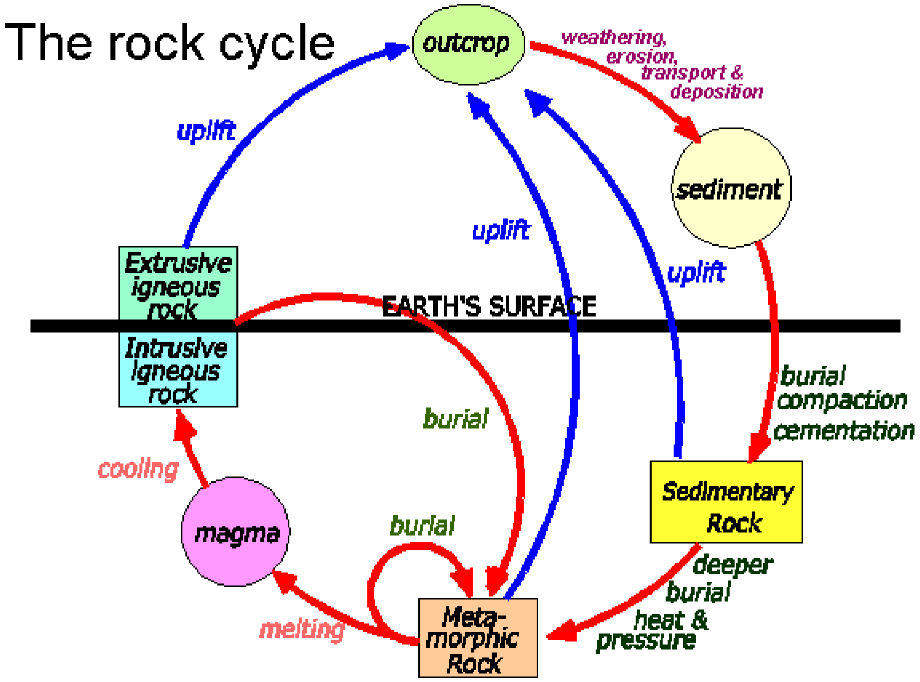
C1 - Rocks and Magmas

A rock is defined as a consolidated mixture of minerals. By *consolidated* we mean hard and solid. A *mixture of minerals* implies the presence of more than one mineral grain, but not necessarily more than one type of mineral. A rock can be composed of only one type of mineral (e.g., limestone is commonly made up of just calcite), but most rocks are composed of several different types of minerals. It is very important to understand the difference between rocks and minerals. A rock can also include non-minerals, such as the organic matter within a coal bed, or within some shales.

Rocks are grouped into three main categories:

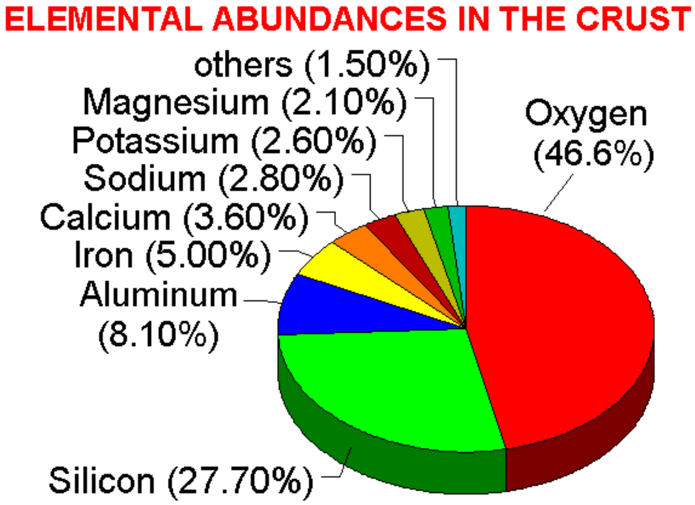
IGNEOUS	formed from the cooling of a magma (i.e., from molten rock)
SEDIMENTARY	formed when weathered fragments of other rocks are compressed and cemented together
METAMORPHIC	formed by alteration (due to heat, pressure and/or chemical action) of a pre-existing igneous or sedimentary rock

The materials that make up the rocks of the crust are slowly but constantly being changed from one form to another. The inter-relationships between rock types can be summarized on what is known as the ***rock cycle*** diagram [see p. 28, and the figure to the left].



Magma can either cool slowly (over centuries to millions of years) within the crust—forming **intrusive igneous rock,** or erupt onto the surface and cool quickly (within seconds to years)—forming **extrusive igneous rock**. Through the various processes of mountain building, all types of rocks are uplifted and exposed at surface. They are weathered, both physically and chemically, and the weathering products are eroded, transported and then deposited as sediments. The sediments are buried and compressed and become hardened and cemented into **sedimentary rock**. Again through various means, largely resulting from plate tectonic forces, different kinds of rocks are buried deep within the crust where they are heated up, squeezed and chemically changed into **metamorphic rock**. If the heat is sufficient, part or all of the rock may melt into magma.

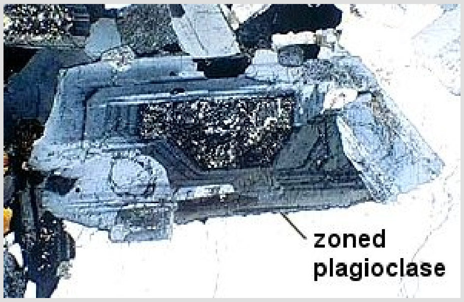
Magmas can have quite widely varying compositions, but they are all made up largely of only eight elements, in order of importance: oxygen, silicon, aluminum, iron, calcium, sodium, magnesium and potassium (see the figure to the right). Magmas derived from recycled crustal material are dominated by oxygen, silicon and aluminum, sodium and potassium. Magmas derived from the mantle material beneath the crust have higher levels of iron, magnesium and calcium, but they are still likely to be dominated by oxygen and silicon. All magmas also have varying proportions of dissolved water as well as gases such as carbon dioxide and hydrogen sulphide.



At temperatures of well over 1000º C magma will be entirely liquid because there is too much energy for anything to bond together. As the temperature drops, usually because the magma is moving upward into a cooler part of the crust, crystals will start to form.

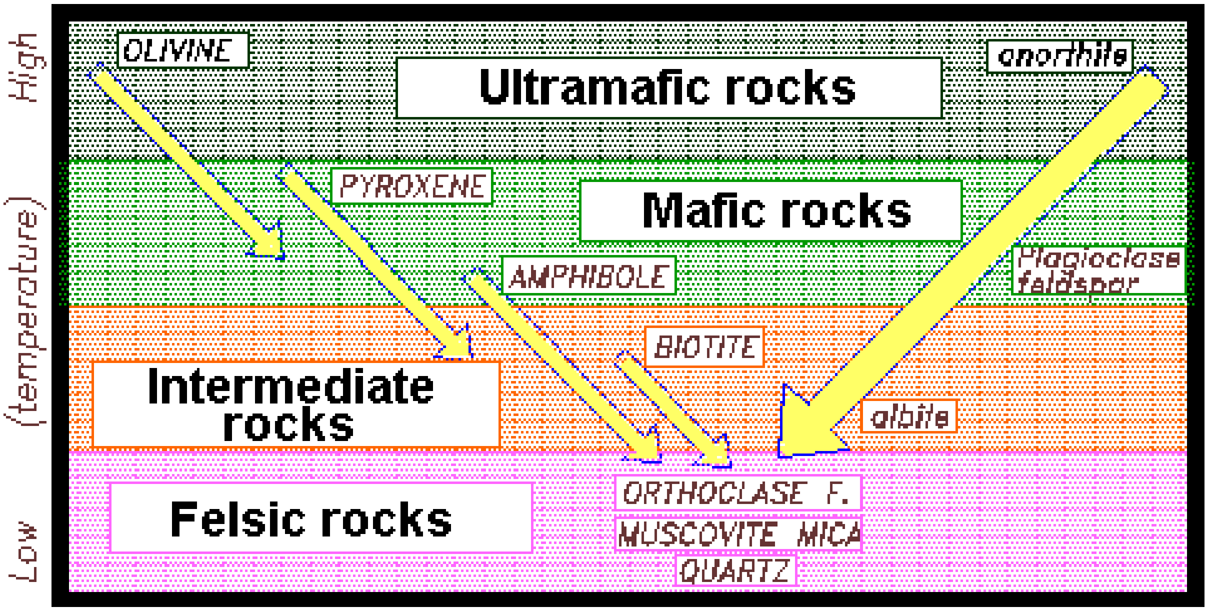
The minerals that make up igneous rocks crystallize at various different temperatures. This explains why a cooling magma can have some crystals within it, and yet remain predominantly liquid. The sequence in which minerals crystallize from a magma is known as the **Bowen Reaction Series** [see the figure on the following page and Figure 3.8 in the text]. Of the common silicate minerals, olivine normally crystallizes first. Olivine is followed by pyroxene, then amphibole and then biotite mica. At about the point where pyroxene begins to crystallize the plagioclase feldspars also begin to crystallize. Calcium-rich plagioclase (anorthite) has the highest melting point, and the more sodium-rich plagioclases have lower melting points.

The plagioclase series is described as a *continuous series* because a plagioclase crystal that forms early in the cooling sequence (when the magma is hot) will tend to be relatively anorthitic (calcium-rich). As the magma cools, plagioclase of progressively more albitic composition (sodium-rich) will form around the original crystal. The result is that plagioclase crystals are commonly zoned, with a relatively calcium-rich core and a relatively sodium-rich rim.



Plagioclase and the various ferromagnesian minerals are followed in sequence by orthoclase feldspar, muscovite and finally quartz.

BOWEN REACTION SERIES



It's called the *Bowen* *Reaction* *Series* because once a mineral has crystallized it may continue to react with the remaining magma to form different minerals. For example, as the temperature drops the olivine crystals might combine (react) with silica left in the magma to form pyroxene, and pyroxene may later combine with more silica to form amphibole. Therefore, although olivine might have been the first mineral to crystallize out of a magma, when that magma is finally completely cooled it may contain no olivine[1].

On the other hand, because some of the minerals which first crystallize are likely to be heavier than the magma, they may settle to the bottom of a magma chamber and thus become essentially isolated from the rest of the magma. (This is especially true for relatively non-viscous mafic magma.) The rest of the magma will then have a different composition than the original magma (for example it will have less iron and magnesium), and if some magma is then forced out of the magma chamber (into a dyke or as a volcanic eruption) it will produce rocks of different composition than the original magma. This process is known as **fractional crystallization**.

If the cooling rate is slow, crystals will continue to form until the entire body is solid. The resulting rock will be composed of relatively large crystals. If the cooling rate is rapid, as in the case of a volcanic eruption, crystals will not have time to form, and the resulting rock will be extremely fine-grained or even glassy.

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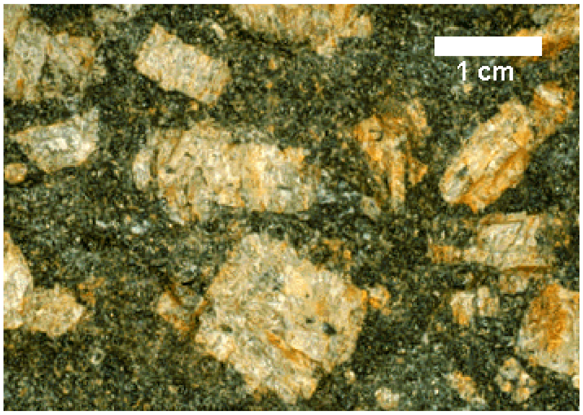
[1] This type of reaction - between a solid mineral and the liquid magma - will only take place at very high temperatures. At lower temperatures (such as at surface temperatures) there would be no tendency for olivine to be altered into pyroxene.

In some cases some crystals will already have formed within a cooling body of magma when some of that magma is forced to the surface in a volcanic eruption. The extruded magma will cool very quickly and the uncrystallized material will harden into very fined grained rock. The result will be a rock that has the relatively large crystals originally present at the time of extrusion suspended in a fine matrix. This texture, which is called **porphyritic**, is illustrated on the figure to the right.



C2 - Igneous Rock Classification

Igneous rocks are classified according to their texture and their composition. In describing texture we are generally referring to the average size of the mineral grains present, but other important characteristics include the relative sizes (i.e., whether a mineral is present in large grains relative to other minerals) and the presence or absence of cavities.

In terms of grain size and texture, igneous rocks are described as:

GLASSY	no mineral grains or crystals are actually present [Fig. 3.13E][2]
APHANITIC	mineral grains are present, but they are too small to distinguish with the naked eye [Fig. 3.13B]
PHANERITIC	individual mineral grains can be seen with the naked eye (average grain sizes range from fine (< 1 mm) to coarse (> 5 mm)) [Fig. 3.13C]
PEGMATITIC	most of the mineral grains are greater than 1 cm across [Box 3.3 on p. 78]
PORPHYRITIC	there are large crystals of one of more minerals set within a groundmass of finer-grained material [Fig. 3.13D and the photo above]
PYROCLASTIC	there are angular fragments of volcanic rock within a finer-grained matrix [Fig. 3.16]

Intrusive igneous rocks are generally **crystalline** (i.e., phaneritic and more rarely pegmatitic) because they have had a long time to cool. The crystals, which are large enough to see with the naked eye, are mostly angular or irregular in shape. **Intrusive porphyritic** textures are formed in cases where some minerals have crystallized from a magma over a long period, and then the

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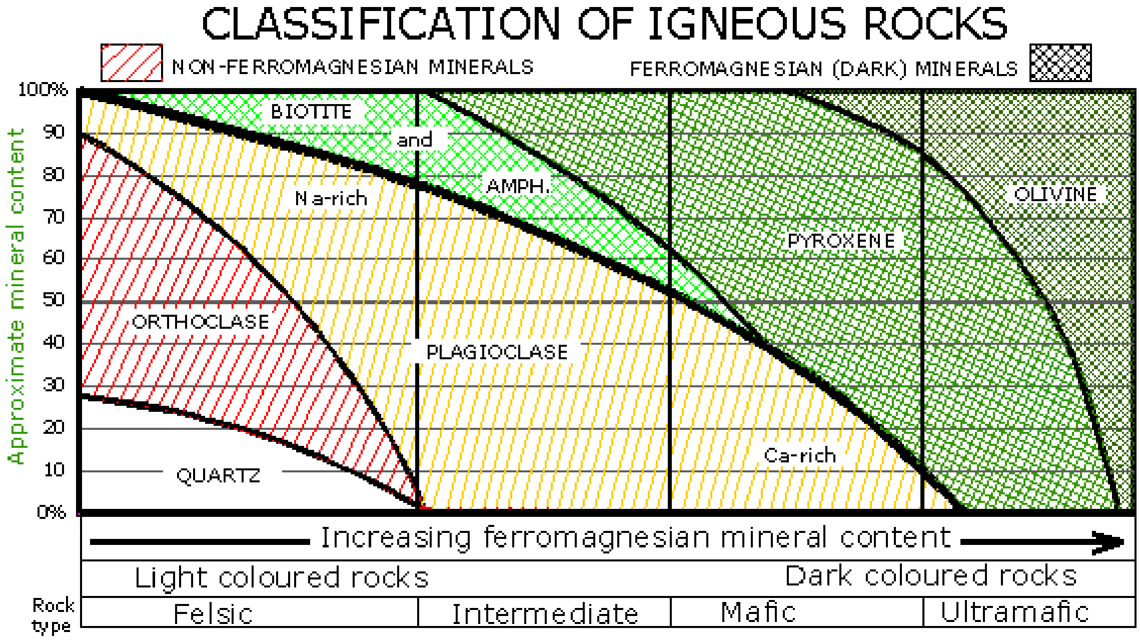
[2] Note that rocks comprised of "glass" (as opposed to mineral grains) do not always look *glassy*. Some do, such as **obsidian**, but others, such as **pumice**, are typically dull in appearance.

magma is pushed up closer to surface where the surrounding rock is cooler and the remaining crystals form quite quickly and are smaller.

Extrusive (i.e., volcanic) rocks can be glassy, aphanitic, porphyritic or pyroclastic. In many cases glassy volcanic rocks are also vesicular, which means that they are full of air cavities created by the gases in the magma [Fig. 3.14]. **Extrusive porphyritic** textures result when some minerals have crystallized from a magma over a long period, and then a volcanic eruption takes place, so that the rest of the magma suddenly cools and crystallizes. Pyroclastic textures result when fragments of rock and glass are ejected explosively during an eruption and then accumulate on the ground around the vent.

The composition of an igneous rock is described on the basis of the minerals present. The broad compositional classes are **felsic** for rocks that are dominated by non-ferromagnesian minerals and **mafic** for rocks that are dominated by ferromagnesian minerals. Rocks with compositions between mafic and felsic are termed **intermediate**, while those with an overwhelming predominance of ferromagnesian minerals are termed **ultramafic**. Felsic and intermediate rocks are also known as **SIALIC** - which refers to the predominance of silica and alumina, while mafic and ultramafic rocks are known as **SIMATIC** - referring to the predominance of magnesium and iron. The classification of igneous rocks is summarized below. There is a equivalent, but slightly different diagram in the textbook [Figure 3.12], but the figure here should be used in this course.



Textures	ROCK NAMES			
Phaneritic	GRANITE	DIORITE	GABBRO	ULTRAMAFIC
Aphanitic	RHYOLITE	ANDESITE	BASALT	
Porphyritic	PORPHYRY			
Glassy	OBSIDIAN or PUMICE			
Pyroclastic	TUFF, AGGLOMERATE or BRECCIA			

Felsic rocks are composed largely of feldspar (either orthoclase feldspar (potassium-feldspar) or sodium-rich plagioclase feldspar (or both)), plus quartz and up to 10% ferromagnesian minerals (either biotite or amphibole). Examples are **granite** (intrusive) and **rhyolite** (extrusive).. **Intermediate** rocks are dominated by plagioclase feldspar. They typically have small between 20 and 50% ferromagnesian minerals (usually pyroxene and amphibole). Examples are **diorite** (intrusive), and **andesite** (extrusive)[3].

Mafic rocks are dominated by plagioclase feldspar and ferromagnesian minerals. They have no quartz or orthoclase feldspar, but they can have up to 50% plagioclase and between 50 and 80% ferromagnesian minerals (primarily pyroxene, with some olivine). Examples are **gabbro** (intrusive), and **basalt** (extrusive).

Ultramafic rocks are dominated by pyroxene or olivine, and may contain a small amount of calcium-rich plagioclase. Examples are **dunite** (olivine rock), **pyroxenite** (pyroxene rock) and **periodotite** (pyroxene and olivine rock), all of which are intrusive.

C3 - Intrusive Igneous Rocks

Most igneous rocks cool within the earth, rather than being extruded to surface by volcanoes. They are known as **intrusive** or **plutonic** igneous rocks. A **pluton** is any body of intrusive igneous rock. Plutonic bodies can be tabular, cylindrical or somewhere between equidimensional and irregular. Various types of plutons are shown on Figures 4.28, 4.29 and 4.30 in the text. Plutonic rocks are always intruded into pre-existing sedimentary, igneous or metamorphic rocks. When we discuss the geology of an area with plutonic rocks, the pre-existing rocks, into which the plutonic rocks have intruded, are referred to as **country rocks**.

The photograph to the left, taken at Caulfeild Cove near to Horseshoe Bay, shows granitic rock (the light-coloured rock on the right) that has intruded into pre-existing metamorphic rock (the dark-coloured rock). In this case the metamorphic rock is called the *country rock*.

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[3] Many igneous rocks related to subduction processes have compositions close to the dividing line between **felsic** and **intermediate**. The intrusive forms are known as **granodiorite**, while the extrusive forms are known as **dacite**. Much of the Coast Range Plutonic Complex of British Columbia is granodiorite. The 1980 eruption of Mt. St. Helens was dacitic in composition.

Tabular plutonic bodies are described as being **concordant** if they lie parallel to the bedding (i.e., in layered sedimentary, metamorphic or volcanic rocks), or **discordant** if they are at some angle to the bedding (in layered rocks) [Fig. 4.30]. In rocks without any pre-existing layering (such as granite) all tabular plutons are considered to be discordant. Whether or not a tabular body is horizontal, inclined or vertical has no bearing on its designation as a dyke or a sill, the critical factor is its relationship to layering in the host rock.

Dykes (or dikes) are discordant tabular bodies intruded into faults and fractures. In order to be fractured the country rocks must already be quite cool. Dykes range in thickness from a few mm to over a km. They are most commonly of mafic composition (largely because mafic magmas are less viscous than felsic magmas, and therefore can flow into smaller cracks). When magma is intruded into a fracture in cool country rock the magma cools down quite quickly, especially at its edges. The effect of this rapid cooling is that the margin of the dyke will commonly be finer grained than the interior of the dyke. This is known as a **chilled margin**. An example of a dyke is shown on Figure 4.29 and on the photo of the Stawamus Chief below.

Sills are concordant tabular bodies intruded along boundaries between sedimentary or volcanic layers. The magma actually pushes the layers apart. This could not happen at significant depth because the overlying weight would not allow the beds to be pushed apart - thus sills are generally shallow features. An example of a sill is shown on Figure 4.30.

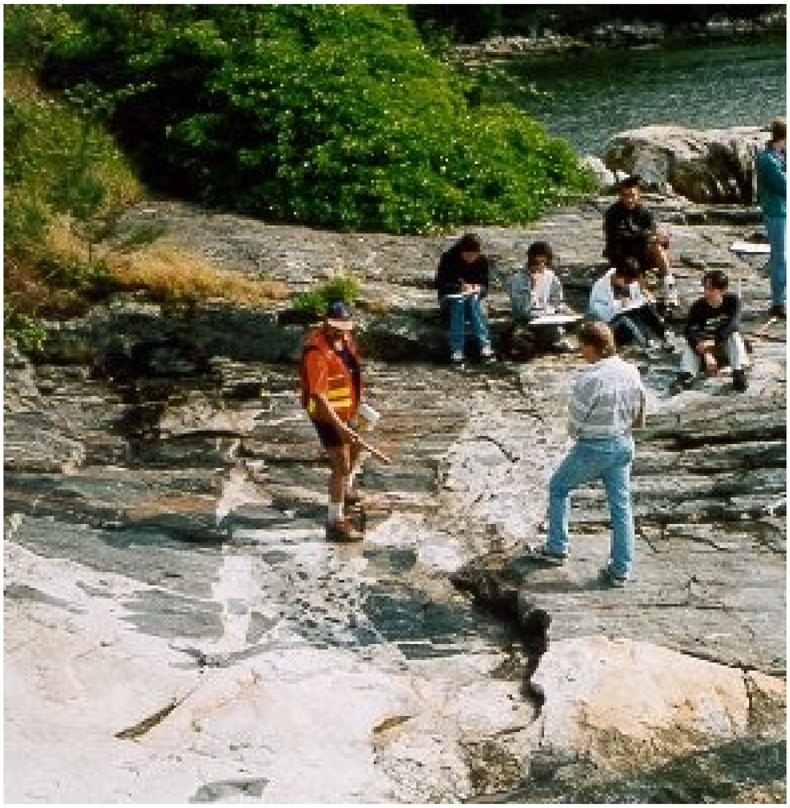
A **laccolith** is formed when a relatively viscous (i.e., felsic magma) is intruded between sedimentary or volcanic layers, and pushes up the overlying strata. A **pipe** is a cylindrical body that was probably a feeder conduit to a volcano or to another intrusive body.

The Stawamus Chief, a 600 m high granite cliff situated near to Squamish. It is part of a batholith within the Coast Range Plutonic Complex.

Note the large mafic dyke extending from bottom to top in the centre of the cliff. The dyke is several metres in width.

Batholiths and **stocks** are large bodies of intrusive rock that are more equidimensional or irregular in shape than sills, dykes and pipes. The distinction between "stock" and "batholith" is based on the area exposed at surface. A batholith has a exposed surface area of at least 100 square km, while a stock has an area of less than 100 square km [see pages 116 and 117]. Most batholiths and stocks are granitic in composition, although dioritic bodies are not uncommon. Some large mafic and ultramafic plutons are known, and they are usually distinctively layered because of the high proportion of heavy ferromagnesian minerals, and, more importantly, because the mafic magma is less viscous than felsic magma (hence the mafic minerals that crystallize early are able to settle to the bottom). Some batholiths are extremely large. Outside of the Pre-Cambrian shield areas, the largest of all batholiths is the Coast Range Plutonic Complex, which extends from southwestern B.C. into the southwestern Yukon (and is easily visible at Horseshoe Bay). Large batholiths, like the Coast Range Batholith, are commonly made up of numerous smaller batholiths and stocks of varying composition, intruded over tens or hundreds of millions of years. Large batholiths are also very thick (in the vertical sense) and may extend down to the base of the crust.

A batholith forces its way upward by pushing the pre-existing rocks aside. This is possible at depth because the country rocks will be warm and relatively plastic. Near to the surface the upward force of the batholith breaks and dislodges the more brittle country rock, which is then incorporated into the magma. This process is known as **stoping**. Pieces of country rock that break off and fall into the magma are known as **xenoliths**[4].



There are lots of dark xenoliths visible in the photograph to the right, which was taken at Caulfeild Cove near to Vancouver.

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[4] *xenolith* - from the Greek: *xeno* - strange, *lith* - rock

C4 - Volcanic Eruptions and Volcanic Rocks

There is a great deal of variability in the characteristics of volcanic eruptions and the resulting volcanic rocks. The factors that are important in determining these characteristics are as follows:

- **The chemical composition of the magma (i.e., whether it is felsic or mafic)**
- **The amount of dissolved gas within the magma**
- **The site of the eruption (e.g., whether it is on land or under water)**

As discussed previously, felsic (rhyolitic) magma is always more viscous (less runny) than mafic (basaltic) magma. (refer to the rock classification diagram above to review the differences between basaltic and rhyolitic compositions). Mafic magmas are generally runny enough—like warm honey— to flow out over large distances, while felsic magmas are much more viscous—like cold porridge—and don't get very far.

All magmas contain gases, such as H_2O, CO_2, SO_2, N_2 and H_2S and. Because they are partly or even largely derived from crustal material (rather than the mantle), felsic magmas tend to have higher gas levels than mafic magmas. At depth in the crust the pressure is sufficiently high that these gasses remain dissolved in the magma— just like the CO_2 in a bottle of pop[5]. The pressure drops as the magma moves closer to surface, and when the pressure has dropped to a critical level (which takes place within hundreds of metres of surface) gases bubble out of the magma and the overall volume increases dramatically. If the pressure of the magma results in rupture of the rock that is confining it (or if there is some other event which results in a pressure drop), then a violent eruption may take place. If the magma is mafic it is likely that the gasses will have a chance to migrate upwards and escape without forcing out a large volume of magma. Even while the gases are venting, a mafic magma may continue to flow out steadily and relatively slowly. If the magma is felsic, on the other hand, its higher viscosity will inhibit the upward migration of gases, and when the pressure on these gases is finally released there will be a very large explosion. Unlike the steady flow of basaltic lava that takes place during a mafic eruption, a felsic magma eruption produces mostly **pyroclastic** material - individual rock fragments, most of which cool and harden in the air. These are accompanied by a great deal of ash (microscopic rock fragments) and hot gases.

Most composite volcanoes are steep-sided, and many are very high, with extensive snow packs and glaciers [Fig. 4.1]—even those in tropical regions. When eruptions take place on these types of mountains it is typical for a lot of ice and snow to melt, producing dangerous floods. Along with the water comes a great deal of unconsolidated pyroclastic material - from both the current eruption and from previous eruptions. This violent flood of water and suspended sediment is

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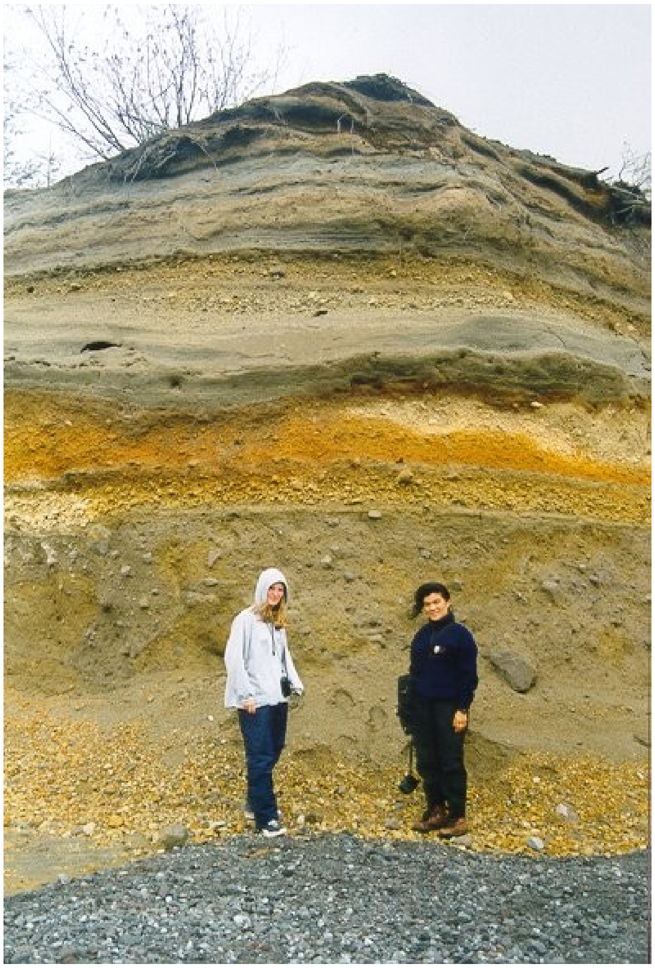
[5] Pop is bottled under pressure with carbon dioxide. As long as the pressure is maintained the CO_2 remains dissolved in the pop - even if it is shaken. As soon as the pressure is released (i.e., when the lid is removed) some of that CO_2 comes bubbling out of the liquid. The continued relatively slow release of CO_2 bubbles gives the pop its fizzy taste. This bubbling process is enhanced dramatically if the contents are shaken because shaking promotes nucleation of the bubbles. A bottle of pop is a good analogue of a volcano. The traditional baking soda and vinegar experiment carried out frequently in elementary schools is not such a good analogue, but the results are more controlled and less sticky!

known as a **lahar**. Lahars can be deadly because they normally extend for tens of kilometres away from the volcano, and because they flow along valleys, areas that are commonly quite densely populated. Some Mt. St. Helens lahar and pyroclastic flow deposits are shown in the photo below.



In this photo the lowermost layer (which ends just above the heads of the geology students) is a lahar deposit. The overlying orange layer is a pyroclastic flow deposit, the next layer is another lahar deposit, and the layer above that is another pyroclastic flow. The upper layers are lahar deposits, including the uppermost one, which is from the 1980 eruption.

The magma that erupts at hot-spot volcanoes like Hawaii is consistently mafic, and it tends to flow relatively gently and steadily. Most terrestrial mafic volcanic deposits are extruded as **lava** that spills out over the land [Figure 4.5 A and B]. When mafic lava erupts in one location over a period of hundreds of thousands or millions of years it is likely to lead to the development of a shield volcano. The volcanic islands and mountains of Hawaii are shield volcanoes [Pages 101 and 102] as are most of the volcanic mountains of Iceland. These mountains have relatively gentle slopes (generally between 2 and 10°) because the lava can spread out over a wide area. Eruptions are frequent, but generally not very violent.

Although the most spectacular volcanoes are on land, most volcanic activity actually takes place under water, particularly along spreading ridges, but also above ocean-ocean subduction zones, and at oceanic hot-spots. At a spreading ridge the relatively liquid mafic magma is forced into the crack between the plates and then out onto the ocean floor. Such an eruption is not likely to be violent, both because most oceanic magmas are mafic, and also because the pressure of the deep ocean water confines the extruding magma. Under water, lava commonly flows out in blobs that accumulate on the ocean floor forming pillows. More intense flows will result in thick layered deposits. The Triassic aged (approx. 220 m.y.) Karmutsen volcanic rocks, which occur over a large proportion of Vancouver Island, are largely sub-marine pillowed basalts, and the pillows can be clearly seen at many locations around Nanaimo, including the Malaspina Cut.

The photo below shows pillows in basalt exposed on the Juan de Fuca Trail (fir cone for scale)

Thick layers of basaltic rocks will cool relatively slowly, and as they do the material will contract slightly and crack at regular intervals forming 5 to 7 sided columns [as on Figure 4.31].

As shown to the left, there are some good examples of columnar basalts visible from the highway between Squamish and Whistler

Most of the volcanoes associated with subduction zones (such as Mt. St. Helens, Mt. Garibaldi, Mt. Fuji) are derived from magmas of intermediate or andesitic composition. Lavas associated with this type of volcano may flow out as relatively viscous lava for a few thousand years, and then be ejected as pyroclastic material for a few thousand years. The resulting volcanic cone is described as a **composite cone** (or composite volcano) because it is made up of both lava and pyroclastic material [see Figure 4.11]. Some textbook diagrams [but not figure 4.11] show cross-sections of composite volcanoes with regularly alternating lava and pyroclastic layers. In fact this is not a realistic picture. The temporal pattern of mafic versus felsic eruptions is not consistent, and thus the spatial patterns of the two types of eruptive materials are commonly quite irregular.

In some cases the varying compositions of composite volcano eruptions can be attributed to vertical zonation in the magma chamber feeding the volcano. Over time the more felsic magma will rise to the top of the chamber while the more mafic material will sink towards the bottom. In such cases successive eruptions may be increasingly mafic - until there is a major influx of new magma from underneath. Another process that may contribute to the differences in composition is the mixing of two types of magma (from different sources) in the magma chamber.

Some continental volcanic magmas are felsic, or rhyolitic, in composition, and eruptions of these magmas are almost always violent. The resulting volcanic rocks are normally pyroclastic or **tuffaceous** in character. Some of the Devonian (approx. 350 m.y.) Sicker Group rocks of Vancouver Island are pyroclastic rhyolites.

Take a look at the U.S. Geological Survey's excellent websites on Mt. St. Helens: http://vulcan.wr.usgs.gov/Volcanoes/MSH and on the volcanoes of Hawaii http://hvo.wr.usgs.gov/

C5 - The 1980 eruption of Mt. St. Helens

Mt. St. Helens from Spirit Lake (U.S. Geol. Survey photo)

Overview of the geology of the Mt. St. Helens area

All of the rocks of the area around Mt. St. Helens are relatively young in geological terms, and the mountain itself is extremely young. The oldest volcanic rocks in the Mt. St. Helens area are about 40 million years old. (Some examples of the older rocks of the Mt. St. Helens area are shown in the photo below.) Intermittent volcanic activity has continued in this area and all along the Juan de Fuca Subduction zone for the past 40 million years, and most of the rocks underneath and surrounding the mountain are the products of this activity. Although it is likely that there have been other similar volcanic mountains in this immediate area during this period, the formation of Mt. St. Helens, as we know it, did not begin until around 40,000 years ago, by which time any previous mountains had been eroded away. The majority of the rock that makes up Mt. St. Helens was formed long after the end of the last ice age (10,000 years ago), and much of it was created within the past 2000 years.

Lava flows, tephra deposits (the dark layers) and a dyke in some of the older rocks of the Mt. St. Helens area

Like most other subduction-related volcanoes, Mt. St. Helens is a *composite volcano*, which means it is made up of both cooled lavas from flows of basaltic composition (such as the columnar-jointed basalts shown below), and from pyroclastic or fragmental deposits from the explosive eruption of lavas of andesitic and dacitic composition (such as those seen in the second photo below)[6]. In fact, however, Mt. St. Helens is dominated by pyroclastic deposits, which means it is made up largely of chunks of rock (ranging in size from "dust" to huge blocks) that were formed during explosive eruptions. Most of these chunks cooled and hardened quickly—in many cases before they even hit the ground, and as a result they are not very well stuck together. One geologist from the Washington State Geological Survey has described Mt. St. Helens as "a pile of junk".

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[6] Dacite is intermediate in composition between andesite and rhyolite.

Columnar basalts in the Lava Canyon area (from an eruption 2000 years ago)

Pyroclastic and lahar deposits in the Lahar Viewpoint area. The uppermost material is from 1980. Note scars on the trees from the 1980 pyroclastic flow.

The 1980 Mt. St. Helens eruption and its deposits[7]

The May 18th 1980 event was a classic pyroclastic eruption of magma that was primarily of dacitic composition. In the several months leading up to the eruption there was significant and increasing seismic activity around, and particularly beneath the mountain. There was also evidence of a growing bulge on the northern side of the mountain - a result of pressure exerted by magma pushing up from underneath. The eruption was triggered by a magnitude 5.1 earthquake. This caused a large part of the side of the mountain (especially the bulge), to collapse and slide down into the valley below. Like the removal of the cap from a shaken bottle of coke, this release of pressure led to the explosive and violent eruption of the gas-charged magma within and beneath the mountain. [see Box 4.1 on page 93]

Approximately one-third of a cubic kilometre of magmatic material released on May 18th—making this a relatively small eruption compared to some others. For example, over 7 km^3 of volcanic material was released during the 1991 eruption of Mt. Pinatubo in the Philippines, and over 30 km^3 was released from Mt. Tambora in Indonesia in 1815. On the other hand, the collapse and rapid descent of the top and a good part of the side of the mountain is considered to be the largest landslide in recorded history. Some 2.5 km^3 of rock and debris (over 7 times the volume of the eruption itself) were removed from the upper part of the mountain. Following this catastrophic event the mountain was over 400 m shorter than it had been before the eruption.

The initial blast, which followed immediately after the slide, released hot rock fragments, dust and gases - at temperatures of up to about 850^o C and velocities of around 1000 km/h. This explosion devastated an area of around 600 square kilometres (25 by 25 km) to the north of the mountain, knocking down whole forests of full-grown trees as far as 15 km away from the crater. The heat from the exploding material also melted much of the glacier ice on the north side of the mountain, resulting in a massive flow of volcanic debris, mud and water—**lahar**—which extended for over 100 km downstream from the mountain. 35 million cubic metres of sediment reached the Columbia River and disrupted shipping for almost two weeks. Even today, nearly 20 years after the eruption, streams and rivers draining Mt. St. Helens are heavily laden with sediment.

During the latter stages of the eruption volcanic material was ejected upward, forming a huge cloud of pumice particles and dust. Most of the larger particles within this cloud settled around the mountain in pumice deposits which are up to 30 m in thickness, but the finer material travelled for hundreds and even thousands of kilometres. A yellowish-grey sulphury smelling cloud extended well into southern Saskatchewan, and very fine material which ascended into the stratosphere and travelled all of the way around the earth.

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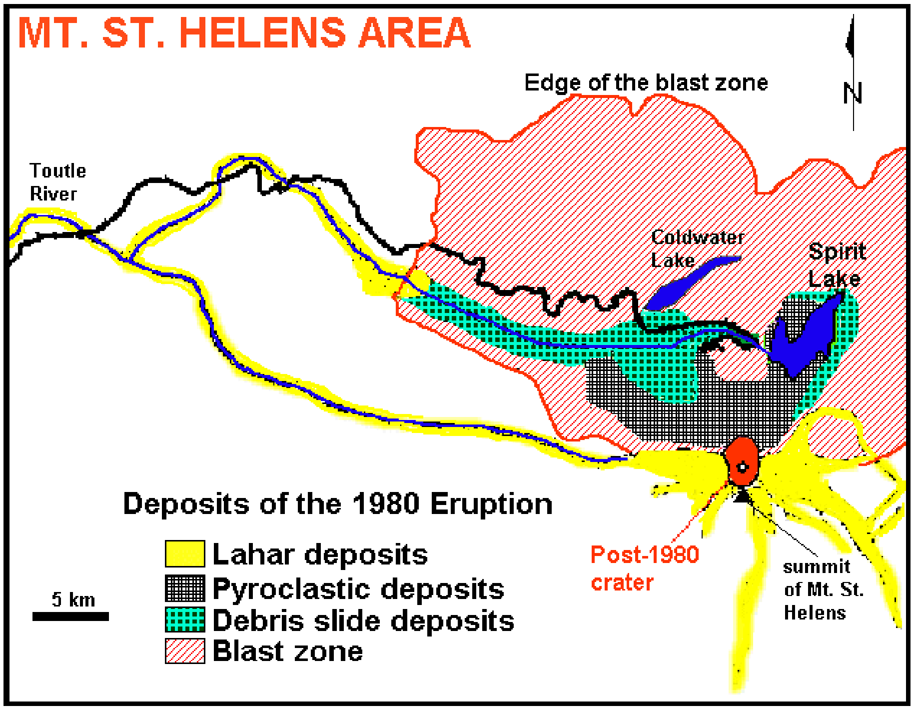
[7] Much of the description here is based on: **Roadside Geology of Mount St. Helens National Volcanic Monument**, by Patrick Pringle, *Washington Department of Natural Resources*, Information Circular 88, published in 1993. The map is also modified from the same source.

The deposits and effects of the 1980 eruption at Mt. St. Helens are shown on the map below. The pyroclastic deposits (fragmental material derived from the erupting magma) are confined to a relatively small area on the north side of the mountain. The slide deposits (or debris avalanche deposits) (made up of material which was within the huge block of rock which slid down the side of the mountain following the triggering earthquake) extends a little further north and also some distance down the valley of the Toutle River. The lahar deposits flowed down all sides of the mountain, but particularly down the valley of the Toutle River (towards the west), and beyond the extent of this map into the Columbia River. The area affected by the initial volcanic blast is shown as the "singe zone". Within this area virtually all trees were knocked down. Most of the area of this map was covered with ash, although, because of prevailing winds most of the ash was directed to the east.

Mt. St. Helens activity since 1980



In the 30 years since the big eruption in May of 1980 a number of small eruptions and explosions have occurred at Mt. St. Helens, and there has been episodic growth of the lava dome within the 1980 crater (as you can see in the USGS photo at the top of this section). This growth is largely attributed to the continued push of lava from underneath. There have also been numerous relatively small earthquakes, both within the mountain, and along a north-northwesterly line trending through the Mt St. Helens area. The seismic and volcanic activity at Mt. St. Helens is monitored closely - probably more closely than at any other volcano in the world. In fact there has been relatively little seismic or volcanic activity in the past 11 years.

In 2004 there was a minor eruption within the Mt. St. Helens crater, and this culminated in lava flows that led to significant growth of the lava dome.

There is a "mountain" of information about Mt. St. Helens on the USGS website: http://vulcan.wr.usgs.gov/Volcanoes/MSH .

C6 - Volcanism in British Columbia[8]

As shown on the map below, all three types of volcanic environments are represented in British Columbia:

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

Subduction volcanism

Southwestern British Columbia is at the very northern end of the Juan de Fuca subduction zone, and there has been a much lower volume of volcanism here than in the U.S. Part of the reason for this may be that there is now some doubt that the northern part of the Juan de Fuca Plate (i.e., the Explorer Plate) is still actually subducting. There are three main volcanic centres in the Garibaldi Volcanic Belt: the Garibaldi centre (including Mt. Garibaldi and the Black Tusk - Mt. Price area adjacent to Garibaldi Lake – see photo below), Mt. Cayley (west of Whistler) and Mt. Meager (northwest of Pemberton). The most recent volcanic activity in this area was at Mt. Meager, some 2400 years ago, but there was significant activity in the Garibaldi area during the last glaciation (at approx. 12,000 and 10,000 years ago).

Mt. Garibaldi (background, centre-left, peak in the clouds). Mt. Price is visible in the centre. Garibaldi Lake was created when a creek was dammed by a lava flow from Mt. Price. Table Mt., the flat-topped mountain in front of Mt. Garibaldi, is a “Tuya”, a volcano formed from lava that erupted beneath glacial ice.

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[8] Most of the material on B.C. volcanism, including the map, comes from an article in May-June 1993 issue of *Canadian Geographic* - **Waiting for another big blast - probing B.C.'s volcanoes**. The article, written by Daniel Wood, is based on material provided by Cathy Hickson, a geologist formerly with the Geological Survey of Canada in Vancouver. There is much more on volcanism in Canada (and BC in particular) at the website of the Geological Survey of Canada: http://www.nrcan.gc.ca/gsc/pacific/vancouver/volcanoes_e.html

from: Canadian Geographic, (May-June 1993)

Hot-spot volcanism

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

The Barrier - a cliff formed when lava from Mt. Price flowed up against glacial ice about 10,000 years ago. The cliff has failed numerous times since then, the most recent incident being in 1865.

Rift-related volcanism

While British Columbia is not about to split into pieces, there are two areas of volcanism that are related to rifting—or at least to extension-produced fractures that extend through the crust. These are the Wells Gray - Clearwater volcanic field southeast of Quesnel, and the Stikine Volcanic Belt, which extends across the northwestern corner of the province. The Stikine area includes Canada's most recent volcanic eruption, a mafic lava flow that took place around 250 years ago at Tseax River Cone in the Nass River area north of Terrace (photo above). The Mount Edziza Volcanic field near to the Stikine River is a huge area of lava flows, sulphurous ridges and cinder cones. The most recent eruption in this area was about 1000 years ago.

Review questions

1. What four processes must take place to transform rocks into sediment?
2. What three processes normally take place in the transformation of sediments to sedimentary rock?
3. What are the processes that lead to creation of a metamorphic rock?
4. According to the Bowen Reaction Series, which mineral will normally be the first to crystallize from a magma, and which the last?
5. What must happen for fractional crystallization to take place?

6. Explain the difference between aphanitic and phaneritic.

7. Explain the difference between porphyritic and pegmatitic.

8. How can **SIMA** and **SIAL** be described in terms of the broad classes of rock compositions?

9. Name the following rocks:

   a) a volcanic rock with 40% plagioclase and 60% pyroxene

   b) an intrusive rock with 65% plagioclase, 25% amphibole and 10% pyroxene

   c) an intrusive rock with 40% quartz, 50% orthoclase and minor amounts of plagioclase and mica

10. With respect to intrusive bodies, what is the difference between concordant and discordant?

11. Why does a dyke or sill commonly have a fine-grained margin?

12. What is the difference between a batholith and a stock?

13. Describe two ways in which batholiths are emplaced into existing rock.

14. Why is compositional layering a common feature of mafic plutons but not of felsic plutons?

15. Why are the viscosity and gas content of a magma important in determining the type of volcanic rocks that will be formed when that magma is extruded?

16. Why do the gases in a magma not form gas bubbles when it is deep within the crust?

17. Where do pillowed lavas form, and from what type of magma?

18. What two kinds of rock textures are typically found in a composite volcano?

19. What is a lahar, and why are they commonly associated with eruptions of composite volcanoes?

20. Explain why the shield volcanoes of Hawaii have such gentle slopes.

21. Is Mt. St. Helens an old volcano? Explain.

22. What geological event triggered the 1980 Mt. St. Helens eruption, and how did this lead to a very violent explosion?

23. The three main deposits of the 1980 eruption of Mt. St. Helens are the debris avalanche, the lahars and the pyroclastic deposits. Which of these has the greatest areal extent, and which the least?

24. What triggered the development of the lahar flows at Mt. St. Helens?

25. What type of eruption at Mt. St. Helens would have produced columnar basalts?

26. Describe the geological origins of the three types of volcanism which are observed in British Columbia.

27. What might be the explanation for the fact that there is much less subduction-related volcanism in southwestern B.C. than in adjacent Washington and Oregon.

28. Which subduction-related B.C. volcano erupted most recently?

29. Which B.C. volcano erupted most recently, and when was it?