iceland, poisoning from the HF resulted in the death of 80% of sheep, 50% of cattle, and the ensuing famine, along with HF poisoning, resulted in more than 10,000 human deaths, about 25% of the population.

Volcanic ash can also have serious implications for aircraft because it can destroy jet engines. For example, over 5 million airline passengers had their travel disrupted by the 2010 Eyjafjallajökull volcanic eruption in Iceland.

Pyroclastic Density Currents (Pyroclastic Flows)

In a typical explosive eruption at a composite volcano, the tephra and gases are ejected with explosive force and are hot enough to be forced high up into the atmosphere. As the eruption proceeds, and the amount of gas in the rising magma starts to decrease, parts will become heavier than air, and they can then flow downward along the flanks of the volcano (Figure 11.23). As they descend, they cool more and flow faster, reaching speeds up to several hundred km/h.

A pyroclastic density current (PDC) consists of tephra ranging in size from boulders to microscopic shards of glass (made up of the edges and junctions of the bubbles of shattered pumice), plus gases (dominated by water vapour, but also...
including other gases). The temperature of this material can be as high as 1000°C. Among the most famous PDCs are the one that destroyed Pompeii in the year 79 CE, killing an estimated 18,000 people, and the one that destroyed the town of St. Pierre, Martinique, in 1902, killing an estimated 30,000.

The buoyant upper parts of pyroclastic density currents can flow over water, in some cases for several kilometres. The 1902 St. Pierre PDC flowed out into the harbour and destroyed several wooden ships anchored there.

**Pyroclastic Fall**

Most of the tephra from an explosive eruption ascends high into the atmosphere, and some of it is distributed around Earth by high-altitude winds. The larger components (larger than 0.1 mm) tend to fall relatively close to the volcano, and the amount produced by large eruptions can cause serious damage and casualties. The large 1991 eruption of Mt. Pinatubo in the Philippines resulted in the accumulation of tens of centimetres of ash in fields and on rooftops in the surrounding populated region. Heavy typhoon rains that hit the island at the same time added to the weight of the tephra, leading to the collapse of thousands of roofs and to at least 300 of the 700 deaths attributed to the eruption.

**Lahar**

A lahar is any mudflow or debris flow that is related to a volcano. Most are caused by melting snow and ice during an eruption, as was the case with the lahar that destroyed the Colombian town of Armero in 1985 when the volcano Nevado del Ruiz caused the ice dam on a glacial lake to fail. The resulting lahar killed 23,000 in Armero, about 50 km from the volcano.

Lahars can also happen when there is no volcanic eruption, because composite volcanoes tend to be weak and easily eroded. In October 1998, category 5 hurricane Mitch slammed into the coast of Central America. Damage was extensive and 19,000 people died. Fatalities were largely because of mudflows and debris flows triggered by intense rainfall — some regions received almost 2 m of rain over a few days.

An example is Casita Volcano in Nicaragua, where the heavy rains weakened rock and volcanic debris on the upper slopes, resulting in a debris flow that rapidly built in volume as it raced down the steep slope. It struck the towns of El Porvenir and Rolando Rodriguez killing more than 2,000 people (Figure 11.24). El Porvenir and Rolando Rodriguez were new towns that had been built without planning approval in an area that was known to be at risk of lahars.

![Figure 11.24 Part of the path of the lahar from Casita Volcano, October 30, 1998. [USGS photo from: http://volcanoes.usgs.gov/hazards/lahar/casita.php]](https://physicalgeology.pressbooks.com)
Sector Collapse and Debris Avalanche

In the context of volcanoes, sector collapse or flank collapse is the catastrophic failure of a significant part of an existing volcano, creating a large debris avalanche. This hazard was first recognized with the failure of the north side of Mt. St. Helens immediately prior to the large eruption on May 18, 1980. In the weeks before the eruption, a large bulge had formed on the side of the volcano, the result of magma transfer from depth into a satellite magma body within the mountain itself. Early on the morning of May 18, a moderate earthquake struck nearby; this is thought to have destabilized the bulge, leading to Earth’s largest observed landslide in historical times. The failure of this part of the volcano exposed the underlying satellite magma chamber, causing it to explode sideways, which exposed the conduit leading to the magma chamber below. The resulting plinian eruption — with a 24 km high eruption column — lasted for nine hours.

In August 2010, a massive part of the flank of B.C.’s Mt. Meager gave way and about 48 million cubic metres of rock rushed down the valley, one of the largest slope failures in Canada in historical times (Figure 11.25). More than 25 slope failures have taken place at Mt. Meager in the past 8,000 years, some of them more than 10 times larger than the 2010 failure.

Lava Flows

As we saw in Exercise 11.4, lava flows at volcanoes like Kilauea do not advance very quickly, and in most cases, people can get out of the way. It is more difficult to move infrastructure, and so buildings and roads are typically the main casualties of lava flows.
Exercise 11.5 Volcanic Hazards in Squamish

The town of Squamish is situated approximately 10 km from Mt. Garibaldi, as shown in the photo. In the event of a major eruption of Mt. Garibaldi, which of the following hazards has the potential to be an issue for the residents of Squamish or for those passing through on Highway 99? Why would they be (or not be) potential hazards?

- Tephra emission
- Gas emission
- Pyroclastic density current
- Pyroclastic fall
- Lahar
- Sector collapse
- Lava flow

[Steven Earle CC-BY 4.0 after Google Earth]

11.5 Monitoring Volcanoes and Predicting Eruptions

In 2005 USGS geologist Chris Newhall made a list of the six most important signs of an imminent volcanic eruption. They are as follows:

1. **Gas leaks** — the release of gases (mostly H$_2$O, CO$_2$, and SO$_2$) from the magma into the atmosphere through cracks in the overlying rock.
2. **Bit of a bulge** — the deformation of part of the volcano, indicating that a magma chamber at depth is swelling or becoming more pressurized.
3. **Getting shaky** — many (hundreds to thousands) of small earthquakes, indicating that magma is on the move. The quakes may be the result of the magma forcing the surrounding rocks to crack, or a harmonic vibration that is evidence of magmatic fluids moving underground.
4. **Dropping fast** — a sudden decrease in the rate of seismicity, which may indicate that magma has stalled, which could mean that something is about to give way.
5. **Big bump** — a pronounced bulge on the side of the volcano (like the one at Mt. St. Helens in 1980), which may indicate that magma has moved close to surface.
6. **Blowing off steam** — steam eruptions (a.k.a. **phreatic eruptions**) that happen when magma near the surface heats groundwater to the boiling point. The water eventually explodes, sending fragments of the overlying rock far into the air.

With these signs in mind, we can make a list of the equipment we should have and the actions we can take to monitor a volcano and predict when it might erupt.
Assessing seismicity

The simplest and cheapest way to monitor a volcano is with seismometers. In an area with several volcanoes that have the potential to erupt (e.g., the Squamish-Pemberton area), a few well-placed seismometers can provide us with an early warning that something is changing beneath one of the volcanoes, and that we need to take a closer look. There are currently enough seismometers in the Lower Mainland and on Vancouver Island to provide this information. If there is seismic evidence that a volcano is coming to life, more seismometers should be placed in locations within a few tens of kilometres of the source of the activity (Figure 11.26). This will allow geologists to determine the exact location and depth of the seismic activity so that they can see where the magma is moving.

Figure 11.26 A seismometer installed in 2007 in the vicinity of the Nazco Cone, B.C. [Cathie Hickson, used with permission]

Detecting gases

Water vapour quickly turns into clouds of liquid water droplets and is relatively easy to detect just by looking, but CO₂ and SO₂ are not as obvious. It’s important to be able to monitor changes in the composition of volcanic gases, and we need instruments to do that. Some can be monitored from a distance (from the ground or even from the air) using infrared devices, but to obtain more accurate data, we need to sample the air and do chemical analysis. This can be achieved with instruments placed on the ground close to the source of the gases (see Figure 11.17), or by collecting samples of the air and analyzing them in a lab.

Measuring deformation

There are two main ways to measure ground deformation at a volcano. One is known as a tiltmeter, which is a sensitive three-directional level that can sense small changes in the tilt of the ground at a specific location. Another is through the use of GPS (global positioning system) technology (Figure 11.27). GPS is more effective than a tiltmeter because it provides information on how far the ground has actually moved — east-west, north-south, and up-down.

By combining information from these types of sources, along with careful observations made on the ground and from the air, and a thorough knowledge of how volcanoes work, geologists can get a good idea of the potential for a volcano to erupt in the near future (months to weeks, but not days).


Figure 11.27 A GPS unit installed at Hualalai volcano, Hawaii. The dish-shaped antenna on the right is the GPS receiver. The antenna on the left is for communication with a base station. [from USGS at: http://hvo.wr.usgs.gov/~volcanowatch/view.php?id=173]
They can then make recommendations to authorities about the need for evacuations and restricting transportation corridors.

Our ability to predict volcanic eruptions has increased dramatically in recent decades because of advances in our understanding of how volcanoes behave and in monitoring technology. Providing that careful work is done, there is no longer a large risk of surprise eruptions, and providing that public warnings are issued and heeded, it is less and less likely that thousands will die from sector collapse, pyroclastic flows, ash falls, or lahars. Indirect hazards are still very real, however, and we can expect the next eruption like the one at Laki in 1783 to take an even greater toll than it did then, especially since there are now roughly eight times as many people on Earth.

**Exercise 11.6 Volcano Alert!**

You’re the chief volcanologist for the Geological Survey of Canada (GSC), based in Vancouver. At 10:30 a.m. on a Tuesday, you receive a report from a seismologist at the GSC in Sidney saying that there has been a sudden increase in the number of small earthquakes in the vicinity of Mt. Garibaldi. You have two technicians available, access to some monitoring equipment, and a four-wheel-drive vehicle. At noon, you meet with your technicians and a couple of other geologists. By the end of the day, you need to have a plan to implement, starting tomorrow morning, and a statement to release to the press. What should your first day’s fieldwork include? What should you say later today in your press release?

**11.6 Volcanoes in British Columbia**

Figure 11.28 shows three types of volcanic environments represented in British Columbia:

- The Cascade Arc (a.k.a. the Garibaldi Volcanic Belt in Canada) is related to subduction of the Juan de Fuca Plate beneath the North America plate.
- The Anahim Volcanic Belt is assumed to be related to a mantle plume.
- The Stikine Volcanic Belt and the Wells Gray-Clearwater Volcanic Field are assumed to be related to crustal rifting.

**Subduction Volcanism**

Southwestern British Columbia is at the northern end of the Juan de Fuca (Cascadia) subduction zone, and the volcanism there is related to magma generation by flux melting in the upper mantle above the subducting plate. In general, there has been a much lower rate and volume of volcanism in the B.C. part of this belt than in the U.S. part. One reason for this is that the northern part of the Juan de Fuca Plate (i.e., the Explorer Plate) is either not subducting, or is subducting at a slower rate than the rest of the plate.

There are several volcanic centres in the Garibaldi Volcanic Belt: the Garibaldi centre (including Mt. Garibaldi and the Black Tusk-Mt. Price area adjacent to Garibaldi Lake (Figures 11.1 and 11.2), Mt. Cayley, and Mt. Meager (Figure 11.25). The most recent volcanic activity in this area was at Mt. Meager. Approximately 2,400 years ago, an explosive eruption of about the same magnitude as the 1980 Mt. St. Helens eruption took place at Mt. Meager. Ash spread as far east as Alberta.
There was also significant eruptive activity at Mts. Price and Garibaldi approximately 12,000 and 10,000 years ago during the last glaciation. In both cases, lava and tephra built up against glacial ice in the adjacent valley (Figure 11.29). The Table in Figure 11.2 at the beginning of this chapter is a **tuya**, a volcano that formed beneath glacial ice and had its top eroded by the lake that formed around it in the ice.

Figure 11.28 Major volcanic centres in British Columbia (base map from Wikipedia (http://commons.wikimedia.org/wiki/File:South-West_Canada.jpg). Volcanic locations from Wood, D., 1993, Waiting for another big blast - probing B.C.’s volcanoes, Canadian Geographic, based on the work of Cathie Hickson)

Figure 11.29 Perspective view of the Garibaldi region (looking east) showing the outlines of two lava flows from Mt. Price. Volcanism in this area last took place when the valley in the foreground was filled with glacial ice. The cliff known as the Barrier formed when part of the Mt. Price lava flow failed after deglaciation. The steep western face of Mt. Garibaldi formed by sector collapse, also because the rocks were no longer supported by glacial ice. [Steven Earle CC-BY 4.0 after Google Earth]
Mantle Plume Volcanism

The chain of volcanic complexes and cones extending from Milbanke Sound to Nazko Cone is interpreted as being related to a mantle plume currently situated close to the Nazko Cone, just west of Quesnel. The North America Plate is moving in a westerly direction at about 2 cm per year with respect to this plume, and the series of now partly eroded shield volcanoes between Nazko and the coast is interpreted to have been formed by the plume as the continent moved over it.

The Rainbow Range, which formed at approximately 8 Ma, is the largest of these older volcanoes. It has a diameter of about 30 km and an elevation of 2,495 m (Figure 11.30). The name “Rainbow” refers to the bright colours displayed by some of the volcanic rocks as they weather.

Rift-Related Volcanism

While B.C. is not about to split into pieces, two areas of volcanism are related to rifting — or at least to stretching-related fractures that might extend through the crust. These are the Wells Gray-Clearwater volcanic field southeast of Quesnel, and the Northern Cordillera Volcanic Field, which ranges across the northwestern corner of the province (as already discussed in section 11.1). This area includes Canada’s most recent volcanic eruption, a cinder cone and mafic lava flow that formed around 250 years ago at the Tseax River Cone in the Nass River area north of Terrace. According to Nisga’a oral history, as many as 2,000 people died during that eruption, in which lava overran their village on the Nass River. Most of the deaths are attributed to asphyxiation from volcanic gases, probably carbon dioxide.

The Mount Edziza Volcanic Field near the Stikine River is a large area of lava flows, sulphurous ridges, and cinder cones. The most recent eruption in this area was about 1,000 years ago. While most of the other volcanism in the Edziza region is mafic and involves lava flows and cinder cones, Mt. Edziza itself (Figure 11.31) is a composite volcano with rock compositions ranging from rhyolite to basalt. A possible explanation for the presence of composite volcanism in an area dominated by mafic flows and cinder cones is that there is a magma chamber beneath this area, within which magma differentiation is taking place.
**Exercise 11.7 Volcanoes Down Under**

The map at right shows the plate tectonic situation in the area around New Zealand.

Based on what you know about volcanoes in B.C., where might you see volcanoes in and around New Zealand?

What type of volcanoes would you expect to find in and around New Zealand?

[from: http://upload.wikimedia.org/wikipedia/commons/8/8a/NZ_faults.png]
Chapter Summary

The topics covered in this chapter can be summarized as follows:

11.1 Plate Tectonics and Volcanism

Volcanism is closely related to plate tectonics. Most volcanoes are associated with convergent plate boundaries (at subduction zones), and there is also a great deal of volcanic activity at divergent boundaries and areas of continental rifting. At convergent boundaries magma is formed where water from a subducting plate acts as a flux to lower the melting temperature of the adjacent mantle rock. At divergent boundaries magma forms because of decompression melting. Decompression melting also takes place within a mantle plume.

11.2 Magma Composition and Eruption Style

The initial magmas in most volcanic regions are mafic in composition, but they can evolve into more felsic types through interaction with crustal rock, and as a result of crystal settling within a magma chamber. Felsic magmas tend to have higher gas contents than mafic magmas, and they are also more viscous. The higher viscosity prevents gases from escaping from the magma, and so felsic magmas are more pressurized and more likely to erupt explosively.

11.3 Types of Volcanoes

Cinder cones, which can form in various volcanic settings, are relatively small volcanoes that are composed mostly of mafic rock fragments that were formed during a single eruptive event. Composite volcanoes are normally associated with subduction, and while their magma tends to be intermediate on average, it can range all the way from felsic to mafic. The corresponding differences in magma viscosity lead to significant differences in eruptions style. Most shield volcanoes are associated with mantle plumes, and have consistently mafic magma which generally erupts as lava flows.

11.4 Volcanic Hazards

Most direct volcanic hazards are related to volcanoes that erupt explosively, especially composite volcanoes. Pyroclastic density currents, some as hot as 1000°C can move at hundreds of km/h and will kill anything in the way. Lahars, volcano-related mudflows, can be large enough to destroy entire towns. Lava flows will destroy anything in their paths, but tend to move slowly enough so that people can get to safety.

11.5 Monitoring Volcanoes and Predicting Eruptions

We have the understanding and technology to predict volcanic eruptions with some success, and to ensure that people are not harmed. The prediction techniques include monitoring seismicity in volcanic regions, detecting volcanic gases, and measuring deformation of the flanks of a volcano.

11.6 Volcanoes in British Columbia

There are examples of all of the important types of volcanoes in British Columbia, including subduction volcanism north of Vancouver, mantle-plume volcanism along the Nazco trend, and rift-related volcanism in the Wells Gray and Stikine regions.
Questions for Review

1. What are the three main tectonic settings for volcanism on Earth?
2. What is the primary mechanism for partial melting at a convergent plate boundary?
3. Why are the viscosity and gas content of a magma important in determining the type of volcanic rocks that will be formed when that magma is extruded?
4. Why do the gases in magma not form gas bubbles when the magma is deep within the crust?
5. Where do pillow lavas form? Why do they form and from what type of magma?
6. What two kinds of rock textures are typically found in a composite volcano?
7. What is a lahar, and why are lahars commonly associated with eruptions of composite volcanoes?
8. Under what other circumstances might a lahar form?
9. Explain why shield volcanoes have such gentle slopes.
10. In very general terms, what is the lifespan difference between a composite volcano and a shield volcano?
11. Why is weak seismic activity (small earthquakes) typically associated with the early stages of a volcanic eruption?
12. How can GPS technology be used to help monitor a volcano in the lead-up to an eruption?
13. What type of eruption at Mt. St. Helens might have produced columnar basalts?
14. What is the likely geological origin of the Nazko Cone?
15. What might be the explanation for southwestern B.C. having much less subduction-related volcanism than adjacent Washington and Oregon?