D1) Weathering and Erosion

As the term implies, **weathering** takes place when a rock is exposed to the "weather", in other words to the forces and conditions that exist at the earth's surface. Most rocks are formed at some depth within the crust, the only exceptions being volcanic rocks. In order for weathering to take place the rock must first be exposed at surface, meaning that any overlying rock must first be weathered away. A rock that is buried beneath other rock cannot be weathered to any extent.

Intrusive igneous rocks form where magma bodies cool at depths of several hundreds of metres to several tens of kilometres. In most cases sediments are turned into sedimentary rocks only when they are buried by other sediments to depths in excess of several hundreds of metres, and most metamorphic rocks are formed at depths of thousands of metres. These rocks are uplifted through various processes of mountain building—most of which are related to plate tectonics—and once the overlying material has been eroded away and the rock is exposed as outcrop, weathering can begin (see the rock cycle diagram in the Igneous Rocks notes).

Both mechanical and chemical processes are important to weathering, and in most cases they act together to reduce solid rocks to fine-grained sediments and dissolved substances. Mechanical weathering provides fresh surfaces for attack by chemical processes, and chemical weathering weakens the rock so that it is more susceptible to mechanical weathering. The important agents of mechanical weathering are as follows:

a) a decrease in pressure that results from removal of overlying rock
b) freezing and thawing of water in cracks in the rock
c) formation of salt crystals within the rock, and
d) plant roots and burrowing animals

When a mass of rock is exposed by weathering and by removal of the overlying rock there is a decrease in the confining pressure on the rock, and a slight expansion of the rock volume. This unloading promotes cracking of the rock – known as **exfoliation -** and the development of cracks leads to other kinds of weathering [see page 127].

Expansion and exfoliation have affected this granite adjacent to the Coquihalla Highway. Erosion in this area is also greatly enhanced by freezing and thawing.

Frost wedging is the process by which the water seeps into cracks in a rock, expands on freezing, and thus enlarges the cracks

[Figure 5.3]. The effectiveness of frost wedging is related to the frequency of freezing and thawing. Frost wedging is most effective in a climate like ours. In warm areas where freezing is infrequent, in very cold areas where thawing is infrequent, or in very dry areas, where there is little water to seep into cracks, the role of frost wedging is limited.

When salty water seeps into rocks, and then the water is evaporated on a hot day, salt crystals grow within cracks in the rock. These crystals exert pressure on the rock and can cause it to weaken and break. There are many examples of this on the rocky shorelines around Nanaimo.

An example of honeycomb weathering (caused by salt crystallization) on Gabriola Island

The effects of plants and animals are significant in mechanical weathering. Roots can force their way into even the tiniest cracks, and then widen those cracks as they grow [Figure 5.7]. Although animals do not normally burrow through solid rock, they excavate and remove huge volumes of soil, and thus expose the rock to weathering by other mechanisms.

The effects of chemical weathering are two-fold. Firstly, the conditions at surface lead to the alteration of many minerals from one type to another. For example feldspar can be altered to clay minerals, or pyrite to limonite. The altered minerals are commonly softer and more easily weathered than the original minerals. Secondly, some minerals – such as calcite – can be completely dissolved in surface and shallow groundwater.

In comparison with the environment in which most rocks are formed, the surface environment is characterized by:

- **oxidizing conditions (i.e., lots of free oxygen)**
- **wet conditions**
- **relatively low temperatures**
- **low pressures**

Many of the minerals present in some rocks are simply not stable under these conditions, and will gradually be altered to other minerals. As a rule-of-thumb, the higher the temperature at which a mineral was formed, the more likely it is to be altered under surface conditions.

The Bowen Reaction Series provides a useful guide to the relative susceptibility of silicate minerals to chemical weathering. Of the silicate minerals, olivine, pyroxene and calcium-rich plagioclase are the least stable at surface, while quartz is the most stable. In fact quartz could almost be considered to be completely resistant to chemical weathering. The unstable minerals will react with water and weak acids to form various other minerals. For example - ferromagnesian silicates such as pyroxene and amphibole are readily altered to chlorite or smectite (a clay mineral), while olivine is commonly transformed into serpentine. In the presence of weak carbonic acid produced by carbon dioxide in the atmosphere, feldspars are transformed into clay minerals such as kaolinite, illite or smectite. These chemical weathering products are all softer and weaker than the original minerals and are much more susceptible to mechanical weathering. Sulphide minerals such as pyrite are also unstable in the oxygen-rich surface environment, and will react with oxygen and water to form sulphuric acid and iron oxide minerals such as hematite or limonite. Acid rock drainage (a.k.a. acid mine drainage) results from the oxidation of sulphide minerals that have been exposed during a mining, quarrying or construction operation.

The general effect of chemical weathering of silicates is that mafic minerals will be broken down much more readily than felsic minerals. When a rock is weathered a large proportion of the mafic mineral grains will be broken down into clay minerals, and much of the iron and magnesium may eventually be dissolved and end up in the oceans. On the other hand, a relatively large proportion of the felsic mineral grains - especially quartz - will remain as fragments. These fragments, along with the clay minerals, will be incorporated into sedimentary rocks. This process is extremely important because it leads to the transformation of mafic rocks originally derived from the mantle (such as volcanic rocks) into the more felsic rocks (such as sandstone and shale) typical of sialic continental crust - and thus contributes to the building of continents.

Limestone is an important example of a rock that will dissolve completely under certain surficial conditions (photo to the right). Water combines with carbon dioxide in the atmosphere (or in the soil) to form a weak acid (carbonic acid). This acid reacts with the calcite in limestone in the same manner as the hydrochloric acid in the lab-kit acid bottles. Some of the calcite's carbonate ion is released as carbon dioxide gas, and the rest, along with the calcium ion, is removed in solution.

Surface water has dissolved this limestone to produce a surficial weathering feature known as epikarst.

The combined effects of mechanical and chemical weathering serve to weaken, soften and break up rocks so that they are more susceptible to erosion. Erosion involves removal and transportation of rock and rock products by water, wind, ice and gravity. Gravity alone is an important agent of erosion in areas of high relief. Steep slopes are eroded by a variety of processes that are collectively known as **mass wasting**, and are summarized in [Chapter 14].

Water is the most important agent of erosion and transportation of geological materials, except in very dry or very cold regions. Water removes loose particles from the surface, and washes them into channels and eventually into streams. Creeks and rivers transport both large and small particles, and promote breakdown of large pieces into smaller pieces. Stream water itself can erode bedrock directly, but the abrasive effect of silt, sand and gravel particles moved by the water is much more significant. Most of the material transported by a river is suspended in the water. This normally includes clay and fine silt, but in fast-flowing rivers or during flood events, sand, gravel and even boulders can be carried suspended within the water. The size of particles that will be moved by water is directly proportional to the velocity of the water. In most streams much more sediment is moved during the infrequent periods of flooding (perhaps only a few days in a year) than during the long periods of normal flow.

Sediments of varying sizes are moved by streams. As the water slows down - either because it reaches an area of lower gradient or because a flood event such as a storm comes to an end - material that was being transported will be deposited. The gradient, and hence the water velocity, tends to decrease over the distance between the headwaters and the mouth of a river, and thus coarse material tends to be deposited in the steeper upper parts, while finer material tends to be deposited in the flatter lower parts. The ultimate decrease in velocity takes place where a river enters the sea (or a large lake). Here the velocity drops to almost zero, and eventually even the fine particles settle out.

The lake in the foreground of this photo is Atlin Lake in northwestern BC. The snow and ice-covered mountains in the background are part of the Coast Range Plutonic Complex along the BC-Alaska border. In its headwaters this river is steep and fast and can move large boulders and cobbles. In its lower reaches the river slows down and is depositing gravel and sand. Where the water enters Atlin Lake it slows down even more, and silt and clay are deposited.

Wave action and longshore currents are an effective means of both erosion and transportation of material along marine shore lines.

Glacial ice sheets are extremely effective in eroding and transporting geological materials. Ice grinds away at bedrock and remove pieces of rock ranging in size from microns to tens of metres. Rock fragments are carried on top, within and at the base of ice sheets. Water from the melting ice also moves a huge amount of material in a glacial environment. Glacial erosion is discussed in more detail later in this course.

Both running water and moving ice erode deep channels into rock masses, creating steep slopes and cliffs. Rock fragments dislodged from these slopes by ice wedging and other mechanisms are moved by mass wasting. In some cases steep slopes are created when bodies of rock are displaced by faults, hence mass wasting can be an important factor even where water and ice erosion have not taken place.

Wind erosion is most effective in arid environments where vegetation is sparse. Its overall contribution to erosion and transportation of geological materials is small compared those of water and ice.

D2) Sediments and Sedimentary Rock Classification

Sediments and sedimentary rocks are grouped into two main subdivisions, namely **detrital**[1]—which includes rocks made up of material transported as solid particles (i.e., fragments), and **chemical**[2]—which includes rocks made up of material that has been transported in solution. Detrital sedimentary rocks—such as shale, sandstone and conglomerate—are the most abundant by far. Chemical sedimentary rocks include limestone and chert, as well as **evaporite** deposits (i.e., salt deposits left behind from evaporation of lakes and inland seas).

Sediments (rock fragments and mineral grains) are transported by flowing ice and moving water, by wind and by gravity. As discussed previously, the size of particles that can be transported depends on the flow rate. When or where the flow rate decreases some of the material being transported will be deposited. When or where the flow rate increases, any previously deposited material may be picked up.

For example, both coarse and fine sediments can be transported by a rapidly flowing mountain stream, but where the stream flows out into flatter terrain, and the water velocity drops, it will no longer transport the coarse particles. These particles will form a gravel deposit, which might include a mixture of cobbles, pebbles, and sand grains. During a flood event, when the flow rate may increase significantly, some of the previously deposited sand and gravel is likely to be eroded, and then re-deposited further downstream where the velocity drops. Where the stream flows into a lake, or the ocean, the velocity will be reduced to essentially nil, and almost all particles will gradually settle out as a deposit of sand, silt and/or mud.

Thick deposits of sediments, some of which may eventually become sedimentary rocks, exist mostly within river flood plains, in river delta areas, in near-shore and offshore shelf deposits and in the deep ocean. Other environments where sediments accumulate include lakes, deserts and glacial environments.

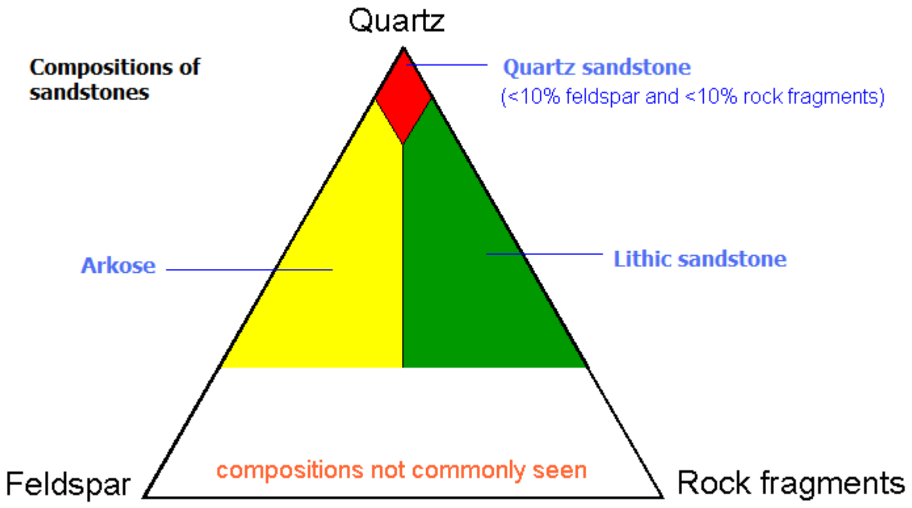
Sediments are converted into sedimentary rocks by **compaction** and **cementation**, a process that is known as **lithification**. Compaction alone may be sufficient to lithify a shale because the particles are small and tabular in shape, but for coarser rocks made up of rounded fragments, the particles must be cemented together. Cements are normally introduced by water percolating through the rock. This water may contain dissolved silica, calcium, carbonate, or iron, and the deposited minerals that comprise the cements include quartz, calcite and iron oxide minerals such as hematite or limonite. These minerals grow in the spaces between the detrital mineral grains.

[1] The words *detrital* and *clastic* are interchangeable. Both can be used to describe sediments or sedimentary rocks that are comprised of fragments of other rock or minerals.
[2] Please don't confuse *chemical sedimentary rocks* with *chemical weathering*. They are two very different things.

Detrital sedimentary rocks are classified on the basis of their maximum grain size and the type of material that they contain. All material smaller than 0.004 mm (1/256 mm) is called **clay**. Clay-sized particles are so fine that you cannot feel them. (Almost all clay-sized particles are **clay minerals**, which are sheet-silicates such as kaolin and illite.) Other sediment-size terms are **silt, sand, granule, pebble, cobble** and **boulder**.

Sediment name	minimum size	Maximum size
Clay	no minimum	0.004 mm (i.e., 1/256 mm)
Silt	0.004 mm	0.063 mm (i.e., 1/16 mm)
Sand	0.063 mm	2.00 mm
Granule	2.0 mm	4.0 mm
Pebble	4 mm	6.4 cm
Cobble	6.4 cm	25 cm
Boulder	25 cm	no maximum

Detrital rocks with particles no larger than silt or clay size are known as **siltstone**, **mudstone** or **claystone** depending on their grain size. Mudstone that splits easily into layers is known as **shale**. Rocks dominated by sand-sized particles (0.063 to 2 mm) are called sandstone. Sandstones which have only a small amount (<10%) of clay-sized material are called **arenite** those with more than 10% clay are called **wacke**.



As shown on the figure to the left, a sandstone that is dominated by quartz sand grains is called a **quartz sandstone**, one that is dominated by feldspar fragments is called an **arkose**, and one that is dominated by rock fragments is called a **lithic sandstone**.

Rocks with maximum particle sizes of 2 mm or more are termed **conglomerate** if the fragments are rounded, or **breccia** if the fragments are angular. The fragments of a conglomerate are normally rounded through the actions of moving water (eg. quartz in a stream or on a beach. The fragments of a breccia are angular because they have been subjected to very little transportation, and certainly no transportation by water.

The composition and texture of a detrital sedimentary rock, particularly sandstone and conglomerate, can tell us a great deal about the history of the rock and the particles of which it is comprised. For example the type of grains (quartz, feldspar, rock fragments) are indicative of the type of rocks and the type of weathering in the area from which the sediments were derived, while the shapes of the grains are indicative of the type and distance of transportation. Some of these features are summarized in the following table.

Feature	Possible interpretation
quartz dominant	strong weathering of feldspar and rock fragments
quartz and feldspar dominant	derivation from an area of granitic rocks, weak to moderate weathering
volcanic rock fragments abundant	derivation from an area of volcanic rocks, weak to moderate weathering
dominantly rounded fragments	significant distance of fluvial (i.e., water) transportation
angular fragments	short distance of transport, or not fluvially transported

Many of the features of detrital sedimentary rocks are also indicative of the depositional environment, and this will be discussed in the next section.

The most common chemical sedimentary rock is **limestone**. Some limestone is formed through biological processes and some limestone is formed through direct precipitation of calcite on the sea-floor. Large thicknesses of limestone accumulate in reefs, as marine animals incorporate the dissolved calcium (derived from weathering of rocks) and carbon dioxide from the atmosphere into their shells and other structures. Limestone is also created in non-reef environments as shells and shell detritus accumulate on the ocean floor. Depending on the environment of deposition, limestone can range from virtually pure calcite, to a shaly mixture of calcite and clay. Significant deposits of limestone accumulate only in areas where there is abundant calcite-producing marine life - that is in shallow warm seawater, typically within about 30^{o} of the equator. The accumulation of huge volumes of carbonate rocks over geological time (such as in the Rocky Mts. – photo to the right) has played a crucial role in the reduction of the proportion of carbon dioxide in the earth's atmosphere.

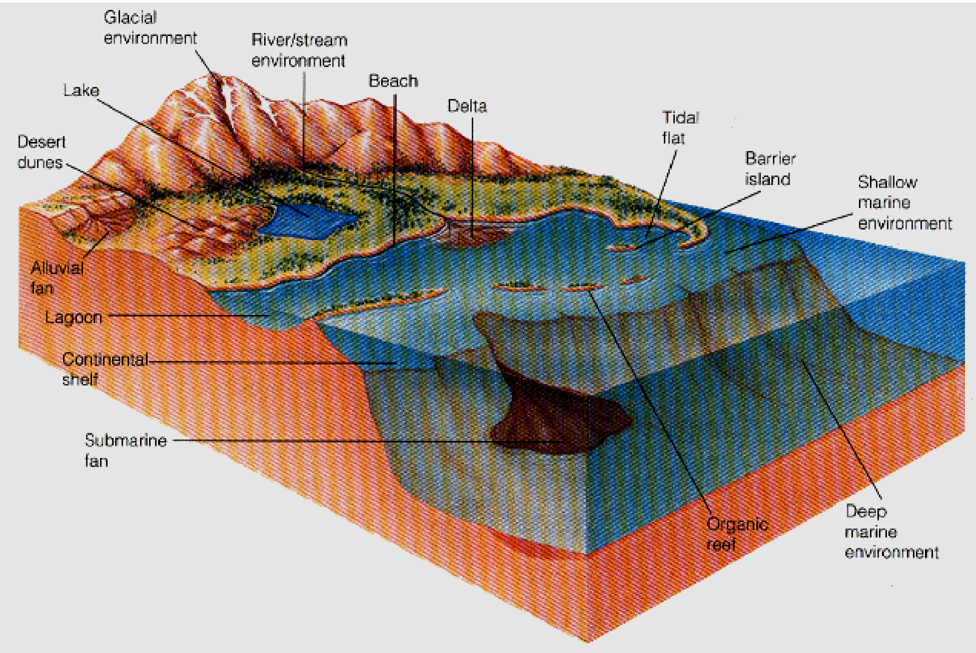
Chert is composed of microcrystalline silica, and is primarily derived from the silica exoskeletons of tiny marine organisms (diatoms and radiolaria), and by precipitation from ocean water. It is not uncommon to find masses and layers of chert within deposits of limestone.

Evaporite deposits form in situations where salt lakes or seas evaporate to the extent that minerals such as gypsum, halite, sylvite (potassium chloride) and others become insoluble. There are very thick and extensive evaporite deposits in Saskatchewan and Manitoba. This area was covered with a huge inland sea around 380 m.y. ago, a sea which dried up periodically leaving salt deposits behind. In some regions these evaporites are rich in sylvite (potassium chloride), and they are mined as a source of potassium fertilizer. Evaporite deposits do not form in the open ocean because the oceans never dry up[3].

[3] Several times in the past few tens of millions of years the Mediterranean Sea has become isolated from the Atlantic Ocean and has eventually dried up leaving behind thick salt deposits. Some of these deposits are still present beneath the more recent clastic sediments on the sea floor.

D4) Sedimentary Environments and Structures

In addition to the classification into **detrital** and **chemical** (as summarized above), sedimentary rocks are divided into two main subdivisions, based on whether they were deposited on the continents or in the oceans. Those deposited on the continents are known as **terrestrial** or **continental** sedimentary rocks, while those deposited within the oceans are known as **marine** sedimentary rocks.



Examples of depositional environments of sediments [There is a diagram like the one above, but more detailed, on pages 156 and 157 of the text.]

Continental sediments are almost exclusively detrital with low levels of organic matter and relatively few fossils. Exceptions are evaporite deposits, which are chemical sediments, and coal-bearing rocks, which are rich in organic matter. Coal-bearing rocks, are sometimes referred to as **organic** in origin.

Marine sediments include detrital rocks such as sandstones and shales, but also chemical rocks such as limestone and chert. Some examples of different continental and marine sedimentary environments are shown on the following figure. A summary of the depositional environments of the common sedimentary rock types is given in the table below.

Rock type	Continental environments	Marine environments
Clastic sediments		
mudrock & shale	lakes and river flood-plains	deep ocean and submarine fans
Sandstone	rivers, deserts (eolian)	deltas, submarine fans
Conglomerate	rivers, glaciers	submarine fans
Breccia	talus slopes	
coal-bearing rock	river-bank or near-shore swamps	
Chemical sediments		
Limestone		shallow to moderately deep ocean
Chert		deep ocean
evaporite deposits	salt lakes and inland seas	

Most continental sediments are transported by flowing water, and deposited on river floodplains or where rivers empty into large lakes. As discussed previously, the ability of a river to transport material is directly related to its velocity. A slowly flowing river will only be able to move relatively small particles - and hence most of its deposits will be fine-grained, including siltstone and fine sandstone. A rapidly flowing river will be able to move larger particles - and hence most of its deposits will be coarse-grained, including coarse sandstone and conglomerate.

During a flood a river will be flowing more rapidly than normal, and will be able to carry large particles. If the river then floods over its bank, the velocity will drop because the water now has a much larger channel in which to flow. The suspended sediments will settle out. The thickest deposits and the coarsest material will be deposited adjacent to the main channel, and thinner deposits of finer material will extend across the flood plain [Figures 15.13]. Coal deposits are created in the flood plains of rivers and in near-shore swamp areas, where there is rich vegetation growth. To eventually become coal the organic matter must remain submerged in water until it is buried by sediment.

Where a river enters a lake, the velocity of the flowing water will also decrease to zero. Coarse material will be deposited at the point where the velocity starts to drop, sand-sized material will be moved on a little further, and silt-sized material further still. Clay sized-material may spread well out into the lake - for up to tens of kilometres (see photo on page 4, above). During flood events the rate of river flow may be many times that of normal flow, and coarse material may be deposited much further out into the lake than under normal conditions.

Marine sediments are derived largely from material transported to the oceans by rivers and streams. As is the case where a river enters a lake, the grain size will decrease away from shore. Sand will be deposited within a few hundred to a few thousand metres of shore, and in the off-shore direction the particle size will gradually decrease to silt and then clay size. As is the case for deposition within lakes, a flood event can result in deposition of coarse material much further offshore than under non-flood conditions. If there is an adequate supply of carbonate material (i.e., calcium-carbonate from marine animal shells), the clay deposits will become increasingly rich in carbonate away from shore and eventually the shale will grade into limestone (at tropical latitudes). These changes in the character of the sediment deposited in what is essentially one sedimentary horizon, are known as **facies changes**[4].

In areas where a rivers empty into the ocean there is commonly very rapid sedimentation and build-up of thick unconsolidated sedimentary deposits. These deposits - which may be a mixture of clay, silt sand and gravel - commonly have a relatively flat profile out to a certain point (a shelf), and then drop off steeply to deeper water[5] (see figure above). The steep slopes at the edges of such shelf deposits are relatively unstable, and they become increasing unstable as more and sediment is loaded onto the shelf. Periodically a shelf deposit will fail (sometimes in response to an earthquake) and a large volume of sediment will flow down the slope creating a **submarine fan** deposit at the base. Such a deposit may be characterized by different grain sizes, depending on the type of material which was within the part of the

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[4] There are some clearly defined facies changes in the Nanaimo Group rocks exposed at the bottom of the Malaspina Cut. Next time you go down the hill, stop near to the bottom of the road cut (just before Jinglepot Rd.) and look at the sedimentary rock on the western side of Highway 19. If you focus on one of the thick layers (i.e., several metres thick), and trace it from the lower edge of the exposure back up the hill towards the unconformity, you should be able to see a change from fine sandstone, to coarse sandstone, to conglomerate, to very coarse conglomerate.

[5] In some cases this steep slope represents the boundary between the continental shelf and the deep ocean (such as on the edge of the Grand Banks in Atlantic Canada), but in others it simply represents a boundary between shallow water and deeper water. (such as in Georgia Strait). The Fraser River is rich in sediment and an extensive shelf exists in the eastern part of Georgia Strait, offshore from Richmond.

shelf which failed - but in most cases the coarser material will settle out close to the source, while the finer material will be transported farther out.

A special type deposit formed within a submarine environment is known as a **turbidite**. In response to a major storm or an earthquake, a plume of sediment-rich water starts to flow down the continental slope, eroding material as it goes. This material is deposited on the deep ocean floor, and as it settles out it forms graded layers, ranging upward from coarse to fine material. The process is repeated tens or hundreds of times forming a sequence of layers with relatively consistent thicknesses in the order of a few centimetres - each layer representing one turbidity flow. Turbidites are quite common in the Nanaimo Group rocks of our area.

Turbidite layers in Nanaimo Gp. rocks of Gabriola Island. The light coloured layers are sandstone that grade upward to the dark material which is mudstone. (See close-up view on the left)

The graded beds of a turbidite are just one example of many different sedimentary rock features and structures [see pages 172 to 176]. The main distinguishing feature of sedimentary rocks is layering or **bedding** [see Figure 6.20]. Bedding is the expression of periodic changes in the nature of sedimentation – such as changes in sediment grain size or composition. Beds can be range in thickness from fractions of a millimetre to tens of metres. Bedding is easily visible in the Nanaimo Group rocks exposed along the Nanaimo Parkway and along shorelines throughout the Gulf Islands. The Rocky Mountains are primarily composed of well bedded sediments.

Deposits formed by moving media (e.g., water or wind) can become bedded along planes that are not horizontal. For example, a river may deposit successive layers of sand along a sloping surface at the down-stream edge of a sand bar, and although the resulting sand deposit may be generally horizontal, it will be made up of a series of sloping layers called **cross-beds** [see Figure 6.21].

The motion of flowing river water or of near-shore waves will create **ripples** in sandy sediments. Symmetrical ripples are created by wave action, and asymmetrical ripples are created by flowing water [Figure 6.25].

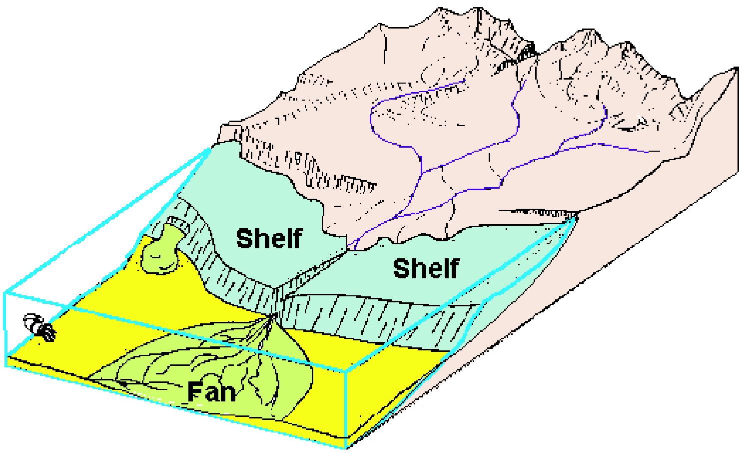
Layers of mud that are allowed to dry will shrink because the clay minerals take up less volume when they are dry than when they are wet. The mud layers will then crack in a characteristic pattern described as **mudcracks** [Figure 6.24].

When the various sedimentary structures described above are preserved in sedimentary rock, they provide valuable clues as to the environment in which the deposits formed (e.g., glacial, fluvial, eolian, deltaic, submarine fan, deep ocean etc.), the direction from which the sediments were transported and whether the rocks are now sitting right-side-up or upside down.

D5) The Nanaimo Group

During the latter part of the Cretaceous Period (from around 85 to 65 million years ago), clastic sediments were deposited in a long trough-shaped basin extending from south of Duncan to north of Campbell River. Deposition probably began just after the micro-continent of Wrangellia - which comprises much of Vancouver Island and some other areas - was accreted onto the edge of North America. The continent-continent collision would have created significant uplift and mountain building, and hence over the period of formation of the Nanaimo Group there would have been rapid erosion and high sediment production in this area. The deposits were derived largely from volcanic, intrusive and metamorphic rocks of the mainland, with some minor contribution from Vancouver Island rocks. The Nanaimo Group includes conglomerate, sandstone and mudstone with important coal beds in some areas[6].

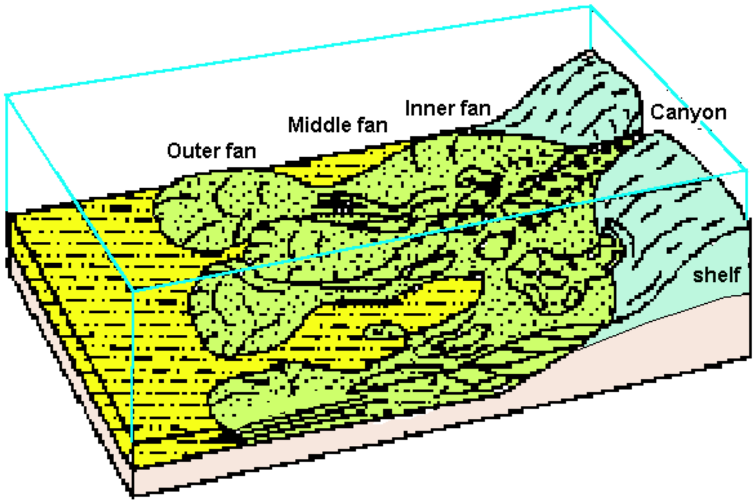
Up until a few years ago it was generally believed that the coarse clastic rocks of the Nanaimo Group (ie. the conglomerate and coarse sandstone) were exclusively the product of deposition by rivers - in continental environments - and that many of the sandy deposits were either fluvial or deltaic in origin. Changes in thinking about similar deposits in other parts of the world, and a better understanding of fossils from the Nanaimo Group, have led to a change in the interpretation of the depositional environment of the Nanaimo Group. It is now believed that most of the Nanaimo Group sediments were deposited in a marine environment, largely as submarine fan deposits.



Sediments of varying grain sizes, which are transported to the ocean in rivers and streams, build up in shelf deposits with extensive nearly flat surfaces, and steep fronts. Periodically the fronts of these shelves collapse, sometimes in response to earthquakes, but also as a result of flooding events. The resulting deposits on the deeper ocean floor are known as sub-marine fan deposits.

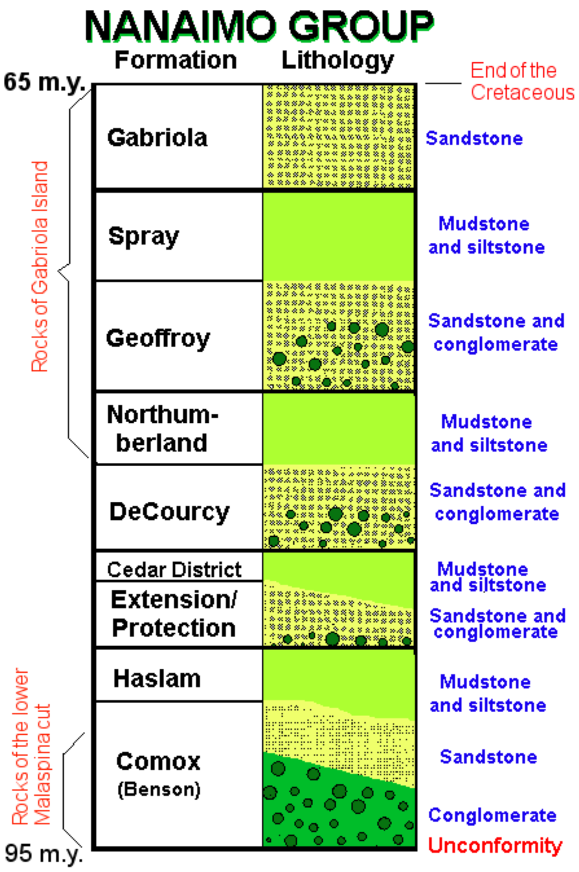
[6] Much of the material presented here, and some of the drawings, are from a Geological Survey of Canada publication: (Mustard, P., (1994) The Upper Cretaceous Nanaimo Group, Georgia Basin, British Columbia, *in* **Geology and geological hazards of the Vancouver Region, southwestern British Columbia**, J. Monger (ed), *Geological Survey of Canada*, Bulletin 481, p. 27-96.), and also from a 1998 field-trip guide to the Nanaimo Group rocks of Pender Island, also by Peter Mustard.

The sub-marine fans reach out to varying degrees onto the abyssal plain. The proximal deposits (inner fan) are generally much coarser grained than the distal deposits (outer fan).



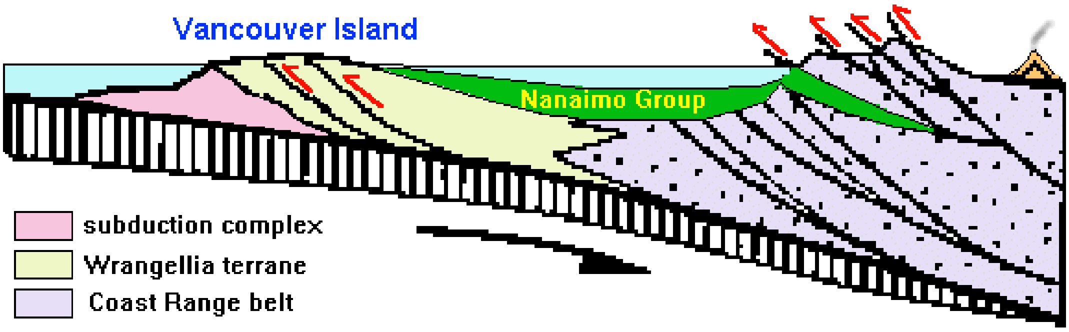
The Nanaimo Group has a total thickness of close to 5000 m. It includes a series of alternating layers of conglomerate, sandstone, siltstone and mudstone.

A likely explanation for the varied nature of Nanaimo Group sedimentation is that there were quite significant variations in the rate of coarse sediment input into the basin. During times when uplift, erosion and sedimentation rates were low, there would have been very slow accumulation of mudstone in the deeper parts of the basin, with coarse material being deposited only near to shore. Following periods of rapid uplift, the sedimentation rates would have been high, high volumes of coarse sediments would have been input, and with the periodic collapse of fan deposits these materials would have been deposited well out into the basin. In this scenario the fine-grained parts of the Nanaimo Group would have been deposited during periods of slow erosion and deposition, while the coarse-grained parts would have been deposited during periods of rapid erosion and deposition.

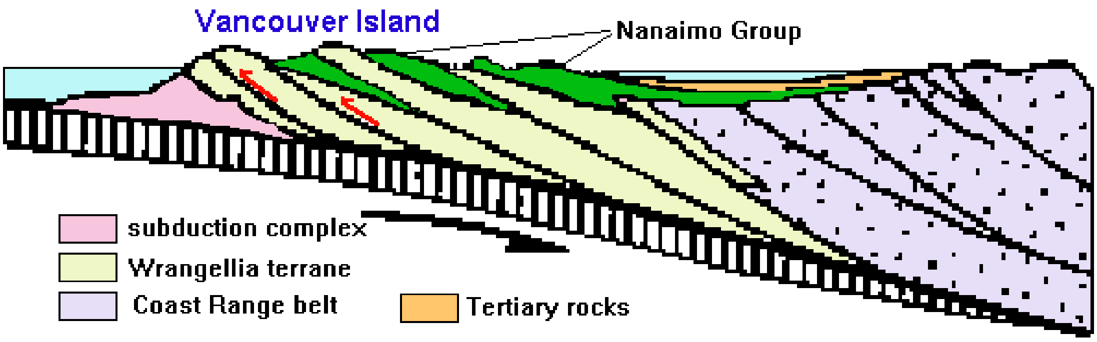


The Nanaimo Group coal deposits, which are largely restricted to the Nanaimo, Courtenay and Campbell River areas, were not deposited in a marine environment. Instead, it is believed that the organic matter which makes up the coal accumulated in near-shore swamps - areas characterized by very rich growth in a tropical environment. For coal beds to be preserved it is essential that the swamp deposits be buried relatively quickly so that the organic matter does not become oxidized. This commonly takes place under conditions of ongoing subsidence (like that in the Nanaimo Basin during the Cretaceous), which results in near-shore swamp areas being periodically inundated and covered with clastic sediments.

During the period in which the Nanaimo Group sediments were deposited (from 95 to 65 m.y. ago), there was continuing subduction of oceanic crust beneath Vancouver Island. As shown below, the area which is now Vancouver Island was probably more topographically subdued than it is now, and hence most of the sedimentation into the basin was derived from the mainland.



During much of the past 65 m.y. both the subduction and the westward thrusting continued. One of the products of this thrusting is that slices of Nanaimo Group rocks have been pushed westward and upward, nearly as far as the central part of Vancouver Island (see below). The rocks of the Wrangellia Terrane (part of the Insular SuperTerrane) have also been pushed up during this time, creating the mountains of Vancouver Island. The Tertiary rocks shown in orange are more recent sediments deposited on top of the Nanaimo Group.



D6) Metamorphic Rocks

Metamorphism is the change that takes place within a body of rock as a result of it being subjected to conditions that are different from those in which it formed. In the strict sense, weathering can be thought of as metamorphism, because under surficial conditions (i.e., low temperature, low pressure, lots of oxygen and water) many minerals formed in igneous environments are not stable and they tend to be altered into other minerals (e.g., feldspar into clay). In general, however, the term metamorphism is used to describe what happens to rocks when they become buried beneath other rocks, and are subjected to higher temperatures and pressures than those at surface.

All minerals are chemically stable only within a specific range of temperatures. As a body of rock becomes buried—through mountain building or subduction—its temperature will rise. The rate of temperature increase is generally between 20 and 30° C for each kilometre of burial[7]. For minerals such

[7] The average rate of temperature change for the crust is 20 to 30° C per kilometre depth. This is known as the **geothermal gradient**. The geothermal gradient differs from place to place, and can be particularly high in areas with volcanic activity, or where there is a magma chamber relatively close to surface.

as clays, a temperature increase of as little as 200° C will be sufficient to cause a transformation into a mineral such as chlorite. At higher temperatures other mineral reactions will take place, resulting in the transformation to minerals such as muscovite, biotite, epidote, garnet and others. Metamorphic reactions commonly result in a general increase in the size of mineral crystals in a rock. For example, a mica-schist will have large crystals of mica, even though its precursor was a shale in which the clay minerals were aphanitic. The presence of water within the rock is critical to the process of metamorphism, and much of that water comes from the minerals themselves. For example, clays have water in their mineral structure and some of that water is released when the clay is converted to a new mineral.

When a body of rock becomes buried it is also subjected to considerable pressure, mostly from the weight of the overlying rock, but also from stresses related to tectonic activity. This normally results in the body of rock being squeezed in one direction, and stretched out in another. The original texture of the rock is changed partly because the body of rock may be stretched or squeezed, but more significantly because the new minerals which are formed tend to be elongated along the direction of the least stress. In other words, if the greatest stress is from east and west, platy minerals like micas or elongated minerals like amphiboles will grow preferentially in the north-south direction. The resulting alignment of minerals is known as **foliation**.

The combined effects of mineral transformation, mineral growth, and deformation, lead to some very distinctive textures in metamorphic rocks. Two well known examples are **schist**, a mica-rich rock in which the mica flakes are aligned to give a platy appearance; and **gneiss**, a quartz and feldspar rich rock in which the minerals are aligned in bands. [see Figure 7.17].

Some examples of the typical products of metamorphism for different rocks under different conditions are listed in the table below. Shale will turn into **slate** at relatively low temperatures, as the clay minerals re-crystallize into very small flakes of mica. At higher temperatures larger mica flakes will develop producing **phyllite**, a rock with a silky texture. Further increases in temperature will produce a mica-schist. Under high-grade metamorphic conditions there will be widespread recrystallization of the minerals to form gneiss, which contains largely feldspar and quartz and some mafic minerals [Fig. 7.2].

Original rock	very low grade	low grade	med-grade	high grade
approx. temp.:	200-350° C	300-550° C	500-650° C	above 650° C
Shale	slate	phyllite	schist	gneiss
Granite	no change	no change	no change	no change
Basalt	chlorite schist	chlorite schist	amphibolite	amphibolite
Sandstone	no change	little change	quartzite	quartzite
Limestone	marble	marble	marble	marble

Granite and rhyolite will be little affected by metamorphism until very high-grade conditions are reached, because most of the minerals which they originally contain were formed at relatively high temperatures, and/or (like quartz) they are stable over a wide range of temperatures. At very high-grades of metamorphism there will be some recrystallization, and gneissic textures will likely be developed.

Basalt will be metamorphosed into **chlorite schist** (a.k.a. **greenschist** or **greenstone** if it is not foliated) at low and medium metamorphic grades[8]. This type of metamorphism is called **retro-grade**

[8] Much of the Karmutsen Fm. basalt around Nanaimo has been weakly to moderately chloritized and some of it is sufficiently strongly chloritized to be called **greenstone**. Most of this rock could not be accurately called chlorite schist or greenshcist because it does not have a schistose texture.

metamorphism because although some heat is necessary to get the minerals to change, the temperature is normally well below the temperature of formation of the basalt in the first place. Basalt is metamorphosed into an amphibole-rich rock (**amphibolite**) at higher grades [see Fig. 7.20].

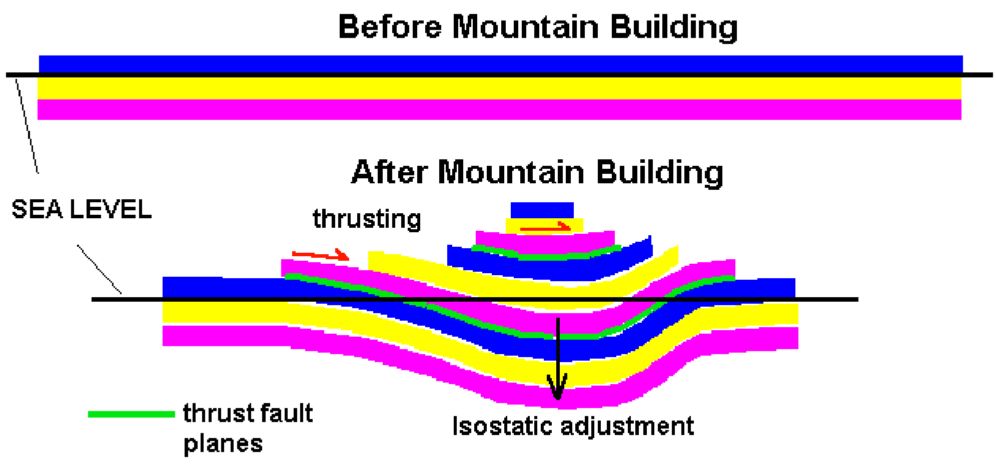
Quartz sandstone will not be significantly affected at low grades, but a higher grades the individual quartz grains will develop quartz overgrowths (i.e., rims of quartz) to produce the very hard rock known as **quartzite**.

At various grades limestone will undergo recrystallization to **marble** - a rock made up of interlocking crystals of calcite or dolomite, but with little or no foliation.

Most metamorphism occurs as a result of deep burial, however there is a special type of metamorphism which takes place adjacent to a magma chamber as it rises through the crust. This is known as **contact metamorphism** and it affects the rocks situated within several hundreds of metres of a hot magma chamber. Since contact metamorphism normally takes place within one or two kilometres of the surface, the rocks affected are not subject to significant pressures, only to very high temperatures. The products of contact metamorphism include **skarn** - when the country rocks include limestone - and **hornfels** - when they don't include limestone.

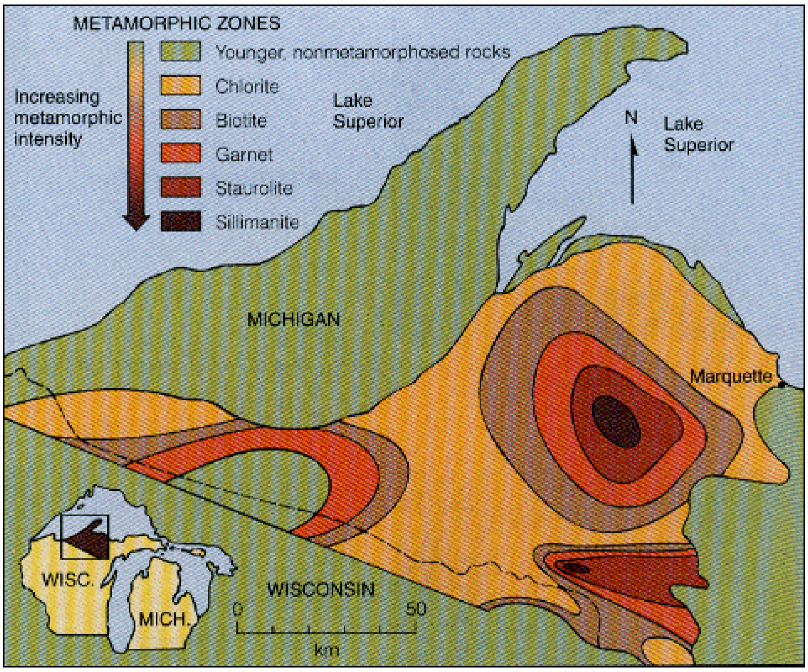
D7) Environments of Metamorphism

Most metamorphic rocks are products of the high temperatures and pressures resulting from deep burial. This burial is commonly a consequence of mountain building, in which large volumes of rock are uplifted or pushed up over top of each other. As the height of the mountains is increased, the depth to which the underlying rock is buried is increased even more because of isostatic adjustment of the crust (see figure below). Burial to a depth of around 20 km (such as that which exists under the Himalayan Mountains) will result in temperatures of 400 to 800° C, and very high pressure, not just from the weight of the overlying rock, but also from the tectonic forces. At these temperatures and pressures mineral transformations will take place and foliation will develop. The rock will become sufficiently plastic to be significantly deformed (e.g., folded and refolded).

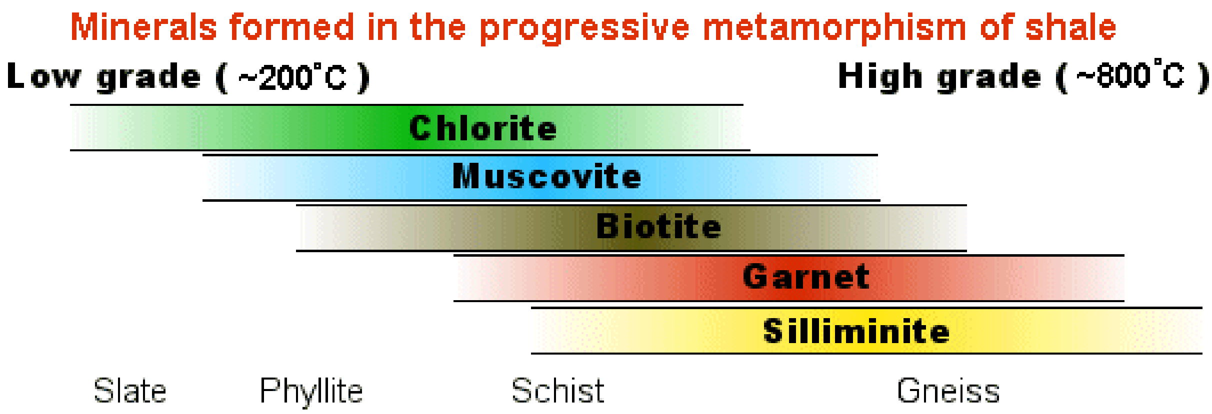


Metamorphism related to tectonic collisions and mountain building is known as **regional metamorphism** because it affects very large areas - areas measured in thousands of square kilometres. The grade of metamorphism is likely to be most extreme beneath the central part of a mountain belt, where the crust is thickest and rocks are buried to the greatest depth. The effects of regional metamorphism are only revealed when a mountain belt is eventually eroded—exposing the rocks which were present deep within the roots of the mountain belt.

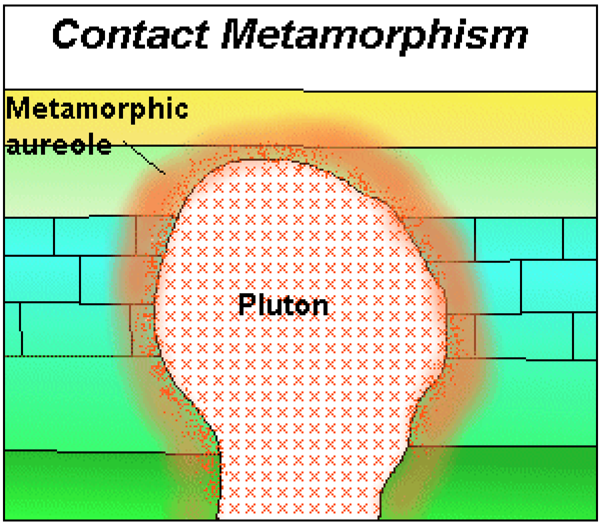
In many areas concentric zones of increasing metamorphic grade have been outlined by examining the metamorphic index minerals within the metamorphosed rock. In the Michigan Peninsula example shown to the right, chlorite is present in metamorphosed rocks at the margins. Towards the centre biotite is present, then garnet, then staurolite and finally sillimanite. (Garnet, staurolite and sillimanite are minerals which are almost always associated with metamorphism (see diagram below).) Granitic rocks are present at the cores of some fold belts, indicating that temperatures there were hot enough to melt the pre-existing rock completely.



Rock can also be buried by being forced down beneath the crust along a subduction zone. There is a relatively low-temperature/high-pressure region in the upper part of a subduction zone. The blue amphibole mineral glaucophane is stable under these conditions and a rock metamorphosed at high pressure and relatively low temperature is known as **blueschist**. Most subducted rock is pushed well down into the mantle where it becomes completely melted, and we rarely see the results of this type of metamorphism. In a few cases, for example where the subduction process is interrupted by continental collision, this type of metamorphic rock will be thrust back up to surface.



Contact metamorphism takes place in areas where hot plutons rise up into the cool upper part of the crust. Under these circumstances the crustal rocks are heated up dramatically, and relatively quickly, but are not subjected to extreme pressures. The zone of alteration is known as an **aureole** and in most cases the altered rock is **hornfels**. Mineral transformations in hornfels result in the growth of minerals which show no preferred orientation. The grade of metamorphism will decrease away from the contact, so that there is likely to be a zonation of metamorphic minerals. For example, garnet or staurolite might be formed near to the contact, while biotite or chlorite may be present farther away. The size of the aureole may range from a few metres to a few hundreds of metres depending on the size of the magma body, and on the difference in temperature between the magma and the country rock.



A special class of contact metamorphism takes place where the country rock is rich in carbonates. In this case the rock produced is known as **skarn**. Minerals commonly present within skarn rocks include garnet, magnetite and epidote.

Metamorphism can also take place along a fault zone where rocks are sliding past one another. In this case the temperature may not be significantly elevated, but the mineral grains can be very finely ground, and the texture of the rock can be completely changed. A common product of fault zone metamorphism is **mylonite**, a fine-grained flinty-looking rock with bands and streaks in the direction of fault movement.

Review questions

1. What must happen to intrusive igneous, sedimentary and metamorphic rock masses before they can be weathered?
2. Explain how chemical and mechanical weathering processes complement each other in breaking down rocks.
3. Why is frost wedging ineffective in very cold environments?
4. What are the characteristics of the surficial environment which lead to instability of many minerals?
5. How can the Bowen Reaction Series be applied to an understanding of chemical weathering, and what implications does this have for the evolution of sialic continental crust?
6. What factor controls the size of particles that can be transported by moving water?
7. Describe the nature of sediments deposited in the upper part of a typical river as compared with those in the lower parts.
8. The material that makes up a rock such as conglomerate cannot be deposited by a slow-flowing river. Why not?
9. What are the two processes of lithification?
10. What is the minimum and maximum size of a sand grain?
11. What is the difference between a lithic arenite and a lithic wacke?
12. What can we say about the source area lithology and weathering and the transportation history of a sandstone which is primarily composed of rounded quartz grains?

13. What is the original source of the carbon which is present within carbonate deposits?
14. List the types of sedimentary rocks which can be deposited (a) in both continental and marine environments, (b) only in continental environments, and (c) only in marine environments.
15. What is a facies change, and what process leads to the development of a facies change?
16. Explain the origin of: a) bedding, b) cross bedding, c) graded bedding and d) mudcracks.
17. When were the Nanaimo Group rocks deposited relative to the time of accretion of Vancouver Island onto the west coast?
18. Describe the type of environment in which most of the Nanaimo Group sediments are thought to have been deposited.
19. Which Nanaimo Groups rocks were clearly not deposited in this type of environment?
20. How can we explain the interlayering of fine-grained and coarse-grained formations in the Nanaimo Group?
21. What mechanism is responsible for the fact that there are Nanaimo Group rocks present at quite high elevations near to the middle of Vancouver Island.
22. What are the two main agents of metamorphism?
23. Into what metamorphic rocks will a clay-rich rock, like shale, be transformed at very low, low, medium-high and high metamorphic grades?
24. How is foliation developed in a metamorphic rock such as schist?
25. Why is a granitic rock largely unaffected by metamorphism?
26. How does regional metamorphism differ from contact metamorphism?
27. Explain how isostasy is important to regional metamorphism?
28. Re-arrange the following minerals in order of increasing metamorphic grade: biotite, garnet, sillimanite and chlorite.
29. Why are "contact" metamorphic rocks not normally foliated?
30. What must be present in the un-metamorphosed rock to produce a skarn?