Chapter 4 Volcanism

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 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 to infrastructure by the different types of volcanic eruptions.
- Describe the symptoms that we can expect to observe when a volcano is ready to erupt, and the techniques that we can use to monitor those volcanic symptoms and predict eruptions.
- Summarize the types of volcanoes that have erupted in British Columbia since 2.6 Ma, and the characteristics of some of those eruptions.

A volcano is any location where magma comes to the surface, or has done so within the past several million years. This can include eruptions on the ocean floor (or even under the water of a lake), where they are called **subaqueous eruptions**, or on land, where they are called **subaerial eruptions**. Not all volcanic eruptions produce the volcanic mountains with which we are familiar; in fact most of Earth's volcanism takes place along the spreading ridges on the sea floor and does not produce volcanic mountains at all—not even sea-floor mountains.

Canada has a great deal 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 since 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 4.0.1 and 4.0.2.

The study of volcanoes is critical to our understanding of the geological evolution of Earth, and to our understanding of significant changes in climate. But, most important of all, understanding volcanic eruptions allows 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.

Figure 4.0.1 Mount Garibaldi, near Squamish B.C., is one of Canada's tallest (2,678 metres (m)) and most recently active volcanoes. It last erupted approximately 10,000 years ago.

Figure 4.0.2 Mount Garibaldi (background left, looking from the north) with Garibaldi Lake in the foreground. The lower volcanic peak in the centre is Mount Price and the dark flat–topped peak to the left of it is The Table. All three of these volcanoes were active during the last glaciation.

Media Attributions

- Figures 4.0.1, 4.0.2: © Steven Earle. CC BY.

4.1 Plate Tectonics and Volcanism

The relationships between plate tectonics and volcanism are shown on Figure 4.1.1. As summarized in Chapter 3, magma is formed at three main plate-tectonic settings: divergent boundaries (decompression melting), convergent boundaries (flux melting), and mantle plumes (decompression melting).

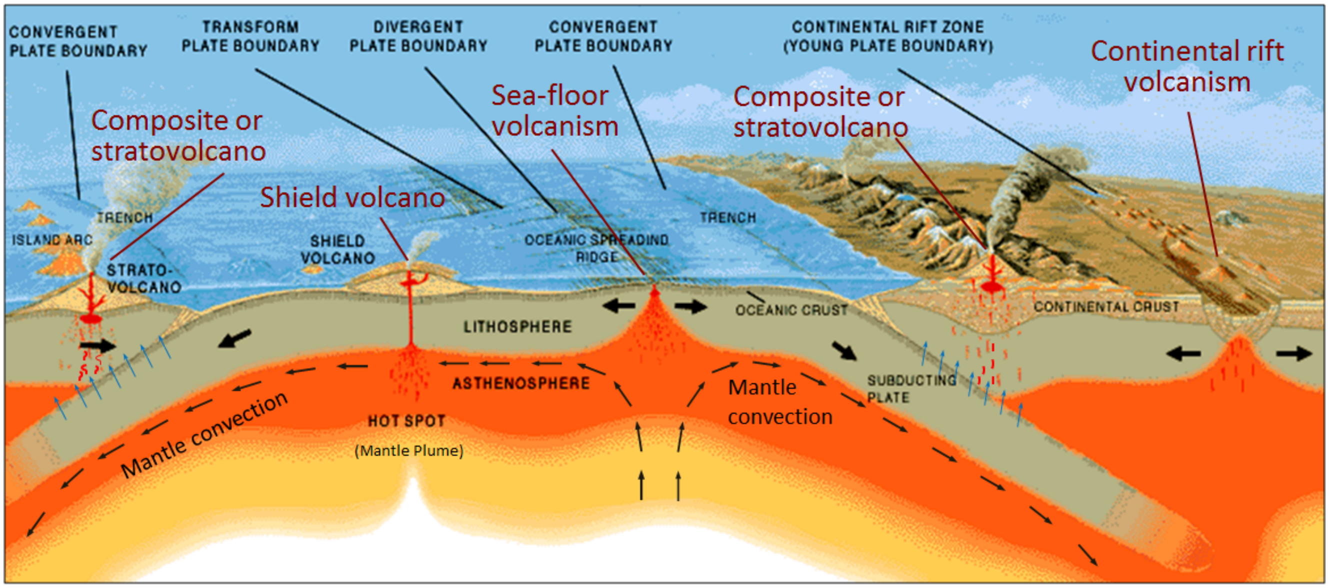

Figure 4.1.1 The plate-tectonic settings of common types of volcanism. Composite volcanoes form at subduction zones, either on ocean-ocean convergent boundaries (left) or ocean-continent convergent boundaries (right). Both shield volcanoes and cinder cones form in areas of continental rifting. Shield volcanoes form above mantle plumes, but can also form at other tectonic settings. Sea-floor volcanism can take place at divergent boundaries, mantle plumes and ocean-ocean-convergent boundaries.

The mantle and crustal processes that take place in areas of volcanism are illustrated in Figure 4.1.2. At a spreading ridge, hot mantle rock moves slowly upward by convection (centimetre/year), and within about 60 kilometres (km) of the surface, partial melting starts because of decompression. Over the triangular area shown in Figure 4.1.2a, 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.

Exercise 4.1 How thick is the oceanic crust?

Figure 4.1.2a 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?

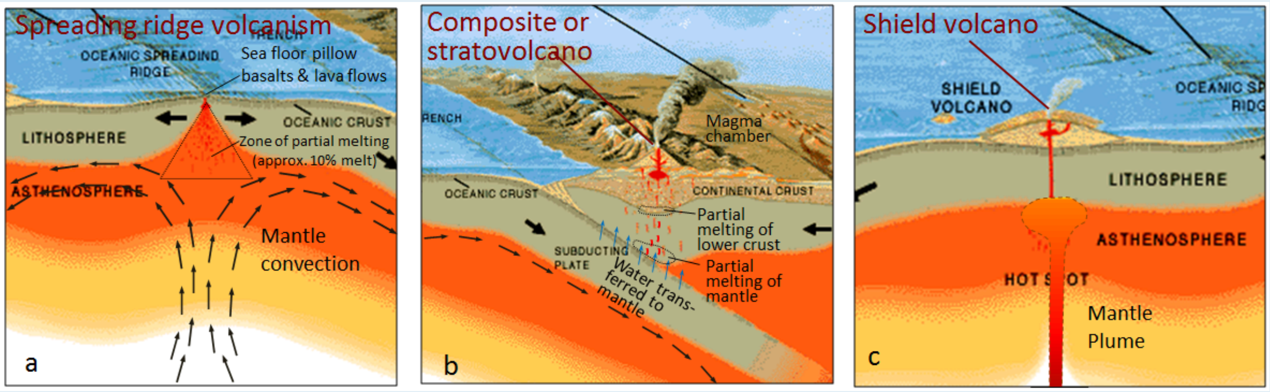

Figure 4.1.2 The processes that lead to volcanism in the three main volcanic settings on Earth: (a) volcanism related to plate divergence, (b) volcanism at an ocean-continent boundary (Similar processes take place at an ocean-ocean convergent boundary), and (c) volcanism related to a mantle plume.

See Appendix 3 for Exercise 4.1 answers.

At an ocean-continent convergent boundary, part of a plate that is made up of oceanic crust is subducting beneath part of another plate made up of continental crust. At an ocean-ocean convergent boundary, oceanic crust is being subducted beneath another oceanic-crust plate.[/footnote] (Figure 4.1.2b). In both situations the oceanic crust is heated up, and while there isn't enough heat to melt the subducting crust, there is enough heat to force the water out of some of its minerals. This released 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 likely 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. Mount Garibaldi (Figures 4.0.1 and 4.0.2) is an example of subduction-related volcanism.

A mantle plume is an ascending column of hot rock (not magma) that originates deep in the mantle, possibly just above the core-mantle boundary. Mantle plumes are thought to rise approximately 10 times faster than the rate of mantle convection. The ascending column may be on the order of kilometres to tens of kilometres across, but near the surface it spreads out to create a mushroom-style head that is several tens to over 100 km across. Near the base of the lithosphere (the rigid part of the mantle), the mantle plume (and possibly some of the surrounding mantle material) partially melts to form mafic magma that rises to feed volcanoes. Since most mantle plumes are beneath the oceans, the early stages of volcanism typically take place on the sea floor. Over time, islands may form like those in Hawaii.

Volcanism in northwestern B.C. (Figures 4.1.3 and 4.1.4) is related to continental rifting. This area is not at a divergent or convergent boundary, and there is no evidence of an underlying mantle plume. A likely explanation is that the crust of northwestern B.C. 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. This may, or may not, be an early stage of continental rifting, such as that found in eastern Africa.

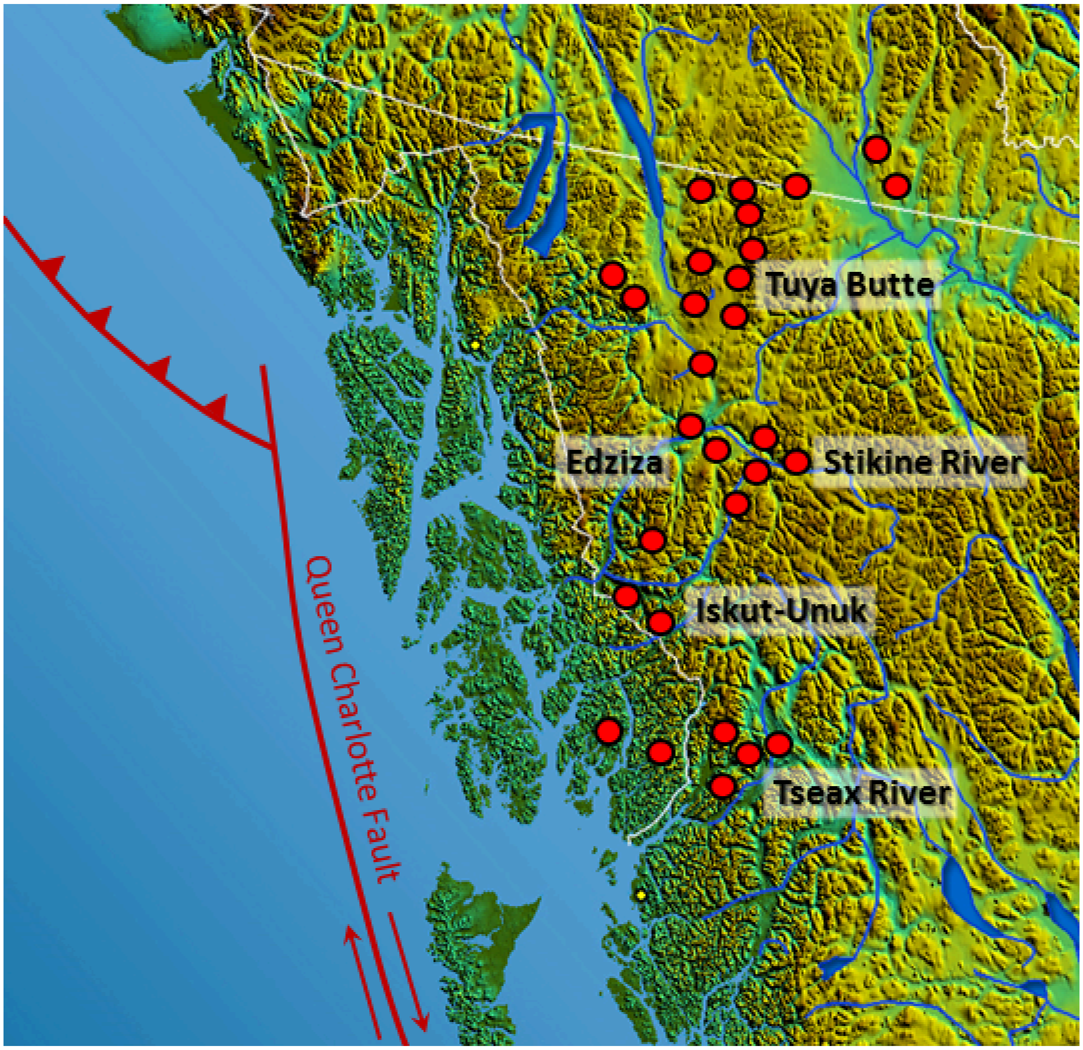

Figure 4.1.3 Volcanoes and volcanic fields in the Northern Cordillera Volcanic Province, B.C.

Figure 4.1.4 Volcanic rock at the Tseax River area, northwestern B.C.

Media Attributions

- Figure 4.1.1: Understanding Plate Motions by USGS. Public domain. Modified by Steven Earle.
- Figure 4.1.2: By USGS. Public domain. Modified by Steven Earle.
- Figure 4.1.3: "South-West Canada" by USGS. Public domain. Modified by Steven Earle. Volcanic locations from Edwards, B. & Russell, J. (2000). Distribution, nature, and origin of Neogene-Quaternary magmatism in the northern Cordilleran volcanic province, Canada. Geological Society of America Bulletin. pp. 1280-1293 [Steven Earle] Cordillera Volcanic Province, B.C.
- Figure 4.1.4: © Steven Earle. CC BY.

4.2 Magma Composition and Eruption Style

As noted in the previous section, the types of magma produced in the various volcanic settings can differ significantly. At divergent boundaries and oceanic mantle plumes, where there is little interaction with crustal materials the magma tends to be consistently mafic. At subduction zones, where the magma ascends through significant thicknesses of crust, interaction between the magma and the crustal rock—some of which is quite felsic—leads to increases in the felsic character of the magma.

As illustrated in Figure 4.2.1, several processes can make magma that is stored in a chamber within the crust more felsic than it was to begin with, and can also contribute to development of vertical zonation from more mafic at the bottom to more felsic at the top. Partial melting of country rock and country-rock xenoliths increases the overall felsic character of the magma; first, because the country rocks tends to be more felsic than the magma, and second, because the more felsic components of the country rock melt preferentially. Settling of ferromagnesian crystals from the upper part of the magma, and possible remelting of those crystals in the lower part can both contribute to the vertical zonation from relatively mafic at the bottom to more felsic at the top.

From the perspective of volcanism there are some important differences between felsic and mafic magmas. First, as we've already discussed, felsic magmas tend to be more viscous because they have more silica, and hence more polymerization. Second, felsic magmas tend to have higher levels of volatiles; that is, components that behave as gases during volcanic eruptions. The most abundant volatile in magma is water (H_2O), followed typically by carbon dioxide (CO_2), and then by sulphur dioxide (SO_2).

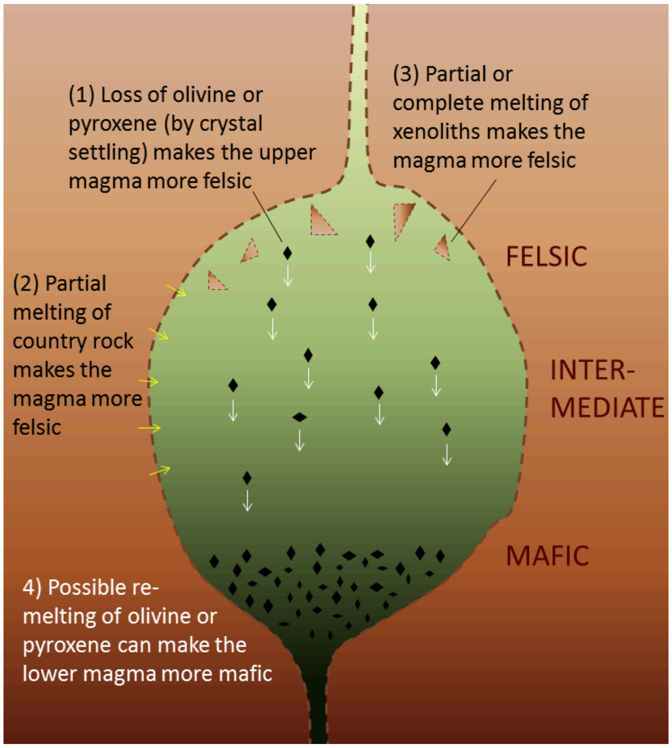

Figure 4.2.1 The important processes that lead to changes in the composition of magmas stored within magma chambers within relatively felsic rocks of the crust. [Image Description]

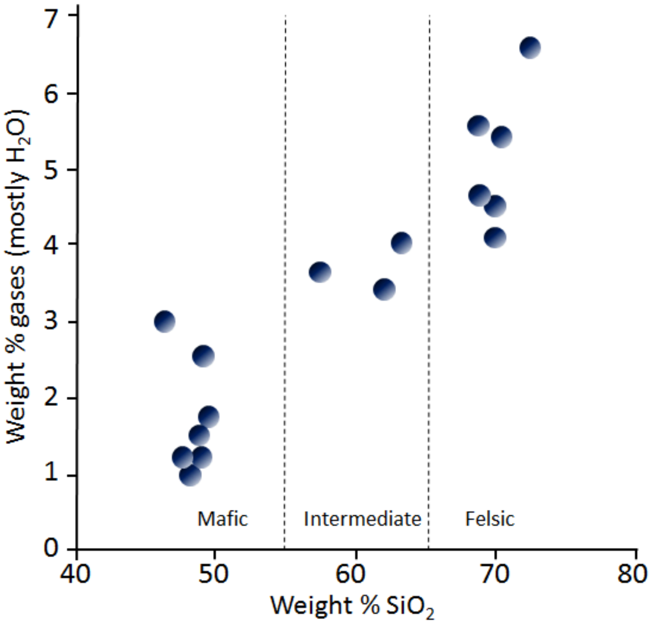

Figure 4.2.2 Variations in the volatile compositions of magmas as a function of silica content. [Image Description]

The general relationship between the SiO_2 content of magma and the amount of volatiles is shown in Figure 4.2.2. Although there are many exceptions to this trend, 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 levels 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 gases remain dissolved. As magma approaches the surface, the pressure exerted on it decreases. Gas bubbles start to form, and the more gas there is in the magma, the more bubbles form. If 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**.

Exercise 4.2 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 (something not too dark). You'll find that the bottle is hard because it was bottled under pressure, and you should be able to see that there are no gas bubbles inside.

Buy a small bottle of pop (you don't have to drink it!) 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, and 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 and the gases come bubbling out, forcing the pop with them.

Figure 4.2.3

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 conduit for it to move towards surface, it may not flow out. Under these circumstances pressure will continue to build as more magma moves up from beneath and gases continue to exsolve.

Eventually some part of the volcano will break and then all of that pent-up pressure will lead to an explosive eruption.

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—even likely. Eruption styles can be correspondingly variable.

Image Descriptions

Figure 4.2.1 image description: Four processes that can affect the composition of magma stored in chambers.

1. Loss of olivine or pyroxene (by crystal settling) makes the upper magma more felsic.
2. Partial melting of country rock makes the magma more felsic.
3. Partial or complete melting of xenoliths makes the magma more felsic.
4. Possible re-melting of olivine or pyroxene can make the lower magma more mafic.

[Return to Figure 4.2.1]

Figure 4.2.2 image description: The following table describes the range of data points adapted from the original scatter plot graph.

Type of Magma	Weight % of gasses (mostly H_2O)	Weight % of SiO_2
Mafic	1 to 3%	47 to 50%
Intermediate	3 to 4%	57 to 64%
Felsic	4 to 7%	69 to 72%

[Return to Figure 4.2.2]

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- Figure 4.2.1: © Steven Earle. CC BY.
- Figure 4.2.2: Original image by Schminke, 2004. (Schminke, H-U., 2004, Volcanism, Springer-Verlag, Heidelberg). Modified by Steven Earle.
- Figure 4.2.3: Champagne uncorking photographed with a high speed air-gap flash © Niels Noordhoek. CC BY-SA.

4.3 Types of Volcanoes

There are numerous types of volcanoes or volcanic sources; some of the more common ones are summarized in Table 4.1.

Table 4.1 A summary of the important types of volcanism

[Skip Table]

Type	Tectonic Setting	Size and Shape	Magma and Eruption Characteristics	Example
Cinder cone	Various; some form on the flanks of larger volcanoes	Small (10s to 100s of metres) and steep (Greater than 20°)	Most are mafic and form from the gas-rich early stages of a shield- or rift-associated eruption	Eve Cone, northern B.C.
Composite volcano	Almost all are at subduction zones	Medium size (1000s of metres high and up to 20 km across) and moderate steepness (10° to 30°)	Magma composition varies from felsic to mafic, and from explosive to effusive	Mount St. Helens
Shield volcano	Most are at mantle plumes; some are on spreading ridges	Large (up to several 1,000 metres high and up to 200 kilometres across), not steep (typically 2° to 10°)	Magma is almost always mafic, and eruptions are typically effusive, although cinder cones are common on the flanks of shield volcanoes	Kilauea, Hawaii
Large igneous provinces	Associated with “super” mantle plumes	Enormous (up to millions of square kiometres) and 100s of metres thick	Magma is always mafic and individual flows can be 10s of metres thick	Columbia River basalts
Sea-floor volcanism	Generally associated with spreading ridges but also with mantle plumes	Large areas of the sea floor associated with spreading ridges	Pillows form at typical eruption rates; lava flows develop if the rare of flow is faster	Juan de Fuca ridge
Kimberlite	Upper-mantle sourced	The remnants are typically 10s to 100s of metres across	Most appear to have had explosive eruptions forming cinder cones; the youngest one is dated at about 10 ka, and all others are at least 30 Ma	Lac de Gras Kimberlite Field, N.W.T.

The sizes and shapes of typical shield, composite, and cinder-cone volcanoes are compared in Figure 4.3.1, although, to be fair, Mauna Loa is the largest shield volcano on Earth; 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. Mount St. Helens, a composite volcano of average size, 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.

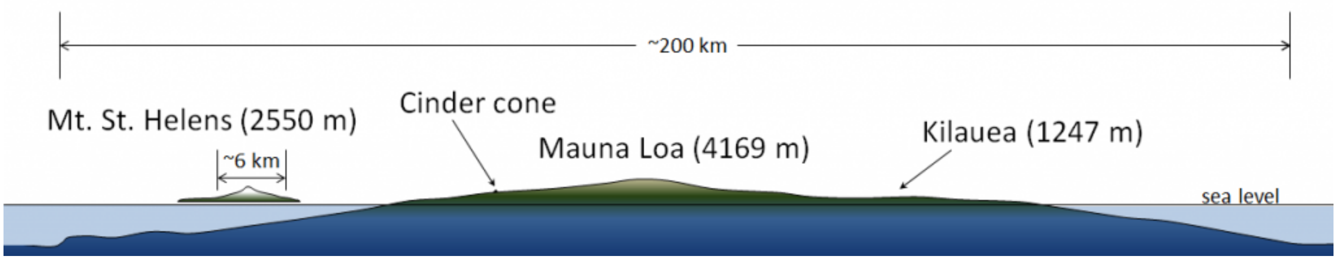

Figure 4.3.1 Profiles of Mauna Loa shield volcano, Mount St. Helens composite volcano, and a large cinder cone.

Cinder Cones

Cinder cones, like Eve Cone in northern B.C. (Figure 4.3.2), 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 the sites of effusive lava flows when the gases were depleted. Most cinder cones are **monogenetic**, meaning that they formed 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.

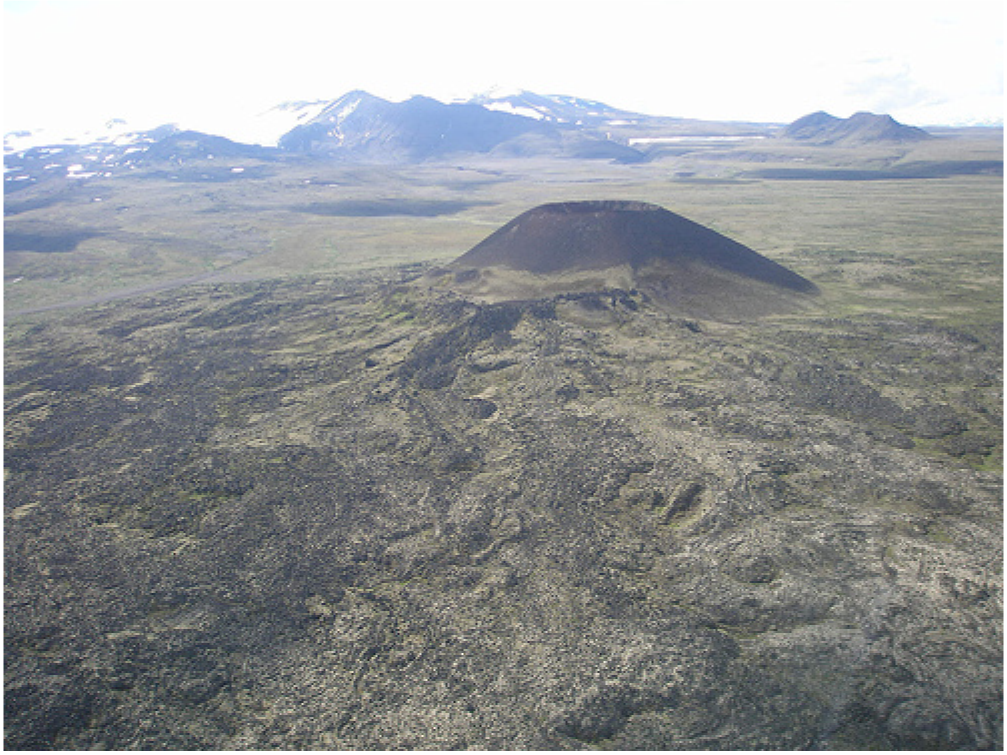

Figure 4.3.2 Eve Cone, situated near to Mount Edziza in northern B.C., formed approximately 700 years ago.

Composite Volcanoes

Composite volcanoes, like Mount St. Helens in Washington State (Figure 4.3.3), are almost all associated with subduction at convergent plate boundaries—either ocean-continent or ocean-ocean boundaries (Figure 4.1.2b). They can extend up to several thousand metres from the surrounding terrain, and, with slopes ranging up to 30˚ They can be up to about 20 km across. At many such volcanoes, magma is stored in a magma chamber in the upper part of the crust. For example, at Mount St. Helens, there is evidence of a magma chamber that is approximately 1 kilometre wide and extends from about 6 km to 14 km below the surface (Figure 4.3.4). Systematic variations in the composition of volcanism over the past several thousand years at Mount St. Helens imply that the magma chamber is zoned, from more felsic at the top to more mafic at the bottom.

Figure 4.3.3 The north side of Mount St. Helens in southwestern Washington State, 2003. The large 1980 eruption reduced the height of the volcano by 400 m, and a sector collapse removed a large part of the northern flank. Between 1980 and 1986 the slow eruption of more mafic and less viscous lava led to construction of a dome inside the crater.

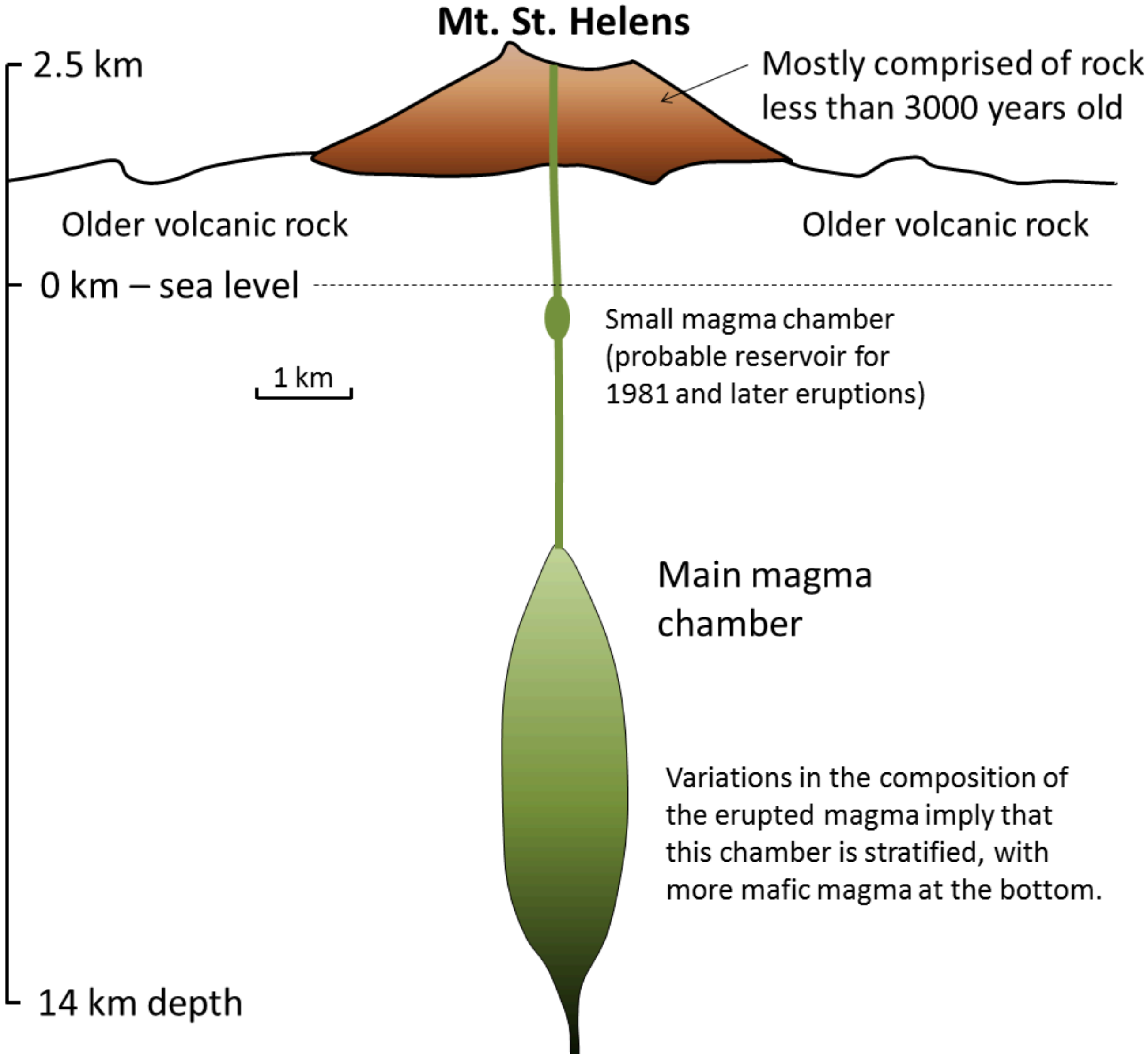

Figure 4.3.4 A cross-section through the upper part of the crust at Mount St. Helens showing the zoned magma chamber. [Image Description]

Mafic eruptions (and some intermediate eruptions), on the other hand, produce lava flows; the one shown in Figure 4.3.5b is thick enough (about 10 m in total) to have cooled in a **columnar jointing** pattern (Figure 4.3.7). 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 Mount St. Helens as a "pile of junk." The rock that makes up Mount St. Helens ranges in composition from rhyolite (Figure 4.3.5a) to basalt (Figure 4.3.5b); 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, as shown on Figure 4.3.5a. This type of eruption can also lead to rapid melting of ice and snow on a volcano, which typically triggers large mudflows known as **lahars** (Figure 4.3.5a). Hot, fast-moving pyroclastic flows and lahars are the two main causes of casualties in volcanic eruptions. Pyroclastic flows killed approximately 30,000 people during the 1902 eruption of Mount. Pelée on the Caribbean island of Martinique. Most were incinerated in their homes. In 1985 a massive lahar, triggered by the eruption of Nevado del Ruiz, killed 23,000 people in the Colombian town of Armero, about 50 km from the volcano.

In a geological context, composite volcanoes tend to form relatively quickly and do not last very long. Mount 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.

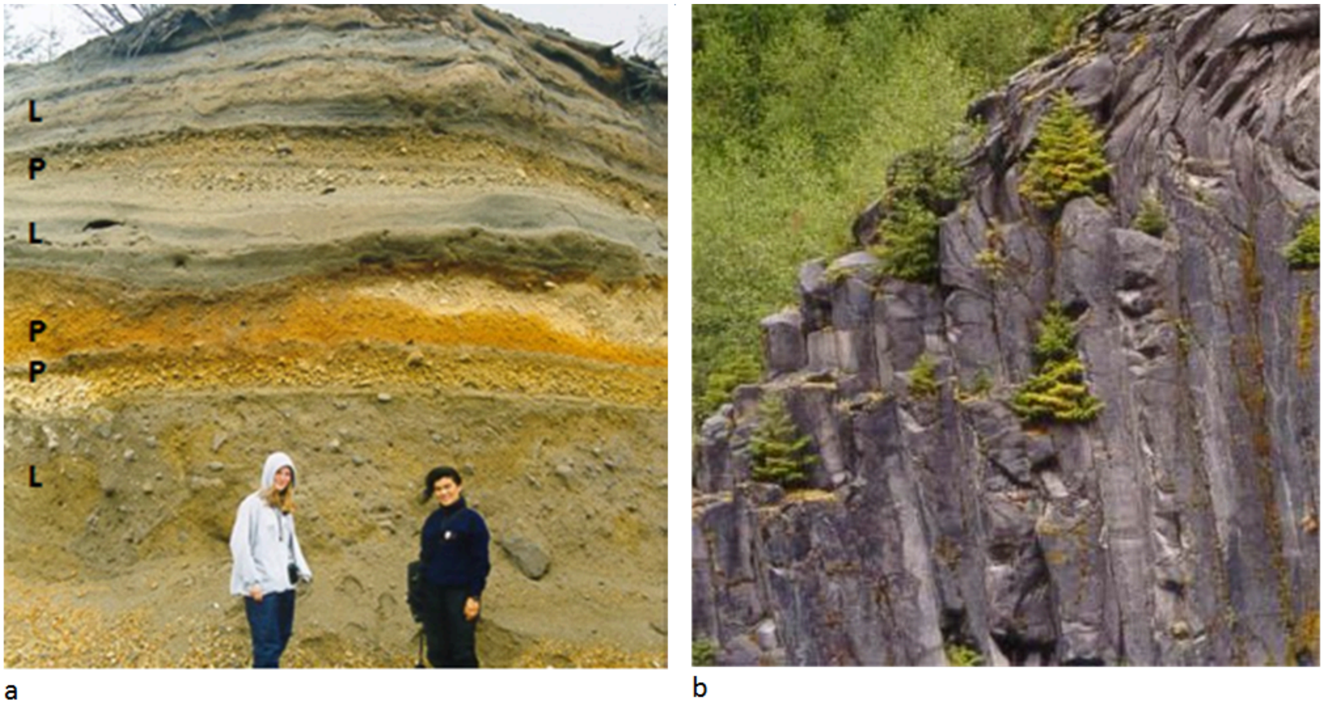

Figure 4.3.5 Mount St. Helens volcanic deposits: (a) lahar deposits (L) and felsic pyroclastic deposits (P) and (b) a columnar basalt lava flow. The two photos were taken at locations only about 500 m apart. [Image Description]

Exercise 4.3 Volcanoes and Subduction

The map shown here illustrates the interactions between the North America, Juan de Fuca, and Pacific Plates off the west coast of Canada and the United States. The Juan de Fuca Plate is forming along the Juan de Fuca ridge, and is then subducted beneath the North America Plate along the red line with teeth on it ("Subduction boundary").

1. Using the scale bar in the lower left of the map, estimate the average distance between the subduction boundary and the Cascadia composite volcanoes.
2. If the subducting Juan de Fuca Plate descends 40 km for every 100 km that it moves inland, what is its likely depth in the area where volcanoes are forming?

See Appendix 3 for Exercise 4.3 answers.

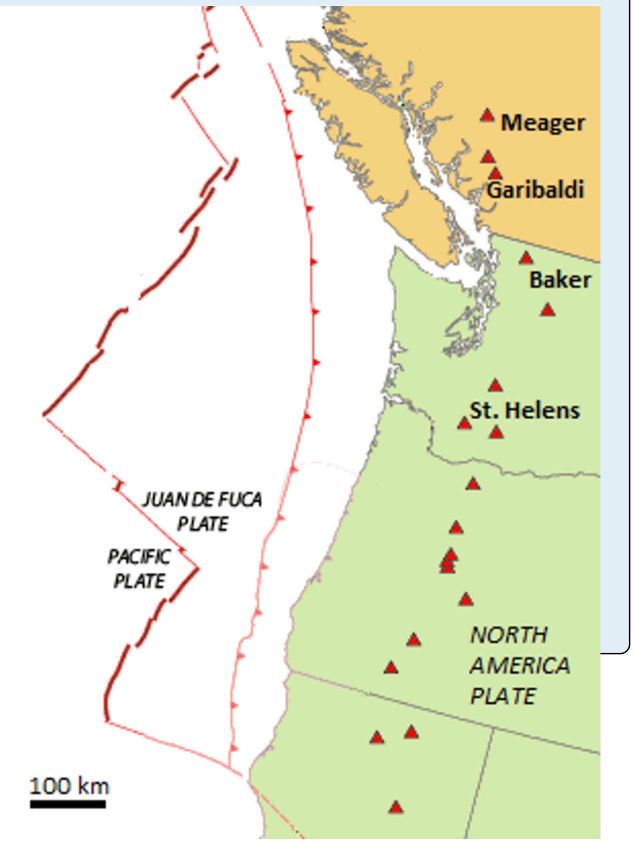

Figure 4.3.6

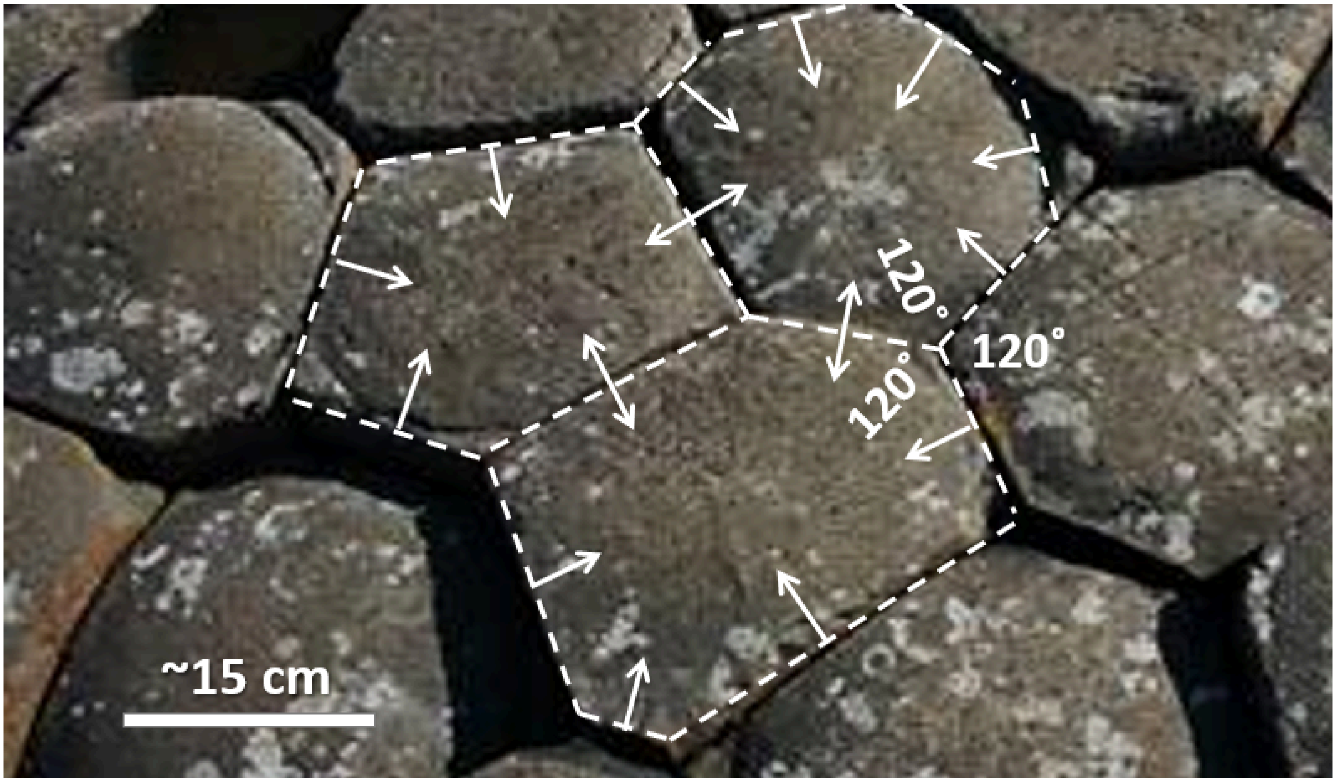

Figure 4.3.7 The development of columnar jointing in basalt, here seen from the top looking down. As the rock cools it shrinks, and because it is very homogenous it shrinks in a systematic way. When the rock breaks it does so with approximately 120˚ angles between the fracture planes. The resulting columns tend to be 6-sided but 5- and 7-sided columns also form.

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 4.3.8). In this area, the Pacific Plate is moving northwest at a rate of about 7 centimetres (cm) per year. This means that the earlier formed — and now extinct — volcanoes have now moved well away from the mantle plume. As shown on Figure 4.3.8, 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]

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[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.

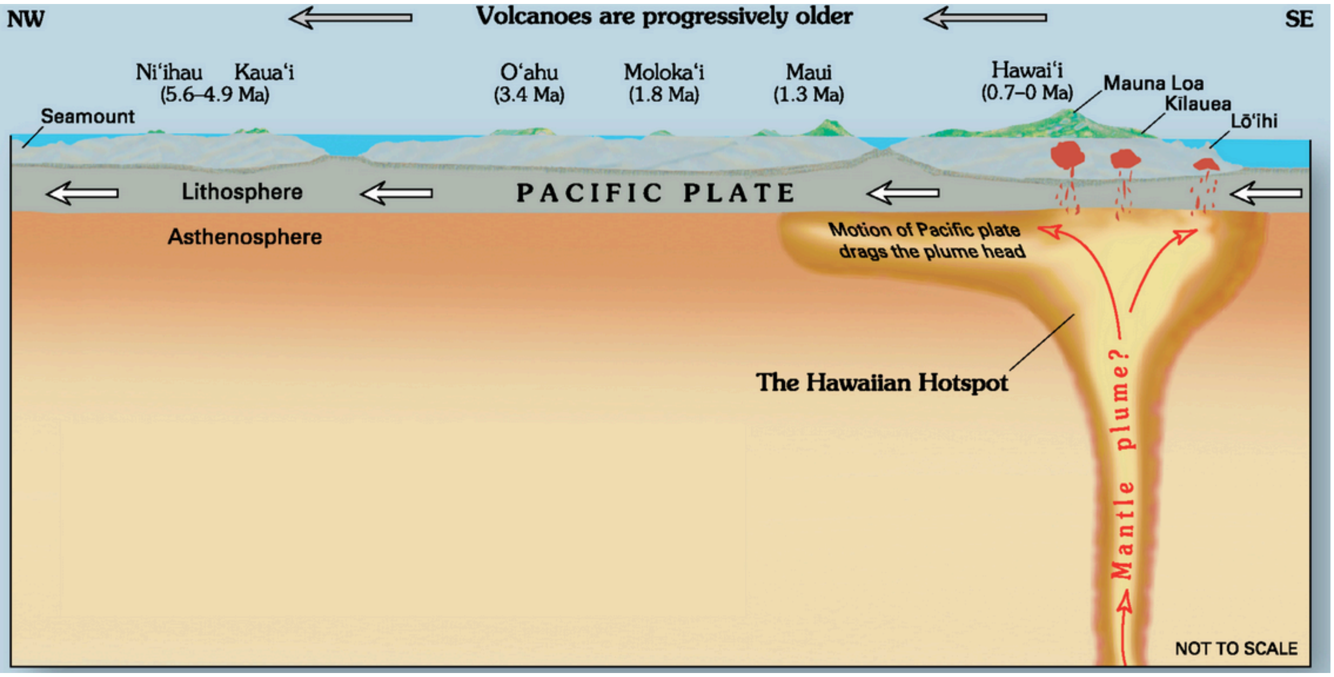

Figure 4.3.8 The mantle plume beneath the volcanoes of the island of Hawaii

Although it is not a prominent mountain (Figure 4.3.2), Kilauea volcano has a large **caldera** in its summit area (Figure 4.3.9). A caldera is a volcanic **crater** that is more than 2 km in diameter; 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. Most volcanic craters and calderas are formed above magma chambers, and the level of the 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.

Figure 4.3.9 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.

One of the conspicuous features of Kilauea caldera is rising water vapour (the white cloud in Figure 4.3.9) and a strong smell of sulphur (Figure 4.3.10). 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 35 years, has been effusive, not explosive.

Figure 4.3.10 A gas-composition monitoring station (left) within the Kilauea caldera close to 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.

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 4.3.11). 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. Lava fountaining and construction of the Pu'u 'O'o cinder cone (Figure 4.3.12a) 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 4.3.12d), emerging at or near the ocean. During 2014 and 2015, the lava flowed northeast toward the community of Pahoa (see Exercise 4.4). In May of 2018 a new eruption started another 15 km east of the 2014/15 flow in the area known as Leilani Estates. The Lower East Rift Flow was active for 6 months. During that time, 35 km^2 of existing land was covered in lava and 3.5 km^2 of new land was created (Figure 4.3.11), about 48 km of road were covered in lava and 716 dwellings were destroyed (see USGS Overview of Kilauea Volcanoe's 2018 eruption[PDF]). Volcanic activity on the East Rift ceased in August 2018, and there has been no activity on Kilauea since then. This appears to mark the end of the eruption cycle that lasted—with only a few short interruptions—for 35 years. Kilauea will almost certainly erupt again within years or decades.

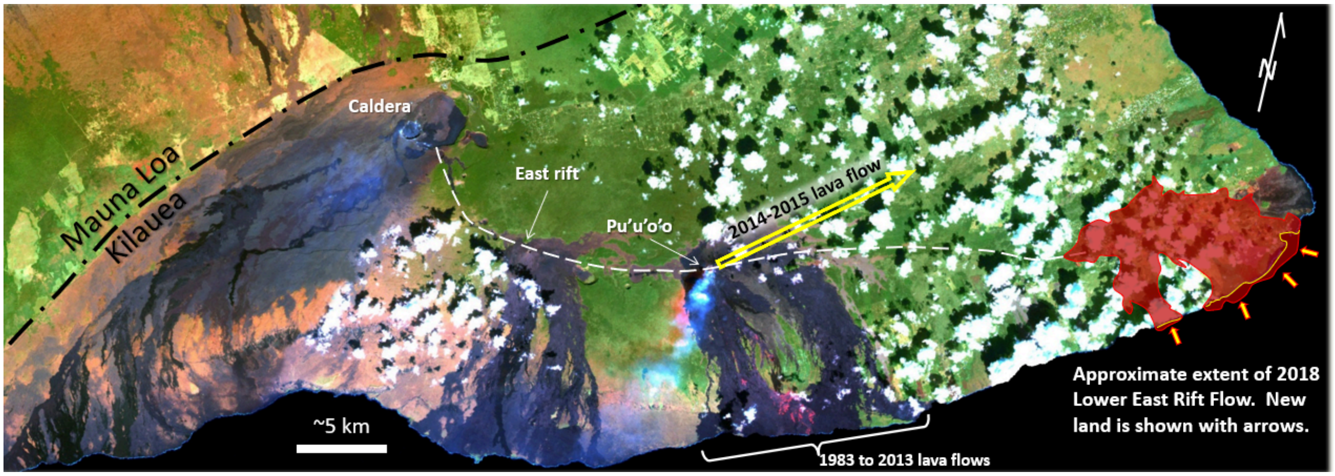

Figure 4.3.11 Satellite image of Kilauea volcano showing the East rift and Pu'u 'O'o, the site of the eruption that started in 1983 and continues to the present day. The 2014-2015 lava flow described in Exercise 4.4 is shown with a yellow arrow, and the area of the 2018 lava flow is shown in red. The puffy white blobs are clouds.

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 4.3.12b, and “lava flow video”). **Aa**, or blocky lava, forms when magma is forced to flow faster than it is able to (down a slope for example) (Figure 4.3.12c). **Tephra** (lava fragments) is produced during explosive eruptions, and accumulates in the vicinity of cinder cones.

Figure 4.3.12d 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 km, 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.

Figure 4.3.12 Images of Kilauea volcano. (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 on Kilauea, (d) Skylight in an active lava tube, Kilauea. Photos B & C taken in 2002 photos A & D taken in 2007.

Kilauea started forming at approximately 300 ka, while neighbouring Mauna Loa dates back to 700 ka and nearby Mauna Kea ito around 1 Ma. If volcanism continues above the Hawaii mantle plume in the same manner that it has since 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 4.3.8).

Exercise 4.4 Kilauea's 2014 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, 2014 (the "June 27th Lava flow," a.k.a. the "East Rift Lava Flow"). The flow reached the nearest settlement, Pahoa, on October 29, 124 days later. 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.

What is the average rate of advance of the flow front from June 27 to October 29, 2014, in metres per day and metres per hour?

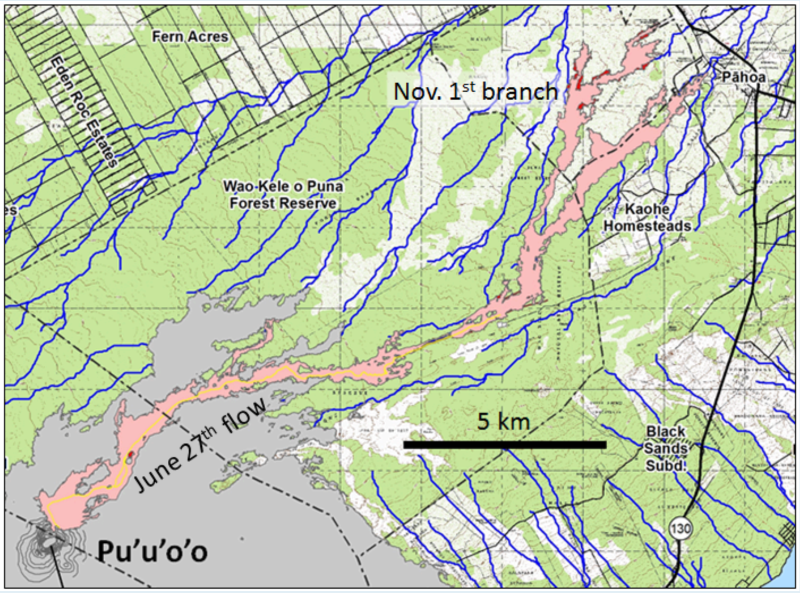

Figure 4.3.13 [Image Description]

See Appendix 3 for Exercise 4.4 Answers.

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 4.3.14). This volcanism, which covered an area of about 160,000 square kilometres (km^2) with basaltic rock up to several hundred metres thick, took place between 17 and 14 Ma.

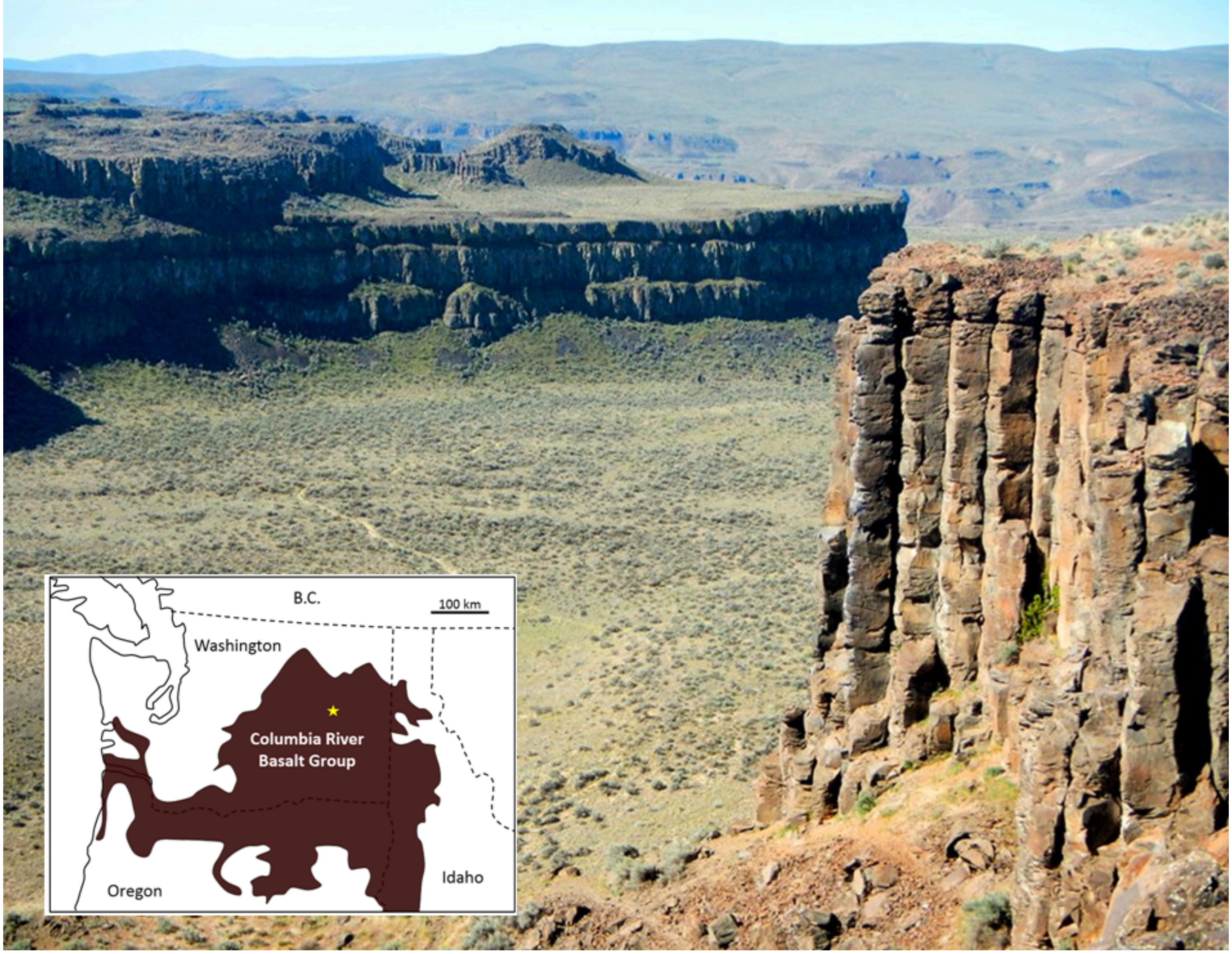

Figure 4.3.14 A part of the Columbia River Basalt Group at Frenchman Coulee, eastern Washington. All of the flows visible here have formed large (up to two m in diameter) columnar basalts, a result of relatively slow cooling of flows that are tens of metres thick. The inset map shows the approximate extent of the 17 to 14 Ma Columbia River Basalts, with the location of the photo shown as a star. *[Image Description]*

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 cubic kilometres (km^3) of felsic magma, about 900 times the volume of the 1980 eruption of Mount St. Helens, but only 5% of the volume of mafic magma in the CRBG.

Sea-Floor Volcanism

Some LIP eruptions occur on the sea floor, the largest known 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 4.3.15). In terms of area, there is very likely more pillow basalt on the sea floor than any other type of rock on Earth.

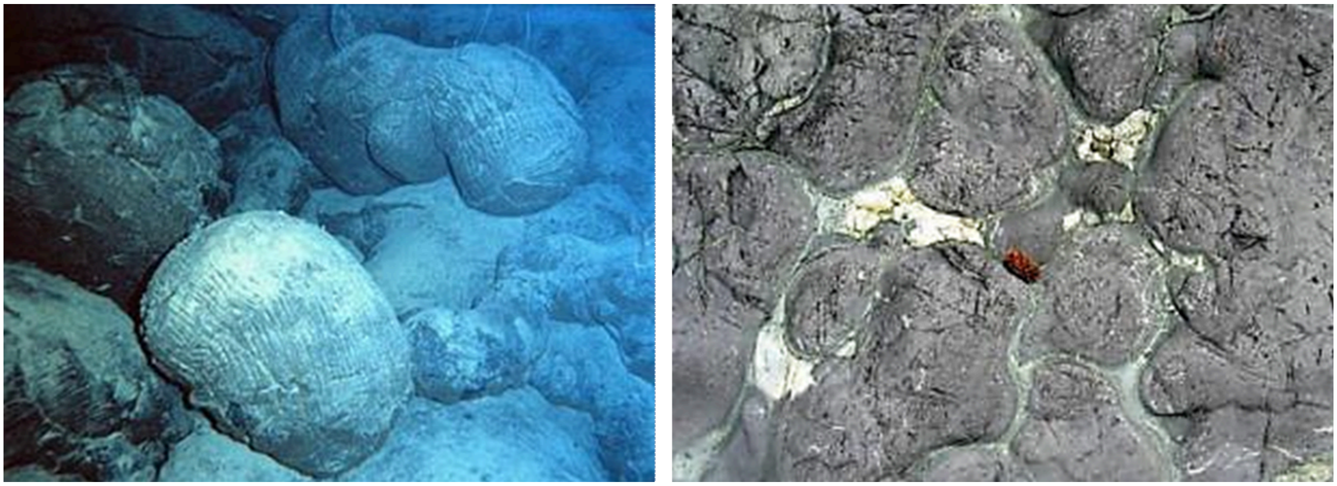

Figure 4.3.15 (Left) Modern sea-floor pillows in the south Pacific. (Right) Ancient sea-floor pillow basalts. Eroded 40 to 50 Ma pillows on the shore of Vancouver Island, near to Sooke. The pillows are 30 to 40 cm in diameter.

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 rich Ekati Mine in the Northwest Territories (Figure 4.3.16).

Figure 4.3.16 Ekati diamond mine, Northwest Territories, part of the Lac de Gras kimberlite field

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 dated to about 30 Ma.

How frequently do volcanoes erupt?

The Smithsonian Institution maintains a comprehensive catalogue of the world's volcanoes, with information and eruptive history for nearly 2700 volcanic sites. If you spend some time looking around that site you'll discover the frequency of eruptions at different volcanoes is enormously variable, although we can make some generalizations. Focusing just on shield volcanoes and composite volcanoes some of the data are as follows:

Table 4.2 Eruptions of composite and shield volcanoes

Composite volcanoes	Shield volcanoes
Avachinsky (Russia): 5 eruptions over the past 7000 years	Fernandina (Galapagos): 31 eruptions over the past 1000 years
Pinatubo (Philippines): 4 eruptions over the past 9000 years	Kilauea (Hawaii): 62 eruptions over the past 250 years
Adams (Oregon, USA): 6 eruptions over the past 7000 years	Nyamuragira (Congo): 48 eruptions over the past 154 years

Based only on these numbers it is evident that, in general, shield volcanoes are much more active than composite volcanoes, but there are many exceptions to this trend. Some composite volcanoes are nearly as active as the shield volcanoes listed here, and some shield volcanoes that are still considered to be "active" are almost as inactive as the composite volcanoes listed here.

Image Descriptions

Figure 4.3.4 image description: Mount St. Helens rises over 2.5 kilometres above sea lever and consists mostly of rock less than 3,000 years old. Underneath the mountain is older volcanic rock. Just below sea level is a small magma chamber, which is a probable reservoir for 1981 and later eruptions. Down 5 to 14 kilometres below sea level is the main magma chamber. Variations in the composition of the erupted magma imply this chamber is stratified, with more magma at the bottom. [Return to Figure 4.3.4]

Figure 4.3.5 image description: Image (A) shows a cliff wall with grey/brown and orange horizontal layers. The sides look soft like they would be easily worn away. The grey/brown layers are lahar deposits and the orange layers are felsic pyroclastic deposits. Image (B) shows a columnar basalt lava flow which looks like a rocky, stone cliff with vertical layers. [Return to Figure 4.3.5]

Figure 4.3.13 image description: The U.S. Geological Survey Hawaii Volcano Observatory (HVO) map, 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. [Return to Figure 4.3.13]

Figure 4.3.14 image description: The Columbia River Basalt Group covers most of south eastern Washington state and stretches along the borders between Washington, Idaho, and Oregon. The columnar basalts shown in the photo are in in eastern Washington. They rise up out of a flat valley as tall cliffs. [Return to Figure 4.3.14]

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- Figure 4.3.10: © Steven Earle. CC BY.
- Figure 4.3.11: Island of Hawai'i – Landsat mosaic by NOAA. Public domain. Modified by Steven Earle.
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- Figure 4.3.15 (Left): Pillow Basalt Crop by NOAA. Public domain.

- Figure 4.3.15 (Right): © Steven Earle. CC BY.
- Figure 4.3.16: “Ekati mine” © Jason Pineau. CC BY-SA.

4.4 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 degradation. It is estimated that 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 4.3.

Table 4.3 A summary of the important volcanic hazards

[Skip Table]

Type	Description	Risk
Tephra emissions	Small particles of volcanic rock emitted into the atmosphere	• Respiration problems for some individuals • Significant climate cooling leading to crop failure and famine • Damage to aircraft
Gas emissions	The emission of gases before, during, and after an eruption	• Climate cooling leading to crop failure and famine • In some cases, widespread poisoning
Pyroclastic density current	A very hot (several 100°C) mixture of gases and volcanic fragments (tephra) that flows rapidly (up to 100s of kilometres per hour (km/h)) down the side of a volcano	Extreme hazard — destroys anything in the way
Pyroclastic fall	Vertical fall of tephra in the area surrounding an eruption	• Thick tephra coverage of areas close to the eruption (1 km to 10s of kilometres) • Collapsed roofs
Lahar	A flow of mud and debris down a channel leading away from a volcano, triggered either by an eruption or a severe rain event	Severe risk of destruction for anything within the channel—lahar mud flows can move at 10s of km/h
Sector collapse/ debris avalanche	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	Severe risk of destruction for anything in the path of the debris avalanche
Lava flow	The flow of lava away from a volcanic vent	People and infrastructure at risk, but lava flows tend to be slow (less than km/h) and are relatively easy to avoid

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 and 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 Mount Pinatubo in the Philippines. A temperature decrease 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

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 4.4.1). As they descend, they cool more and flow faster, reaching speeds up to several hundred kilometres per hour. 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 city’s harbour and destroyed several wooden ships anchored there.

Figure 4.4.1 The plinian eruption of Mount Mayon, Philippines. in 1984. Although most of the eruption column is ascending into the atmosphere, there are pyroclastic density currents flowing down the sides of the volcano in several places.

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 Mount 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 (described earlier). Lahars can also happen when there is no volcanic eruption, and one of the reasons is that, as we’ve seen, 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, not so much because of high winds but because of intense rainfall—some regions received almost 2 m of rain over a few days! Mudflows and debris flows occurred in many areas, especially in Honduras and Nicaragua. An example is at the 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, and then ripped through the towns of El Porvenir and Rolando Rodriguez killing more than 2,000 people (Figure 4.4.2). 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 4.4.2 Part of the path of the lahar from Casita Volcano, October 30, 1998.

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 Mount 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 ever observed slope failure. The failure of this part of the volcano exposed the underlying satellite magma chamber, causing it to explode sideways, which then exposed the conduit leading to the magma chamber below. The resulting plinian eruption—with a 24 kilometre high eruption column—lasted for nine hours.

In August 2010, a massive part of the flank of B.C.'s Mount Meager gave way and about 48 million cubic metres (m^3) of rock rushed down the valley, one of the largest slope failures in Canada in historical times (Figure 4.4.3). More than 25 slope failures have taken place at Mount Meager in the past 8,000 years, some of them more than 10 times larger than the 2010 failure.

Figure 4.4.3 The August 2010 Mount Meager rock avalanche, showing where the slide originated (arrow, 4 km upstream), its path down a steep narrow valley, and the debris field (and the stream that eventually cut through it) in the foreground.

Lava Flows

As we saw in Exercise 4.4, lava flows at volcanoes like Kilauea do not advance very quickly, and in most cases, people can get out of the way. Of course, it is more difficult to move infrastructure, and so buildings and roads are typically the main casualties of lava flows.

Exercise 4.5 Volcanic hazards in Squamish

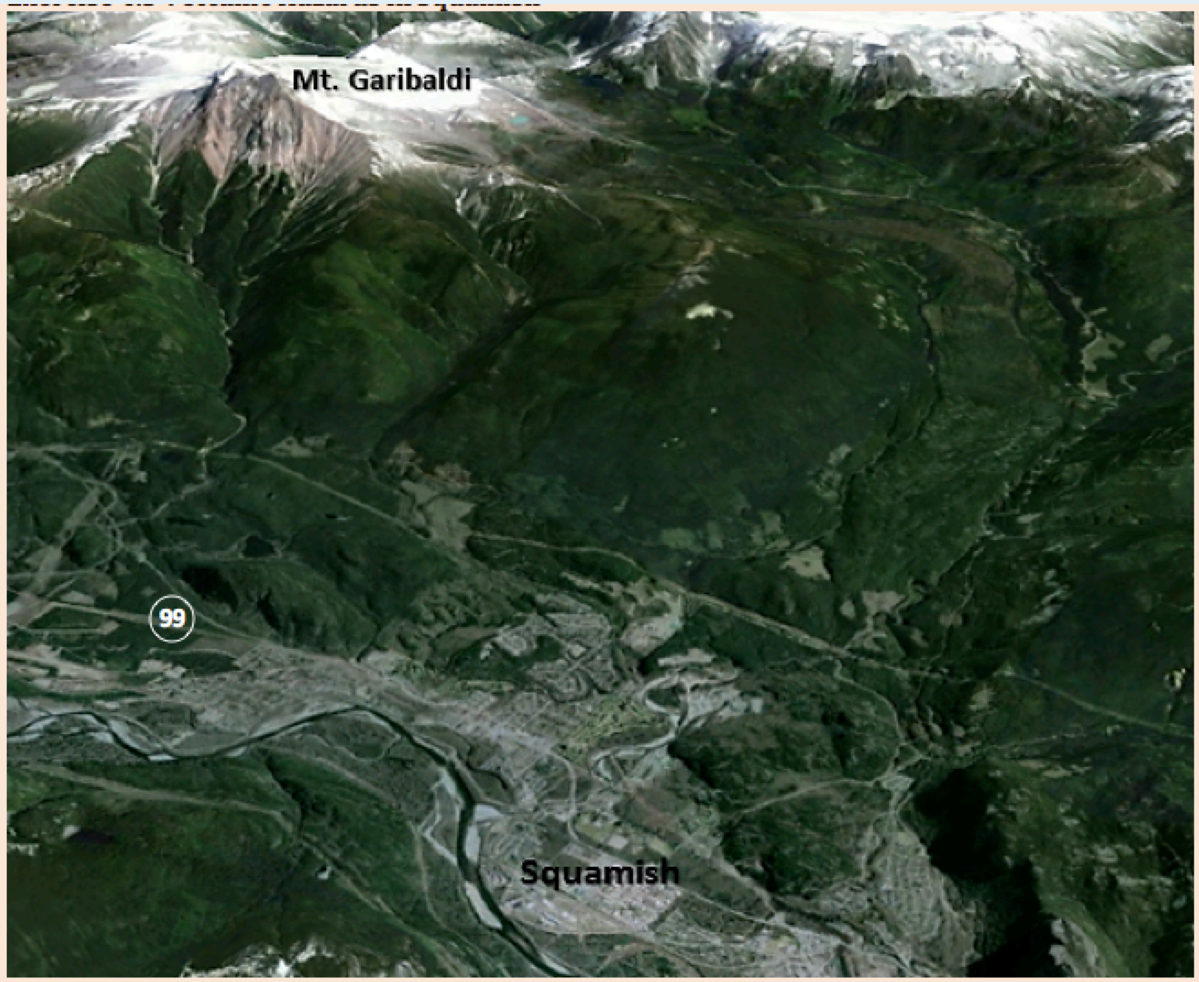

Figure 4.4.4

The town of Squamish is situated approximately 10 km from Mount Garibaldi, as shown in the photo. If Mount Garibaldi were to erupt, which of the following hazards could be an issue for people in and around Squamish? Explain why or why not.

1. Tephra emission.
2. Gas emission.
3. Pyroclastic denisty current.
4. Pyroclastic fall.
5. Lahar.
6. Sector collapse.
7. Lava flow.

See Appendix 3 for [Exercise 4.5 answers](#).

Media Attributions

- Figure 4.4.1: "Pyroclastic flows at Mayon Volcano" by USGS. Public domain.
- Figure 4.4.2: "Casita Volcano" by USGS. Public domain.
- Figure 4.4.3: August 2010 Mt. Meager landslide, BC © Mika McKinnon. All rights reserved. Used with permission.
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4.5 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_2O, 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 Mount 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.[1]

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 4.5.1). 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.

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[1] See: http://www.earthquakescanada.nrcan.gc.ca/stndon/CNSN-RNSC/stnbook-cahierstn/index-eng.php?tpl_sorting=map&CHIS_SZ=west

Figure 4.5.1 A seismometer and related power and communication equipment installed in 2007 in the vicinity of the Nazco Cone, British Columbia

Detecting Gases

Water vapour quickly turns into clouds of liquid water droplets and is relatively easy to detect just by looking, but CO_2 and SO_2 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 4.3.12), or by collecting samples of the air and analyzing them in a lab.

Measuring Deformation

Measurement of deformation allows us to determine if a volcano is expanding or contracting. That can typically be related to the movement of magma into or out of a magma chamber near to surface and so is an indicator of the potential for an eruption. There are two main ways to measure ground deformation. 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 4.5.2). Both are effective, but GPS provides more information than a tiltmeter because it can tell us how far the ground has actually moved in the east-west, north-south, and up-down directions.

Figure 4.5.2 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.

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). 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 4.6 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 Mount 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?

See Appendix 3 for Exercise 4.6 Answers.

Media Attributions

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- Figure 4.5.2: A Typical GPS Monitoring Station by USGS. Public domain.

4.6 Volcanoes in British Columbia

As shown on the Figure 4.6.1, three types of volcanic environments are 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. This extends along the south coast from the U.S. border to the northern end of Vancouver Island.
- The Anahim Volcanic Belt is assumed to be related to a mantle plume. It is in central BC and stretches inland from the coast.
- The Stikine Volcanic Belt (northwestern BC) and the Wells Gray-Clearwater Volcanic Field (central Alberta border area) are assumed to be related to crustal rifting.

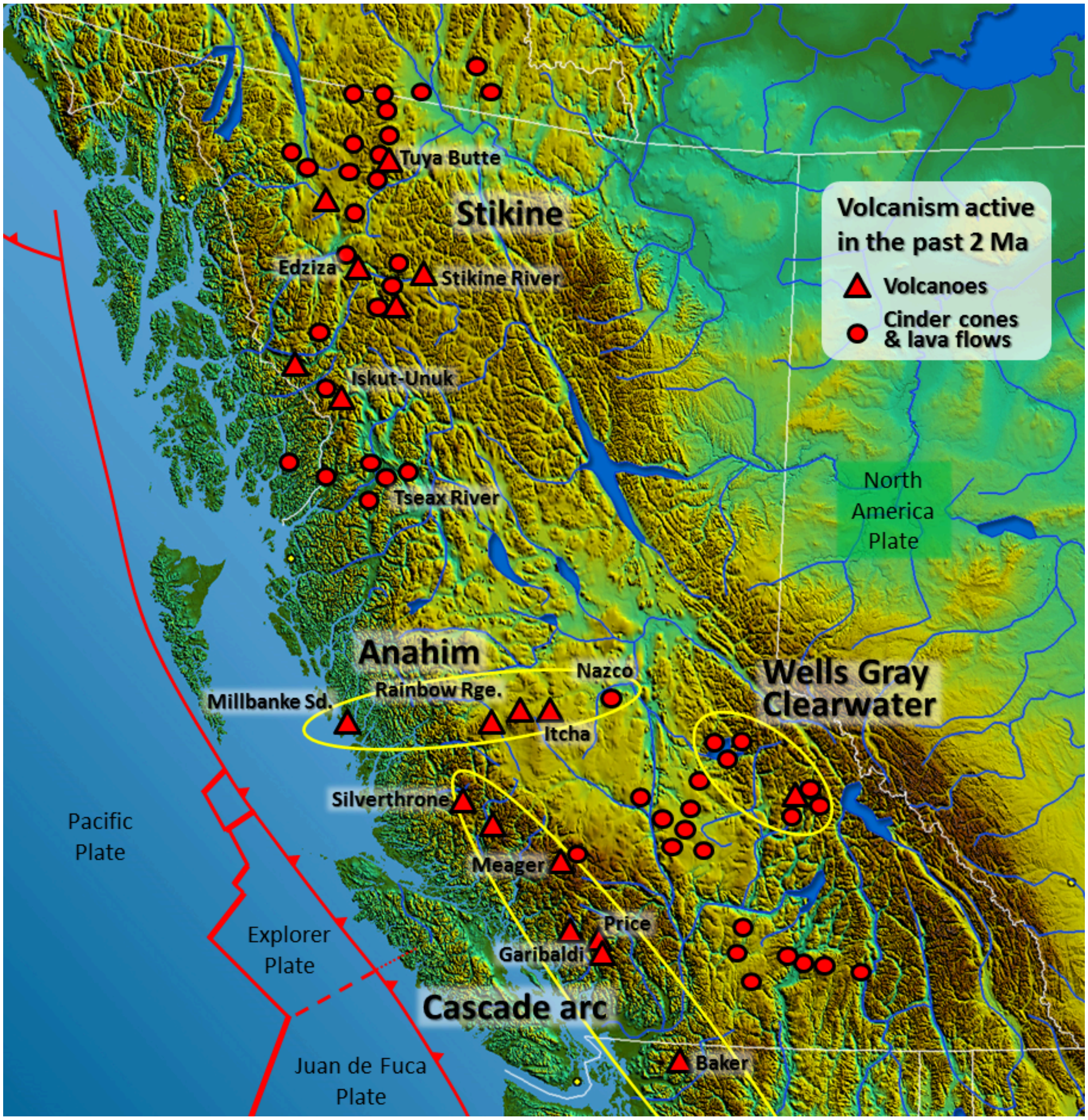

Figure 4.6.1 Major volcanic centres in British Columbia active within the last 2 million years

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 possible 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 Mount Garibaldi and the Black Tusk-Mount Price area adjacent to Garibaldi Lake (Figures 4.0.1 and 4.0.2), Mount Cayley, and Mount. Meager (Figure 4.4.3). The most recent volcanic activity in this area was at Mount Meager. Approximately 2,400 years ago, an explosive eruption of about the same magnitude as the 1980 Mount St. Helens eruption took place at Mount Meager. Ash spread as far east as Alberta. There was also significant eruptive activity at Mounts 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 4.6.2). The Table in Figure 4.0.2 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.

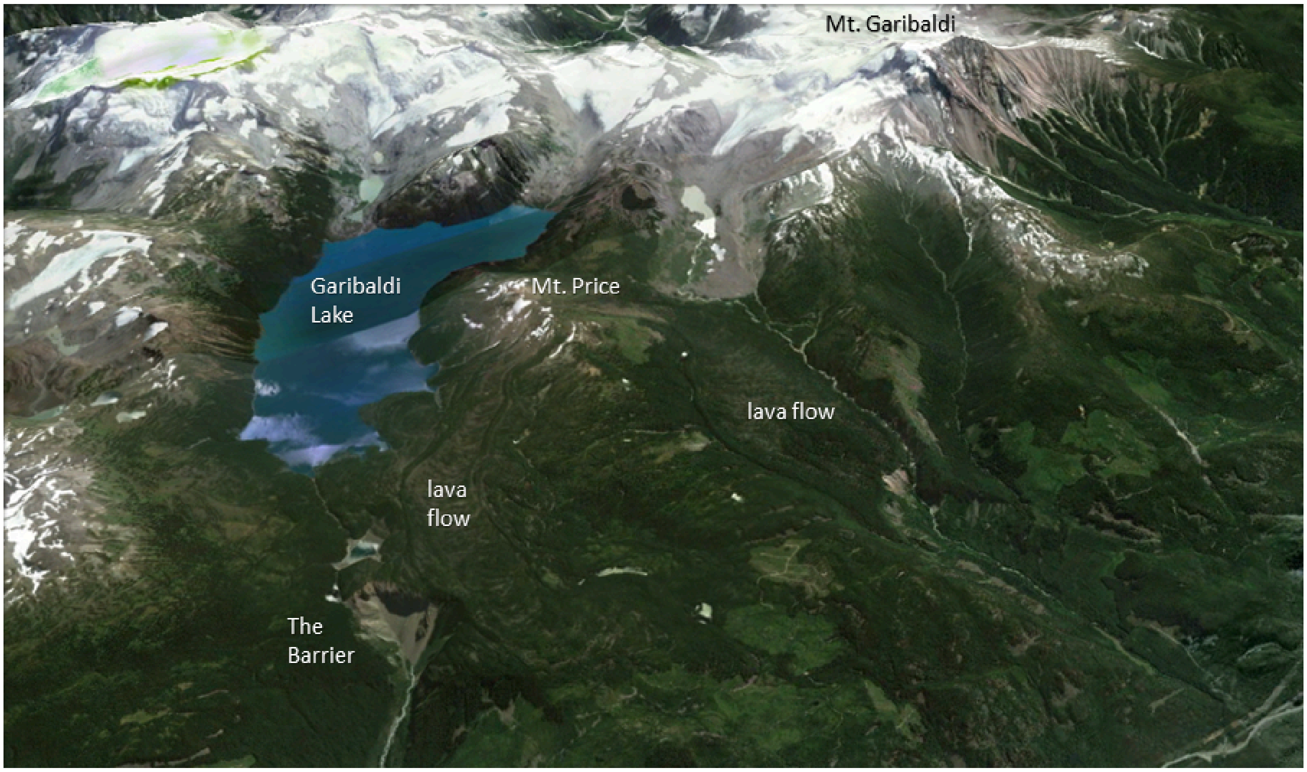

Figure 4.6.2 Perspective view of the Garibaldi region (looking east) showing the outlines of two lava flows from Mount Price. Volcanism in this area last took place when the valley in the foreground was filled with glacial ice. The cliff known as the Barrier formed when part of the Mount Price lava flow failed after deglaciation. The steep western face of Mount Garibaldi formed by sector collapse, also because the rocks were no longer supported by glacial ice.

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 Nazco 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 4.6.3). The name “Rainbow” refers to the bright colours displayed by some of the volcanic rocks as they weather.

Figure 4.6.3 Rainbow Range, Chilcotin Plateau, B.C.

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 4.1). 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, Mount Edziza itself (Figure 4.6.4) 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.

Figure 4.6.4 Mount Edziza, in the Stikine area, B.C., with Eve Cone in the foreground.

Exercise 4.7 Volcanoes down under

This map shows the plate tectonic situation in the area around New Zealand.

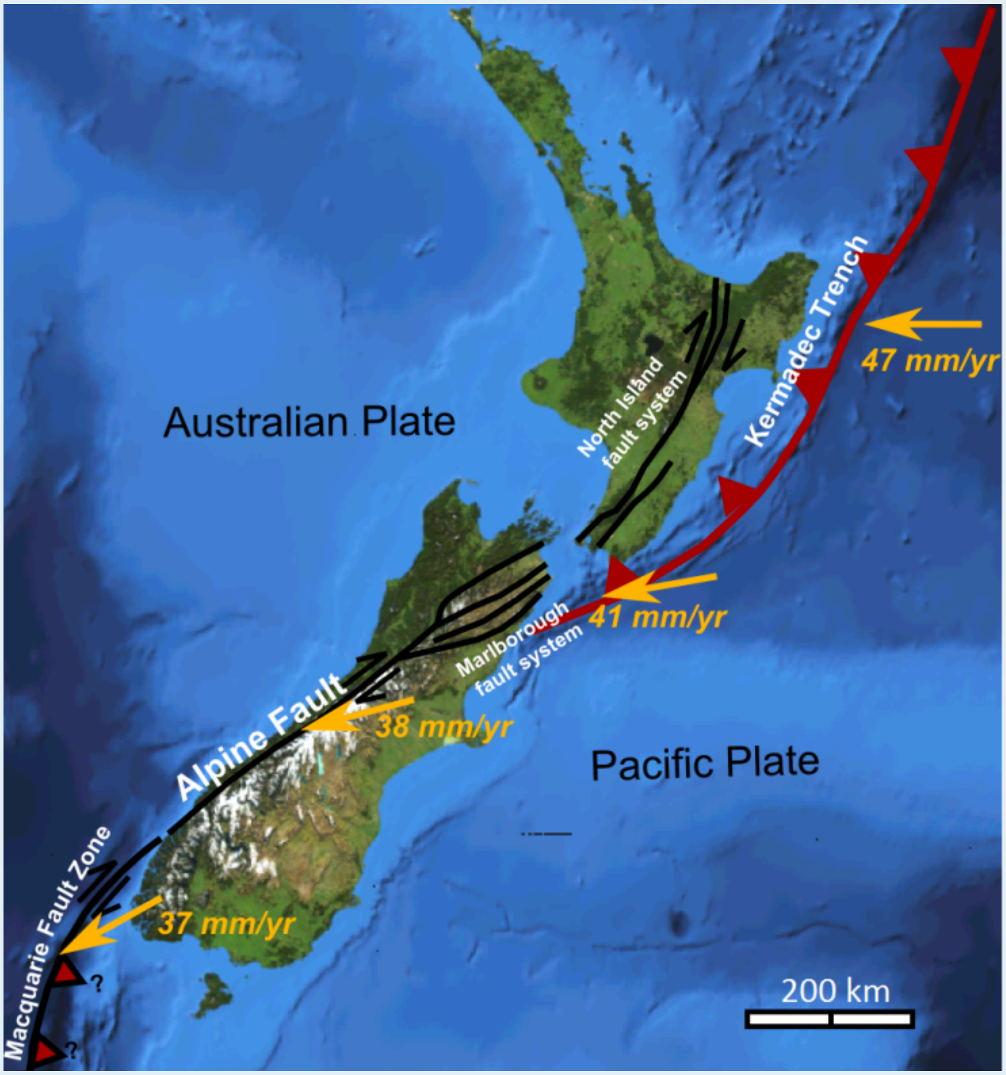

Figure 4.6.5

1. Based on what you know about volcanoes in B.C., predict where you might expect to see volcanoes in and around New Zealand.
2. What type of volcanoes would you expect to find in and around New Zealand?

See Appendix 3 for Exercise 4.7 Answers.

Media Attributions

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Summary

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

Section	Summary
4.1 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.
4.2 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.
4.3 Types of Volcanoes	Cinder cones, which can form in various volcanic settings, are relatively small volcanoes that were formed during a single eruptive event and are composed mostly of mafic rock fragments. 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 typically erupts as lava flows.
4.4 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 kilometres per hour 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. But the indirect effects of volcanism have been more deadly in the past, mostly because volcanic ash and gases can lead to short-term significant climate cooling.
4.5 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.
4.6 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

Answers to Review Questions at the end of each chapter are provided in Appendix 2.

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 Mount 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?
16. What was the likely cause of most of the deaths from the most recent eruption at the Tseax River Cone?