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The Breadknife, in Warrumbungle National Park, NSW Australia.
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Vulcanian style eruption from Tavurvur volcano, Papua New Guinea.
Source: Wikimedia Commons, photograph by T Taylor 2008

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Contents

What is a volcano?

A **volcano** is an opening in the Earth's crust from which lava, ash, and hot gases can be ejected during an eruption. The word volcano evokes scenes of running molten rocks, huge towering eruption clouds, explosions, ash and destruction. Volcanic eruptions can vary wildly from 'calm' lava and gas emissions to highly explosive mixtures of volcanic rocks, ash and gases.

The word volcano comes from the name of the ancient Roman god, **Vulcan**, who was known as the blacksmith of the gods—the god of fire—and was the son of the gods Jupiter and Juno. The Romans believed they could hear the sound of his forge at night and see the lights of his fires on an island off the coast of Sicily. Therefore it is no surprise that this small island was named Vulcano after him (Figure 1).

The study of volcanoes and their associated phenomena is known as **Volcanology**. This includes studying the origin, the structure and the kind of material that lies within, or is ejected from, a volcano.

Figure 1: In the foreground, Vulcano, a volcanic island in the Aeolian Islands, Southern Italy. Source: A. Bear 2007, Geoscience Australia.

Volcano types

Volcanoes are often recognised by their characteristic cone shapes. Each cone develops over the course of many eruptions. A cone is usually made of cooled lava together with solids such as ash and larger particles. Volcanoes are classified according to their shape and what comes out of them.

Volcano shapes

The shape of a volcano is strongly controlled by the type of eruption. In turn, the type of eruption is mostly dictated by the viscosity of the lava extruded from a volcano (Figure 2). Runny lava with a low viscosity can flow for long distances away from the vent, forming gently sloping volcanoes. Thick, viscous lava form steep sided plugs over the vent, called a lava dome. This lava, in combination with explosions of other material, can result in volcanoes with steep sides of 30 degrees of more.

There are three main types of volcanoes: shield, stratovolcano and caldera.

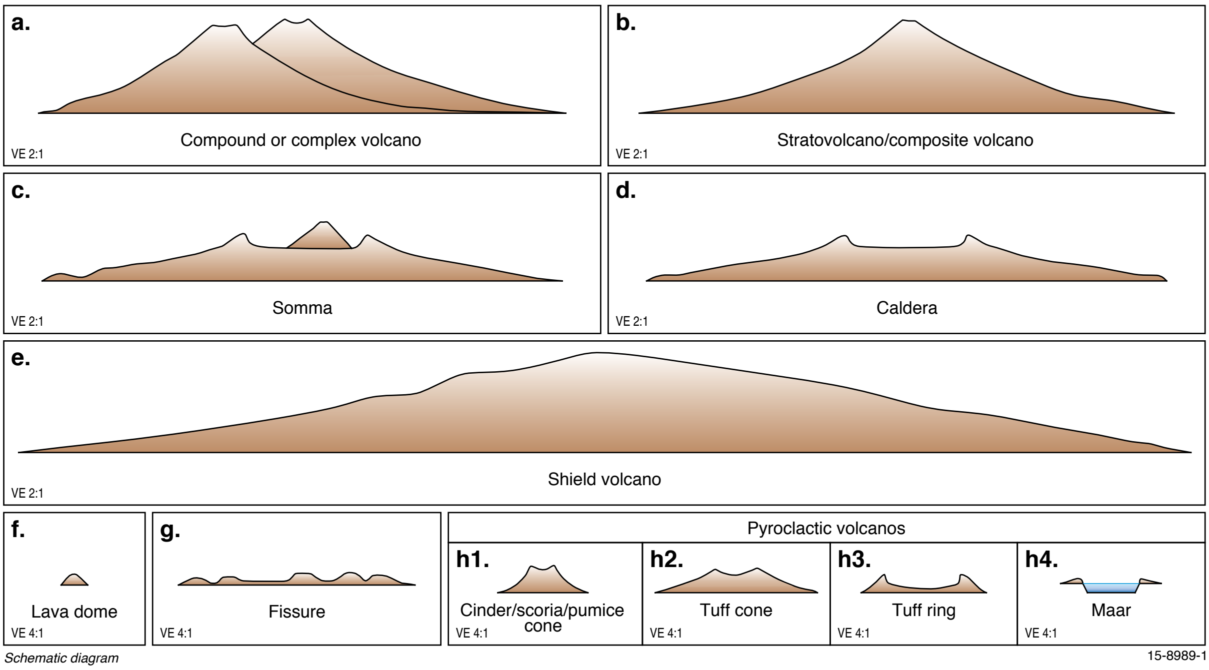


Figure 2: Volcano shapes and relative sizes. Figures a to e are vertically exaggerated by a ratio of 2:1. Figures f to h4 are vertically exaggerated by a ratio of 4:1. Image adapted from Volcanoes of the world: A regional directory, gazetteer, and chronology of volcanism during the last 10 000 years by Tom Simkin & Lee Siebert; with the collaboration of Russell Blong, et al. Tucson, Ariz.: Geoscience Press; 1994.

Shield volcano

Lavas low in silica (SiO_2 basaltic, or mafic lavas) have a low viscosity and can flow for long distances away from the vent. Over time they develop gently sloping volcanoes called **shield volcanoes** (Figure 2). Shield volcanoes get their name because they resemble a warrior's shield lying face-up on the ground and are created by relatively gentle volcanic eruptions. For example, Hawaiian island volcanoes like Mauna Loa (Figure 3) and Kilauea, Piton de la Fournaise on Reunion Island, and the volcanoes on the Galapagos Islands and in Iceland are shield volcanoes. The largest volcano in our solar system, Olympus Mons, is a shield volcano located on the planet Mars (Figure 4). It is about 25 kilometres tall, which is 2.6 times taller than Mount Everest, and over 600 km in diameter.

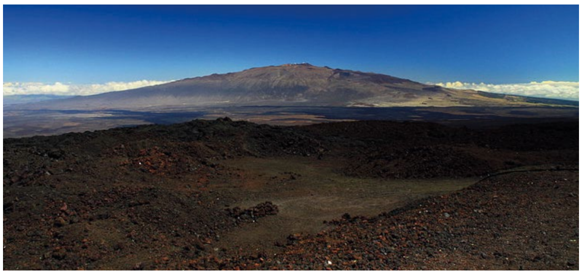


Figure 3: The Mauna Loa shield volcano on the island of Hawaii. From *http://en.wikipedia.org/wiki/Shield_volcano.*

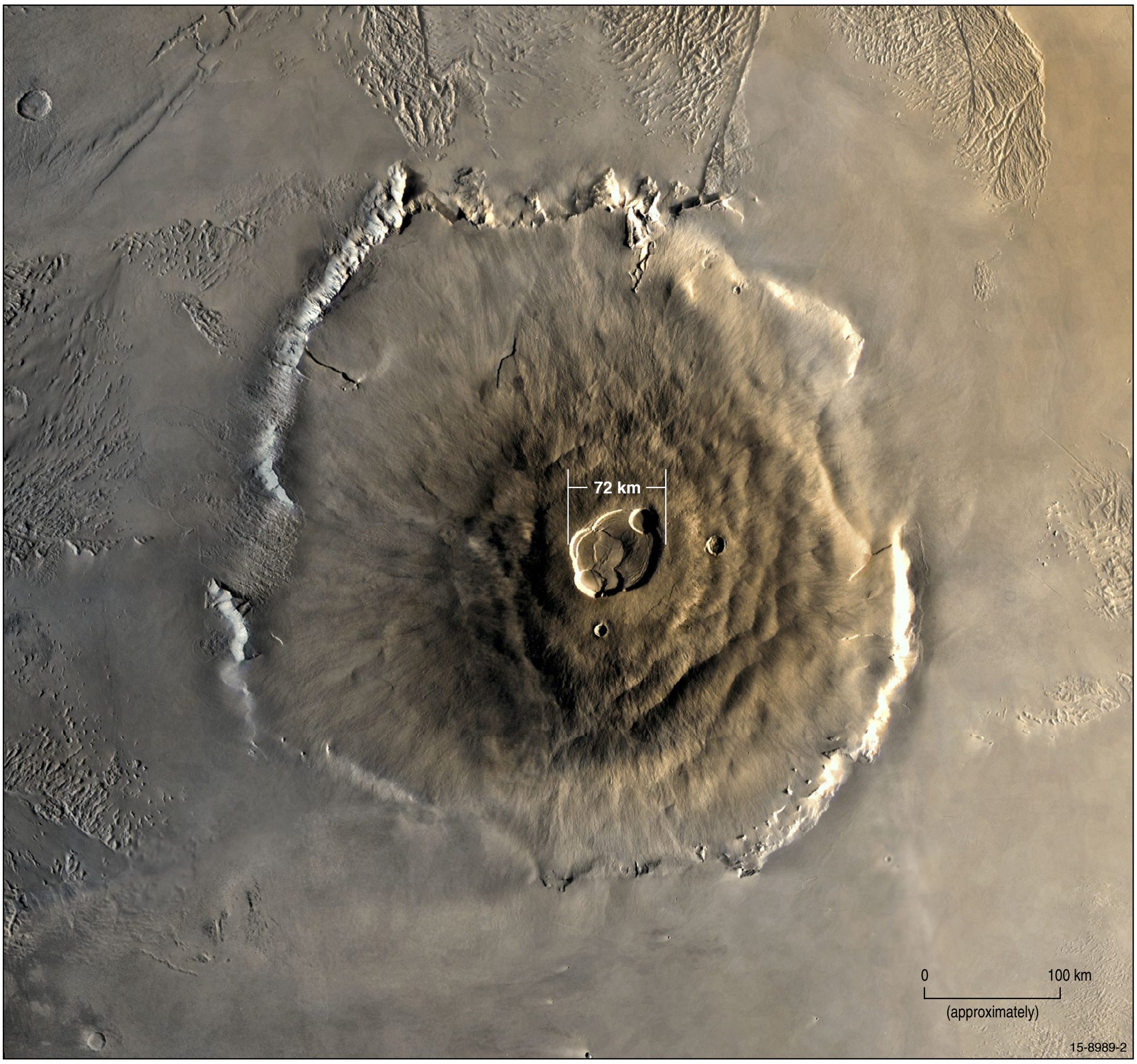


Figure 4: The Olympus Mons shield volcano on Mars. The base of the volcano is about 600 km in diameter, roughly six times the diameter of Mauna Loa. Source: Wikimedia Commons, photograph by NASA, modifications by Seddon 1978.

Shield volcanoes are built up by numerous lava flows and perhaps some thin layers of volcanic ash and other minor **volcaniclastics** (Figure 5) surrounding a volcanic **vent** (the opening on the Earth's surface where volcanic material is emitted).

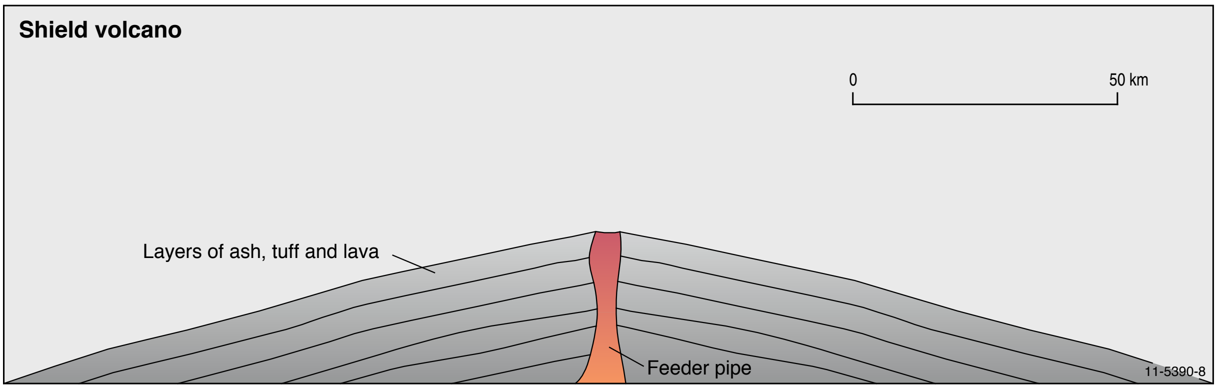


Figure 5: A shield volcano. Shield volcanoes are broad, gently sloping structures that are built up by layers of very fluid basaltic lava flows and minor volcaniclastics. The lava can be erupted from numerous vents (roughly circular or oval-shaped) and/or fissures (thin, linear opening).

Stratovolcano

More viscous lavas (with a higher silica content – for example, **andesites** and **dacites**) form a steep sided plug over the vent called a **lava dome**. Explosions, as part of eruptions, throw solid fragments from the vent or crater that form cones of pyroclastic material. These volcanoes, made up of layers of **pyroclastic** materials like **ash**, **lapilli**, **scoria** and **volcanic bombs** and lava, can have slopes of 30 degrees or more and are known as **stratovolcanoes** or **composite volcanoes** (Figure 6). Some examples of stratovolcanoes are Mount Mayon (Philippines) (Figure 7), Mount Fuji (Japan), Mount Ruapehu (New Zealand) and Mount Yasur (Vanuatu).

In some cases, when the lava becomes very viscous it plugs the vent causing pressure to build up as it expands. This pressure can cause the volcano to explode leaving only the outer shell of the original volcanic structure (crater). This is what caused the lateral explosion of Mount St. Helens (Figure 31). In this case, the collapse of one flank produced a lateral explosion and destruction of the original volcanic structure.

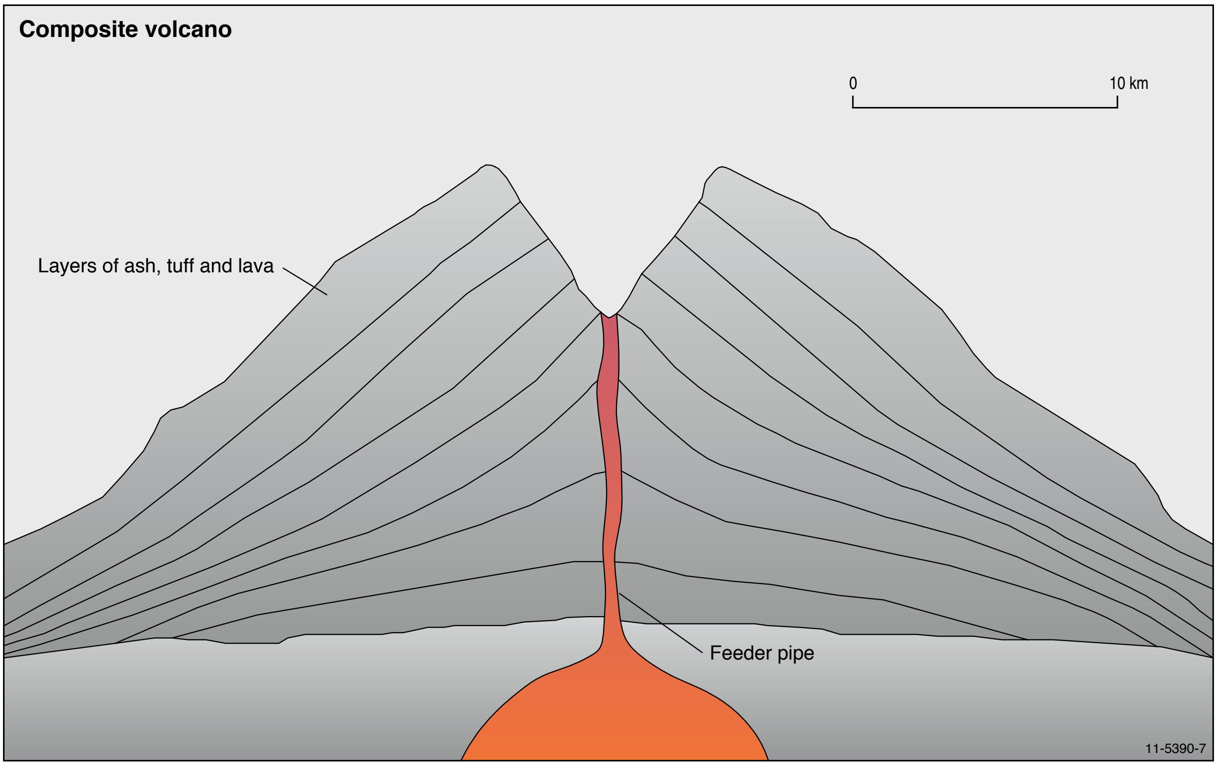


Figure 6: A graphic of a composite volcano (also known as a stratovolcano). Composite volcanoes are structures built around a main central vent, formed by many eruptions that deposit layers of lava, pyroclastic and volcaniclastic material.

Figure 7: The typical shape of a stratovolcano is demonstrated by Mount Mayon in the Philippines. Fresh lava flows can be seen on the near-side. Source: Wikimedia Commons, original uploader was Tam3rd at en.wikipedia.

Caldera

A **caldera** is a large bowl-shaped volcanic depression that forms after an explosive eruption of magma forms ash and **pumice** by emptying the magma chamber beneath the volcano. The volcanic cone collapses into the empty magma chamber, forming the caldera. These volcanic features can be tens of kilometres in diameter and often fill with water to form large lakes. Some examples of a caldera include Aniakchak caldera (Alaska) (Figure 8), Lake Taupo (New Zealand), Yellowstone caldera (United States) and Lake Toba (Indonesia).

Did you know?

The world's largest calderas are caused by supervolcanoes. These are enormous events involving the eruption of a 1000 cubic kilometres of material or greater. After eruption, the magma chamber collapses to form a caldera at the surface. Later the calderas may become filled with water forming large caldera lakes like Lake Toba (Indonesia) and Lake Taupo (New Zealand), or rings of volcanic islands like Santorini (Greece). If a supervolcano were to erupt today, it would affect air traffic around the world, and cause prolonged winters for several years due to ash particles blocking sunlight and lowering global air temperatures.

Bible stories related to the Exodus from Egypt including rains of fire, a pillar of smoke, dust storms, plagues of locusts and the parting of the Red Sea may be related to the eruption of the Santorini volcano between about 1645 BC to 1500 BC. These stories form part of Christian, Islamic and Jewish faiths.

Probably the largest caldera is at the summit of Olympus Mons on Mars, which is a 90 km by 60 km ellipse.

Figure 8: Aniakchak Caldera, Alaska approximately 10 km in diameter. Notice the younger scoria cones formed within the caldera, indicating renewed volcanic activity after the caldera was formed. Source: Wikimedia Commons, photograph by M Williams, National Park Service 1977.

What comes out of a volcano?

The material erupting from a volcano can be divided into gases, aerosols, liquids and solids.

Gases

By volume, gases are the most abundant volcanic product, but make up only a few percent of the total weight of erupted material. It is estimated that during the eruption of Paricutin in Mexico in 1945, 13 000 tonnes of steam (water vapour) was released every day.

Collecting samples of volcanic gases can be a very dangerous activity for volcanologists (Figure 9), with a number of fatalities reported. However, samples volcanologists have retrieved have provided information on the primary components of **volcanic gas** (Table 1.1).

Figure 9: A volcanologist collects volcanic gasses. Notice the use of a respirator mask and hazardous materials suit due to the poisonous vapours, and a helmet in case of flying rocks! Source: USGS *http://volcanoes.usgs.gov/Imgs/Jpg/Monitoring/Gas/GasMageik_large.jpg*

Table 1.1 Primary components of volcanic gas

Volcanic Gas	Average percentage (%)
Water (steam) (H_2O)	77.0
Carbon dioxide (CO_2)	11.7
Carbon monoxide (CO)	0.5
Hydrogen (H)	0.5
Sulfur dioxide (SO_2)	6.5
Sulfur (S)	0.3
Chlorine (Cl)	0.05
Nitrogen (N)	3.0
Argon (Ar)	0.05

The amount of **carbon dioxide** (a major greenhouse gas) in the Earth's atmosphere suggests that volcanic eruptions contribute greatly to the Earth's natural greenhouse effect by trapping heat within the atmosphere. In the past, during periods of extensive **volcanism** (volcanic activity), the Earth's climate may have been significantly altered by the addition of carbon dioxide from volcanoes and consequent global warming[1]. However, this may not always be the case (see Aerosols on page 8).

The power of volcanic eruptions is caused, in part, by the expansion of volcanic gases dissolved in the rising magma. As the magma reaches the surface, the dissolved gases exsolve (escape) from the magma and expand up to 1000 times their volume due to the lower atmospheric pressures.

Often labelled as the loudest explosion ever heard by humans, the eruption of the volcanic island of Krakatau in 1883 shows how the force of expanding gases can cause an eruption. The main blast occurred on 27 August 1883 and was heard over 2000 kilometres away. The cause of the explosion is thought to have been from the rapid expansion of sea water that seeped through a rift in the side of the island and boiled when it came into contact with the molten rock, as well as from gasses dissolved in the magma. It has been estimated that 36 000 people died as a result of the eruption and consequent tsunami.

Did you know? Volcanic explosions

A volcanic eruption is a similar process to what happens when you unscrew the lid of a soft-drink bottle, only much more violently! The pressurised drink represents the gas-rich magma with carbon dioxide dissolved in the liquid. Opening the lid (possibly after shaking) releases the pressure and the bubbles immediately expand and may push up through the neck of the bottle. The release of this great pressure causes volcanic explosions, such as the major catastrophic eruption of Krakatau in 1883 (Figure 10).

Figure 10: Anak Krakatau, Sunda Strait, Indonesia (between the islands of Java and Sumatra). Source: Wikimedia Commons, photograph by flydime 2008.

1. http://volcanoes.usgs.gov/hazards/gas/climate.php

Aerosols

Of all the gases released by volcanic eruptions, sulfur dioxide is the most important. During an eruption, vast amounts of sulfur dioxide (SO_2) are released into the atmosphere where, over a period of hours, days or weeks, it reacts with water to form liquid aerosol particles of sulfuric acid (H_2SO_4). This contributes to acid rain causing plant death and rapid weathering of rocks and infrastructure such as concrete, limestone and marble buildings. Smaller amounts of other nasty acids such as hydrochloric (HCl), nitric (HNO_3) and hydrofluoric (HF) acids are also created.

Aerosol particles are a natural phenomenon and are normally only a few microns (a few thousandths of a millimetre) in diameter. Some of these particles form around tiny ash flecks. The larger aerosol particles may settle out of the atmosphere after a few weeks, but the smaller aerosol particles can remain in the stratosphere for two or three years long after the ash and pumice of the same eruption have been deposited onto the Earth's surface.

While there is evidence that the Earth's climate may have been altered by the addition of CO_2, aerosols derived from volcanoes have been also shown to reduce regional or global temperatures by blocking infra-red radiation from the Sun.

Liquids

Magma is a molten rock that collects in the Earth below a volcano that, when erupted from a volcano onto the Earth's surface, becomes known as **lava**.

The chemical composition of lava, in particular the amount of **silica** (SiO_2), determines its **viscosity.** Lava viscosity affects the speed and distance lava can flow away from the **volcanic vent**, therefore viscosity also governs the ultimate shape of volcanic cones.

Igneous rocks (solidified lava/magma) are primarily classified by their silica content and the size of their constituent crystals. The simplified classification scheme for igneous rocks in Table 1.2 is based on their silica content and whether they are **extrusive** or **intrusive**. Extrusive rocks (lavas) tend to have smaller crystal sizes because they cool rapidly. Intrusive rocks tend to have larger grain sizes because they cool more slowly, allowing their crystals to grow larger before the molten rock finally freezes.

Lavas that are relatively low in silica (45 to 53 percent) are the *least* viscous and flow quickly, and for many kilometres, away from the volcanic vent. These are known as the **basaltic lavas.** This lava type is, by volume, the most abundant lava type on Earth. Most of the lavas that erupt underwater at plate boundary 'spreading centres' are basaltic in composition.

Table 1.2 A simple classification scheme for igneous rocks

Silica Content %	Extrusive type	Intrusive type
45–53	Basalt	Gabbro
54–62	Andesite	Diorite
62–70	Dacite	Granodiorite
70–78	Rhyolite	Granite

Did you know? The year without summer

In 1783 much of northern Europe was covered in a dense "smoky fog" that stretched from Greenland and Ireland to Italy, and perhaps as far as northern Siberia, causing an unusually hot summer. Benjamin Franklin, who was the ambassador of the United States of America to France at that time, commented that the following winter, of 1783–4, was unusually harsh in Paris. The next summer was so cool that many crops failed in northern Europe and caused a famine in Iceland, where 25 percent of the human population and 75 percent of livestock died. This weather was the result of the Laki fissure eruption in Iceland, which lasted for about 8 months over 1783–4. It is estimated that the Laki fissure eruption alone blasted about 120 million tonnes of sulphur dioxide (SO_2) into the Earth's atmosphere, as well as other nasties like hydrogen chloride (hydrochloric acid), hydrogen fluoride (hydrofluoric acid) and large amounts of fine volcanic ash. This had the effect of blocking the Sun for more than one year so crops could not ripen, covering plants in volcanic ash and killing animals that ate the contaminated vegetation through a disease called fluorosis—the ingestion of the toxic element fluorine.

Lavas that are relatively high in silica content (70 to 78 percent) are the *most* viscous and are classified as **rhyolites**. These lavas flow very slowly, for very short distances, and form expanding domes which plug up the volcanic vent. This can result in a blocked vent, which traps the expanding gases below and can increase pressure inside the vent resulting in violent volcanic explosions.

Magmatic differentation

Different magma sources produce different types of molten material and therefore different types of lava. However, the same volcano may produce different types of lava during different eruptions due to **magmatic differentiation** (Figure 12). Magmatic differentiation refers to the splitting of a parent magma into various components with some being silica-rich and others silica-poor. This occurs because as minerals are formed from the magma some sink to the **magma chamber** floor, and others float to the top, leaving the remaining magma with a different chemical composition to the original parent magma. New parent magma may also be injected into a chamber from adjacent chambers. These changes in the magma chamber can produce different lava types over a period of time. The sequence of mineral crystallisation is well known and is referred to as the **Bowen's Reaction Series** (Figure 11).

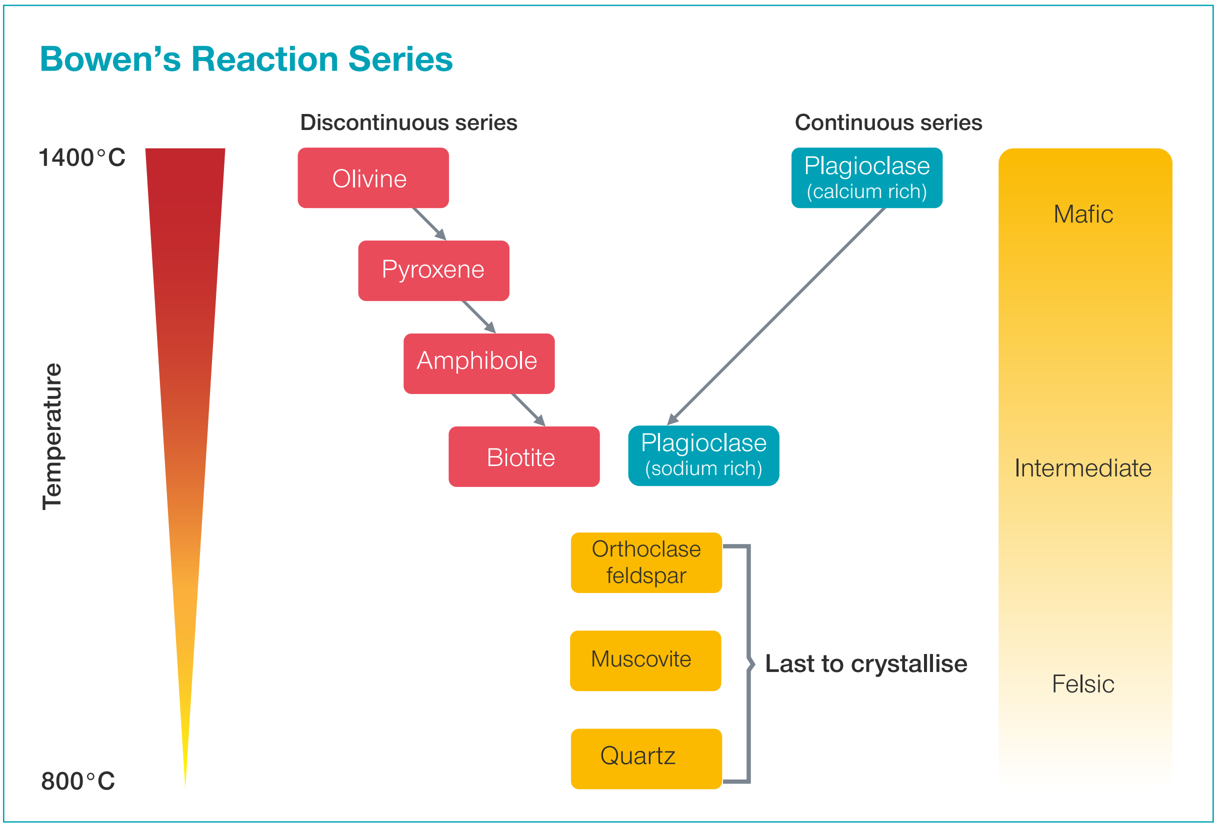


Figure 11: Bowen's Reaction Series describes the broad sequence of mineral crystallisation from a magma.

Activity: Magma Chamber Chemistry

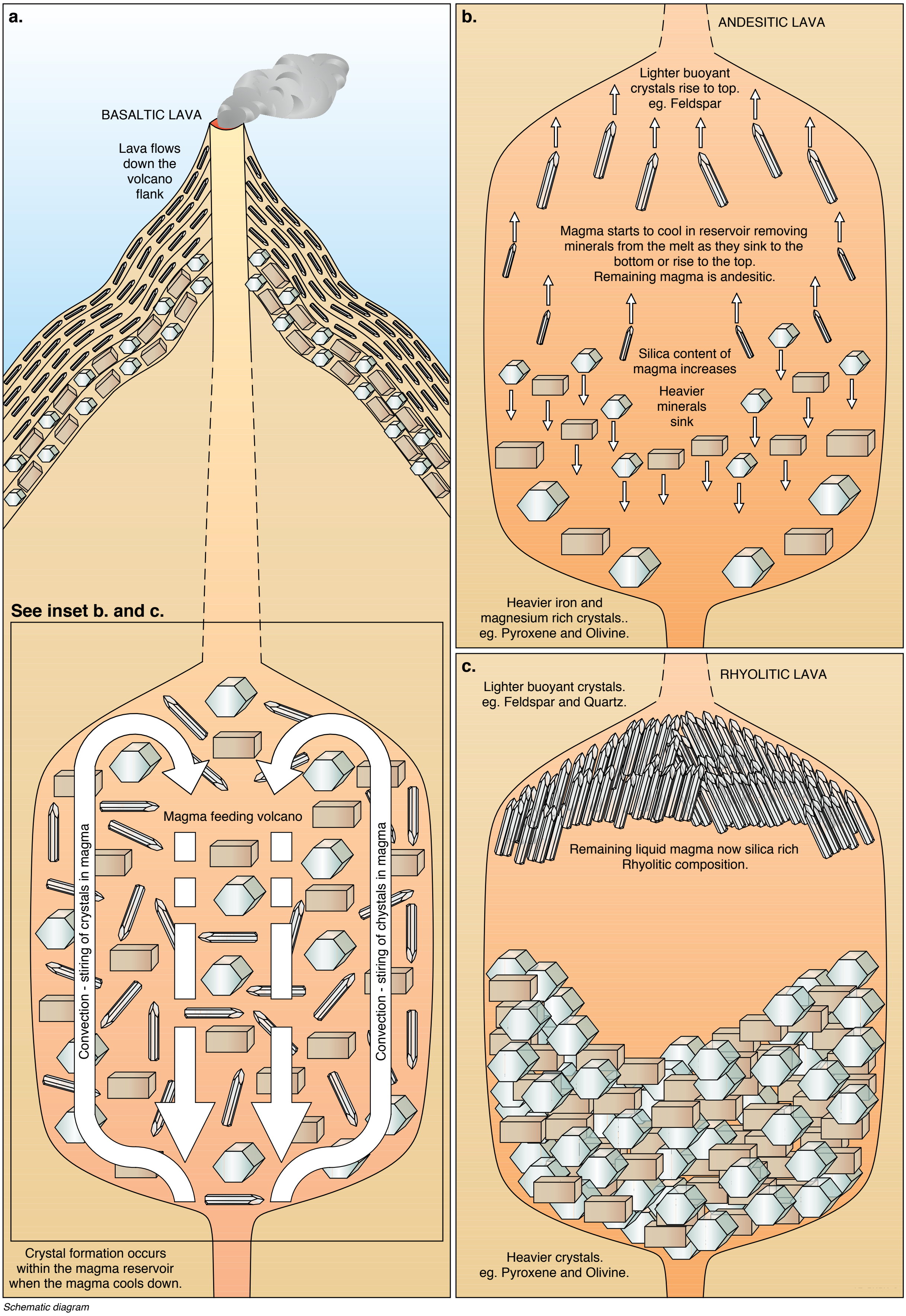


Figure 12: Stages of magmatic differentiation: a) magma chamber beneath an erupting volcano—basaltic lava b) partial crystallisation of magma chamber—andesitic lava eruptions, c) further cooling and crystallisation in magma chamber—rhyolitic lava erupting.

If no additional magma is added to a chamber, a volcano may initially erupt lava relatively low in silica like **basalts** (Figure 13) and then erupt lavas progressively richer in silica, for example **andesite** (Figure 14) and even **rhyolite** if there is still magma that hasn't erupted or solidified (Figure 15).

Figure 13: Basalt.

Figure 14: Andesite.

Figure 15: Rhyolite.

As cooling continues the igneous body shrinks causing cracking around the body. The residual magma and magmatic fluids may escape into the surrounding **country rocks** (crustal rocks intruded by and surrounding an igneous intrusion). As the magma cools, fluids are released, from which rare elements (like gold and platinum) and minerals (like sulfides) can precipitate in veins or where they react with the country rock. Over time, if these processes continue, deposits of minerals such as gold may form. The most common **host mineral** in these veins is quartz (Figure 16).

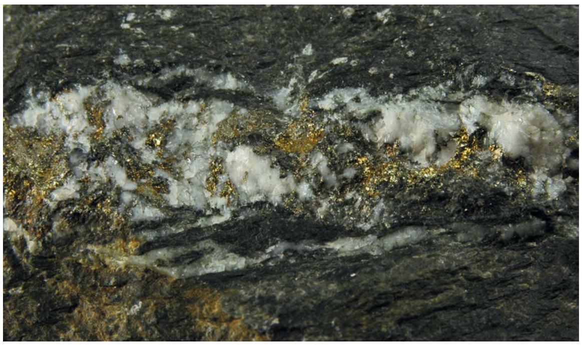


Figure 16: Pyrite and gold in a quartz vein.

The heat of lava as it flows from a volcano is hard to measure using standard equipment; specialised thermal cameras are needed. However, volcanologists use a **colour scale** to work out an approximate heat when recording details about **lava flows** (Table 1.3).

Table 1.3 The igneous rock temperature colour scale.

Heat Colour	Temp ºC
Incipient red	540
Bright red	870
Yellowish red	1100
Incipient white	1260
White	1480

Lava flow types

The textures of lava flows are often classified into two types—pahoehoe (pronounced 'pa-HOY-hoy') and a'a (pronounced 'AH-ah'); these are both Hawaiian words. **Pahoehoe** is commonly referred to as 'ropey' lava because its surface can resemble strands of rope or toothpaste. As the lava cools its skin congeals and becomes elastic, like a rubber sheet, and forms a ropey texture on the outer surface (Figure 18, Figure 19). Beneath this skin the lava can still be molten hot, and can continue to flow. **A'a** lava is more viscous and forms a mass of chunky broken fragments as it flows, and has a rough spiny surface (Figure 17, Figure 19). The uneven surface of the broken lava is known as **clinker**. As pahoehoe lava moves down slope it may change to a'a, but never the other way around. These different types of lava are formed due to **viscosity**, with a'a having a higher viscosity compared to pahoehoe.

Figure 17: A'a Lava forming over a pahoehoe flow in Hawaii. Source: Photograph courtesy of the Unites States Geological Survey 1998 [Public Domain].

Figure 18: Pahoehoe lava flow at Kilauea Volcano, Hawaii. Source: Wikimedia Commons, photograph by TN Mattox 1995, courtesy of the United States Geological Survey.

Figure 19: Ropey textured pahoehoe lava wrapping around clinkery a'a lava, Kilauea volcano, Hawaii. Notice how the pahoehoe is breaking up into brittle glassy shards. Photo: Ian Roach.

Once a crust forms on a pahoehoe lava flow, the molten lava inside may continue to flow down slope within a **lava tube**. As the eruption progresses, lava tubes may be re-used many times by new batches of lava. Once cooled and drained of molten lava (which flows downhill like water), lava tubes can be many kilometres long and up to 20 metres in height. Australia has a number of good examples of lava tubes—at the Undara National Park in northeast Queensland (Figure 20), and the Byaduk Lava Caves in western Victoria.

Figure 20: Lava tube in Undara, Queensland. Source: Wikimedia commons.

Did you know? Australian lava tubes

Australia has the world's longest lava tube and the world's longest lava flow! The Undara Volcano in the McBride Volcanic Province (northwest of Townsville in Queensland) has the world's longest lava tube (> 110 km) and the world's longest lava flow (> 160 km). You would have to travel to the Moon, Mars or Venus to find longer lava flows and lava tubes!

Lava erupted under water cools rapidly, forming spherical shapes known as **pillow lava** (Figure 21). It flows like toothpaste to form pillow-like structures. This is the result of the lava surface cooling as it comes into contact with the water, forming an elastic skin with molten lava underneath.

Pillow lavas are found in deep mid-ocean ridges, submarine volcanoes, underneath glaciers and where lava has erupted on land and flowed into the sea or a lake. Ancient pillow lava flows found in rocks indicate that in the past, they were located in an under-water environment.

Figure 21: Pillow Lavas, Pacific Ocean seafloor.
Source: Photograph by United States National Oceanic and Atmospheric Administration, Photo Library 1998 [Public Domain].

Solids

Solid material ejected from a volcano includes a range of fragments, such as solidified **lava blocks** or **bombs** (Figure 22) through to **fine ash** which is so light it can drift around the Earth in air currents. All the fragmental material formed by a volcanic eruption is given the term **pyroclastic** (pyro meaning 'fire' and clastic meaning 'broken') and is classified based on particle size (Table 1.4). As pyroclasts accumulate around the vent over time, a **volcanic cone** is built up. Other components of the volcanic cone include lava flows, **agglutinate** and volcaniclastic material, which is made up of broken lava and re-deposited pyroclasts.

Figure 22: A tear-drop volcanic bomb. Bombs can develop tear-drop shapes as solid material is coated in molten lava and spat out of the volcano, trailing molten lava which solidifies in the air.

Table 1.4 Pyroclast particle size classification table.

Particle	Size
Fine ash	< 0.062 mm
Coarse ash	0.062 mm–2.0 mm
Lapilli	2.0 mm–64 mm
Bombs and blocks	> 64 mm

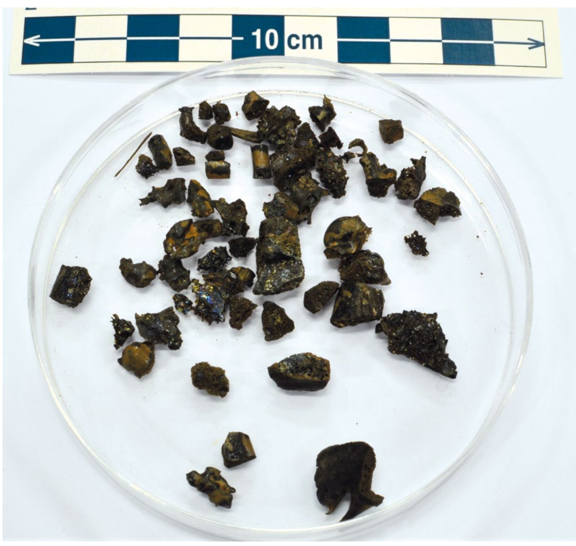


Figure 23: Lapilli from Hawaii.

Eruption types

Although the viscosity of the magma and the quantity and type of dissolved gases control the eruption type, the easiest way to describe how volcanoes behave is to consider how explosive they are. A volcano's explosiveness controls how well fragmented the volcanic products are, and the height of the eruption column. The height of the eruption column controls how well dispersed the volcanic products are (dispersal).

Types of volcanoes and eruption features

Volcanologists classify the styles of volcanic eruptions according to the explosiveness and height of the eruption column (dispersal), using a D–F (Dispersion–Fragmentation) plot (Figure 24). The major eruption types, in order of increasing explosiveness, are: Icelandic, Hawaiian, Strombolian, Vulcanian, Sub–Plinian, Plinian and Ultra–Plinian. Volcanic eruptions involving water include Surtseyan and Phreatoplinian types and fall on a different part of the D–F plot.

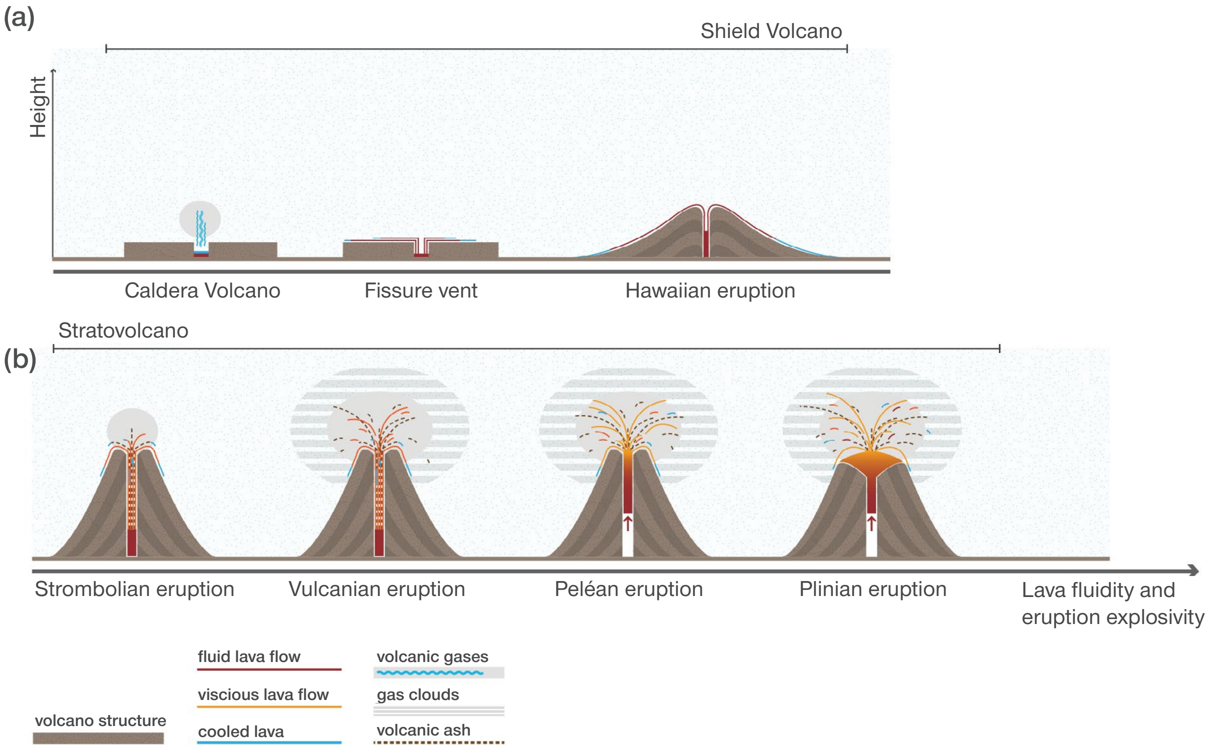


Figure 24: Cartoon explaining the D-F (Dispersion-Fragmentation) plot used to classify volcanic eruption styles. a) low explosiveness eruption types, b) high explosiveness eruption types. Image from Chiara Cingottini, DensityDesign Research Lab.

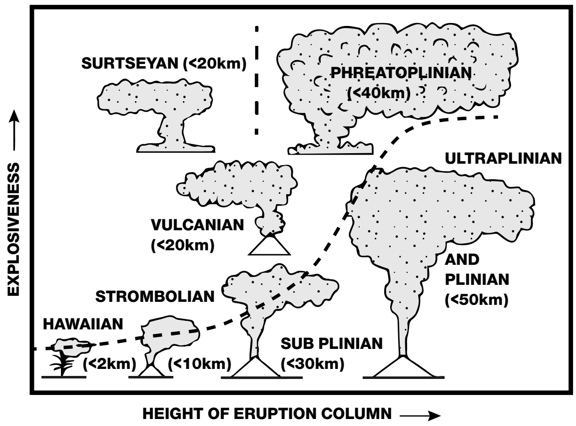


Figure 25: Explosiveness of an eruption versus the height of an eruption column for different types of volcanoes. Source: *http://volcanoes.usgs.gov/ash/properties.html*, credit to Cas and Wright 1987.

Icelandic eruptions (fissure-style)

Icelandic eruptions, named after the style of the Iceland volcanoes, are the least explosive eruption type.

These eruptions take place along **fissures**, or long cracks, rather than a **central vent**. The fissures may be several kilometres in length (Figure 26). Lavas with low viscosity erupt from the fissures and form great lava sheets or **flood lavas** that flow across the landscape. It may be impossible to find the location of the original fissure in ancient volcanic areas as no volcanic cone is formed.

The volcano is formed by a low spatter rampart. Icelandic eruptions occur from volcanoes that are generally basaltic in composition. While the eruption style is relatively gentle, the eruptions may continue for months and can occasionally emit large amounts of ash and gas. Volcanoes occurring along the mid-ocean ridges are an example of Icelandic eruptions in a submarine environment. Many eruptions in Hawaii also begin their life as fissure-style eruptions, originating along underwater fissures.

Figure 26: Volcanic fissure, Lakagigar volcano, Iceland. Source: Wikimedia Commons, photograph by Chmee2/Valtameria 2009.

Figure 27: Fissure eruption, Pu'u O'o volcano (Kilauea), Hawaii. Photographed by G.E. Ulrich. From *http://hvo.wr.usgs.gov/gallery/kilauea/erupt/24ds182_caption.html*

Hawaiian eruptions

Hawaiian eruptions are named after the style of volcanic activity most commonly found on the Hawaiian Islands.

Hawaiian eruptions take place along vents or fissures which spray jets of lava high skyward (Figure 28). These jets are referred to as **fire fountains** and can reach many hundreds of metres into the air. Some fire fountains may erupt for hours. The lava may cool in the air before falling to the ground or hit the ground in a still semi-molten state and form spatter fragments which weld together (agglutinate). Large volumes of erupted lava can form lava streams that flow from the vent down the **flanks** of the volcano. They can start as fissure eruptions (Icelandic eruptions), however the fissures gradually close down to form one or more discrete vents. Hawaiian eruptions are generally basaltic in composition.

Figure 28: Hawaiian style fire fountaining at Kilauea volcano, Hawaii. Source: Wikimedia Commons, photograph by C. Heliker (United States Geological Survey).

Strombolian eruptions

Strombolian eruptions are named after the small volcanic island Stromboli, which is one of the Aeolian Islands in Italy.

Strombolian eruptions consist of intermittent explosive bursts that eject red-hot pyroclastic fragments up to a few hundred metres into the air (Figure 29). Each eruptive burst lasts a few seconds and there may be breaks of up to 30 minutes before bursts of activity. This type of eruption is usually restricted to within the volcanic cone and therefore is not as dangerous as Vulcanian or Plinian style eruptions (see later). Strombolian eruptions occur from volcanoes which are mainly basaltic or andesitic in composition. The Italian island of Stromboli has been erupting in this way for thousands of years. Other volcanoes which erupt in this way are Mount Etna (Italy), Mount Erebus (Antarctica) and Mount Yasur (Vanuatu).

Figure 29: Strombolian style eruption from Stromboli Volcano, Aeolian Islands, Southern Italy. Source: Wikimedia Commons, photograph by W Beyer 1980.

Vulcanian eruptions

Vulcanian eruptions are named after a volcanic island, Vulcano, in the Aeolian Islands off the coast of Sicily in Italy.

Vulcanian eruptions are violent, usually ejecting less than one cubic kilometre of material, and are characterised by viscous lava, large quantities of pyroclastic **ejecta** (particles ejected from a volcanic vent) and ash clouds. High eruption columns can reach 10 to 20 kilometres into the atmosphere (Figure 30), and as material in this eruption column settles, the volcanic ash can spread over a wide area. Vulcanian eruptions have phases of intense explosive activity interspersed with short-lived explosions. Explosions often blast away part of the volcanic cone. Vulcanian eruptions occur from volcanoes which are generally andesitic in composition. Vulcanian eruptions have occurred at Mount Lamington (Papua New Guinea), Mount Pelée (Martinique in the Caribbean) and Sakurajima (Japan). These volcanoes have also displayed Plinian (see later) activity during their eruption history.

Figure 30: Vulcanian eruption from Tavurvur volcano, Papua New Guinea. Source: Wikimedia Commons, photograph by T. Taylor 2008.

Plinian eruptions

Plinian eruptions are named after Pliny the Elder, a widely respected Roman Admiral who died in the eruption of Vesuvius (Italy) in 79 AD. Pliny's nephew, Pliny the Younger, observed the same eruption from a boat and wrote an account of the eruption plume which ultimately buried the towns of Pompeii and Herculaneum. These styles of eruptions occur in a continuum from Sub-Plinian to Plinian to Ultraplinian, each more explosive and larger than the previous.

Plinian eruptions are extremely violent explosive eruptions. They involve huge **eruption columns**, some reaching 45 kilometres or more into the atmosphere (Figure 31). The eruption may last for hours or days, with high volumes of ash and pumice ejected. Pyroclastic material that has fallen out of the eruption column can cover millions of square kilometres. Plinian eruptions usually occur from volcanoes which are andesitic to rhyolitic in composition (refer to Table 1.2). However, some basaltic volcanoes, such as Tarawera in New Zealand, have had Plinian eruptions (1886).

Fortunately, Plinian eruptions are rare events with only two or three occurring each century. Volcanoes which have displayed this type of eruption are Vesuvius (Italy) 79 AD, Mount Pinatubo (Philippines) 1991, Mount St. Helens (United States) in 1980 and Puyehue (Chile) in 2011.

Ash from Plinian eruptions can affect crops and air travel, as the fine ash remains in the atmosphere for days after the eruption ceases.

Figure 31: Plinian eruption from Mount St. Helens, USA.
Source: Photograph by Austin Post 1980, United States Geological Survey [Public Domain].

Figure 32: Plinian eruption column over Redoubt volcano, Alaska.
Source: *http://en.wikipedia.org/wiki/Eruption_column*.

Surtseyan eruptions: Eruptions involving water

Surtseyan eruptions take place in shallow seas or lakes and are named after the island of Surtsey off the southern coast of Iceland (Figure 33). **Surtseyan eruptions** are violent explosions caused by **phreatomagmatic processes** due to rising basaltic or andesitic magma coming into contact with abundant, shallow groundwater or surface water.

Figure 33: Eruption of the Surtsey volcano off the coast of Iceland in 1963. The eruption involves basaltic lava and sea water resulting in voluminous steam and the creation of a small pyroclastic ring around the vent.
Source: *http://en.wikipedia.org/wiki/Surtseyan_eruption*.

Where are volcanoes found?

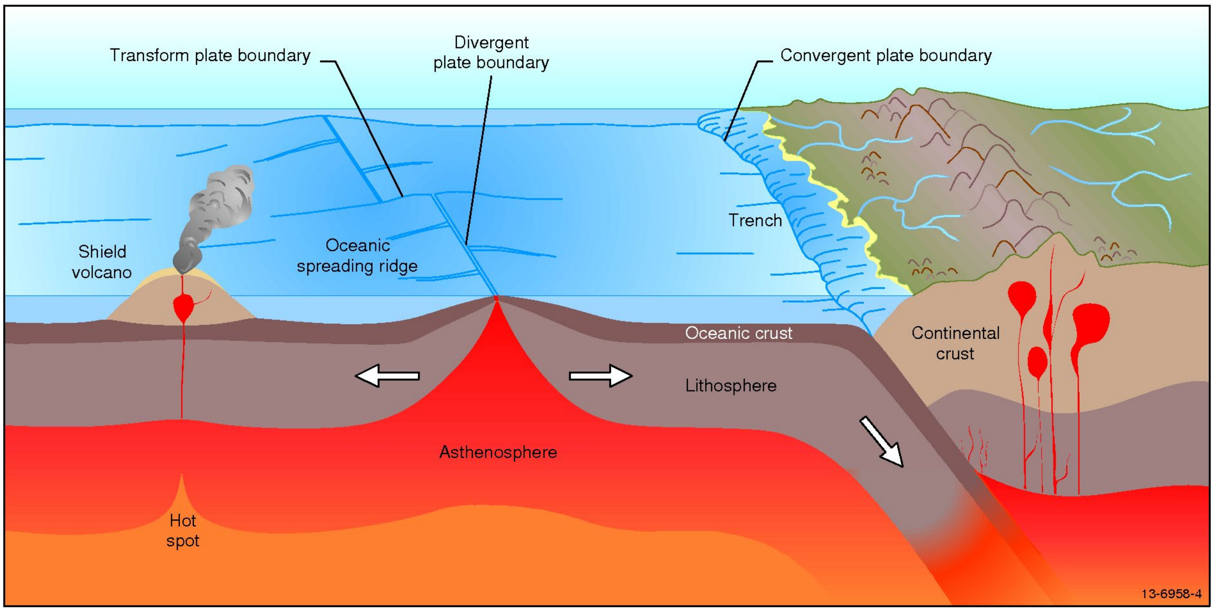
When the positions of active volcanoes are plotted on a world map they follow a pattern which corresponds with the boundaries of the Earth's tectonic plates. There are two distinctive zones along these boundaries: the basaltic volcano zone and the andesitic volcano zone. Each zone corresponds to the type of plate boundary on which it occurs.

Plate tectonics

The Theory of Plate Tectonics states that the Earth's lithosphere (the crust and upper mantle) is broken up into about 12 rigid plates which slide over the semi-molten plastic layer of the mantle. The tectonic plates meet at boundaries, of which three main types are recognised:

1. Divergent or spreading boundaries—where plates are moving apart.
2. Transform fault boundaries—where plates are moving past each other.
3. Convergent or subduction boundaries—where one plates slides under another.

Each plate is bounded by some combination of these three plate boundary types (Figure 35).



Source: Geoscience Australia

Figure 34: Volcanism resulting from two different plate boundaries. 1) Convergent tectonic plate boundary, where oceanic crust is being subducted beneath another plate; 2) Divergent plate boundary where basaltic magma wells up into the spreading centre to create a ridge.

Composite volcanoes (or stratovolcanoes) are generally located along subduction zones, which are plate boundaries where one plate (usually composed of denser, oceanic crust) slides under the other (usually lighter continental crust). As the plate is subducted it takes with it some ocean sediments and water. As the subducting crust heats up these components enter the overlying mantle, helping to melt part of it and form magma that rises up to the surface forming a chain of volcanoes, known as a **volcanic arc**. The resulting magma is generally **dioritic** in composition and feeds andesitic (composite) volcanoes (Figure 34). Where plates are **diverging** (spreading apart) the solid molten mantle material, poor in silica and therefore basaltic in composition, begins to melt due to lower pressure, and wells up in the space between the plates. The result is a chain of volcanoes that produce Icelandic-style eruptions along the fissure.

The **Pacific Ring of Fire** borders the Pacific Ocean and is a zone of high volcanic and earthquake activity, largely associated with the movement of the Pacific Plate. Over 75 percent of the world's active and dormant volcanoes occur along these volcanic belts, volcanic island arcs and volcanic trenches. Many volcanoes around the Pacific Ring of Fire, like Mount Pinatubo in the Philippines, are formed by subduction.

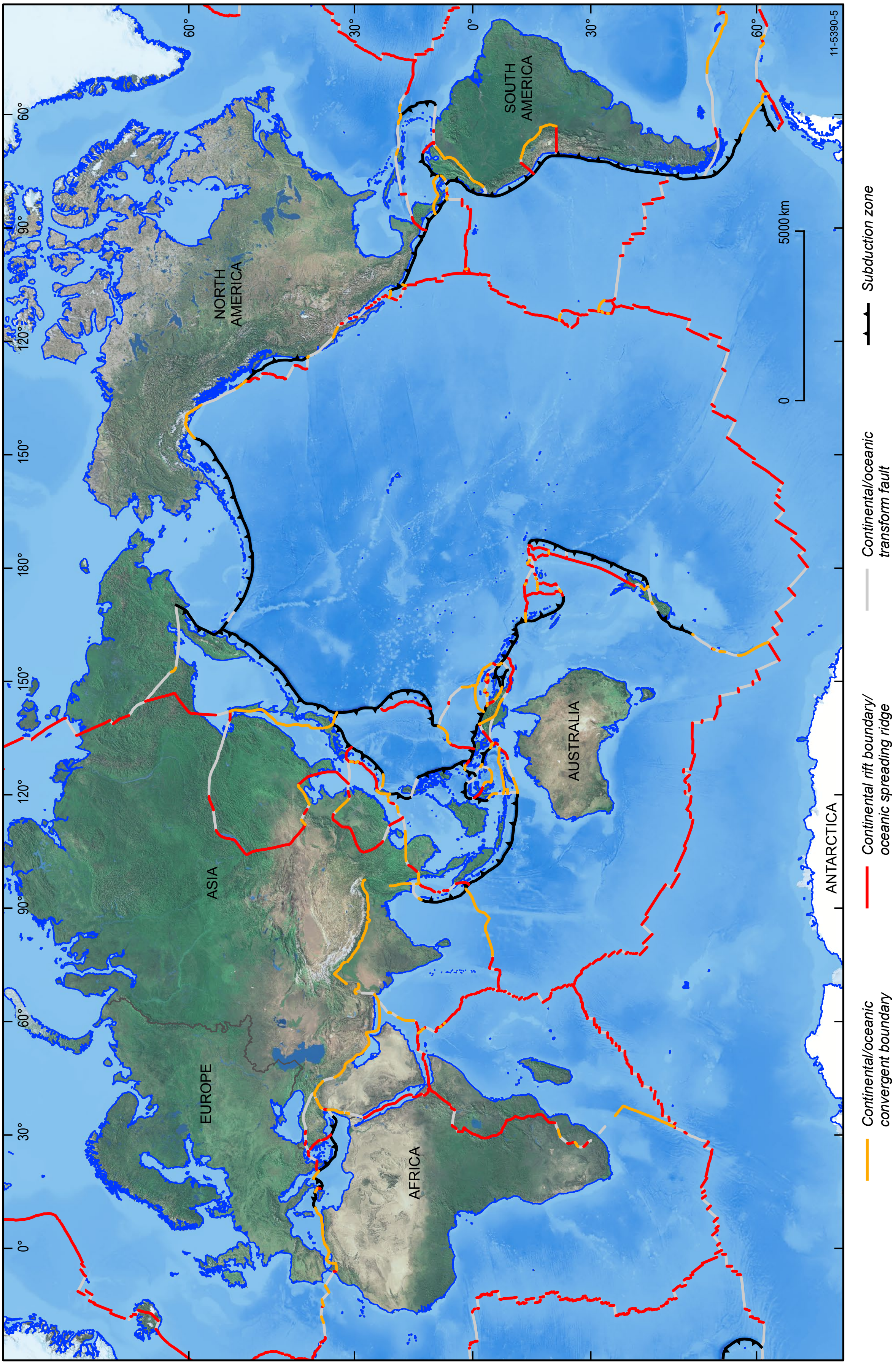


Figure 35: Plate tectonic boundaries—convergent, divergent and transform. Source: Creative Commons.

Hot-spot volcanoes

As well as the volcanoes which line the edges of tectonic plates, some occur away from the boundaries of plates. These volcanoes are thought to have formed from mantle hot-spots from deep in the Earth, producing mantle plumes that send magma towards the Earth's surface. **Hot-spot volcanoes** are normally basaltic in composition, but can include more silica rich material over time. Large shield volcanoes develop over these hot-spot locations. Mauna Loa on Hawaii rises to over 4000 metres above sea level and the flanks of the volcano continue beneath the sea for five more kilometres.

Figure 36: Kilauea shield volcano on Hawaii. Source: Wikimedia Commons, photograph by Quinn Dombrowski 2007.

The Hawaiian Islands are a chain of volcanoes that formed as the Pacific Plate moved across a hot-spot. The direction of movement can be identified using the ages of the volcanoes. They are older towards the northwest which is the current movement direction of the Pacific Plate. (Figure 37).

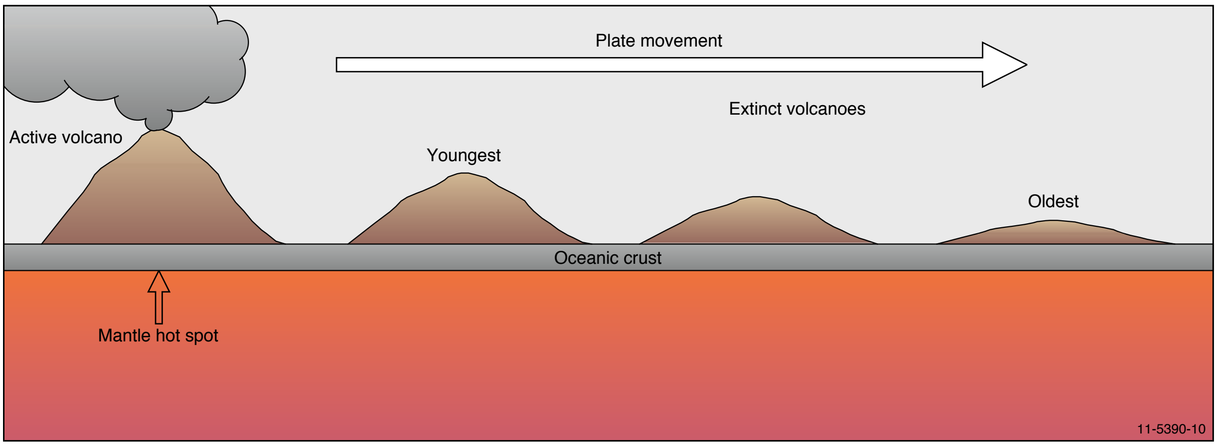


Figure 37: Hot-spot volcanoes such as Hawaii form over an anomalously hot region of the mantle. High volumes of magma produce volcanic activity over millions of years. A chain of volcanoes form as the tectonic plate moves over the hot-spot, which increase in age away from current volcanic activity.

Likewise, the Australian Plate is moving over a hot-spot with broken chains of ancient volcanoes found down the east coast from the oldest in north Queensland to the youngest in New South Wales (Figure 38). The hot-spot is now thought to be between Victoria and the west coast of Tasmania but it is not currently causing volcanic activity. The youngest volcanic feature in Australia is Mount Gambier in South Australia. Volcanoes in Victoria and South Australia may have been formed by hot-spots, with some other contributions of magma formation; research is still on-going. Certainly, Mount Gambier is known to have last erupted around 4500 years ago.

Activity: Basic Island

Figure 38: Australia has a chain of extinct volcanoes along the east coast formed between 16-35 million years (Ma) ago.

Volcanic activity

Volcanoes are often classified by their history of activity as being active, dormant or extinct.

Active

An **active volcano** is any volcano that shows some form of current volcanic activity, such as the eruption of lava, release of gas or any seismic activity.

Over the last millennium a number of active volcanoes have caused numerous fatalities around the world (Table 1.5).

Table 1.5 Examples of some active volcanoes.

Volcano	Country	Year	Estimated Casualties
Mayon	Philippines	1814	1200
Tambora	Indonesia	1815	12 000
Galgunggung	Indonesia	1822	5500
Mayon	Philippines	1825	1500
Awu	Indonesia	1826	3000
Cotopaxi	Ecuador	1877	1000
Krakatau	Indonesia	1883	36 417
Awu	Indonesia	1892	1532
Sourfriere	St Vincent	1902	1565
Mt Pelee	Martinique	1902	29 000
Santa Maria	Guatemala	1902	6000
Taal	Philippines	1911	1332
Kelud	Indonesia	1919	5110
Merapi	Indonesia	1930	1300
Lamington	Papua New Guinea	1951	2942
Agung	Indonesia	1963	1900
El Chichon	Mexico	1982	1700
Nevado del Ruiz	Columbia	1985	23 000

From a report by the Task Group for the International Decade of Natural Disaster Reduction, published in Bull. Volcano. Soc. Japan, Series 2, Vol. 35, No. 1 (1990): 80–95.

Dormant

A **dormant volcano** is one which has not erupted historically (since people have been aware of it) but which is likely to erupt again. For example, Mount Gambier in South Australia and Mauna Kea in Hawaii.

Extinct

An **extinct volcano** is a volcano that is highly unlikely to ever erupt again. These volcanoes may now exist as remnants including lava flows, central volcanic pipes and dykes. Australia has many extinct volcanoes like the Tweed Volcano in north-eastern New South Wales and Mount Canobolas near Orange in central-west New South Wales, and in the Monaro region near Cooma in southern New South Wales.

Did you know? Active Australian Volcanoes

Australia has active volcanoes! Well, not actually on the mainland, but the Big Ben volcano on Heard Island in the southern Indian Ocean is Australia's most active volcano. The summit of Big Ben is often shrouded in cloud, and very few people pass by the island because it is so remote, so the activity often goes unreported. Volcanic activity on Big Ben is normally reported by infra-red (heat) sensing satellites passing overhead. McDonald Island, west of Heard Island, is also an active volcano.

Can we truly say that all volcanic activity on the Australian mainland is extinct? Not really—the average age between eruptions in the Western Districts of Victoria and southeastern South Australia is about 100 000 years. The last volcano erupted about 4500 years ago (Mt Schank near Mount Gambier in South Australia). Seismic activity (small earthquakes) beneath western Victoria, and also the Atherton Tableland of north Queensland, indicates the presence of magma beneath the Earth's crust in these locations. Perhaps these areas are dormant, rather than extinct?

Extra-terrestrial volcanism

Volcanism does not occur only on the Earth, but can be seen on the Earth's Moon and other planets and their moons. The terrestrial (rocky) planets—Mercury, Venus, Earth, Mars—all have silicate volcanism, as does the Moon. The volcanism comprises volcanoes and lava flows of many of the types discussed above, consisting mostly of basalt lava.

What about the really cold planets and dwarf planets like Jupiter, Saturn, Uranus and Neptune? Do they have volcanism? Jupiter, Saturn, Uranus and Neptune are all giant gas planets, so they do not have visible solid surfaces. However, their moons do show evidence of **cryovolcanism**. Cryovolcanism occurs where the molten material is not rock, but another liquid like water, nitrogen, ammonia or a hydrocarbon like methane, ethane, propane, etc. Some materials may not actually melt, but go directly to gas, causing explosions and **geysers**.

Cryovolcanism is known to occur on Triton around Neptune, Titan and Enceladus around Saturn and Io, Europa and Ganymede around Jupiter. Io is a special case; the bulk density of Io is high enough for it to have a silicate core, so volcanism is believed to involve both high temperature silicate melts (basalt) and low temperature sulfur melts. The dominant ejecta is sulfur/sulfur dioxide vapour.

The Voyager 2 flyby of Neptune's largest moon Triton first recognised cryovolcanism at sub-zero temperatures. Geysers of nitrogen gas vent up to 100 km into the satellite's thin atmosphere, caused by tidal heating from Neptune. The geysers are coloured by complex hydrocarbons (soot) and are clearly visible from spacecraft.

On Enceladus, Ganymede, Callisto and Europa (all moons of Jupiter), ice crusts behave similarly to the mid-ocean ridge network on Earth. As tidal forces pull and push each of the satellite's surfaces, cracks form and heal as liquid water seeps up along these, forming 'continental plates' of ice separated by jagged scars. In Earthly mid ocean ridges, the tectonic plates are slowly drifting apart (at up to 15 cm per year), and basaltic magma intrudes the cracks, forming a series of vertical dykes. Ganymede, Callisto and Europa may also have geysers similar to those on Triton; these have been observed on Enceladus.

In 2015, the Cassini radar experiment detected water-rich plumes from volcanoes on Titan, Saturn's largest moon. These are thought to replenish the methane in Titan's atmosphere, which naturally breaks down under ultraviolet light.

The cryovolcanism on the icy moons of the gas giant planets is probably not caused by radioactive decay and internal heating like on the Earth and the other terrestrial planets. Instead, very strong tidal forces caused by the gravity of the planets and their other moons are believed to keep water and other molecules liquid underneath the icy crusts of these satellites due to heating by friction. Jupiter's moon Io is pushed and pulled by Jupiter and the other large moons Europa, Ganymede and Callisto, causing it to be the most volcanic body in the entire solar system.

Figure 39: Volcanic plumes visible on Jupiter's moon Io captured during Galileo's ninth orbit around Jupiter. One plume was captured on the bright limb or edge of the moon, erupting over a caldera (volcanic depression) named Pillan Patera.
Source: NASA's Galileo spacecraft (*http://photojournal.jpl.nasa.gov/catalog/PIA01081*) [Public domain], via Wikimedia Commons.

Did you know? Volcano on Mars

The solar system's largest known volcano is Olympus Mons, on Mars. Olympus Mons is about 600 km in diameter and stands over 26 km high—it is so tall it pokes through the atmosphere! Olympus Mons is so large because Mars does not have plate tectonics. Unlike on the Earth, where the tectonic plates move over hot spots creating strings of volcanic islands, on Mars the crust does not move, so Olympus Mons sits stationary over a hotspot and has built up a large volcanic edifice.

Why are volcanoes dangerous?

It is often thought that the most dangerous part of a volcanic eruption is a lava flow rushing down volcanic slopes. This is reinforced by movie and television programs that show people running away from the red hot lava. In reality the threat posed by flowing lava is very small because of its slow rate of movement. In contrast, volcanic ash fall, pyroclastic flows, sector collapses and volcanic gases are far more dangerous.

Figure 40: The city of Pompeii was buried by volcanic ash during the 79 AD eruption of Vesuvius. Source: Photograph by A. Bear 2007.

Ash fall

The amount of material erupted from explosive Plinian eruptions is immense. The majority of the material is volcanic ash which is blasted up into the eruption column above the vent. As the ash falls and settles it covers a vast area.

During some eruptions the settling of volcanic ash occurs quickly and close to the vent. This means that often people who have tried to escape from the disaster have become trapped. The excavation of Pompeii in Italy, for example, revealed a township caught by the fast deposition of ash fall, which had subsequently become buried in pyroclastic flows from the eruption of Vesuvius in 79 AD (Figure 40).

The deposition of ash on the roofs of houses causes an immediate threat to the occupants as the roof can collapse from the heavy weight of ash. This was evident in the eruption in Rabaul, Papua New Guinea (1994) where townships covered in ash saw many buildings collapse.

Of wider implication is the damage to local agriculture through the burying of crops and pasture land. Many volcanic eruptions have left populations in famine because the once highly productive land is rendered useless by a few centimetres of volcanic ash and drops in temperature caused from the ash and aerosols in the atmosphere. These symptoms can affect crops for several years after the volcanic eruption. An example of this was in 1783 where many people died from the volcanic haze caused by the eruption of Laki in Iceland covering parts of west Europe.

Pyroclastic flows

Of all the destructive volcanic phenomena, pyroclastic flows rate as potentially the most destructive. **Pyroclastic flows** are a cloud of hot gaseous volcanic debris that flow rapidly down the flank of a volcano as part of the eruption process. Flows may include **vesicular** rock materials, such as pumice, or hot hard rock fragments which move down the volcano.

The main cause of pyroclastic flows is the partial or total collapse of the eruption column itself. This often occurs at the end of an eruption. After the initial eruption blast, gravity starts to pull ash and pumice back towards the Earth's surface. In some cases, the initial eruption is so strong that the weight of the eruption column can no longer be supported after the blast has subsided. The cloud, along with its ash and pumice, collapses back onto the volcano and flows down the slope (Figure 41). The collapsed cloud then descends down valleys carrying hot ash and pumice away from the volcano while burning and destroying everything in its path. People living in low-lying areas are at major risk from the pyroclastic flows.

Figure 41: Pyroclastic flows descend the flanks of Mount Mayon, Philippines.
Source: Wikimedia Commons, photograph by C.G Newhall, United States Geological Survey 1984.

These flows produce deposits called **ignimbrites** which can be tens of metres thick (Figure 42). Some ancient ignimbrite deposits are up to 250 metres thick near the volcanic vent and are evidence that devastating pyroclastic flows occurred in the past. While no event of this magnitude has been observed, the threat of a similar event is present from volcanoes that produce Plinian eruptions.

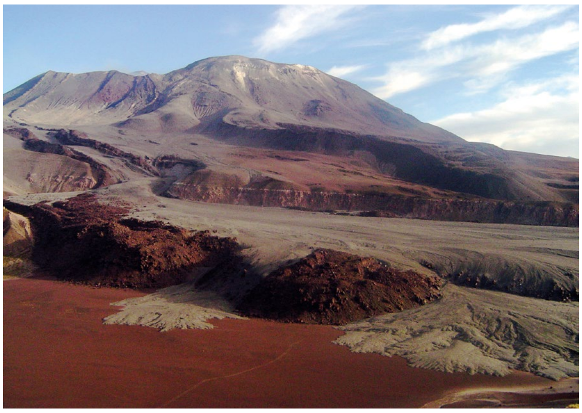


Figure 42: Ignimbrites (light grey rocks) deposited by pyroclastic flows during the 1993 eruption of Lascar Volcano, Chile. Source: Photograph by A Bear 2004.

Pyroclastic flows can also form during an eruption when the flank of a volcanic dome collapses and hot rocks roll down-slope. The pyroclastic material is suspended by volcanic gases and large boulders can be moved by the flow. Eventually the gases can no longer support the weight of the flow and the material is dumped.

Figure 43: Left: Mount St. Helens, one day before the devastating eruption of 1980. The view is from Johnston Ridge, 10 kilometers northwest of the volcano. Source: Wikimedia Commons, photograph by Harry Glicken, USGS/CVO.
Right: The changed shape of Mount St. Helens after the eruption in 1982. The view is from Harrys Ridge, 8 km north of the mountain. Source: Wikimedia Commons, photograph by Lyn Topinka.

Sector collapse

Sometimes a volcanic eruption takes place and causes the side of the volcano to collapse. The eruption of Mount St. Helens in 1980 produced such a phenomenon with one side of the volcano being pushed out producing a landslide into the valley below. The material then mixed with water in a lake and flowed down the valley as a deep **debris flow** or lahar.

Volcanic collapses close to sea level or underwater can cause huge waves known as **volcanic tsunamis**. The collapse of a volcanic cone during the eruption of Krakatau in 1883 caused tsunamis that killed 30 000 people on the coastlines of Java and Sumatra several hundred kilometres away. These waves may have been as high as 40 metres.

Volcanic gases

The escape of volcanic gases, even in a minor eruption, can cause a real threat to local inhabitants. Some volcanic gases are extremely poisonous. Carbon dioxide, for example, only needs to be at levels of 0.4 percent in the air for it to be deadly. Being colourless, odourless and heavier than air, carbon dioxide can flood into low and sheltered areas close to a volcano and kill the livestock and inhabitants. In 1986, Lake Nyos (a crater lake in Cameroon) emitted a large cloud of carbon dioxide which caused the suffocation of over 1000 people and 3000 livestock. At even smaller concentrations it can reduce plant growth.

Ash cloud

While Australia has no currently active volcanoes on the mainland, the threat that volcanoes pose to Australians is from potential damage to aircraft flying through ash clouds. All aircraft routes from Australian capital cities into Asia fly over areas of active volcanism (mainly Indonesian volcanoes). Volcanoes from South America can also affect flights in Australia. In June 2011 ash from Puyehue-Cordon Caulle volcano in Chile travelled around the globe several times to cause flight disruptions in the southern Australian capital cities and New Zealand (Figure 45). Aircraft can be severely affected when flying through ash and/or aerosol clouds, in particular the fine particles in the ash cloud can cause serious damage to aircraft engines.

Figure 44: The erupting Puyehue-Cordon Volcano Complex in Chile sent a thick layer of ash behind deposited east of the volcano. Source: NASA image courtesy Jeff Schmaltz, MODIS Rapid Response Team at NASA GSFC [Public Domain].

Threat to aircraft: case studies

1. Galunggung volcano, Indonesia

On 23 June 1982 a British Airways 747 flying from Kuala Lumpur, Malaysia, to Perth, Australia, flew through the ash cloud of the Galunggung volcano in Indonesia. The fine volcanic ash entered the cabin, seeming like fine smoke, but soon clogged the engines so badly that all four engines stopped working. The aircraft glided from 37 000 feet (11 000 m) until the crew were able to restart the engines at 13 500 feet (4 100 m). The aircraft eventually made an emergency landing at Jakarta airport in Indonesia, but the crew had to look out of the side windows of the aircraft's cockpit to see the runway—the forward windows had been sandblasted opaque by the volcanic ash. When engineers later opened the engines, they found that the insides were clogged with volcanic glass (caused by ash particles glued together by the heat of the engines) and small rocks. In flight, the engines could only be restarted once enough of the volcanic glass had cooled and cracked off the insides of the engines to allow the fuel to burn properly.

2. Redoubt volcano, Alaska

On 15 December 1989 a KLM Boeing 747–400 flew into the ash cloud of the Mount Redoubt volcano in Alaska at an altitude 25 000 feet. Within 60 seconds all four engines had stopped, putting the aircraft into a steep descent. After dropping 13 000 feet the crew managed to restart the engines and return to the airport. A study of the engine showed that the ash had melted and resolidified on the engine fans reducing the airflow and causing the engine to stall.

3. Eyjafjallajökull volcano, Iceland

More recently, the 2010 eruptions of Eyjafjallajökull volcano in Iceland forced the closure of the airspace in northern Europe, preventing local and international flights and stranding passengers for over six days.

When do volcanoes erupt?

One of the major challenges for volcanologists is to forecast when a volcano is going to erupt. Information that can be used to increase the accuracy of eruption forecasts includes past eruptive history, earthquake activity around the volcano, surface deformation, temperature and gas emissions.

The eruptive history of a volcano can provide information on the regularity or irregularity of past events. In many cases, it has been found that the period of dormancy between eruptions affects the size and type of eruptive event. Looking at the volcanic deposits preserved around volcanoes can provide information about what type of eruptions occurred in the past. Unfortunately, only a small fraction of the world's volcanoes have had their eruptive histories studied in detail.

Earthquake studies of volcanoes have been shown to be good indictors of the movement of magma below a volcano. **Earthquake swarms** (hundreds of small quakes) have been recorded prior to eruptions caused by magma forcing its way towards the surface, such as at Mount St. Helens in 1980. However, some eruptions occur with no change in seismic activity immediately before the eruption. **Volcanic tremors** are recognised more-or-less by their continuous ground vibrations that are almost always present during an eruption. It is thought that volcanic tremors are caused by the release of gases as magma rises towards the surface.

Survey points on the summits and slopes of monitored volcanoes are used to measure changes in the surface of a volcano. **Deformation monitoring** is used to measure changes to the volcano's surface, caused by the rise of magma. Prior to the eruption of Mount St. Helens, deformation measurements indicated the onset and growth of a bulge on the volcano flank. These changes informed volcanologists that there was potential for an eruption and to start evacuating people from vulnerable areas.

Some volcanic regions display large fluctuations in temperature that may, or may not be, related to any volcanic eruption. However, in some locations, an increase in the temperature of groundwater or lake waters may be used as an early detection tool.

Changes in the volume and chemical composition of volcanic gases are useful indicators of eruptions. Change to gas emissions may indicate movement of magma or injection of new material at depth, which could come before an eruption. A large, rapid change in the acidity (pH) of groundwater and/or surface water (e.g. lakes) near a volcano may also indicate an imminent eruption.

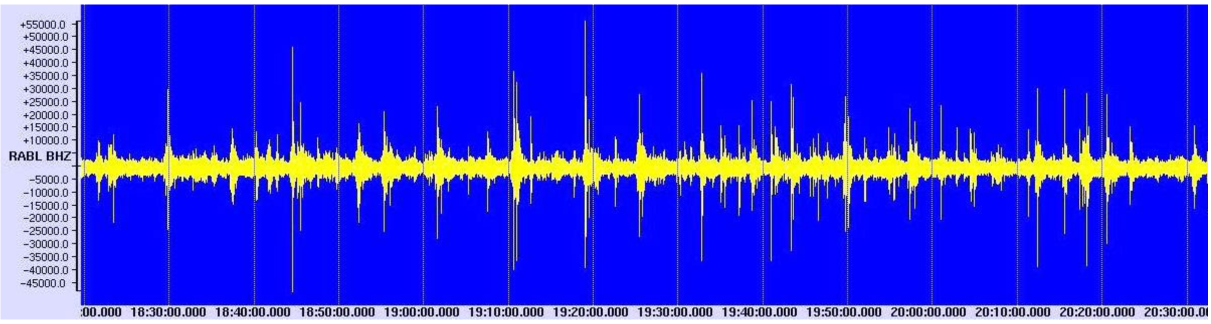


Figure 45: **Digital seismogram showing volcanic tremor over two hours, Rabaul, Papua New Guinea.**

Activity: Thunder Island role play

The effects of volcanic aerosols

The effects of volcanic aerosols suspended in the atmosphere after volcanic eruptions can be observed in a number of ways. The most visible of these are optical effects such as vividly coloured sunsets (Figure 46), altered colours of stars and planets, dulled starlight, rings around the sun and coloured twilight afterglows. These effects were once attributed to volcanic ash but are now recognised to be caused from tiny acid aerosol droplets, not solid particles.

The existence of volcanic aerosols forming layers in the upper atmosphere was first pointed out by an American atmospheric scientist, Christian Junge, in 1961. The aerosol layer, sometimes called the Junge layer, is not a permanent feature but exists only after periods of volcanic activity. During volcanically 'quiet' periods the stratosphere may become clear of the volcanic acid droplets. Not all volcanic aerosols end up in the stratosphere. Non-explosive volcanism can also form dry volcanic fogs that cling close to the Earth's surface.

Aerosols can have immediate economic effects. For example, the acid aerosols released during the 1982 El Chichon eruption in Mexico caused windows of aircraft to crack when they flew the trans-Arctic route, with one airline reporting the cost of the damage to be US $1 million.

Like all of the Earth's atmospheric circulation, aerosol layers and volcanic clouds migrate around the Earth eventually returning to the vicinity of the volcano that first released them. For example, it took the eruption cloud of Pinatubo, which erupted in June 1991, 22 days to travel completely around the globe. The eruption clouds of volcanoes at higher latitudes take even less time to travel around the globe due to high-speed winds in the upper atmosphere.

Eruption clouds also move towards the polar regions due to the effects of the Earth's rotation and the transfer of heat from the tropics to the poles. The eruption cloud of volcanoes in high latitudes will only affect one hemisphere. Those close to the equator may spread eruption clouds around the entire globe. Therefore, large explosive eruptions close to the equator have a greater chance of affecting global climate and disrupting air travel.

Figure 46: An Icelandic volcano Eyjafjallajökull spewed tonnes of dust, ash and sulfur dioxide upwards of 35 000 feet, which created a volcanic aerosol in the stratosphere. Source: Wikimedia Commons, photograph by TJBlackwell 2010.

Case study: Tambora eruption, Indonesia

Aerosol layers from the equatorial eruption at Tambora in Indonesia on April 1815 caused prolonged and brilliantly coloured sunsets. The next year became known as the 'year without summer'. Low temperatures were experienced, caused by the blocking of some sunlight from reaching the lower atmosphere and surface of the Earth. A persistent dry fog was reported in the north eastern United States and was considered a stratospheric phenomenon. It was during that cold summer that the author Mary Shelley spent the hours of her European holiday writing Frankenstein.

Australian volcanoes

Despite the popular misconception that there are no volcanoes in mainland Australia, young volcanic rocks are widespread in the eastern states. Australia's indigenous people were likely witnesses to this volcanism, especially in the Mount Gambier region around 4500 years ago. Aboriginal stone tools have been found in Victoria buried beneath **volcanic tuff** (rock type) deposits. A belt of relatively recent volcanism associated with hot-spot activity occurs down the eastern states starting in far north Queensland (Torres Strait) and stretching down to the Victorian-South Australian coastline. This volcanism can be divided into two broad types—central vent volcanoes and lava fields.

Central vent volcanoes

Central vent volcanoes are predominantly basaltic volcanoes, but they can have silica-rich (rhyolitic) lava flows and intrusions. The volcanic rocks were produced from either a single central vent or a cluster of vents. The largest of these is the Tweed Volcano with Mount Warning (NSW) representing the central vent. Other central volcanoes include the Glasshouse Mountains (Qld), the Warrumbungles (NSW), Canobolas (NSW) and Mount Macedon (Vic.). The eruption types of these volcanoes were likely Hawaiian-style fire-fountaining or Strombolian-style.

Figure 47: Mount Warning, New South Wales. the central vent of the Tweed volcano.
Source: Wikimedia Commons, photograph by Miles Goodhew.

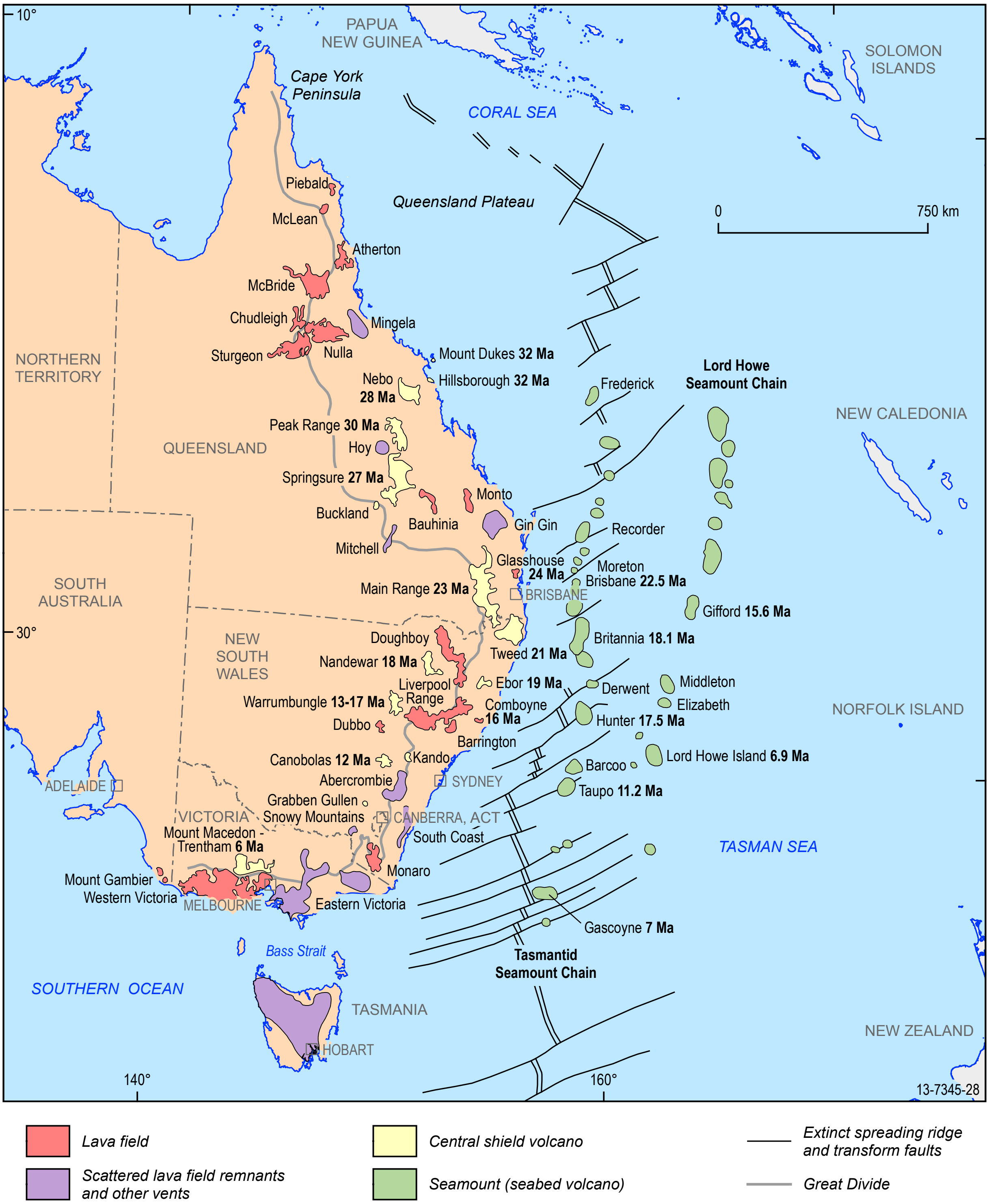


Figure 48: Distribution of volcanoes and lava fields in eastern Australia. Note the southward decrease in age of shield volcanoes in three parallel tracks. These volcanoes were formed as the Australian Plate moved north-northeast over a series of mantle plumes. (Source: after Johnson, 2009)

Seamount chains

To the east of the Australian continent there are two chains of **seamounts** running north-south in the Tasman Sea. They are eroded volcanoes that formed within the last 25 million years as the Australian plate moved northwards over one or more mantle plumes. These hot-spot volcanoes get younger to the south in the same way that the younger eastern Australian volcanoes are found at the southern end of the chain (Figure 48).

Lava fields

Lava fields are areas of basaltic lava where large amounts of lava flowed from **feeder dykes** and pipes, erupting through fissures and vents. The lavas are normally very thin (compared to their lateral extent) and are now cap ridges and mountain tops. Lava fields can be found along the eastern parts of Queensland, New South Wales, Victoria and Tasmania and were most likely Icelandic fissure-style eruptions.

The remnant of one of the most extensive sequence of **flood basalts** in the world is found in the East Kimberly region of Western Australia. These are very old (530 million years) and outcrop over an area of 35 000 square kilometres.

Examples of Australian volcanoes

There are two active volcanoes on Australian Territory. Big Ben, located on Heard Island in the Southern Ocean, is 4100 kilometres south west of Perth (Figure 49). It occupies Mawson Peak, which is the highest mountain in the Australian Territory. Mawson Peak is a 2745 metre high volcanic complex; in comparison, Mount Kosciuszko, on mainland Australia, is 2228 metres high, but is not a volcano.

Figure 49: Big Ben, Heard Island, one of Australia's active volcanoes and the highest mountain the Australian territory.

McDonald Island, 44 kilometres west of Heard Island, became active in 1992 after a prolonged period of inactivity. Satellite imagery taken in 2004 shows that McDonald Island joined up with Flat Island. Volcanic activity created new land, which doubled the size of McDonald Island.

Over time, weathering and erosion have worn away ancient volcanic cones and exposed subsurface igneous features such as the **feeder pipe** and **magma plumbing system** associated with volcanism. An example of this includes The Breadknife in the Warrumbungles of NSW that is an eroded dyke (Figure 50).

Figure 50: The Breadknife in the Warrumbungle National Park, New South Wales is a volcanic dyke that was part of a large shield volcano. Source: Wikimedia Commons, photograph by Mgillaus 2009.

The Glasshouse Mountains in southeast Queensland are **volcanic plugs**. The surrounding material has disappeared leaving the harder plug material as the highest features in the landscape (Figure 51).

Figure 51: The Glasshouse Mountains National Park, Queensland consists of rhyolite and trachyte volcanic plugs, the cores of extinct volcanoes. Source: Wikimedia Commons, photograph by Bidgee 2005.

Columnar jointing can be seen on Mount Wellington in Tasmania and at Kiama, south of Sydney. This feature develops when molten rock shrinks as it cools and solidifies (Figure 52) and is famous for forming the Giant's Causeway and Fingal's Cave in Great Britain. (Figure 53)

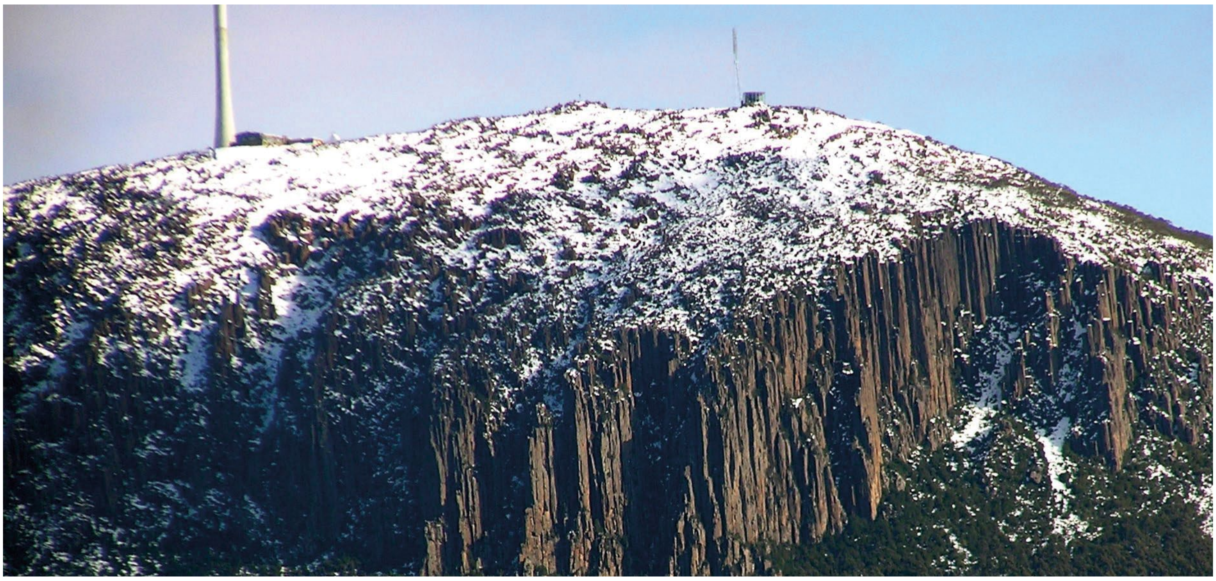


Figure 52: Columnar jointing on Mount Wellington, Tasmania. Shrinkage cracks developed while the molten magma cooled, forming large vertical columns with polygonal cross-sections. Source: Graeme Bartlett (Own work) [CC BY-SA 3.0 (*http://creativecommons.org/licenses/by-sa/3.0*) or GFDL (*http://www.gnu.org/copyleft/fdl.html*)], via Wikimedia Commons.

Figure 53: Columnar jointing, Fingal's Cave in Great Britain. Richard Blewett (Geoscience Australia)

Why study volcanoes?

Other than the obvious desire to better understand the risk a volcano poses to life, limb and property, much of the Earth's richest agricultural land and mineral deposits are found in the vicinity of ancient volcanoes. Volcanoes also have the potential to affect the Earth's climate and can provide clues as to the formation of the Earth's primitive atmosphere.

Agriculture

Volcanic material, when mixed with organic matter, makes up the richest soils on Earth. Some of the most productive farming land is found in volcanic areas. It is the main reason why people live so close to potentially hazardous volcanoes. For example, rice is grown on terraced flanks of Indonesian volcanoes. As the Earth's human population expands, more and more people will rely on rich volcanic soil for agricultural land.

Some of Australia's most productive land, such as around Toowoomba and the Darling Downs in Queensland, is on red-brown soils that formed from the volcanic rocks below. The deep volcanic soils of New Zealand are also excellent for pasture growth.

Mineral deposits

Volcanic activity is an important process in the concentration of useful and valuable minerals such as copper, silver and gold. These deposits are either concentrated as part of the magmatic processes or by the secondary heating of groundwater in the volcanic rock to high temperatures, making mineral-rich fluids mobile.

Magmatic differentiation

The process of **magmatic differentiation** can concentrate a number of elements into fluids which later cool to form rich mineral veins. In some locations, entire magma reservoirs below volcanically active areas have become enriched in copper. Once cooled they form **porphyry copper** deposits, such as the Cadia Hill gold and copper mine in western New South Wales.

Epithermal deposits

Closer to the surface, magma rising into a volcanic vent heats the surrounding rocks and their contained water. If the water becomes hot enough, large convection cells develop which circulate through the surrounding rock and the volcanic accumulations, leaching out (extracting) metals from the minerals they pass through. These fluids become superheated and extremely acidic. Occasionally these waters move into a **fracture** in the rock which leads towards the surface, where it boils and precipitates metallic minerals. These are known as **epithermal deposits**. An example of a mine in Australia where epithermal minerals are extracted is Pajingo gold mine in central-eastern Queensland.

Black smokers

In some settings the hot metallic rich waters break through to the Earth's surface. These have been found in deep ocean areas, for example, off the coast of southern California (United States). Here the hot waters emerge onto the ocean floor where they mix with the cold seawater. This process can form metre high pipes of precipitated minerals which are known as **black-smokers** (Figure 54). The metallic minerals precipitate from the waters released from the smokers and form a blanket on the sea floor. Over time these will form large accumulations. Some of Australia's largest deposits of lead, zinc and copper (Mount Isa, Broken Hill and Woodlawn) may have been formed in this way.

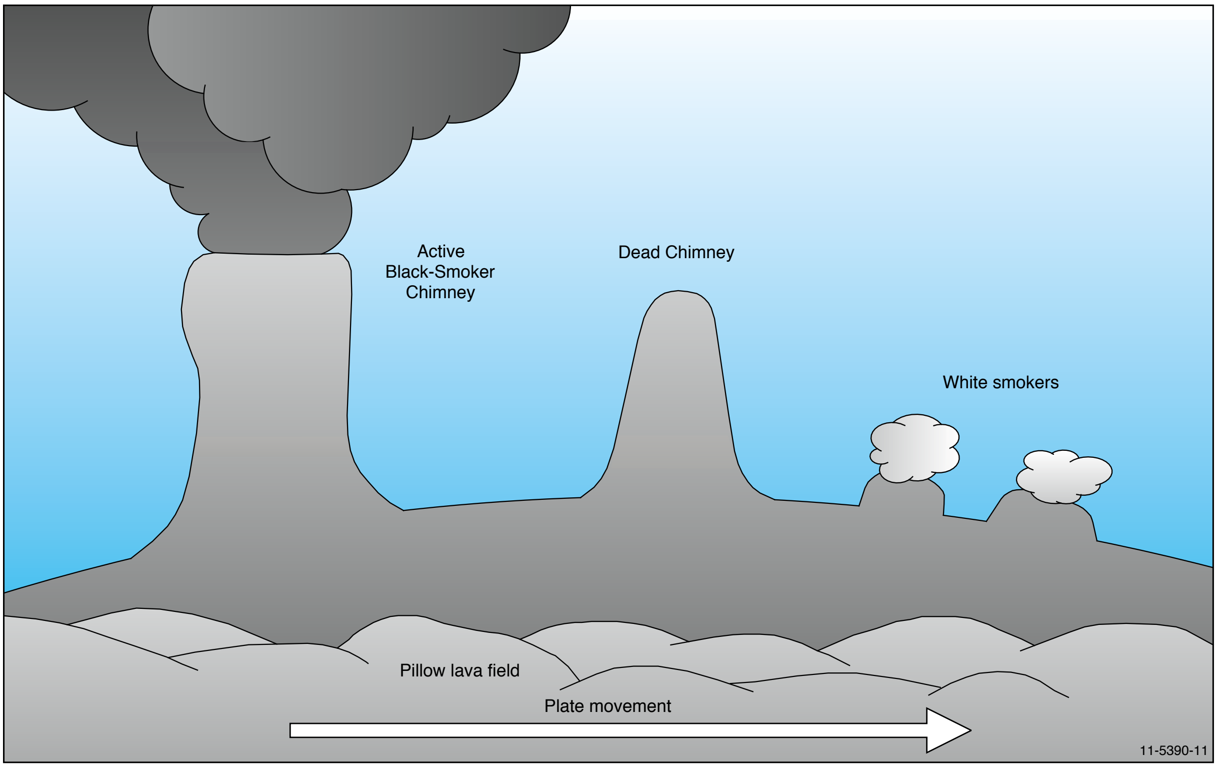


Figure 54: Mineralisation associated with mid-ocean black smokers.

Other volcanic products

As well as the associated mineral deposits, there has been an increase in the use of volcanic products such as pumice, as both an abrasive and as filters (Figure 55). Vesicular volcanic rocks also retain heat and are often used in barbecues.

Figure 55: Pumice rock. Source: Wikimedia Commons, Amcyrus2012.

Geothermal power

In conventional coal-fired power stations, the fuel is burnt to convert water into steam which then drives turbines generating electricity. In volcanic areas, the amount of heat stored in rocks close to the Earth's surface produces large reservoirs of superheated groundwater and steam which can be directly tapped to generate power.

Exploring for suitable geothermal power sites is similar to exploring for oil—you need a geological formation that will trap the superheated water. Once these are found, the trapped water is drilled and tapped into a generator. In places like New Zealand and Iceland this type of **geothermal power** is widely used (Figure 56).

In Australia, a lack of volcanic areas with current or recent activity limits the use of direct **geothermal energy**. However, geoscientists have been investigating tapping the heat of deep granite bodies. These old igneous rocks are hot because they contain minerals that undergo radioactive decay and generate heat. Once drilled into, these rocks can be fractured using water pumped at high pressures which is then circulated through the rocks before returning via pipes to the surface. This super hot water (200 °C) is then converted to steam to drive generators. This type of geothermal energy is known as **hot dry rock technology**. Areas in Australia that have the potential to generate geothermal power include the Cooper Basin in south-west Queensland/north-east South Australia.

Figure 56: Geothermal power station in New Zealand.

Volcanoes and the birth of an atmosphere

Volcanoes played an important part in the formation of the Earth's atmosphere. It is thought that the Earth formed approximately 4.6 billion years ago from a swirling body of cosmic dust left over from the universe's explosive beginnings. As the body contracted, elements separated based on their mass, with the heavier elements forming the core and mantle of the primitive planet and the lighter elements an outer ring or primitive atmosphere, not unlike present day Saturn or Jupiter.

Volcanic activity on the cooling crust of the planet released large amounts of **water vapour** (steam), carbon dioxide, nitrogen and hydrogen sulphide gas. Some of the water vapour molecules that reached the upper atmosphere were broken down into oxygen and hydrogen. Oxygen in the atmosphere was converted to ozone, that started to screen the Earth's surface from ultraviolet rays. Over time, a primitive atmosphere evolved to form the atmospheric conditions suitable for supporting the earliest life. In a similar way today, every volcanic eruption adds gases to the atmosphere which in turn became trapped in the Earth's crust for millions of years.

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Further resources

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Have you visited Geoscience Australia's website?
www.ga.gov.au/education

Useful websites

Earth Learning Idea: ***www.earthlearningidea.com/***

Forces of Nature section of the National Geographic (US) website:
http://environment.nationalgeographic.com.au/environment/natural-disasters/forces-of-nature/
Some information provided plus interactive features such as a volcanic eruption simulation where you determine if the amounts of dissolved gases and silica are low or high (there are also sections on earthquakes, hurricanes and tornadoes [all with a USA emphasis]).

Geoscience Australia: ***http://www.ga.gov.au/scientific-topics/hazards/volcano/basics***

GNS (New Zealand Geological Survey): ***http://www.gns.cri.nz/Home/Learning/Science-Topics/Volcanoes***. Practical teaching activities including many relating to volcanoes.

Smithsonian Institute—Global Volcanism Program: ***http://www.volcano.si.edu/index.cfm***

United States Geological Survey: ***http://volcanoes.usgs.gov/***

Volcano World (US): ***http://volcano.oregonstate.edu/***

Your Planet Earth: ***http://www.earth4567.com/***

Geological Society & Geologists association (UK)—PowerPoint talks aimed at geoscientists talking to students but great pictures, speaker notes and discussion exercises that teachers can use.

WASP: Woodside Australian Science Project: ***http://www.wasp.edu.au*** — Extensive support packages of teacher notes and student activities. Particularly Geological Changes Package (Year 6) and Earth and Physical Sciences (Year 9).

Glossary

A'a:	Hawaiian word used to describe a lava flow whose surface is broken into rough angular blocks or clinker.
Acidic/felsic:	A descriptive term applied to igneous rocks with more than 60 percent silica (SiO_2).
Active volcano:	A volcano which has erupted within the last 10 000 years and is expected to erupt again in the future.
Aerosol particles:	Small solids suspended in the atmosphere.
Agglutinate:	Partially molten volcanic spatter.
Andesite:	Volcanic rock containing 54 to 62 percent silica.
Andesitic volcano zone:	The zone where andesitic volcanoes are commonly found. An example would be oceanic-continental crust subduction zones.
Ash:	Fine particles of pulverized rock ejected from a volcano, measuring less than 2 millimetres in diameter.
Basalt:	Volcanic rock that contains 45 to 54 percent silica.
Basaltic lava:	A lava made from molten rock often originating from partial melting of the mantle.
Basaltic volcano zone:	The zone where basaltic volcanoes are commonly found. An example would be intraplate or mantle plume hot-spot volcanic fields.
Black-smokers:	Hydrothermal vent on the ocean floor, common in volcanically active places.
Block:	Angular chunk of solid rock ejected from a volcano greater than 64 millimetres in diameter.
Bomb:	Fragment of molten or semi-molten rock ejected during an eruption ranging from 64 millimetres to several metres in diameter. Bombs are often modified in shape during flight or upon impact due to their plastic state.
Bowen's reaction series:	This lists common rock forming minerals in the sequence that they would normally crystallise from a cooling melt.
Caldera:	A large cauldron-shaped depression resulting from collapse of the magma chamber roof during or following an eruption. Known calderas on Earth range in diameter from 1–90 kilometres.
Central Vent:	An opening on the Earth's surface that acts as a conduit for volcanic materials. Central vents take the shape of a pipe.
Central Volcano:	A volcano that is produced by lava and debris flows from a common point. This results in a virtually symmetrical cone.
Clinker:	The uneven, irregular surface of A'a broken lava.
Colour scale:	When rocks are heated they emit light. The hotter the rock, the more the colour shifts towards the blue end of the spectrum.
Columnar jointing:	Regularly spaced cracks, usually vertical, form a geometric pattern of adjoining (usually) hexagonal prisms. More often found in volcanic rocks (e.g. lava), and formed as the lava cools and contracts.
Composite volcano:	Structures built around a main central vent, formed by many eruptions that deposit alternating layers of lava and volcaniclastic materials.

Country rocks:	The rock intruded by and surrounding an igneous intrusion.
Crater:	Usually a circular depression, with steep walls, in the Earth's surface created either by an explosion or collapse of a volcanic vent.
Cryovolcanism:	Ice volcanism.
Dacite:	Volcanic rock that contains 62 to 69 percent silica.
Debris flow:	A mixture of water-saturated volcanic ash and debris that flow down volcanic slopes under the force of gravity (also called lahar or mudflow).
Deformation monitoring:	Measurements of the changes in the shape of the surface of a volcano. Can be used to monitor and forecast volcanic activity.
Dioritic:	Magma of intermediate composition, usually formed by melting at subduction zones
Dome:	A steep-sided mass of viscous (doughy) lava extruded from a volcanic vent (often circular in planar view) and spiny, rounded, or flat on top. Its surface is often rough and blocky as a result of fragmentation of the cooler, outer crust during growth of the dome.
Dormant volcano:	Dormant literally means 'sleeping', however, in this case the term is used to describe a volcano which is presently inactive but is likely to erupt again.
Dyke:	An upright (vertical) body of igneous rock that was intruded into the country rock when it was molten.
Earthquake storm:	Also known as an earthquake storm. A series of earthquakes in a localised area which may last for days or even months. None of the earthquakes are noticeably larger than the others, so there is no mainshock that distinguishes swarms from foreshock and aftershock sequences.
Ejecta:	Particles ejected from a volcanic vent through the air (or sometimes water).
Epithermal deposit:	Mineral deposits which are the result of hot fluids leaching out substances from rocks and precipitating metallic minerals.
Eruption cloud:	The column of gases, ash, and larger rock fragments rising from a crater or other vent. If it is of sufficient volume and velocity, this gaseous column may reach many kilometres into the stratosphere, where high winds will carry it great distances.
Eruption column:	A cloud of hot particles (containing volcanic ash, crystals, pumice/scoria, country rock fragments and gas) generated during a volcanic eruption.
Eruption:	The process by which solid, liquid, and gaseous materials are ejected into the earth's atmosphere and onto the earth's surface by volcanic activity. Eruptions range from the quiet overflow of liquid rock to tremendously violent expulsion of pyroclastic material.
Extinct volcano:	A volcano that is not presently erupting and is not likely to do so in the future.
Extrusive or Extrusion (opposite of intrusion):	Volcanic products erupted onto the Earth's surface. For example, lava or tephra.
Fault:	A crack or fracture in the Earth's surface crust. Movement along a fault causes earthquakes or, in the process of mountain-building, can release underlying magma and permit it to rise to the surface.
Feeder dyke:	Fractures in the crust which act as the plumbing system for transporting magma to the earth's surface or volcanic centre to produce lava.
Feeder pipe:	Underground pipes resulting from violent eruptions of deep volcanoes. The pipe may be kilometres long.

Fine ash:	Pulverised volcanic rock and crystals forming fragments 2 millimetres across or smaller.
Fire fountain:	A vertical fountain-like eruption of lava.
Fissures:	Elongated fractures or cracks on the slopes of a volcano. Fissure eruptions typically produce lava flows, but pyroclastics may also be ejected.
Flank eruption:	An eruption from the side of a volcano (in contrast to a summit eruption.)
Flanks:	Part of the volcanic edifice containing deposited lava, pyroclastic and volcaniclastic material.
Flood basalt:	A large area of land or ocean floor that is covered with basaltic lava.
Flood lava:	Refer to 'flood basalt'.
Fracture:	The manner of breaking due to intense folding or faulting.
Geothermal energy:	Energy derived from the internal heat of the Earth.
Geothermal power:	Power generated by using the internal heat energy of the Earth.
Geyser:	A spring that intermittently spurts water turbulently, often with steam.
Hawaiian eruption:	An eruption style named after the volcanic activity style found on the Hawaiian Islands. Typically they take place along vents or fissures and involve relatively runny (basaltic) lava that may flow many kilometres and spray jets of lava 10s to 100s of metres in the air.
Host mineral:	The mineral that is the main component that houses or 'hosts' economically valuable minerals.
Hot dry rock technology:	A form of technology for generating electricity where water is pumped underground, is heated under pressure by naturally hot rocks and returns to the surface to drive turbines for power generation.
Hot spot:	A volcanic centre persistent for at least a few tens of millions of years, that is thought to be the surface expression of a persistent rising plume of hot mantle material (i.e. Hawaiian islands and Iceland).
Igneous rocks:	Solidified lava and intrusives, such as granite.
Ignimbrite:	A volcanic rock formed from pyroclastic flow deposit fragments that 'glue' together from heat and compaction. Can be welded or non-welded.
Intrusion:	Molten rock forced into the surrounding rock as a dyke or pluton.
Intrusive:	Magma solidified below the Earth's surface.
Lahar:	See debris flow.
Lapilli:	Volcanic rock fragments ranging in size from 2 millimetres to 64 millimetres in diameter which can be ejected in either a solid or molten state.
Lava blocks:	Refer to 'bomb'.
Lava dome:	A circular mound that piles up around the volcano vent, formed by viscous lava eruptions.
Lava flow:	An outpouring of lava onto the surface of the earth from a vent or fissure, which can take the form of a solidified tongue or sheet-like body.
Lava tube:	A tunnel formed when the surface of a lava flow cools and solidifies while the molten interior continues to flow through and drain away.
Lava:	Magma which has reached the surface through a volcanic eruption. The term is most commonly applied to streams of liquid rock that flow from a crater or fissure. It also refers to cooled and solidified molten rock.

Lithosphere:	The rigid outer part of the Earth consisting of the crust and upper mantle.
Magma chamber:	A reservoir of liquid rock underground. When put under sufficient pressure, the surrounding solid rock can fracture and allow the magma to escape.
Magma plumbing system:	The inside workings of a volcano that include magma reservoirs, fractures and channels.
Magma reservoir:	The subterranean region containing the gas-rich liquid magma which feeds a volcano.
Magma:	Molten rock beneath the surface of the Earth.
Magmatic differentiation:	A process where the chemical make-up of a magma is changed as certain minerals crystallise out of solution over time.
Magnitude:	A numerical expression of the amount of energy released by an earthquake, determined by measuring earthquake waves on standardised recording instruments (seismographs.)
Mantle:	The zone of the Earth beneath the crust and above the core.
Obsidian:	Dark-coloured volcanic glass formed by rapid cooling of rhyolitic lava.
Pahoehoe:	A Hawaiian term for lava with a smooth, billowy, or ropy surface.
Parasitic cone:	Accumulation of volcanic material due to eruptions on the flanks of a volcano rather than the central vent.
Phreatomagmatic:	An explosive volcanic eruption that results from the interaction of surface or subsurface water and magma.
Pillow lava:	Solidified lavas that contain characteristic pillow-shaped structures that are attributed to the extrusion of the lava underwater.
Pipe:	A vertical conduit through the Earth's crust below a volcano, through which magmatic materials have passed.
Plastic:	Capable of being moulded into any form, which is retained.
Plate tectonics:	The theory that the Earth's lithosphere is broken into plates which move in relation to one another, shifting continents, forming new oceanic crust, and stimulating volcanic eruptions.
Plinian eruption:	An explosive eruption in which a steady, turbulent stream of fragmented magma and magmatic gases is released at a high velocity from a vent. Large volumes of tephra and tall eruption columns are characteristic.
Plug:	Solidified lava that fills the edifice of a volcano. It is usually more resistant to erosion than the material making up the surrounding cone, and may remain standing as a solitary pinnacle when the rest of the original structure has been worn away.
Porphyry copper:	Copper deposits formed from hydrothermal fluids originating in magma reservoirs.
Pumice:	Light-coloured, frothy volcanic rock formed by the explosive expansion of gases in erupting magma, capable of floating on water.
Pyroclastic flow:	A turbulent mixture of hot gases and unsorted pyroclastic material that can flow at high speed (up to and exceeding 100 kilometres per hour) down the flanks of a volcano resulting from collapse of the eruption column or collapse of a lava dome.
Pyroclastic:	Pertaining to hot (pyro) fragmented (clastic) rock material formed by a volcanic explosion or ejection from a volcanic vent. For example, ash, pumice or bombs. Sometimes called tephra, and forms tuff/ignimbrite when solidified into rock.

Rhyolite:	Volcanic rock that contains 69 percent silica or more.
Scoria:	Basaltic material that has been ejected from a volcano. Typically, it has a frothy texture and is dark brown or red in colour.
Seamount:	An underwater mountain that rises from the ocean floor but doesn't reach the water's surface. Often formed from extinct volcanoes.
Shield Volcano:	A gently sloping volcano in the shape of a flattened dome and built almost exclusively of (basaltic/mafic) lava flows.
Silica:	A chemical combination of silicon and oxygen, quartz being the most common form.
Stratovolcano:	A volcano composed of both lava flows and pyroclastic material.
Strombolian eruption:	A type of volcanic eruption characterised by episodic explosions of fluid basaltic to andesitic magma from a central crater.
Subduction zone:	The zone of convergence of two tectonic plates, where one (usually denser oceanic lithosphere) slides beneath the other.
Surtseyan eruption:	Violent explosions caused by phreatomagmatic processes due to rising basaltic or andesitic magma coming into contact with shallow seas or lakes. Named after the Island of Surtsey off the south coast of Iceland.
Tephra:	Same as pyroclastic material.
Tremor:	Low amplitude, continuous earthquake activity often associated with magma movement.
Tsunami:	A great sea wave produced by a submarine earthquake, volcanic eruption, or large landslide.
Tuff:	Rock made of small fragments that have been ejected from a volcano.
Vent:	The opening at the Earth's surface through which volcanic material is emitted.
Vesicular:	Igneous rock containing gas bubbles, such as pumice.
Viscosity:	A measure of resistance to flow in a liquid (water has low viscosity while honey has a higher viscosity).
Volcanic arc:	A chain of volcanoes formed above a subducting slab/zone. Viewed from above, they form a curved arc shape.
Volcanic bomb:	Refer to 'bomb'.
Volcanic cone:	The result of volcanic ejecta building up around the volcanic vent, forming a cone shape.
Volcanic gas:	Gases produced emanating from volcanic activity. Can be produced at the site of a volcano (e.g. volcanic cone) or from gases escaping from magma (underground) or from lava flows at the surface. In large quantities can pollute groundwater, surface water and the atmosphere. Major constituents of volcanic gases are water vapour, carbon dioxide and carbon monoxide, sulphur dioxide, fluorine, chlorine.
Volcanic plug:	Rock that was once sticky lava that has cooled and hardened within a vent of an active volcano. Can cause magma pressure to build up below the plug.
Volcanic tremor:	Bursts of continuous vibration caused by pressure changes in the rock from unsteady transport of magma in a volcano. May indicate a pending volcanic eruption.
Volcanic tsunami:	A tsunami resulting from an underwater volcanic eruption or caldera collapse.
Volcanic tuff:	A volcanic rock formed from (mostly) compressed volcanic ash. Formed in a similar way to an ignimbrite.

Volcanic vent:	The opening on the Earth's surface from where volcanic material is emitted.
Volcaniclastics:	Fragmented particles originating from volcanoes.
Volcanism:	Volcanic activity
Volcano:	An opening in the Earth's crust from which lava, volcanic ash, hot gases and other material can be ejected during an eruption.
Volcanology:	The study of volcanos and volcanic activity.
Vulcan:	The Roman god of fire after whom volcanoes are named.
Vulcanian:	A type of eruption consisting of the repeated explosive ejection of extremely bright fragments of new viscous lava.

Australian Government
Geoscience Australia

EDUCATION PROGRAM

Volcanoes—Student activities

Magma chamber chemistry

Recommended Age: Middle to senior secondary school.

A magma chamber full of molten rock has formed below the surface of the Earth. Over time the chamber will slowly cool and some minerals from the magma will crystallise and fall to the bottom, leaving a residual pool of magma on the top. Occasionally this residual pool feeds a volcano on the Earth's surface.

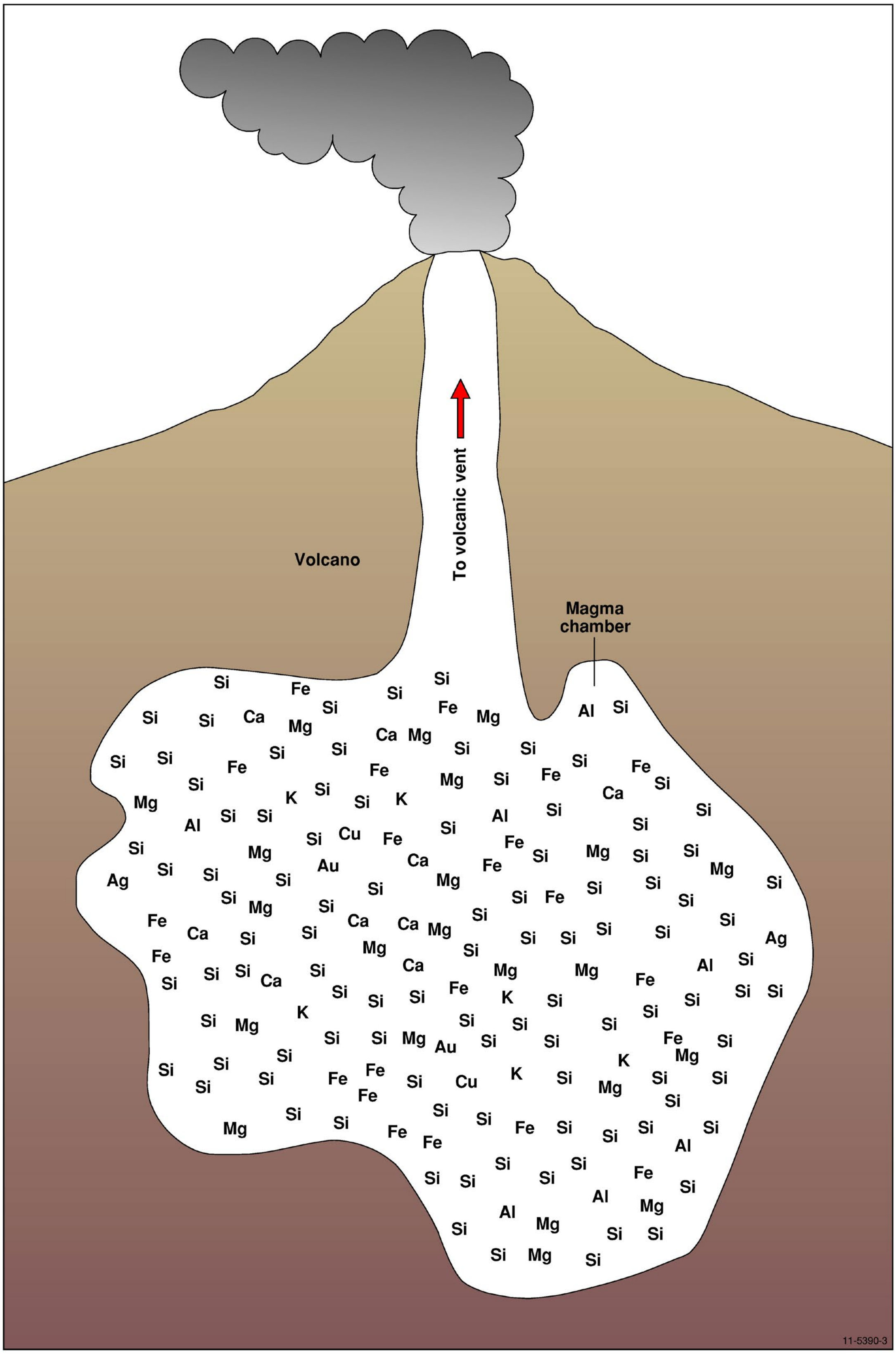
The original magma is made up from the following:

Component	Symbol
Silica	SiO_2
Magnesium	Mg
Iron	Fe
Calcium	Ca
Potassium	K
Aluminium	Al
Silver	Ag
Gold	Au
Copper	Cu

Your task is to work out what lava rock type will be forced out from this volcano as the magma chamber cools. Use the silica content data in the table below to work this out.

Silica Content	Volcanic Rock
45–54%	basalt
54–62%	andesite
62–70%	dacite
70–78%	rhyolite

Magma chamber chemistry



1. **Using the diagram, we have counted the total number of each component in the magma chamber and calculated its percentage of the total of components (to four significant figures).**

	Number	Percentage
Silica	101	58.38
Magnesium	22	12.72
Iron	22	12.72
Calcium	9	5.202
Potassium	6	3.468
Aluminium	7	4.046
Silver	2	1.156
Gold	2	1.156
Copper	2	1.156
Total	173	

1a. If this magma fed the volcano above, which volcanic rock type would you expect to be formed?

1b. Calculate the total percentage. Do the percentages add up to 100? Y/N

1c. Is this a problem? Why/why not?

After a few thousand years, the magma cooled and three different minerals crystallised and sank to the bottom of the chamber. These minerals were olivine, pyroxene and amphibole and they removed the following components from the melt (illustrated in the table below).

2. We have calculated the total number of each individual element that was removed from the melt. (For example, how much silica was removed.)

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Olivine	5	5	5	0	0	0	0	0	0
Pyroxene	5	3	3	2	0	0	0	0	0
Amphibole	5	2	2	2	0	0	0	0	0
Total # removed	15	10	10	4	0	0	0	0	0

2a. Now calculate the remaining components left in the melt and the percentage of each component (to four significant figures).

Component	Number in Original Magma	Number Lost	Number Remaining in Magma B	Percentage
Silica	101	15	86	64.18
Magnesium	22			
Iron	22			
Calcium	9			
Potassium	6			
Aluminium	7			
Silver	2			
Gold	2			
Copper	2			
Total	173			

2b. If the remaining Magma B fed the volcano above, what type of volcanic rock would you expect to be formed? Hint: Look at the silica content.

3. **Calculate again how much more of each individual element was removed from the melt.**

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Pyroxene	5	3	3	2	0	0	0	0	0
Amphibole	5	2	2	2	0	0	0	0	0
Biotite	5	2	2	0	2	2	0	0	0
Total # removed									

3a. Using a pencil, colour over the components in the magma chamber that have now been removed from the molten material. Calculate the remaining components left in the melt and the percentage of each component to the new total number of components (to four significant figures).

Component	Number in Magma B	Number Lost	Number Remaining in Magma C	Percentage
Silica				
Magnesium				
Iron				
Calcium				
Potassium				
Aluminium				
Silver				
Gold				
Copper				
Total				

3b. If the remaining magma fed the volcano above, what type of volcanic rock would you expect to be formed?

Several more thousand years pass and the magma cools. More amphibole and biotite crystallise as well as the mineral orthoclase feldspar. They removed the following components from the melt (illustrated in the following table).

4. Calculate once again the total number of each individual element that was removed from the melt.

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Amphibole	5	2	2	1	0	0	0	0	0
Biotite	5	2	2	0	2	2	0	0	0
Orthoclase	4	0	0	0	2	2	0	0	0
Total # removed									

4a. Calculate the remaining components left in the melt and the percentage of each component to the new total number of components (to four significant figures).

Component	Number in Magma C	Number Lost	Number Remaining	Percentage
Silica				
Magnesium				
Iron				
Calcium				
Potassium				
Aluminium				
Silver				
Gold				
Copper				
Total				

By this stage, the material in the volcanic vent has solidified and plugged the magma chamber and no more material can escape to the surface. The remaining magma gets squeezed into cracks in the surrounding rocks where it forms veins.

4b. What percentage of gold is in the veins?

A gold ore body is deemed as viable for mining when there is at least 1 gram of gold available for every tonne of ore dug out of the ground.

4c. What is 1 gram per tonne (1 g/t) as a percentage?

A mining company exploring the area drilled for samples and found an average of 0.002% gold from veins and the surrounding rocks.

Note: 1000 kilograms = 1 tonne

1000 grams = 1 kilogram

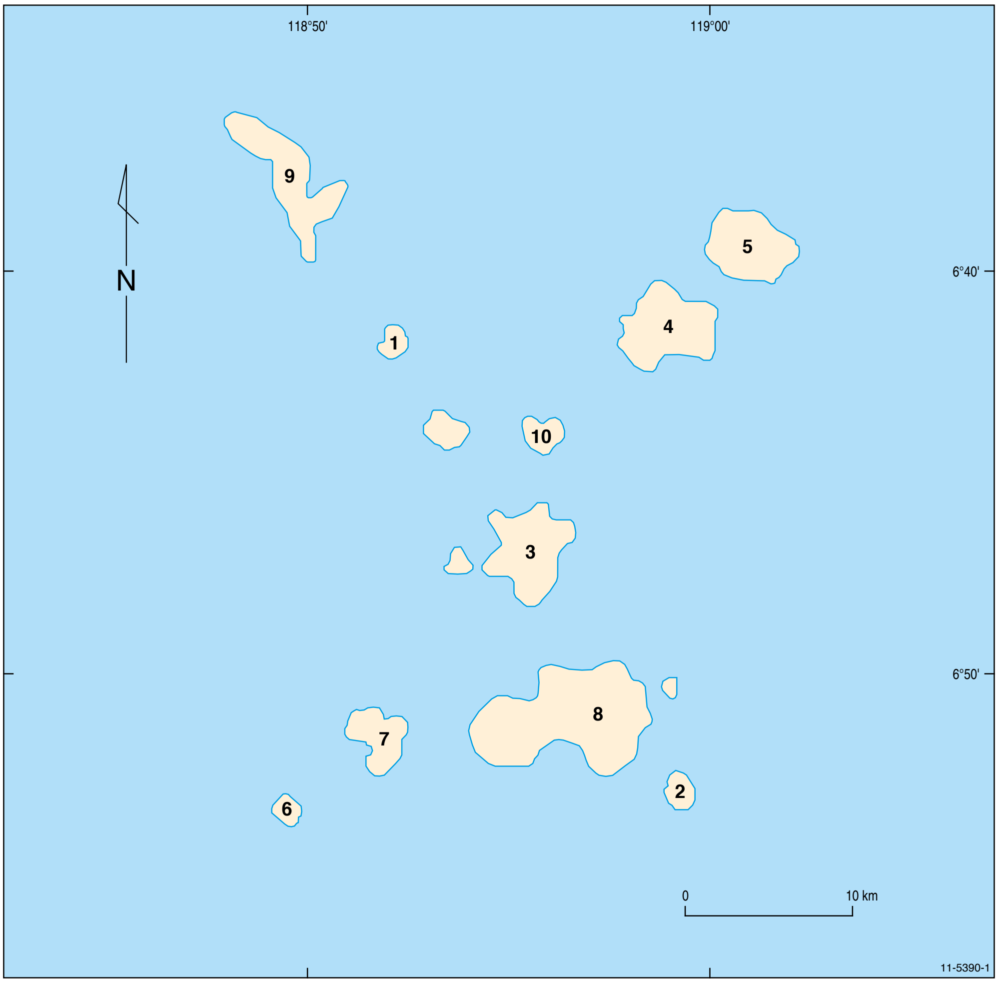
4d. Does this percentage of gold make this area a viable gold mine in the future? Y/N

Basic Islands

Recommended Age: Middle to senior secondary school.

A hot-spot problem

In the year 2050, a group of scientists start studying a planet not unlike Earth. It was recognised that plate tectonics were active on the planet. A geologist collected a number of volcanic rock samples from 10 islands in the Basic Island Group. She developed a theory that these islands were all volcanoes because the crustal plate they located on had moved over a hot-spot which caused melting. The only volcano that was still active was identified from her number five sample.



Basic Islands

To find support for her theory, she sent the samples back to Earth to analyse their radioactive element composition. This would enable her to find out the age of each of the islands and she hoped this would show that the islands became older as you moved towards the south.

1. **Using the radioactive element composition and the radioactive decay curves, calculate the age for each of the islands and complete the table.**

Island	Element	Percent of original mass remaining	Age in billions of years
1	U^{238}	44	
2	U^{238}	95	
3	Rb^{87}	95	
4	U^{235}	85	
5	U^{235}	96	
6	U^{235}	3	
7	Th^{232}	85	
8	U^{235}	61	
9	Rb_{87}	93	
10	U^{238}	48	

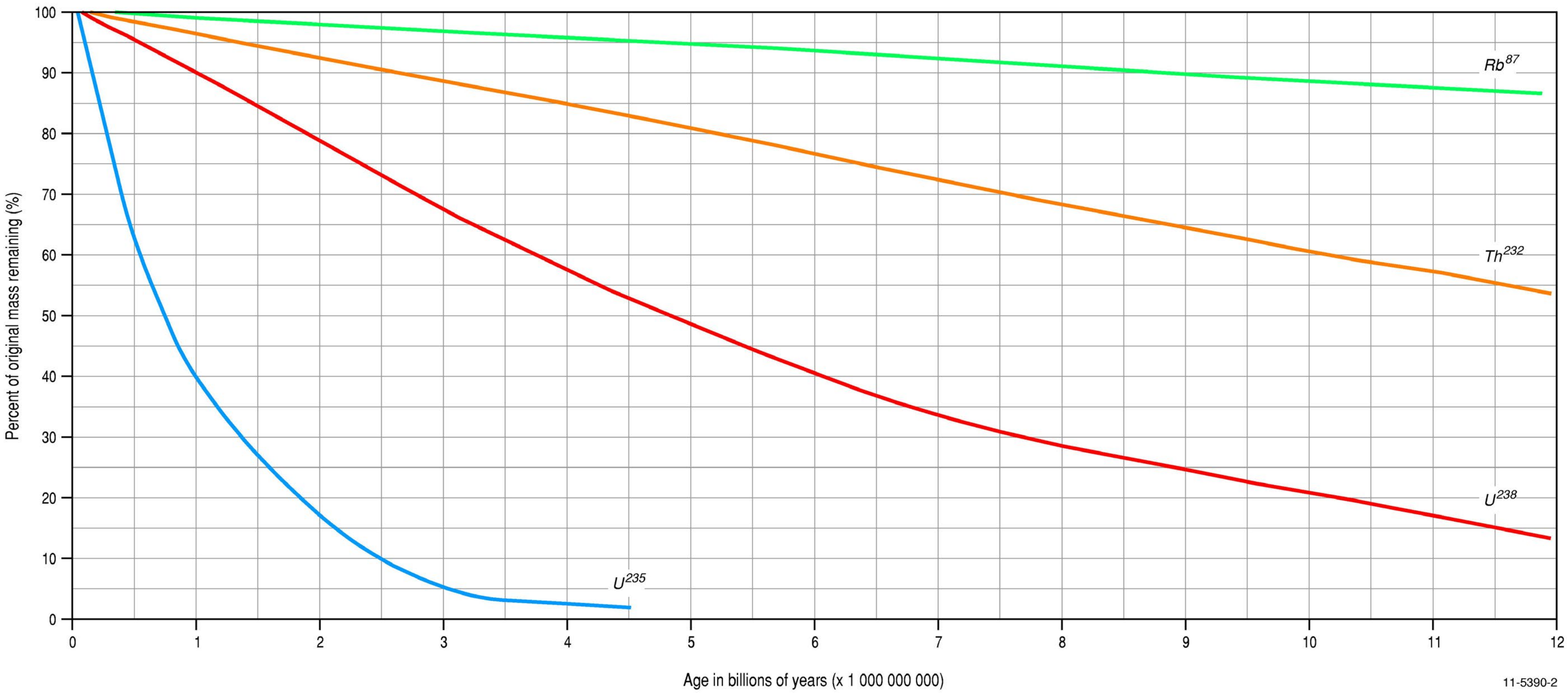
2. **List the order of islands from oldest to youngest.**

The geologist recognised that the ages of the islands seemed to fall into two age groups, those over 3 billion years old and those under 2 billion years old. She changed her theory to say that the islands formed when their plate moved over two hot-spots at different periods of time.

3. **For the islands which are more than 4 billion years old, join the dots starting with the oldest island through to the youngest island. Using a different coloured pen, do the same with the islands which are under 3 billion years old. Describe and draw the shape of these lines and think of a possible reason they are this shape.**

Draw the shapes here:

Radioactive decay curves



Thunder Island role play

Recommended Age: Upper primary to secondary school.

The following pages contain information to carry out the Thunder Island role play scenario which can be run as an individual or group class activity.

Thunder Island is a volcanically active island, your class will be split into four teams that monitor the island on an hourly basis and provide information and warnings.

The four teams are:

1. Seismic Team
2. Deformation Monitoring Team
3. Well Water and Weather Team
4. Eruption Centre Team

Teams 1 to 3 collect information and provide advice to the Eruption Centre. The Eruption Centre advises the island's occupants on the need to evacuate the island.

Preparation

Print background sheets and maps for each team.

Print briefing sheets for each team.

Print and cut up hourly data updates for each team.

Each team will receive a Thunder Island Background sheet, a Thunder Island map and a copy of their team Briefing sheet. The team briefing sheet supplies information on what each team is studying and some example results to help their understanding of the task.

Once the scenario starts the teams will periodically get information for the station they are monitoring (The Eruption Centre receives information from each team). There are six hourly data updates for each team that will need to be interpreted and passed onto the Eruption Centre. Teachers can decide how much time is given for each analysis before the next data update is supplied.

Running the scenario

Explain the scenario and give students enough time to familiarise themselves with their team tasks and how to evaluate the information (10 to 15 minutes).

Provide the first hourly update and allow time for analysis (5 to 10 minutes each).

When the teams provide the Eruption Centre with the results the Centre then sets the eruption status to the colour they assess it to be as well as sending warnings to the settlements on the islands regarding ash fall and other hazards.

Provide the next hourly update and continue until you reach update hour 6.

Background information on Thunder Island

Thunder Island is a small volcanic island in the south western Pacific Ocean. It has a population of 3500 people located in five small townships.

The island was discovered by the Dutch in 1720 and a small settlement grew up around Safe Bay. The bay was used by the Dutch as a safe place to anchor trading ships during the monsoon storm season. Within ten years, Shakey Harbour was established as a jail for convicts (mostly pirates) and a small township started to grow around a fresh water stream at Valleyside. After the year 1750, released convicts moved into Hermitside. In 1978 a tourist resort, called The Resort, was built. It caters for 200 people.

Estimated township population (including tourists):

- Safe Bay 1300
- Shakey Harbour 800
- Valleyside 100
- Hermitside 50
- The Resort 250

The island has no roads and all transport is by foot or boat. A telephone system operates in all townships except Hermitside which is a 20 minute walk from Safe Bay or 35 minutes boat ride.

Volcanic history

Two active volcanoes are present on the island, Big Thunder and Little Thunder.

Big Thunder volcano

Big Thunder erupts approximately once every nine years. It normally produces volcanic ash and an occasional andesitic lava flow. Eruptions are preceded by a rise in the temperature of water in the local wells and by increased seismic activity. During the last eruption eleven years ago, large amounts of ash covered Valleyside and a lava flow ran down a valley between The Resort and Safe Bay. No one was injured, but Valleyside residents were forced to evacuate.

Little Thunder volcano

Little Thunder has an erratic eruption history. It is known to have erupted eight times since settlement, releasing vast amounts of basaltic lava and ash every time. Many buildings in Shakey Harbour were destroyed in 1823 by a lava flow. The last eruption in 1916 was prior to the setting up of monitoring devices on the island.

In 1984 seismic stations and distance measuring equipment were set up on the island to monitor future eruptions.

Thunder Island

1. Seismic Team briefing

Shakey Harbour headquarters

Your role is to monitor seismic activity as recorded by the five seismic stations located on Thunder Island (1–5). The seismic recorders only measure strong ground motions in the close vicinity of the recorder. The information is sent by Internet to your headquarters in Shakey Harbour.

Each recorder produces an average reading of seismic intensity every five minutes. These are sent to you each hour as a stream of 12 numbers from each centre. The scale for these readings is:

0—no activity

1—very minor activity

2—minor activity

3—substantial activity

4—sub-major activity

5—major activity

6—dramatic activity

7—extreme activity

Eruptions are normally preceded by intensities of 5 or more being recorded by stations surrounding the volcanic vent. The recorders are built to withstand intensity 7 readings for 10 minutes only, after which they may cease to operate.

Your job is to analyse the information and provide advice to the Eruption Control Centre on the location and your assessment of the eruption risk.

Example Hourly Update – Information you will receive and need to interpret.

1. Station 1) 3,4,3,4,5,6,6,5,6,5,6,6
   Station 2) 2,1,2,1,0,0,1,0,1,2,0,0
   Station 3) 3,4,4,3,4,5,4,3,4,5,6,4
   Station 4) 3,2,3,1,2,1,2,3,2,3,2,3
   Station 5) 3,4,4,4,3,2,3,2,3,2,3,2

Activity is taking place on the western side of Little Thunder with 'dramatic activity' as the maximum intensity being recorded. The intensity has increased over time and this is confirmed by a station on the eastern side of Little Thunder. All other stations have recorded high but stable intensities. Your conclusion is that Little Thunder may erupt. **WARN ERUPTION CONTROL CENTRE**.

2. Station 1) 1,2,2,3,2,3,2,1,2,3,2,2
   Station 2) 3,2,3,2,3,4,3,2,3,2,3,2
   Station 3) 1,2,2,3,2,2,1,2,2,1,2,2
   Station 4) 3,2,3,3,2,3,2,2,2,2,3,2
   Station 5) 2,1,2,1,2,2,3,3,2,1,2,1

Activity is stable. Fluctuations are within normal limits. **NO WARNINGS NEEDED**.

Seismic Team updates

Hour 1	SEISMIC UPDATE											
Station 1	1	2	1	2	0	1	2	1	2	0	1	1
Station 2	2	3	2	3	2	2	3	3	2	1	2	3
Station 3	3	4	3	4	3	4	4	4	4	3	4	4
Station 4	4	4	4	3	4	4	3	4	3	3	2	2
Station 5	3	2	3	2	2	2	3	2	3	2	3	2
Advice for Eruption Centre												

Hour 2	SEISMIC UPDATE											
Station 1	1	2	3	2	3	2	1	2	3	2	1	1
Station 2	2	3	3	2	3	3	3	2	3	2	3	2
Station 3	3	4	4	4	5	4	4	3	4	4	4	5
Station 4	2	3	3	3	4	4	4	3	4	4	4	3
Station 5	3	3	3	3	3	3	3	4	3	3	3	3
Advice for Eruption Centre												

Hour 3	SEISMIC UPDATE											
Station 1	2	3	2	3	2	3	2	2	2	2	3	2
Station 2	3	4	3	3	2	3	2	3	4	4	3	4
Station 3	4	4	3	4	4	3	4	3	4	3	4	4
Station 4	4	4	4	4	3	4	4	4	4	3	4	4
Station 5	2	3	2	3	4	2	3	2	3	2	1	3
Advice for Eruption Centre												

Hour 4	SEISMIC UPDATE											
Station 1	3	4	4	3	2	1	2	1	2	2	2	1
Station 2	3	2	2	3	2	1	1	2	3	2	3	2
Station 3	4	4	4	4	3	4	3	4	3	4	3	4
Station 4	3	3	3	4	3	4	4	3	3	3	4	5
Station 5	3	2	2	2	3	2	3	2	3	1	3	2
Advice for Eruption Centre												

Hour 5	SEISMIC UPDATE											
Station 1	2	3	2	1	2	2	1	2	2	2	1	2
Station 2	3	4	3	4	3	2	3	4	3	2	3	2
Station 3	4	5	5	4	5	5	6		3	4	5	4
Station 4	4	4	4	5	5	5	6	6	5	6	4	5
Station 5	2	3	4	4	4	4	4	5	6	4	4	4
Advice for Eruption Centre												

Hour 6	SEISMIC UPDATE											
Station 1	3	4	5	4	3	4	4	4	3	4	3	4
Station 2	4	4	4	3	4	4	4	3	4	5	4	3
Station 3	5	6	5	6	5	5	5	6	7	7	7	-
Station 4	4	5	6	7	7	7	-					
Station 5	4	5	6	5	4	5	4	3	4	3	4	3
Advice for Eruption Centre												

2. Deformation Monitoring Team briefing

Valleyside headquarters

Your role is to monitor deformation of the slopes of the volcano. Your information comes from accurate laser measurements between five distance measuring stations (a–e) on Thunder Island.

The process of measuring the distances is automatic and is done every 15 minutes and the four readings which are sent to you every hour. The normal readings are:

a–b	**5110 m**
a–c	**7600 m**
c–d	**6000 m**
c–e	**5870 m**
e–d	**6130 m**
d–b	**1155 m**

The instruments vary in their readings by ± 1 metre. However, it is not uncommon for some readings to change by as much as 3 metres during non-eruptive times. Any change greater than this which lasts for more than one hour may indicate the rise of magma in the volcanic vent. The readings are fed into a computer which prints out the variation from the normal measurements in metres.

Your job is to analyse the information and provide advice to the Eruption Control Centre on the location and your assessment of the eruption risk.

2. Deformation Monitoring Team updates

Hour 1					Advice for Eruption Centre
DISTANCES					
a–b	1	2	1	2	
a–c	2	3	1	1	
c–d	2	2	1	1	
c–e	2	2	1	1	
e–d	1	2	1	1	
d–b	0	3	2	1	

Hour 2					Advice for Eruption Centre
DISTANCES					
a–b	2	2	1	2	
a–c	2	1	0	1	
c–d	3	3	2	3	
c–e	4	3	2	3	
e–d	4	1	1	3	
d–b	3	2	9	3	

Hour 3					Advice for Eruption Centre
DISTANCES					
a–b	1	1	1	2	
a–c	2	3	2	1	
c–d	4	5	4	5	
c–e	1	2	3	2	
e–d	6	5	4	5	
d–b	2	1	2	3	

2. Deformation Monitoring Team updates cont'd

Hour 4					Advice for Eruption Centre
DISTANCES					
a–b	2	3	4	2	
a–c	1	2	2	2	
c–d	1	2	3	3	
c–e	3	3	3	3	
e–d	3	4	3	3	
d–b	4	5	3	2	

Hour 5					Advice for Eruption Centre
DISTANCES					
a–b	2	2	3	2	
a–c	1	1	0	2	
c–d	5	6	4	5	
c–e	6	6	7	8	
e–d	9	6	7	5	
d–b	4	3	2	5	

Hour 6					Advice for Eruption Centre
DISTANCES					
a–b	2	2	3	2	
a–c	1	1	0	2	
c–d	5	6	4	5	
c–e	6	6	7	8	
e–d	9	6	7	5	
d–b	4	3	2	5	

3. Well Water and Weather Team briefing

Safe Bay headquarters

Your role is to monitor the temperature changes in the five wells (V–Z) dotted around Thunder Island. Automatic thermometers are located in each well and information is sent to the headquarters where it is recorded by a computer. The computer prints out the maximum variation from the normal temperature of the water in the wells each hour. A fluctuation of 10 °C is not uncommon, however, any rise beyond 10 °C is a warning of moving magma.

Attached to a post near well W is a device which measures speed and direction of winds at the centre of the island. Past eruption studies have shown the distance volcanic ash is blown equal to one kilometre x the wind speed.

Your job is to analyse the information and provide advice to the Eruption Control Centre on the location and your assessment of the eruption risk.

Example Hourly Update – Information you will receive and need to interpret.

1. V: 6
W: 4
X: 8
Y: 4
Z: 3

Wind speed: 5 km/h
Wind direction (from): S

Well temperatures are within limits. Well X is getting hot and further reading will need to be recorded. Ash falls could occur to the north of both volcanoes for five kilometres. Safe Bay is located in an ash fall zone. **ADVISE ERUPTION CENTRE OF WELL X READINGS AND WEATHER CONDITIONS.**

2. V: 2
W: 12
X: 3
Y: 8
Z: 16

Wind speed: 10 km/h
Wind direction (from): SE

Well temperatures indicate the rise of magma under Big Thunder. The ash fall zone from Big Thunder will be 10 kilometres to the northwest. Safe Bay is under threat.
WARN ERUPTION CENTRE.

3. Well Water and Weather Team updates

Hour 1		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 2		
W 3	Wind direction W	
X 2		
Y 4	Wind speed 15 km/h	
Z 5		

Hour 2		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 7		
W 7	Wind direction WSW	
X 3		
Y 8	Wind speed 13 km/h	
Z 7		

Hour 3		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 8		
W 7	Wind direction SW	
X 5		
Y 6	Wind speed 10 km/h	
Z 7		

Hour 4		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 9		
W 9	Wind direction SSW	
X 8		
Y 10	Wind speed 14 km/h	
Z 11		

Hour 5		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 12		
W 19	Wind direction SW	
X 3		
Y 8	Wind speed 10 km/h	
Z 24		

Hour 6		Advice for Eruption Centre
TEMPERATURES	Wind details	
V 10		
W 12	Wind direction S	
X 5		
Y 9	Wind speed 16 km/h	
Z 26		

4. Eruption Centre

The Resort headquarters

Your role is to advise the local population of the eruption risk every hour. You need to assess the information provided by the other three teams and release the following warnings if necessary:

NO ALERT-TESTING WARNING SYSTEM
This is issued when there is no activity warning from any team. It lets the local population know that the warning system is working.

ERUPTION GREEN
This is issued if any two teams advise of unusual activity. People should keep listening for further warnings.

ERUPTION ORANGE
This is issued if any two teams give warning of activity at either of the volcanoes, people in ash fall areas are on notice of evacuation.

ERUPTION RED
This is issued if all three teams give warnings of activity. People in ash fall areas are evacuated to safer townships.

ERUPTION—ERUPTION—ERUPTION
An eruption is occurring.

ERUPTION DOWNGRADE (ORANGE/GREEN/NO ALERT)
The risk of eruption is decreasing.

While you wish to advise people of risk, you do not wish to cause panic among the local population as it is important that they trust your judgement. (Remember the story of the boy who cried 'Wolf'!)

Draft a media release advising local populations of volcanic conditions.

4. Eruption Team updates

Hour 1		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Hour 2		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Hour 3		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Hour 4		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Hour 5		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Hour 6		Alert Level
Team	**Advice**	
Seismic Team		No Alert—Test
		Eruption Green
Deformation Team		Eruption Orange
		Eruption Red
Well and Weather		Eruption/Eruption/Eruption
		Eruption Downgrade
Population Warnings		

Australian Government
Geoscience Australia

EDUCATION PROGRAM

Answers

Magma chamber chemistry

1. **Using the diagram, we have counted the total number of each component in the magma chamber and calculated its percentage of the total of components (to four significant figures).**

	Number	Percentage
Silica	101	58.38
Magnesium	22	12.72
Iron	22	12.72
Calcium	9	5.202
Potassium	6	3.468
Aluminium	7	4.046
Silver	2	1.156
Gold	2	1.156
Copper	2	1.156
Total	173	100

1a. If this magma fed the volcano above, which volcanic rock type would you expect to be formed?

Andesite

1b. Calculate the total percentage. Did your percentages add up to 100? Y / N

1c. Is this a problem? Why/why not?

Teachers: This is an opportunity to discuss with the students rounding errors, and the fact that real world data never adds up. Ask the students what they might do with the calculations to obtain a number closer to 100.

2. **We have calculated the total number of each element that was removed from the melt. (For example, how much silica was removed.)**

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Olivine	5	5	5	0	0	0	0	0	0
Pyroxene	5	3	3	2	0	0	0	0	0
Amphibole	5	2	2	2	0	0	0	0	0
Total # removed	15	10	10	4	0	0	0	0	0

2a. Now calculate the remaining components left in the melt and the percentage of each component (to four significant figures).

Component	Number in Original Magma	Number Lost	Number Remaining in Magma B	Percentage
Silica	101	15	86	64.18
Magnesium	22	10	12	8.955
Iron	22	10	12	8.955
Calcium	9	4	5	3.731
Potassium	6	0	6	4.478
Aluminium	7	0	7	5.224
Silver	2	0	2	1.493
Gold	2	0	2	1.493
Copper	2	0	2	1.493
Total	173	39	134	100

2b. If the remaining Magma B fed the volcano above, what type of volcanic rock would you expect to be formed? Hint: Look at the silica content.

Dacite

3. Calculate again how much more of each individual element was removed from the melt.

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Pyroxene	5	3	3	2	0	0	0	0	0
Amphibole	5	2	2	2	0	0	0	0	0
Biotite	5	2	2	0	2	2	0	0	0
Total # removed	15	7	7	4	2	2	0	0	0

3a. Calculate the remaining components left in the melt and the percentage of each component to the new total number of components (to four significant figures).

Component	Number in Magma B	Number Lost	Number Remaining in Magma C	Percentage
Silica	86	15	71	73.20
Magnesium	12	7	5	5.155
Iron	12	7	5	5.155
Calcium	5	4	1	1.031
Potassium	6	2	4	4.124
Aluminium	7	2	5	5.155
Silver	2	0	2	2.062
Gold	2	0	2	2.062
Copper	2	0	2	2.062
Total	134	37	97	100

3b. If the remaining magma fed the volcano above, what type of volcanic rock would you expect to be formed?

Rhyolite

4. Calculate once again the total number of each individual element that was removed from the melt.

	Si	Mg	Fe	Ca	K	Al	Ag	Au	Cu
Amphibole	5	2	2	1	0	0	0	0	0
Biotite	5	2	2	0	2	2	0	0	0
Orthoclase	4	0	0	0	2	2	0	0	0
Total # removed	**14**	**4**	**4**	**1**	**4**	**4**	**0**	**0**	**0**

4a. Calculate the remaining components left in the melt and the percentage of each component to the new total number of components (to four significant figures).

Component	Number in Magma C	Number Lost	Number Remaining	Percentage
Silica	**71**	**14**	**57**	**86.36**
Magnesium	**5**	**4**	**1**	**1.515**
Iron	**5**	**4**	**1**	**1.515**
Calcium	**1**	**1**	**0**	**0**
Potassium	**4**	**4**	**0**	**0**
Aluminium	**5**	**4**	**1**	**1.515**
Silver	**2**	**0**	**2**	**3.030**
Gold	**2**	**0**	**2**	**3.030**
Copper	**2**	**0**	**2**	**3.030**
Total	**97**	**21**	**66**	**100**

4b. What percentage of gold is in the veins?

3.03 %

A gold ore body is deemed as viable for mining when there is at least 1 gram of gold available for every tonne of ore dug out of the ground.

4c. What is 1 gram per tonne (1 g/t) as a percentage?

0.0001 %

A mining company exploring the area undertook drill samples and found an average of 0.002% gold from veins and the surrounding rocks.

4d. Does the percentage of gold make this area a viable gold mine in the future? **Y**

1.

Basic islands

1. **Using the radioactive element composition and the radioactive decay curves, calculate the age for each of the islands and complete the table.**

Island	Element	Percent of original mass remaining	Age in billions of years
1	U^{238}	44	**~ 5.7**
2	U^{238}	95	**~ 0.6**
3	Rb^{87}	95	**~ 4.5**
4	U^{235}	85	**~ 0.25**
5	U^{235}	96	**~ 0.1**
6	U^{235}	3	**~ 3.4**
7	TH^{232}	85	**~ 4.0**
8	U^{235}	61	**~ 0.5**
9	Rb^{87}	93	**~ 7.0**
10	U^{238}	48	**~ 4.9**

2. **What is the order of islands from oldest to youngest?**

9 – 1 – 10 – 3 – 7 – 6 – 2 – 8 – 4 – 5

3. **For the islands which are more than 4 billion years old, join the dots starting with the oldest island through to the youngest island. Using a different coloured pen, do the same with the islands which are 4 billion years old or less. Describe and draw the shape of these lines and think of a possible reason they are this shape.**

Islands over 3 billion => the line is a band line (boomerang) shape with oldest at top.

Islands under 3 billion => the line is also a boomerang but bent in the opposite way with the oldest at the bottom.

The plate on which these islands lay has moved northwards in a curve between 7.0 billion years and 3.4 billion, then southwards in the opposite curve from 0.6 billion to the present day.

4. **Draw the shapes here**

Oldest

Youngest

Youngest

Oldest