Chapter 7 Metamorphism and Metamorphic Rocks

Learning Objectives

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

- Summarize the factors that influence the nature of metamorphic rocks and explain why each one is important.
- Describe foliation and explain the mechanisms for its formation in metamorphic rocks.
- Classify metamorphic rocks on the basis of their texture and mineral content, and explain the origins of these differences.
- Describe the various settings in which metamorphic rocks are formed and the links between plate tectonics and metamorphism.
- Summarize the important processes of regional metamorphism, and explain how rocks that were metamorphosed at depths of 10 kilometres or 20 kilometres can now be found on Earth's surface.
- Describe the important processes of contact metamorphism and metasomatism, and the key role hydrothermal fluids.

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 most cases—but not all—this involves the rock being deeply buried beneath other rocks, where it is subjected to higher temperatures and pressures than those under which it formed. Metamorphic rocks typically have different mineral assemblages and different textures from their parent rocks (Figure 7.0.1) but they may have the same overall chemical composition.

Figure 7.0.1 Metamorphic rock (gneiss) of the Okanagan Metamorphic and Igneous Complex at Skaha Lake, B.C. The dark bands are amphibole-rich, the light bands are feldspar-rich.

Most metamorphism results from the burial of igneous, sedimentary, or pre-existing metamorphic rocks to the point where they experience different pressures and temperatures than those at which they formed (Figure 7.0.2). Metamorphism can also take place if cold rock near the surface is intruded and heated by a hot igneous body. Although most metamorphism involves temperatures above 150°C, some metamorphism takes place at temperatures lower than those at which the parent rock formed.

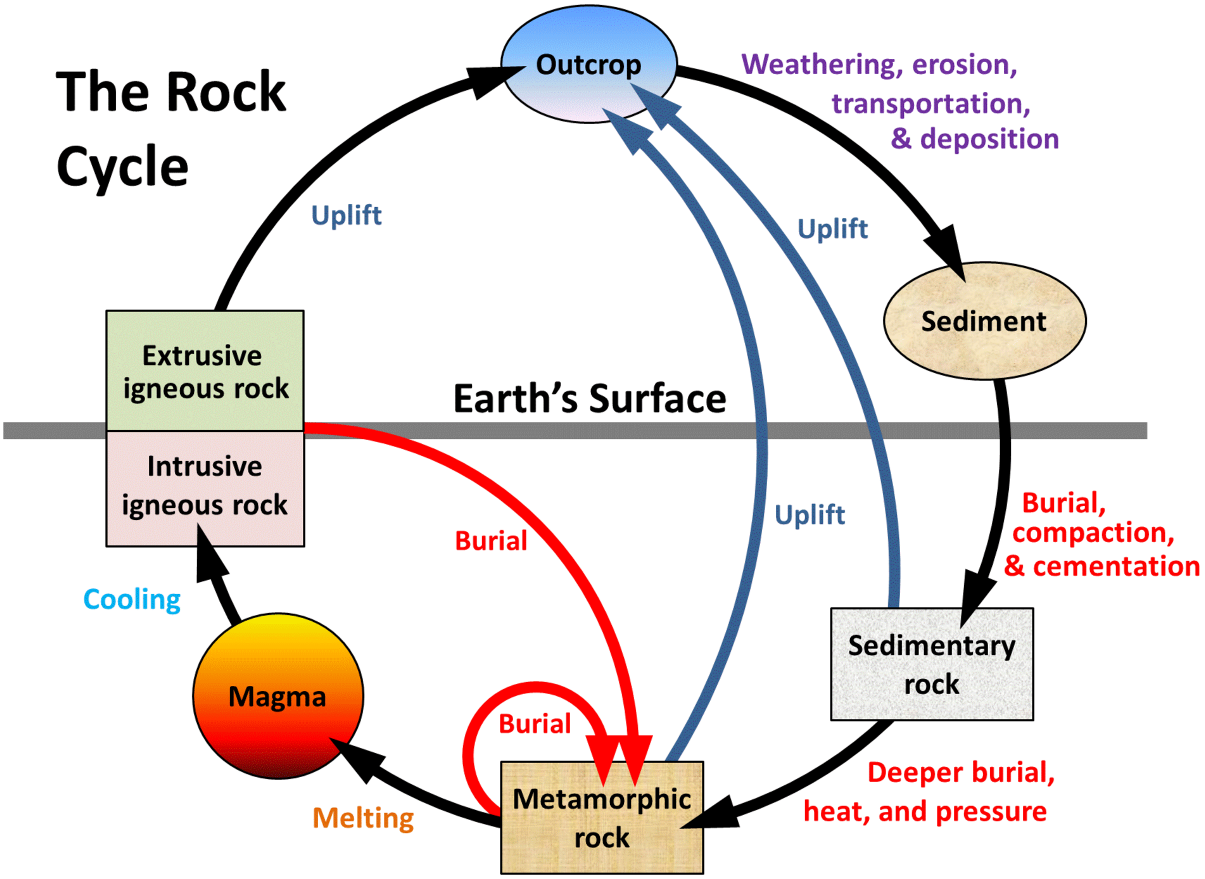

Figure 7.0.2 The rock cycle, showing the processes related to metamorphic rocks at the bottom. [Image description]

Image Descriptions

Figure 7.0.2 image description: As sedimentary rock (or igneous rock) gets buried deeper and comes under increased heat and pressure, it can turn into metamorphic rock. That rock may be returned to surface for us to see, but if it gets buried deeper still it may partially melt to become magma. [Return to Figure 7.0.2]

Media Attributions

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7.1 Controls Over Metamorphic Processes

The main factors that control metamorphic processes are:

- the mineral composition of the parent rock,
- the temperature at which metamorphism takes place,
- the amount and type of pressure during metamorphism,
- the types of fluids (mostly water) that are present during metamorphism, and
- the amount of time available for metamorphism.

Parent Rock

The **parent rock** is the rock that exists before metamorphism starts. Sedimentary or igneous rocks can be considered the parent rocks for metamorphic rocks. Although an existing metamorphic rock can be further metamorphosed or re-metamorphosed, metamorphic rock doesn't normally qualify as a "parent rock". For example, if a mudstone is metamorphosed to slate and then buried deeper where it is metamorphosed to schist, the parent rock of the schist is mudstone, not slate. The critical feature of the parent rock is its mineral composition because it is the stability of minerals that counts when metamorphism takes place. In other words, when a rock is subjected to increased temperatures, certain minerals may become unstable and start to recrystallize into new minerals.

Temperature

The temperature that the rock is subjected to is a key variable in controlling the type of metamorphism that takes place. As we learned in the context of igneous rocks, mineral stability is a function of temperature, pressure, and the presence of fluids (especially water). All minerals are stable over a specific range of temperatures. For example, quartz is stable from environmental temperatures (whatever the weather can throw at it) all the way up to about 1800°C. If the pressure is higher, that upper limit will be even higher. If there is water present, it will be lower. On the other hand, most clay minerals are only stable up to about 150° or 200°C; above that, they transform into micas. Most feldspars are stable up to between 1000°C and 1200°C. Most other common minerals have upper limits between 150°C and 1000°C.

Some minerals will crystallize into different **polymorphs** (same composition, but different crystalline structure) depending on the temperature and pressure. The minerals kyanite, andalusite, and sillimanite are polymorphs with the composition Al_2SiO_5. They are stable at different pressures and temperatures, and, as we will see later, they are important indicators of the pressures and temperatures that existed during the formation of metamorphic rocks (Figure 7.1.1).

Pressure

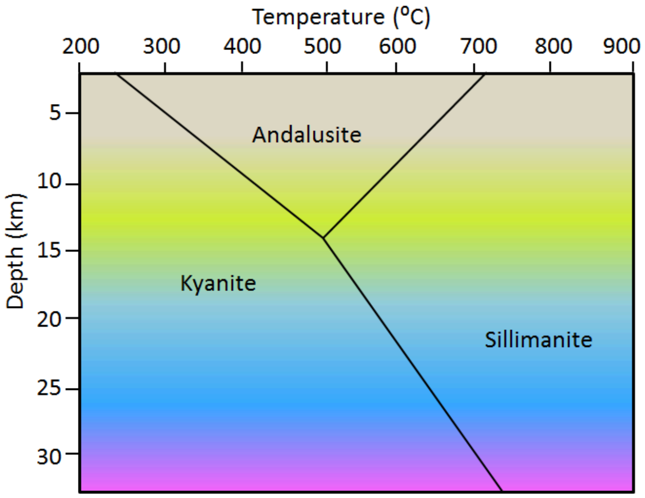

Figure 7.1.1 The temperature and pressure stability fields of the three polymorphs of Al_2SiO_5 (Pressure is equivalent to depth. Kyanite is stable at low to moderate temperatures and low to high pressures, andalusite at moderate temperatures and low pressures, and sillimanite at higher temperatures.) [Image Description]

Pressure is important in metamorphic processes for two main reasons. First, it has implications for mineral stability (Figure 7.1.1). Second, it has implications for the texture of metamorphic rocks. Rocks that are subjected to very high confining pressures are typically denser than others because the mineral grains are squeezed together (Figure 7.1.2a), and also because they may contain minerals that have greater density because the atoms are more closely packed.

Because of plate tectonics, pressures within the crust are typically not applied equally in all directions. In areas of plate convergence, for example, the pressure in one direction (perpendicular to the direction of convergence) is typically greater than in the other directions (Figure 7.1.2b). In situations where different blocks of the crust are being pushed in different directions, the rocks will likely be subjected to sheer stress (Figure 7.1.2c).

One of the results of directed pressure and shear stress is that rocks become **foliated**—meaning that they'll have a directional fabric. Foliation a very important aspect of metamorphic rocks, and is described in more detail later in this chapter.

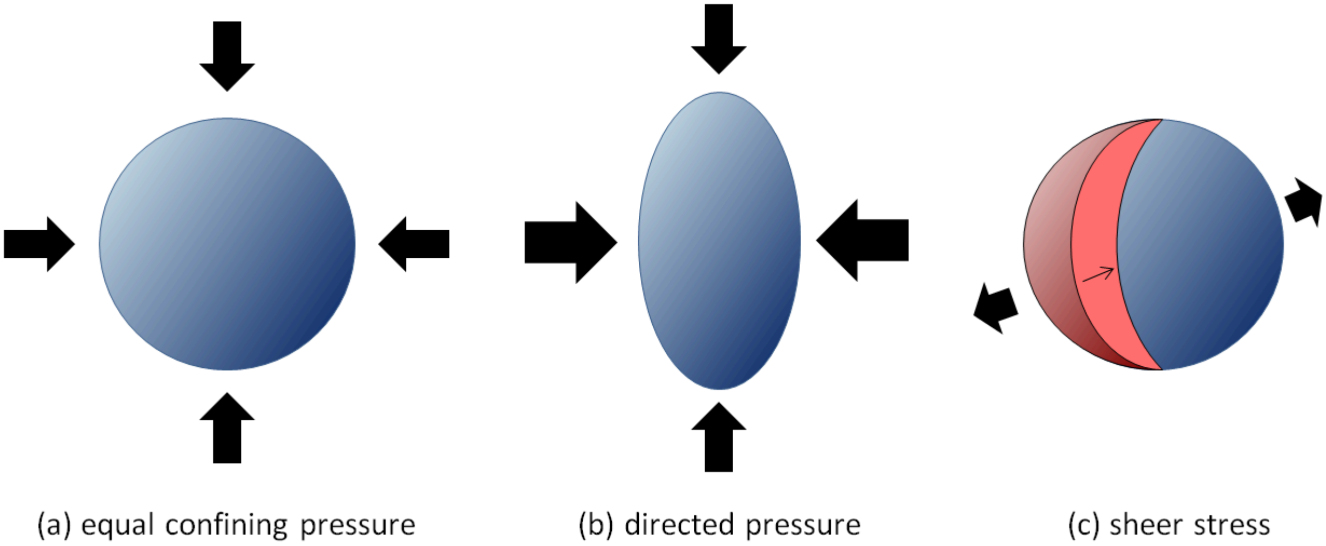

Figure 7.1.2 An illustration of different types of pressure on rocks. (a) confining pressure, where the pressure is essentially equal in all directions, (b) directed pressure, where the pressure form the sides is greater than that from the top and bottom, and (c) shear stress caused by different blocks of rock being pushed in different directions. (In a and b there is also pressure in and out of the page.)

Fluids

Water is the main fluid present within rocks of the crust, and the only one that we'll consider here. The presence of water is important for two main reasons. First, water facilitates the transfer of ions between minerals and within minerals, and therefore increases the rates at which metamorphic reactions take place. So, while the water doesn't necessarily change the outcome of a metamorphic process, it speeds the process up so metamorphism might take place over a shorter time period, or metamorphic processes that might not otherwise have had time to be completed are completed.

Secondly, water, especially hot water, can have elevated concentrations of dissolved elements (ions), and therefore it is an important medium for moving certain elements around within the crust. So not only does water facilitate metamorphic reactions on a grain-to-grain basis, it also allows for the transportation of elements from one place to another. This is very important in hydrothermal processes, which are discussed toward the end of this chapter, and in the formation of mineral deposits.

Time

Most metamorphic reactions take place at very slow rates. For example, the growth of new minerals within a rock during metamorphism has been estimated to be about 1 millimetre per million years. For this reason, it is very difficult to study metamorphic processes in a lab.

While the rate of metamorphism is slow, the tectonic processes that lead to metamorphism are also very slow, so in most cases, the chance for metamorphic reactions to be completed is high. For example, one important metamorphic setting is many kilometres deep within the roots of mountain ranges. A mountain range takes tens of millions of years to form, and tens of millions of years more to be eroded to the extent that we can see the rocks that were metamorphosed deep beneath it.

Exercise 7.1

Figure 7.1.3 Garnets in a rock. Euro coin (23 mm) is for scale.

This photo shows a sample of garnet-mica schist from the Greek island of Syros. The large reddish crystals are garnet, and the surrounding light coloured rock is dominated by muscovite mica. The Euro coin is 23 millimetres in diameter. Assume that the diameters of the garnets increased at a rate of 1 millimetre per million years.

Based on the approximate average diameter of the garnets visible, estimate how long this metamorphic process might have taken.

See Appendix 3 for Exercise 7.1 answers.

Image Descriptions

Figure 7.1.1 image description: The temperature ranges that polymorphs of Al_2SiO_5 are stable at at various depths.

Depth (kilometres)	Kyanite	Andalusite	Sillimanite
5	Less than 300°C	300 to 650°C	Greater than 670°C
10	Less than 400°C	410 to 580°C	Greater than 590°C
15	Less than 500°C	Not stable	Greater than 500°C
20	Less than 570°C	Not stable	Greater than 590°C
25	Less than 640°C	Not stable	Greater than 620°C
30	Less than 700°C	Not stable	Greater than 700°C

[Return to Figure 7.1.1]

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- Figure 7.1.3: Garnet Mica Schist Syros Greece © Graeme Churchard. CC BY.

7.2 Classification of Metamorphic Rocks

There are two main types of metamorphic rocks: those that are foliated because they have formed in an environment with either directed pressure or shear stress, and those that are not foliated because they have formed in an environment without directed pressure or relatively near the surface with very little pressure at all. Some types of metamorphic rocks, such as quartzite and marble, which can form whether there is directed-pressure or not, do not typically exhibit foliation because their minerals (quartz and calcite respectively) do not tend to show alignment (see Figure 7.2.8).

When a rock is squeezed under directed pressure during metamorphism it is likely to be deformed, and this can result in a textural change such that the minerals appear elongated in the direction perpendicular to the main stress (Figure 7.2.1). This contributes to the formation of foliation.

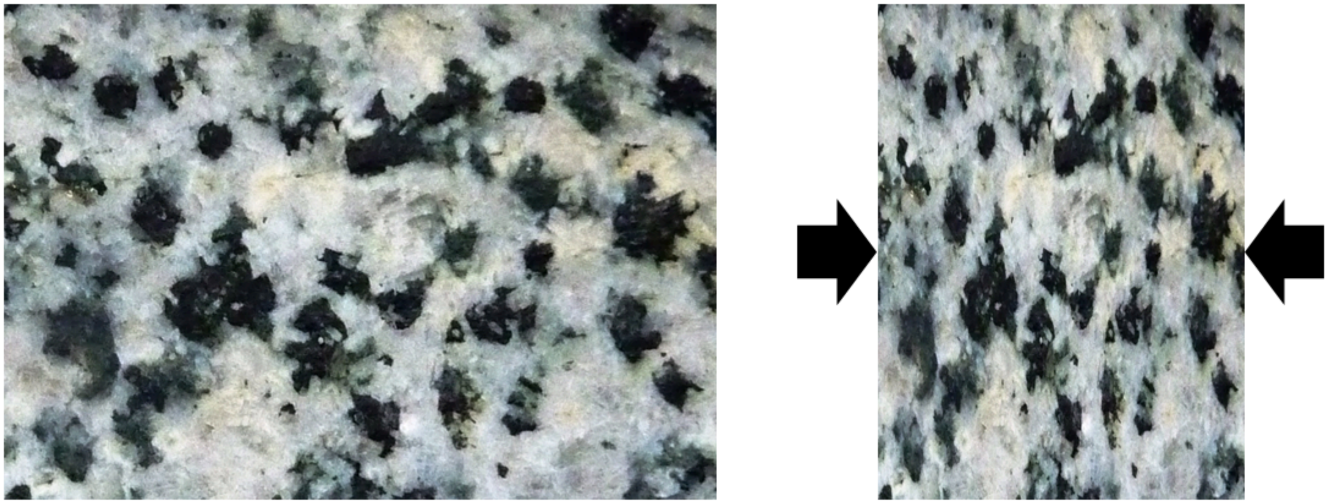


Figure 7.2.1 The textural effects of squeezing during metamorphism. In the original rock (left) there is no alignment of minerals. In the squeezed rock (right) the minerals have been elongated in the direction perpendicular to the squeezing.

When a rock is both heated and squeezed during metamorphism, and the temperature change is enough for new minerals to form from existing ones, there is a strong tendency for new minerals to grow with their long axes perpendicular to the direction of squeezing. This is illustrated in Figure 7.2.2, where the parent rock is shale, with bedding as shown. After both heating and squeezing, new minerals have formed within the rock, generally parallel to each other, and the original bedding has been largely obliterated.

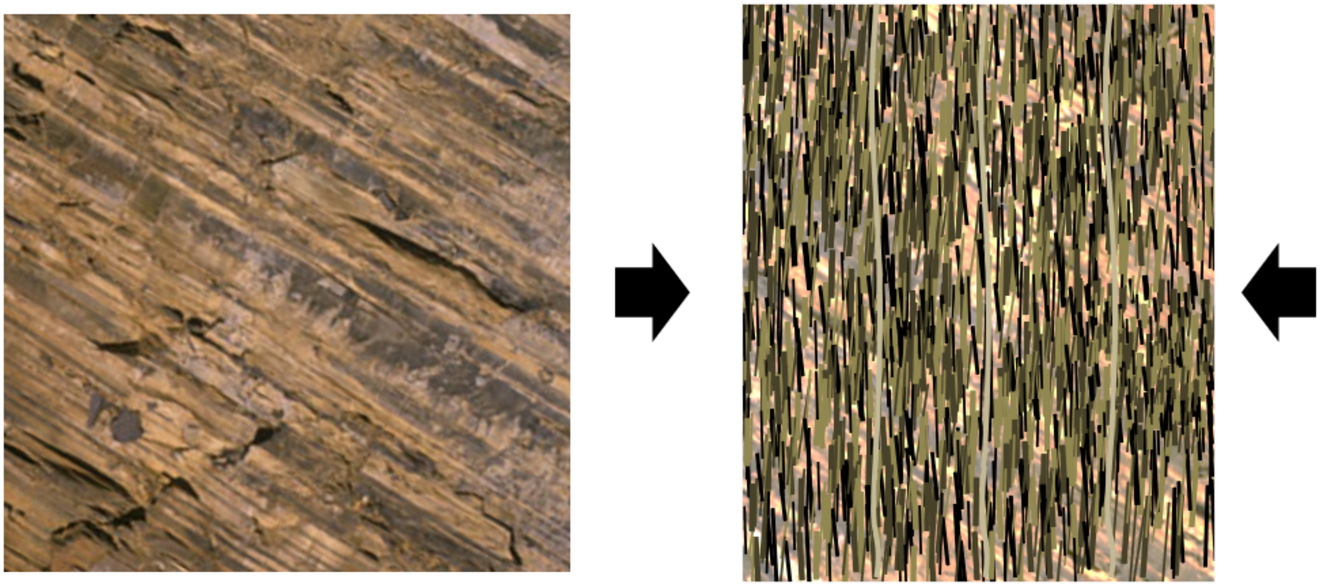


Figure 7.2.2 The textural effects of squeezing and mineral growth during regional metamorphism. The left diagram is shale with bedding slanting down to the right. The right diagram represents schist (derived from that shale), with mica crystals orientated perpendicular to the main stress direction and the original bedding no longer easily visible.

Figure 7.2.3 shows an example of this effect. This large boulder has bedding visible as dark and light bands sloping steeply down to the right. The rock also has a strong slaty foliation, which is horizontal in this view (parallel to the surface that the person is sitting on), and has developed because the rock was being squeezed during metamorphism. The rock has split from bedrock along this foliation plane, and you can see that other weaknesses are present in the same orientation.

Squeezing and heating alone (as shown in Figure 7.2.1) can contribute to foliation, but most foliation develops when new minerals are formed and are forced to grow perpendicular to the direction of greatest stress (Figure 7.2.2). This effect is especially strong if the new minerals are platy like mica or elongated like amphibole. The mineral crystals don’t have to be large to produce foliation. Slate, for example, is characterized by aligned flakes of mica that are too small to see.

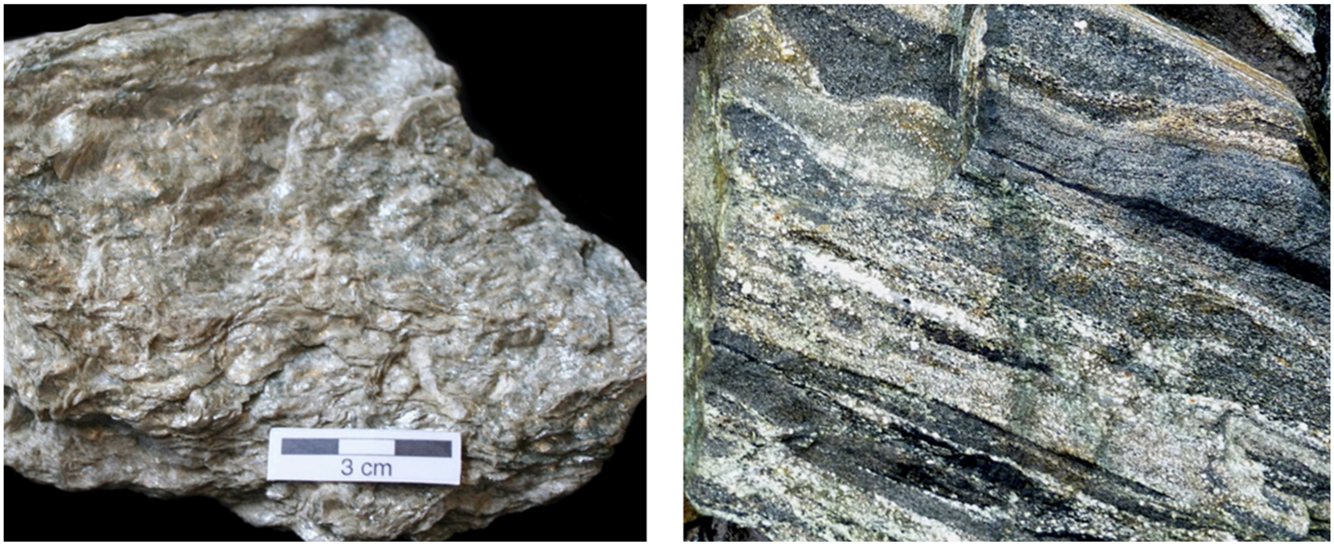
Figure 7.2.3 A slate boulder on the side of Mt. Wapta in the Rockies near Field, BC. Bedding is visible as light and dark bands sloping steeply to the right (yellow arrows). Slaty cleavage is evident from the way the rock has broken (along the flat surface that the person is sitting on) and also from lines of weakness that are parallel to that same trend (red arrows).

The various types of foliated metamorphic rocks, listed in order of the **grade** or intensity of metamorphism and the type of foliation are: **slate**, **phyllite**, **schist**, and **gneiss** (Figure 7.2.4). As already noted, slate is formed from the low-grade metamorphism of shale, and has microscopic clay and mica crystals that have grown perpendicular to the stress. Slate tends to break into flat sheets. Phyllite is similar to slate, but has typically been heated to a higher temperature; the micas have grown larger and are visible as a sheen on the surface. Where slate is typically planar, phyllite can form in wavy layers. In the formation of schist, the temperature has been hot enough so that individual mica crystals are big enough to be visible, and other mineral crystals, such as quartz, feldspar, or garnet may also be visible. In gneiss, the minerals may have separated into bands of different colours. In the example shown in Figure 7.2.4d, the dark bands are largely amphibole while the light-coloured bands are feldspar and quartz. Most gneiss has little or no mica because it forms at temperatures higher than those under which micas are stable. Unlike slate and phyllite, which typically only form from mudrock, schist, and especially gneiss, can form from a variety of parent rocks, including mudrock, sandstone, conglomerate, and a range of both volcanic and intrusive igneous rocks.

Schist and gneiss can be named on the basis of important minerals that are present. For example a schist derived from basalt is typically rich in the mineral chlorite, so we call it chlorite schist. One derived from shale may be a muscovite-biotite schist, or just a mica schist, or if there are garnets present it might be mica-garnet schist. Similarly, a gneiss that originated as basalt and is dominated by amphibole, is an amphibole gneiss or, more accurately, an **amphibolite**.

a) Slate, near to Golden, BC

b) Phyllite, location unknown



c) Schist, location unknown

d) Gneiss from the Victoria area, BC

Figure 7.2.4 Examples of foliated metamorphic rocks: (A) Slate, (B) Phyllite, (C) Schist, (D) Gneiss.

If a rock is buried to a great depth and encounters temperatures that are close to its melting point, it may partially melt. The resulting rock, which includes both metamorphosed and igneous material, is known as **migmatite** (Figure 7.2.5).

Figure 7.2.5 Migmatite from Prague, Czech Republic

As already noted, the nature of the parent rock controls the types of metamorphic rocks that can form from it under differing metamorphic conditions. The kinds of rocks that can be expected to form at different metamorphic grades from various parent rocks are listed in Table 7.1. Some rocks, such as granite, do not change much at the lower metamorphic grades because their minerals are still stable up to several hundred degrees.

Table 7.1 A rough guide to the types of metamorphic rocks that form from different parent rocks at different grades of regional metamorphism.

Parent Rock	**Very Low Grade (150-300°C)**	**Low Grade (300-450°C)**	**Medium Grade (450-550°C)**	**High Grade (Above 550°C)**
Mudrock	slate	phyllite	schist	gneiss
Granite	no change	no change	almost no change	granite gneiss
Basalt	chlorite schist	chlorite schist	amphibolite	amphibolite
Sandstone	no change	little change	quartzite	quartzite
Limestone	little change	marble	marble	marble

Metamorphic rocks that form under either low-pressure conditions or just confining pressure do not become foliated. In most cases, this is because they are not buried deeply, and the heat for the metamorphism comes from a body of magma that has moved into the upper part of the crust. This is **contact metamorphism**. Some examples of non-foliated metamorphic rocks are **marble**, **quartzite**, and **hornfels**.

Marble is metamorphosed limestone. When it forms, the calcite crystals tend to grow larger, and any sedimentary textures and fossils that might have been present are destroyed. If the original limestone was pure calcite, then the marble will likely be white (as in Figure 7.2.6), but if it had various impurities, such as clay, silica, or magnesium, the marble could be "marbled" in appearance. Marble that forms during regional metamorphism—and in fact that includes most marble—may or may not develop a foliated texture, but foliation is typically not easy to see in marble.

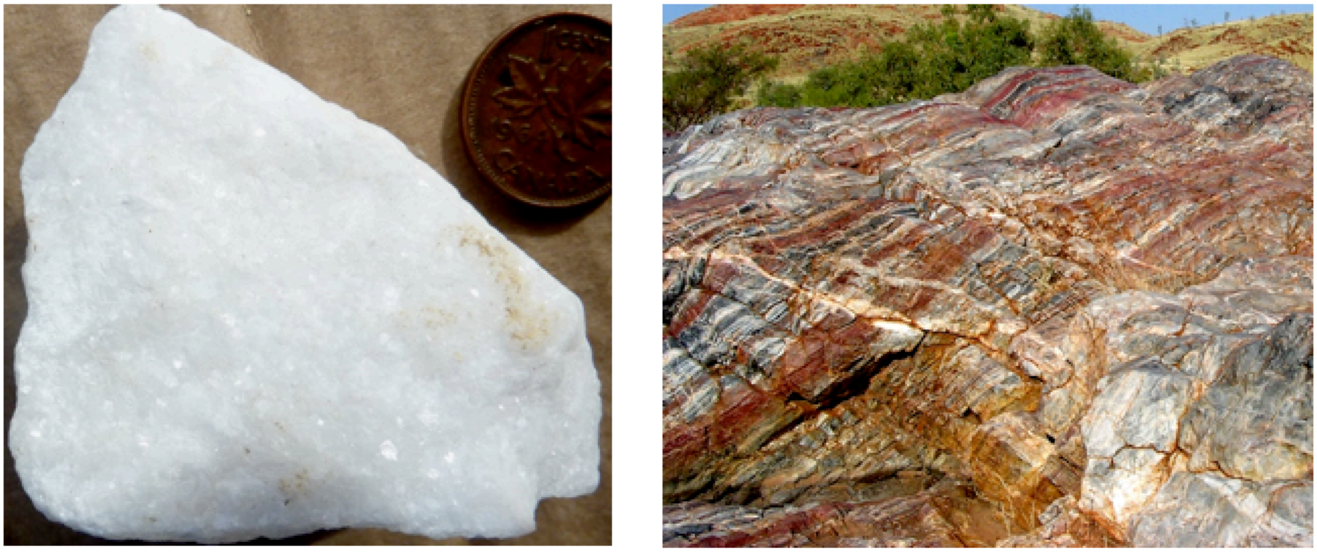


Figure 7.2.6 Marble with visible calcite crystals (left) and an outcrop of banded marble (right).

Quartzite is metamorphosed sandstone (Figure 7.2.7). It is dominated by quartz, and in many cases, the original quartz grains of the sandstone are welded together with additional silica. Most sandstone contains some clay minerals and may also include other minerals such as feldspar or fragments of rock, so most quartzite has some impurities with the quartz.

Figure 7.2.7 Quartzite from the Rocky Mountains, found in the Bow River at Cochrane, Alberta.

Even if formed during **regional metamorphism**, quartzite (like marble) does not tend to look foliated because quartz crystals don’t align with the directional pressure. On the other hand, any clay present in the original sandstone is likely to be converted to mica during metamorphism, and any such mica is likely to align with the directional pressure. An example of this is shown in Figure 7.2.8. The quartz crystals show no alignment, but the micas are all aligned, indicating that there was directional pressure during regional metamorphism of this rock. Since these micas are very small, this rock would not appear to be foliated to the naked eye.

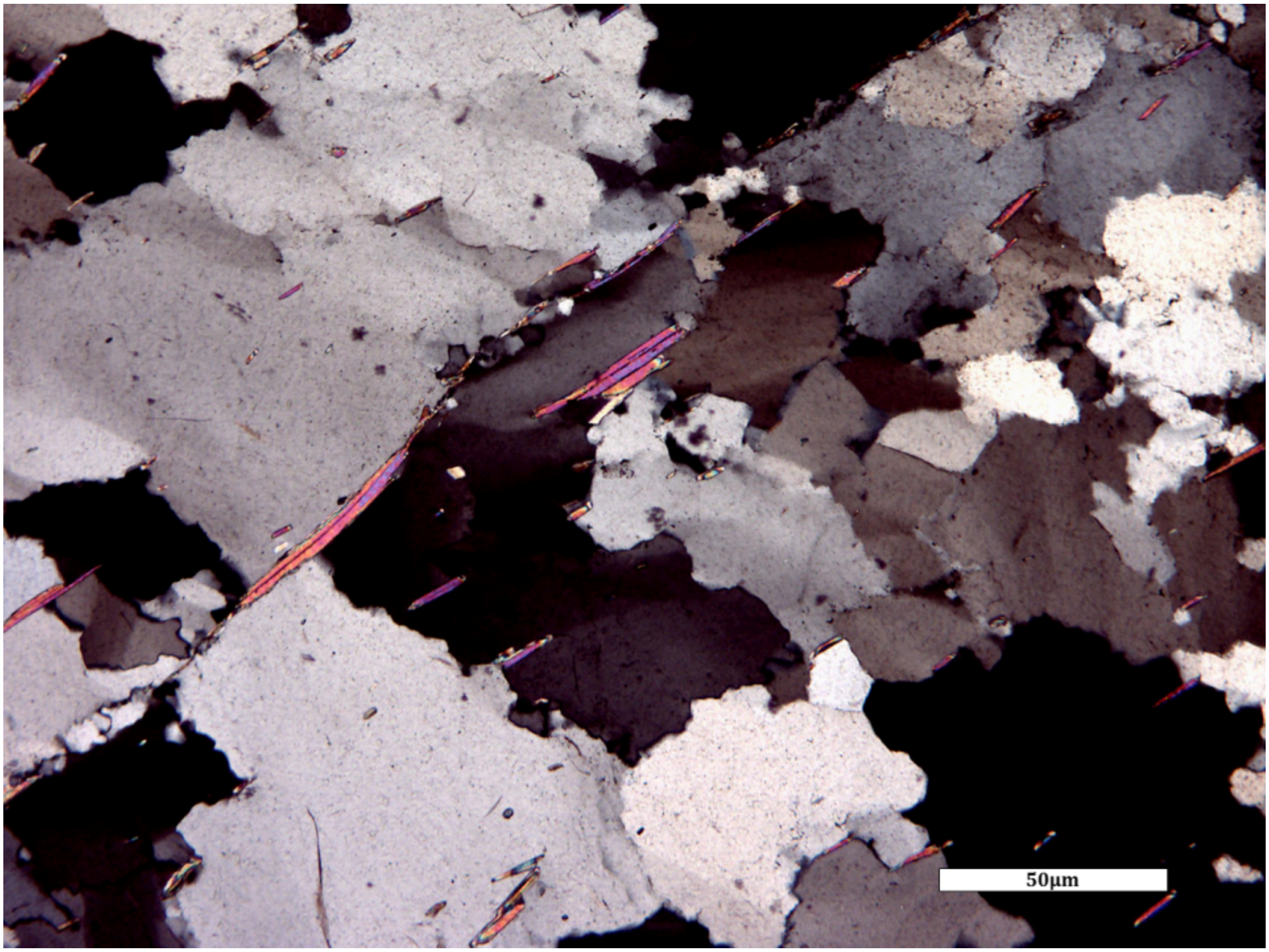


Figure 7.2.8 Magnified thin section of quartzite in polarized light. The irregular-shaped white, grey, and black crystals are all quartz. The small, thin, brightly coloured crystals are mica. This rock is foliated, even though it might not appear to be if examined without a microscope, and so it must have formed under directed-pressure conditions.

Hornfels is another non-foliated metamorphic rock that normally forms during contact metamorphism of fine-grained rocks like mudstone or volcanic rock (Figure 7.2.9). In some cases, hornfels has visible crystals of minerals like biotite or andalusite. If the hornfels formed in a situation without directed pressure, then these minerals would be randomly orientated, not aligned with one-another, as they would be if formed with directed pressure.

Figure 7.2.9 Hornfels from the Novosibirsk region of Russia. The dark and light bands are bedding. The rock has been recrystallized during contact metamorphism and does not display foliation. (scale in centimetres).

Exercise 7.2 Naming metamorphic rocks

Provide reasonable names for the following metamorphic rocks based on the description:

1. A rock with visible crystals of mica and with small crystals of andalusite. The mica crystals are consistently parallel to one another.
2. A very hard rock with a granular appearance and a glassy lustre. There is no evidence of foliation.
3. A fine-grained rock that splits into wavy sheets. The surfaces of the sheets have a sheen to them.
4. A rock that is dominated by aligned crystals of amphibole.

See Appendix 3 for Exercise 7.2 answers.

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- Figure 7.2.5: Migmatite in Geopark on Albertov © Chmee2. CC BY.
- Figure 7.2.6 (right): An outcrop of banded marble by the USGS. Public domain.
- Figure 7.2.7: © Steven Earle. CC BY.
- Figure 7.2.8: © Sandra Johnstone. CC BY.
- Figure 7.2.9: Hornfels by Fed. Public domain.

7.3 Plate Tectonics and Metamorphism

All of the important processes of metamorphism that we are familiar with can be understood in the context of geological processes related to plate tectonics. The relationships between plate tectonics and metamorphism are summarized in Figure 7.3.1, and in more detail in Figures 7.3.2, 7.3.3, 7.3.4, and 7.3.6.

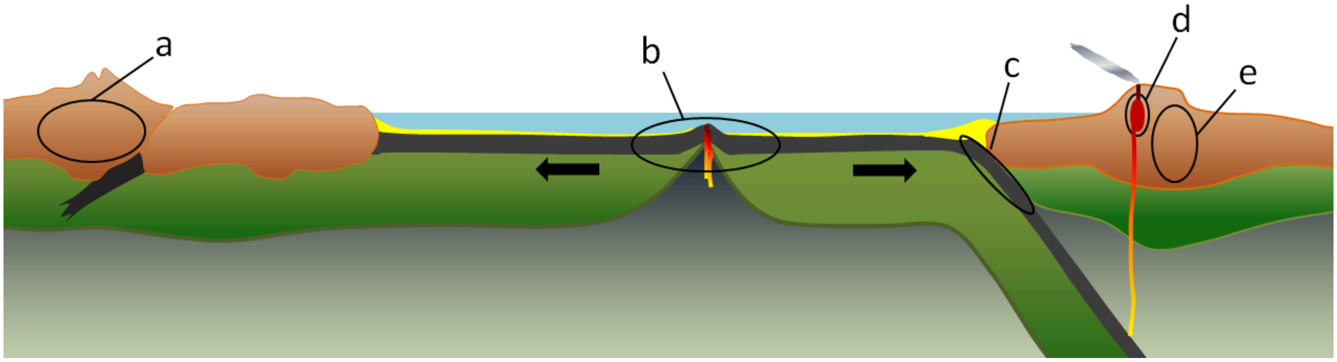

Figure 7.3.1 Environments of metamorphism in the context of plate tectonics: (a) regional metamorphism related to mountain building at a continent-continent convergent boundary, (b) regional metamorphism of oceanic crust in the area on either side of a spreading ridge, (c) regional metamorphism of oceanic crustal rocks within a subduction zone, (d) contact metamorphism adjacent to a magma body at a high level in the crust, and (e) regional metamorphism related to mountain building at a convergent boundary.

Most regional metamorphism takes place within the continental crust. While rocks can be metamorphosed at depth in most areas, the potential for metamorphism is greatest in the roots of mountain ranges where there is a strong likelihood for burial of relatively young sedimentary rock to great depths, as depicted in Figure 7.3.2. An example would be the Himalayan Range. At this continent-continent convergent boundary, sedimentary rocks have been both thrust up to great heights (nearly 9,000 metres above sea level) and also buried to great depths. Considering that the normal geothermal gradient (the rate of increase in temperature with depth) is around 30°C per kilometre, rock buried to 9 kilometres below sea level in this situation could be close to 18 kilometres below the surface of the ground, and it is reasonable to expect temperatures up to 500°C. Metamorphic rocks formed there are likely to be foliated because of the strong directional pressure (compression) of converging plates.

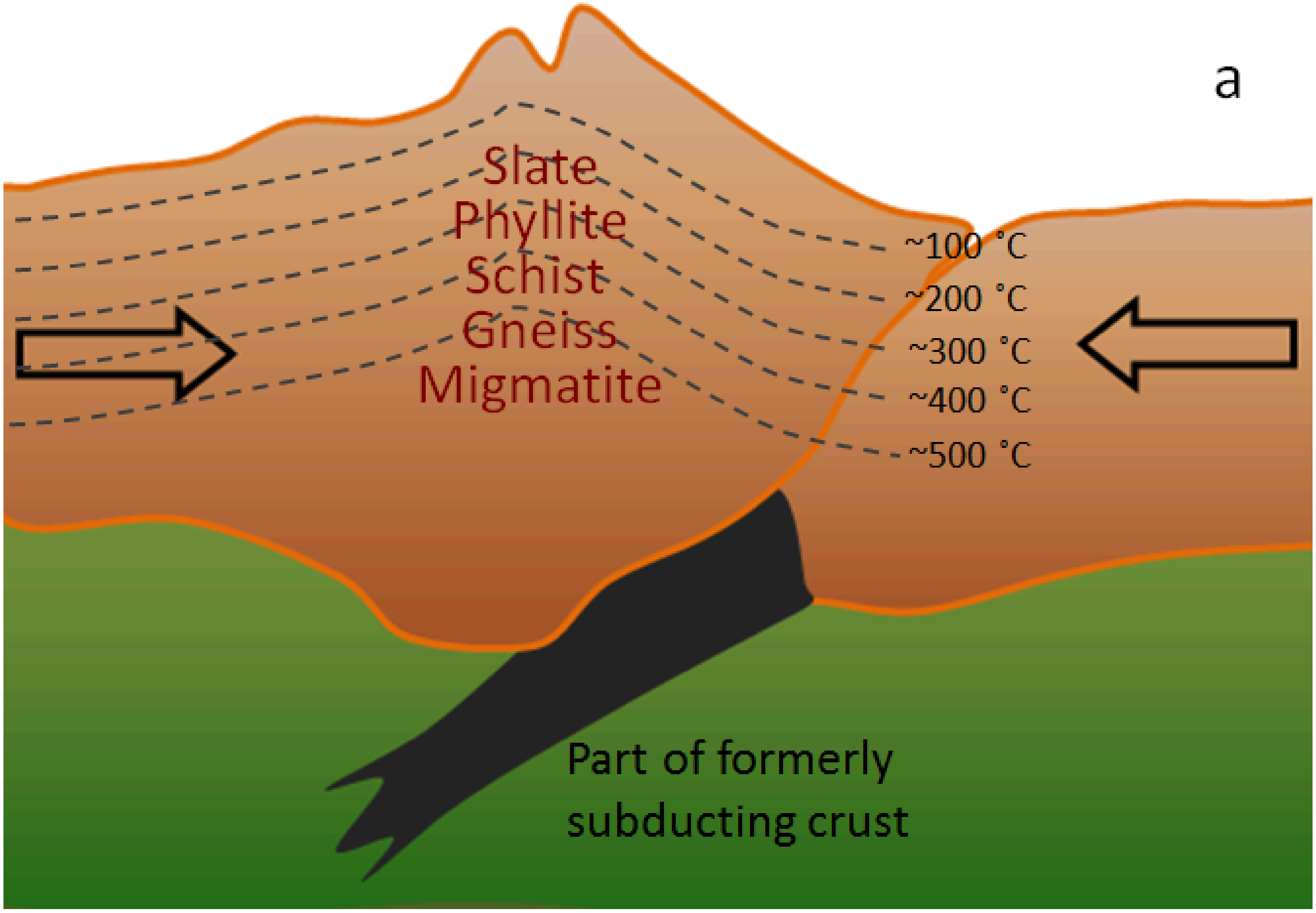

Figure 7.3.2 Regional metamorphism beneath a mountain range related to continent-continent collision (typical geothermal gradient). (Example: Himalayan Range) [Image Description]

At an oceanic spreading ridge, recently formed oceanic crust of gabbro and basalt is slowly moving away from the plate boundary (Figure 7.3.3). Water within the crust is forced to rise in the area close to the source of volcanic heat, and this draws more water in from farther out, which eventually creates a convective system where cold seawater is drawn into the crust and then out again onto the sea floor near the ridge. The passage of this water through the oceanic crust at 200° to 300°C promotes metamorphic reactions that change the original pyroxene in the rock to chlorite and serpentine. Because this metamorphism takes place at temperatures well below the temperature at which the rock originally formed (~1200°C), it is known as **retrograde metamorphism**. The rock that forms in this way is known as **greenstone** if it isn't foliated, or **greenschist** if it is. Chlorite ($(Mg_5Al)(AlSi_3)O_{10}(OH)_8$) and serpentine ($(Mg, Fe)_3Si_2O_5(OH)_4$) are both "**hydrated minerals**" meaning that they have water (as OH) in their chemical formulas. When metamorphosed ocean crust is later subducted, the chlorite and serpentine are converted into new non-hydrous minerals (e.g., garnet and pyroxene) and the water that is released migrates into the overlying mantle, where it contributes to flux melting (Chapter 3, section 3.2).

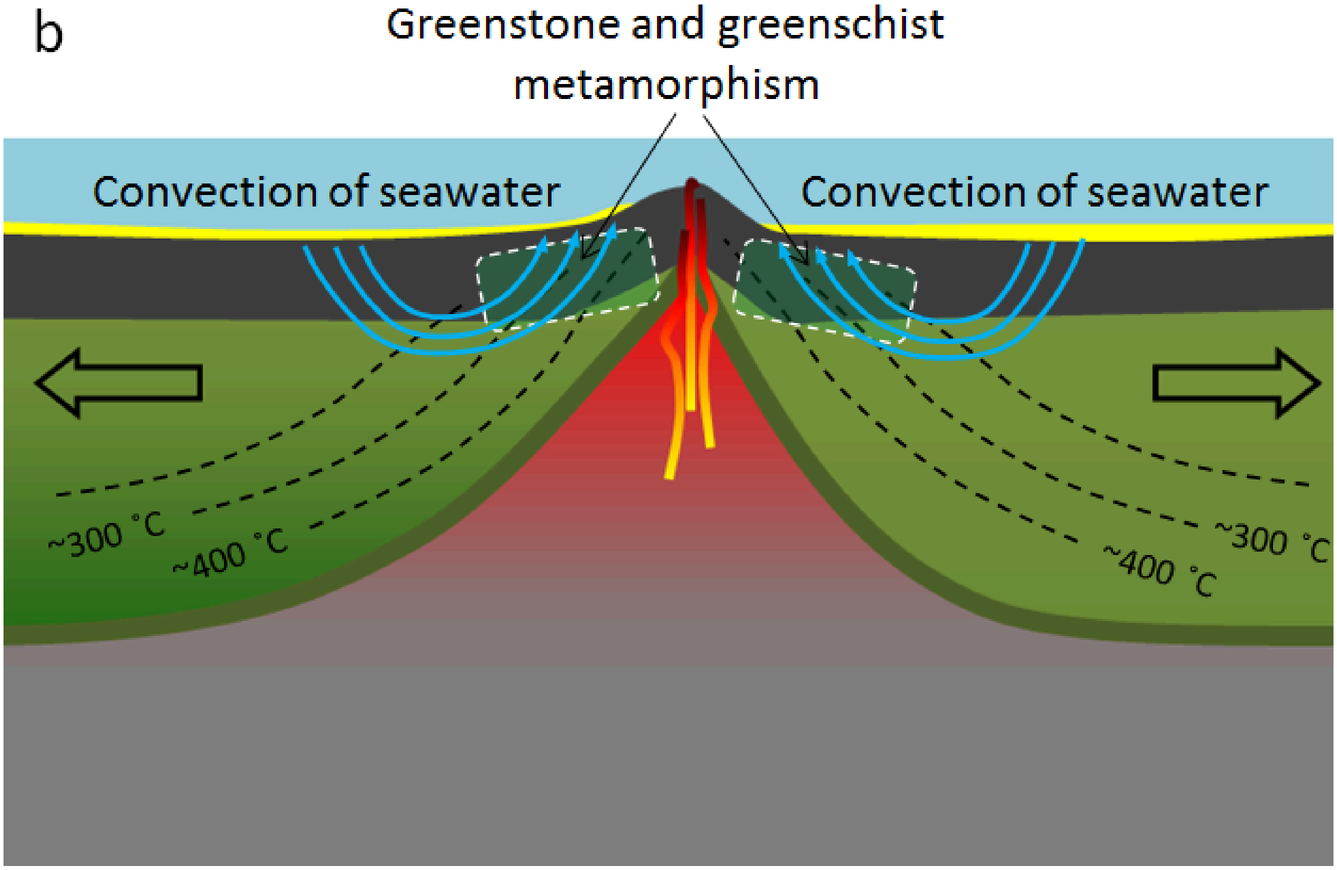

Figure 7.3.3 Regional metamorphism of oceanic crustal rock on either side of a spreading ridge. The dotted rectangles are the areas where metamorphism is taking place. (Example: Juan de Fuca spreading ridge)

At a subduction zone, oceanic crust is forced down into the hot mantle. But because the oceanic crust is now relatively cool, especially along its sea-floor upper surface, it does not heat up quickly, and the subducting rock remains several hundreds of degrees cooler than the surrounding mantle (Figure 7.3.4). A special type of metamorphism takes place under these very high-pressure but relatively low-temperature conditions, producing an amphibole mineral known as **glaucophane** ($Na_2(Mg_3Al_2)Si_8O_{22}(OH)_2$), which is blue in colour, and is an important component of a rock known as **blueschist**.

You've probably never seen or even heard of blueschist; that's not surprising. What is a little surprising is that anyone has seen it! Most blueschist forms in subduction zones, continues to be subducted, turns into **eclogite** at about 35 kilometres depth, and then eventually sinks deep into the mantle—never to be seen again because that rock will eventually melt. In only a few places in the world, where the subduction process has been interrupted by some other tectonic process, has partially subducted blueschist rock returned to the surface. One such place is the area around San Francisco; the rock is known as the Franciscan Complex (Figure 7.3.5).

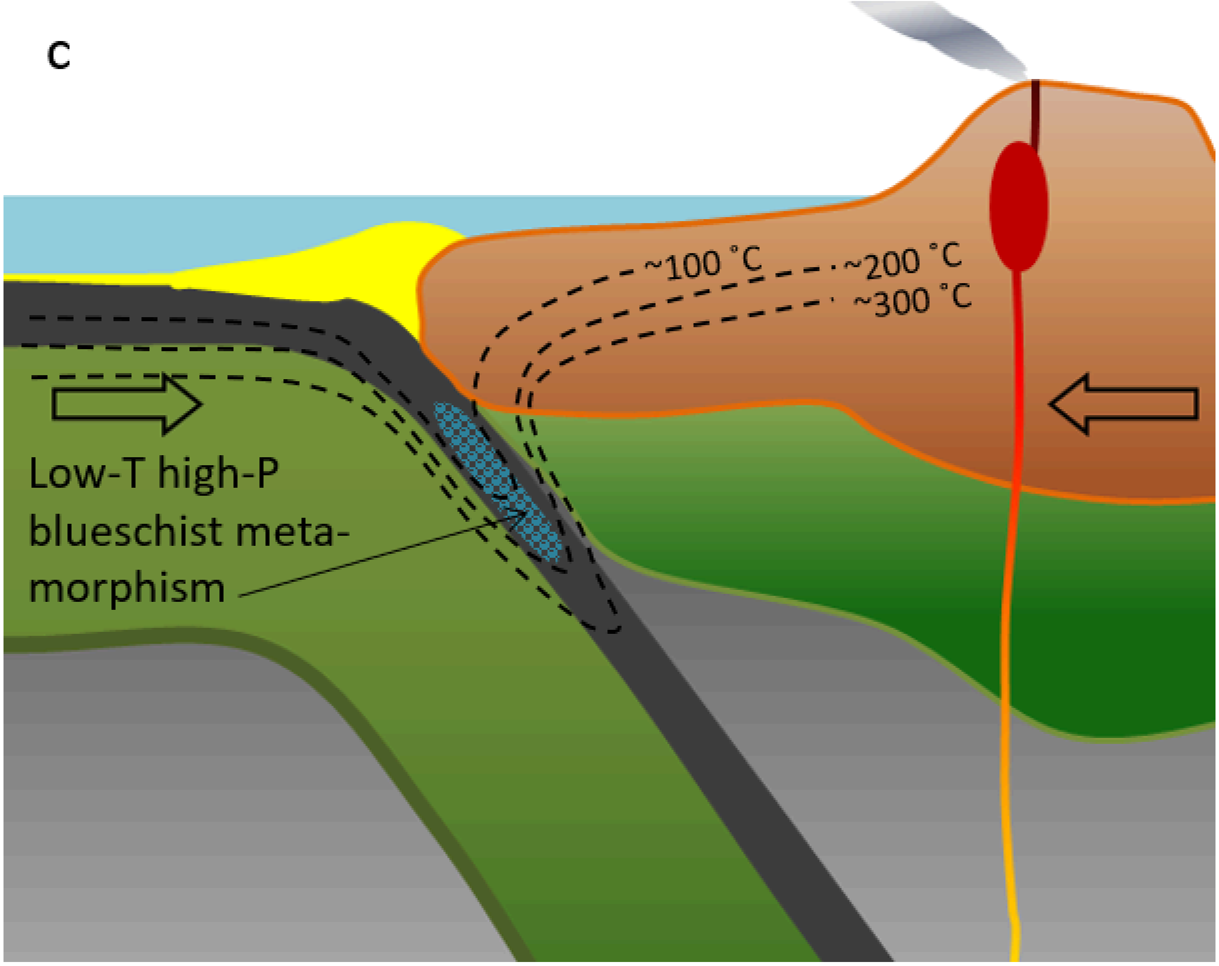

Figure 7.3.4 Regional metamorphism of oceanic crust at a subduction zone. (Example: Cascadia subduction zone. Rock of this type is exposed in the San Francisco area.)

Figure 7.3.5 Franciscan Complex blueschist rock exposed north of San Francisco. The blue colour of rock is due to the presence of the amphibole mineral glaucophane.

Magma is produced at convergent boundaries and rises toward the surface, where it can form magma bodies in the upper part of the crust. Such magma bodies, at temperatures of around 1000°C, heat up the surrounding rock, leading to contact metamorphism (Figure 7.3.6). Because this happens at relatively shallow depths, in the absence of directed pressure, the resulting rock does not normally develop foliation. The zone of contact metamorphism around an intrusion is very small (typically metres to tens of metres) compared with the extent of regional metamorphism in other settings (tens of thousands of square kilometres).

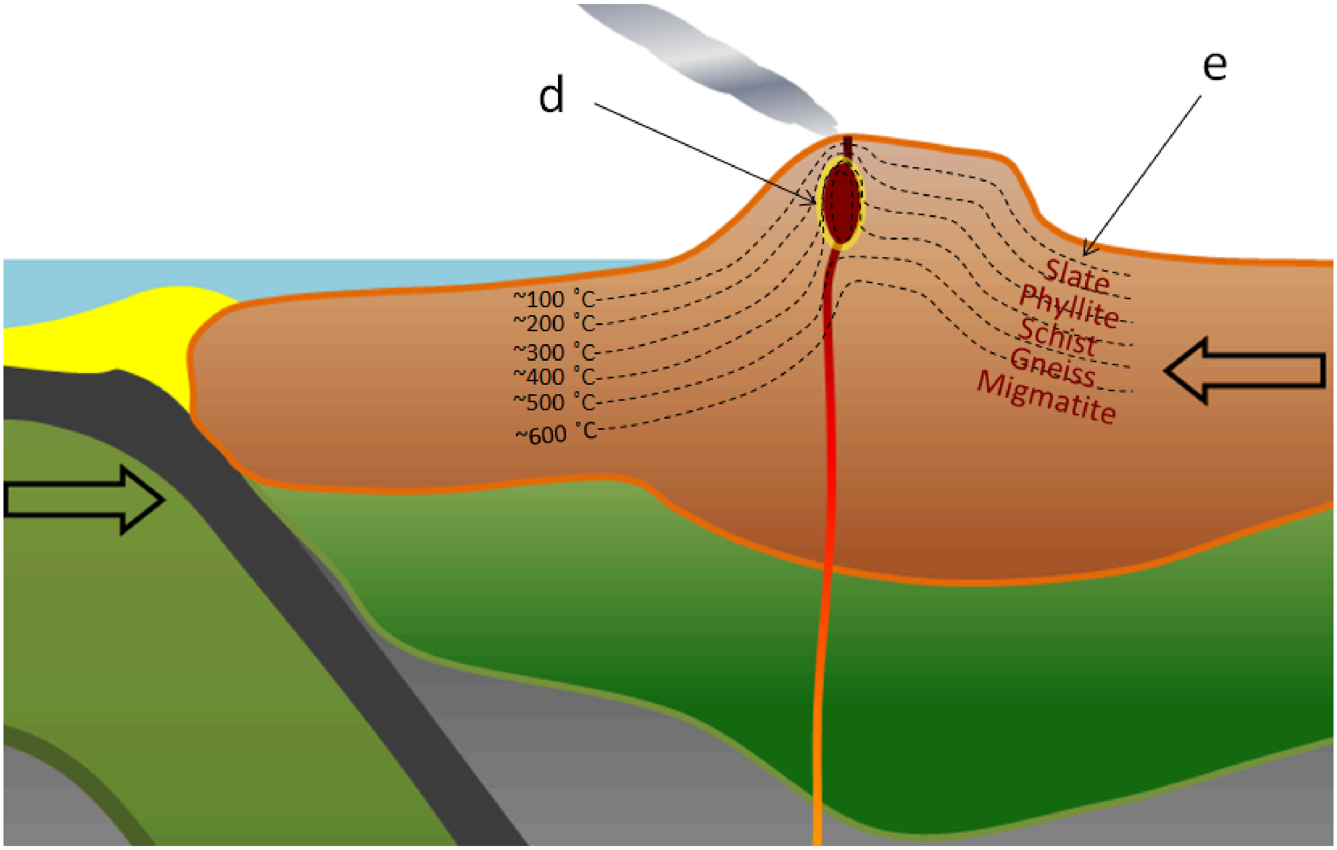

Figure 7.3.6 d: Contact metamorphism around a high-level crustal magma chamber (Example: the magma chamber beneath Mt. St. Helens.) e: Regional metamorphism in a volcanic-arc related mountain range (volcanic-region temperature gradient) (Example: The southern part of the Coast Range, B.C.)

Regional metamorphism also takes place within volcanic-arc mountain ranges, and because of the extra heat associated with the volcanism, the geothermal gradient is typically a little steeper in these settings (somewhere between 40° and 50°C per kilometre). As a result higher grades of metamorphism can take place closer to surface than is the case in other areas (Figure 7.3.6).

Another way to understand metamorphism is by using a diagram that shows temperature on one axis and depth—which is equivalent to pressure—on the other (Figure 7.3.7). The three heavy dotted lines on this diagram represent Earth's geothermal gradients under different conditions. In most areas, the rate of increase in temperature with depth is 30°C per kilometre. In other words, if you go 1,000 metres down into a mine, the temperature will be roughly 30°C warmer than the average temperature at the surface. In most parts of southern Canada, the average surface temperature is about 10°C, so at a 1,000 metre depth, it will be about 40°C. That's uncomfortably hot, so deep mines must have effective ventilation systems. This typical geothermal gradient is shown by the green dotted line in Figure 7.3.7. At a 10 kilometre depth, the temperature is about 300°C and at 20 kilometres it's about 600°C.

In volcanic areas, the geothermal gradient is more like 40° to 50°C per kilometre, so the temperature at a 10 kilometre depth is in the 400° to 500°C range. Along subduction zones, as described above, the cold oceanic crust keeps temperatures low, so the gradient is typically less than 10°C per kilometre. The various types of metamorphism described above are represented in Figure 7.3.7 with the same letters (a through e) used in Figures 7.3.1 to 7.3.4 and 7.3.6.

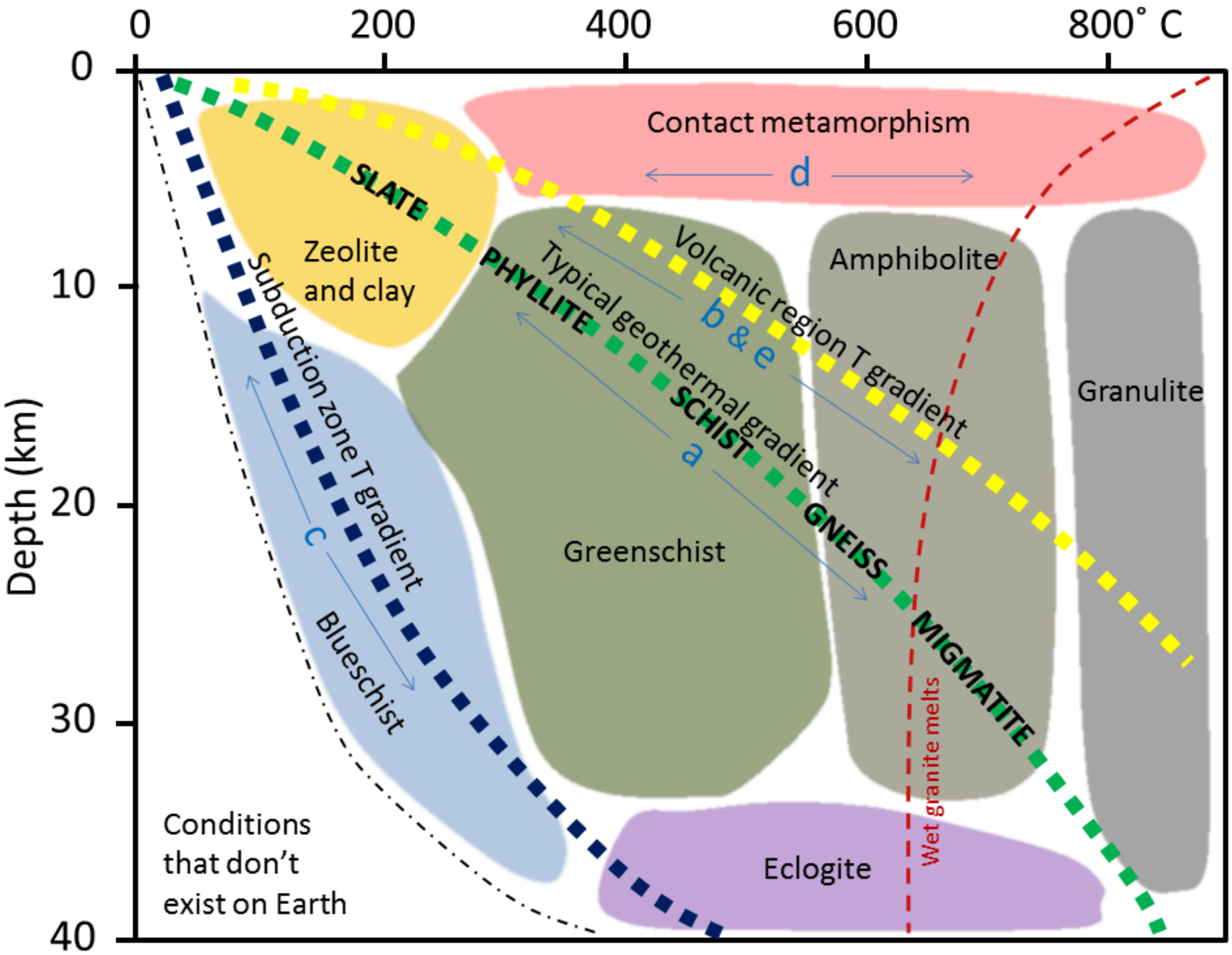

Figure 7.3.7 Types of metamorphism shown in the context of depth and temperature under different conditions. The metamorphic rocks formed from mudrock under regional metamorphosis with a typical geothermal gradient are listed. The letters a through e correspond with those shown in Figures 7.3.1 to 7.3.4 and 7.3.6.

By way of example, if we look at regional metamorphism in areas with typical geothermal gradients, we can see that burial in the 5 kilometre to 10 kilometre range puts us in the zeolite[1] and clay mineral zone (see Figure 7.3.7), which is equivalent to the formation of slate. At 10 to 15 kilometres, we are in the greenschist zone (where chlorite would form in mafic volcanic rock) and very fine micas form in mudrock, to produce phyllite. At 15 to 20 kilometres, larger micas form to produce schist, and at 20 to 25 kilometres amphibole, feldspar, and quartz form to produce gneiss. Beyond a depth of 25 kilometres in this setting, we cross the partial melting line for granite (or gneiss) with water present, and so we can expect migmatite to form.

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[1] Zeolites are silicate minerals that typically form during low-grade metamorphism of volcanic rocks.

Exercise 7.3 Metamorphic rocks in areas with higher geothermal gradients

Figure 7.3.7 shows the types of rock that might form from mudrock at various points along the curve of the "typical" geothermal gradient (dotted green line). Looking at the geothermal gradient for volcanic regions (dotted yellow line in Figure 7.3.7), estimate the depths at which you would expect to find the same types of rock forming from a mudrock parent.

1. Slate
2. Phyllite
3. Schist
4. Gneiss
5. Migmatite

See Appendix 3 for Exercise 7.3 answers.

Image Descriptions

Figure 7.3.2 image description: Regional metamorphism occurring beneath a mountain range due to continent-continent collision. The typical geothermal gradient for slate is 100°C, for phyllite 200°C, for schist 300°C, for gneiss °C, for migmatite 500°C. [Return to Figure 7.3.2]

Media Attributions

- Figures 7.3.1, 7.3.2, 7.3.3, 7.3.4, 7.3.5, 7.3.6, 7.3.7: © Steven Earle. CC BY.

7.4 Regional Metamorphism

As described above, regional metamorphism occurs when rocks are buried deep in the crust. This is commonly associated with convergent plate boundaries and the formation of mountain ranges. Because burial to 10 to 20 kilometres is required, the areas affected tend to be large—thousands of square kilometres.

Rather than focusing on metamorphic rock textures (slate, schist, gneiss, etc.), geologists tend to look at specific minerals within the rocks that are indicative of different grades of metamorphism. Some common minerals in metamorphic rocks are shown in Figure 7.4.1, arranged in order of the temperature ranges over which they tend to be stable. The upper and lower limits of the ranges are intentionally vague because these limits depend on a number of different factors, such as the pressure, the amount of water present, and the overall composition of the rock.

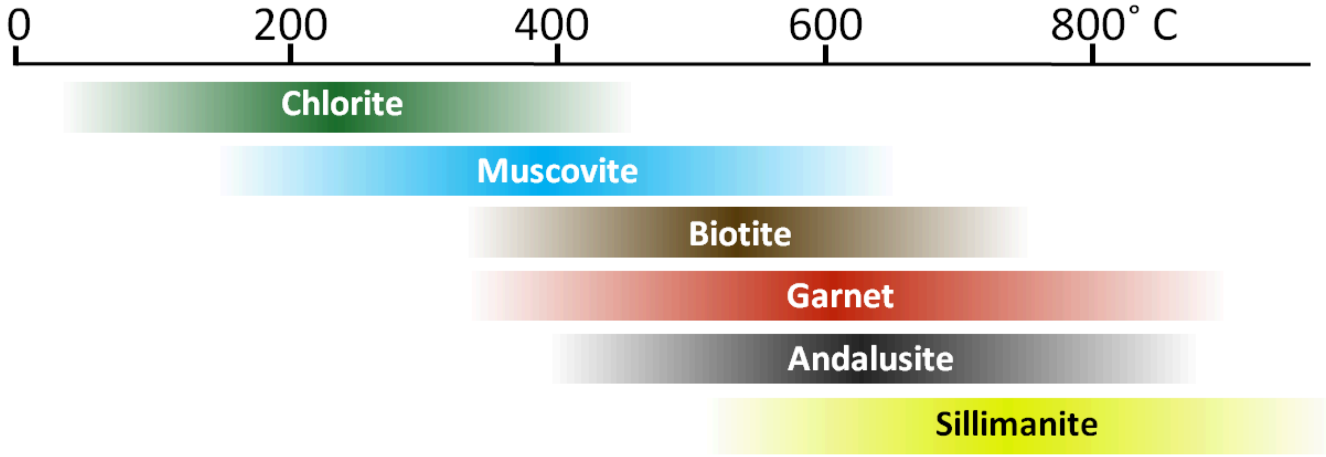

Figure 7.4.1 Metamorphic index minerals and their approximate temperature ranges [Image Description]

The southern and southwestern parts of Nova Scotia were regionally metamorphosed during the Devonian Acadian Orogeny (around 400 Ma), when a relatively small continental block (the Meguma **Terrane**[1]) was pushed up against the existing eastern margin of North America. As shown in Figure 7.4.2, clastic sedimentary rocks within this terrane were variably metamorphosed, with the strongest metamorphism in the southwest (the sillimanite zone), and progressively weaker metamorphism toward the east and north. The rocks of the sillimanite zone were likely heated to over 700°C, and therefore must have buried to depths between 20 and 25 kilometres. The surrounding lower-grade rocks were not buried as deep, and the rocks within the peripheral chlorite zone were likely not buried to more than about 5 kilometres.

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[1] No, it's not a spelling mistake! A terrane is a distinctive block of crust that is now part of a continent, but is thought to have come from elsewhere, and was added on by plate-tectonic processes.

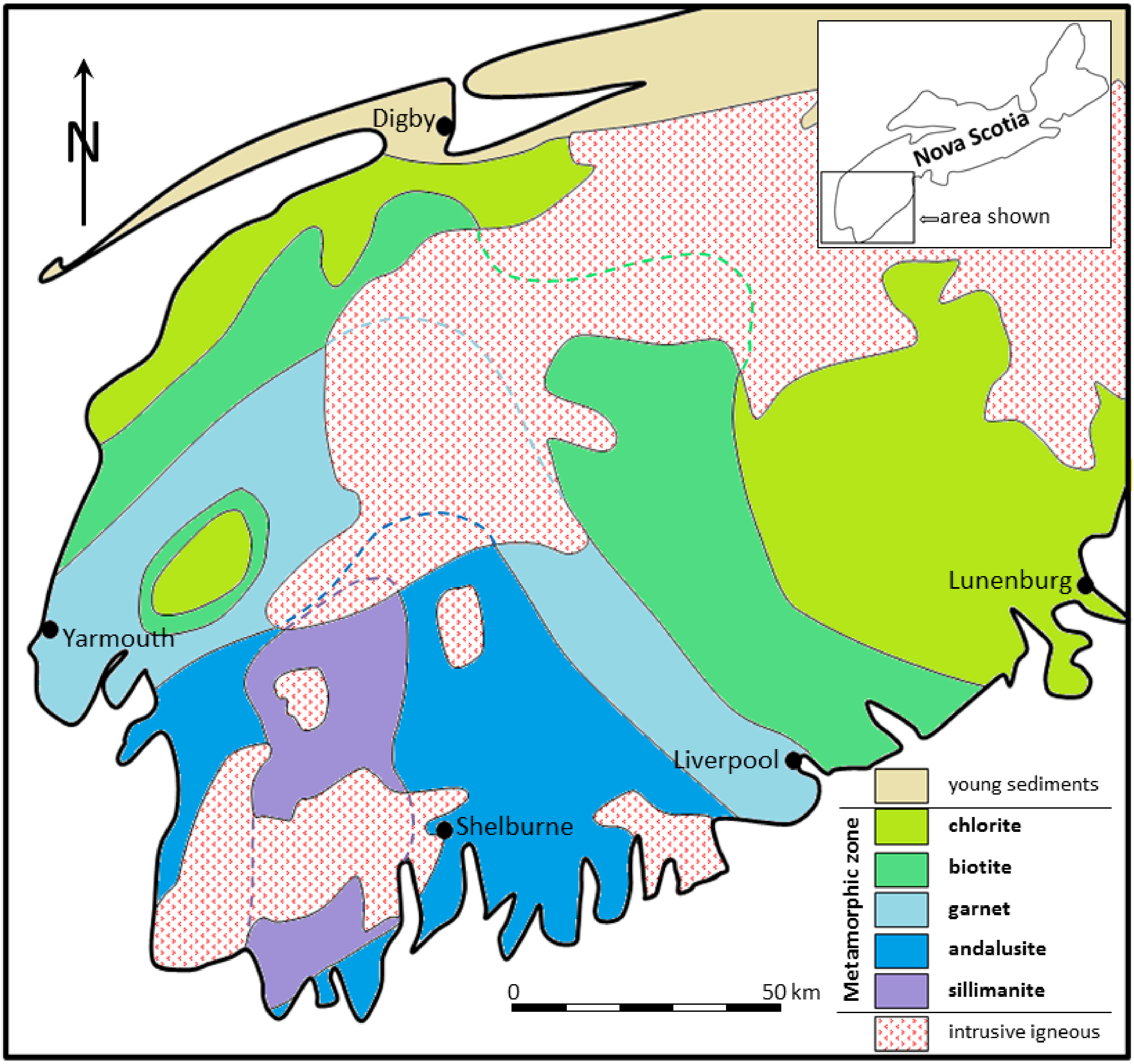

Figure 7.4.2 Regional metamorphic zones in the Meguma Terrane of southwestern Nova Scotia.

A probable explanation for this pattern is that the area with the highest-grade rocks was buried beneath the central part of a mountain range formed by the collision of the Meguma Terrane with North America. As is the case with all mountain ranges, the crust became thickened as the mountains grew, and it was pushed farther down into the mantle than the surrounding crust. This happens because Earth's crust is floating on the underlying mantle—and that is known as an isostatic relationship. As the formation of mountains adds weight, the crust in that area sinks farther down into the mantle to compensate for the added weight. The likely pattern of metamorphism in this situation is shown in cross-section in Figure 7.4.3a. The mountains were eventually eroded (over tens of millions of years), allowing the crust to rebound upward, thus exposing the metamorphic rock (Figure 7.4.3b).

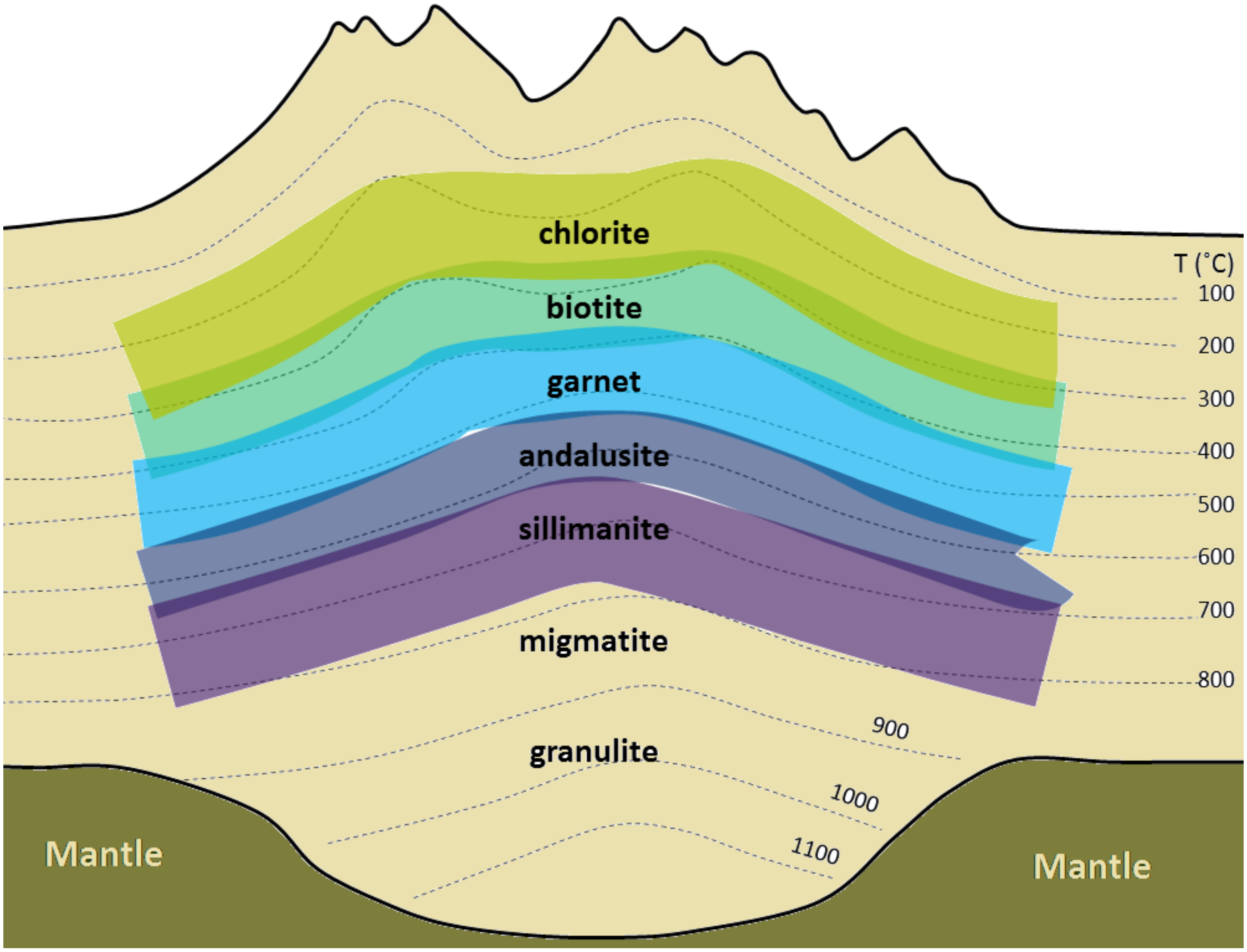

Figure 7.4.3a Schematic cross-section through the Meguma Terrane during the Devonian period. The crust is thickened underneath the mountain range to compensate for the added weight of the mountains above and has sunk into the mantle.

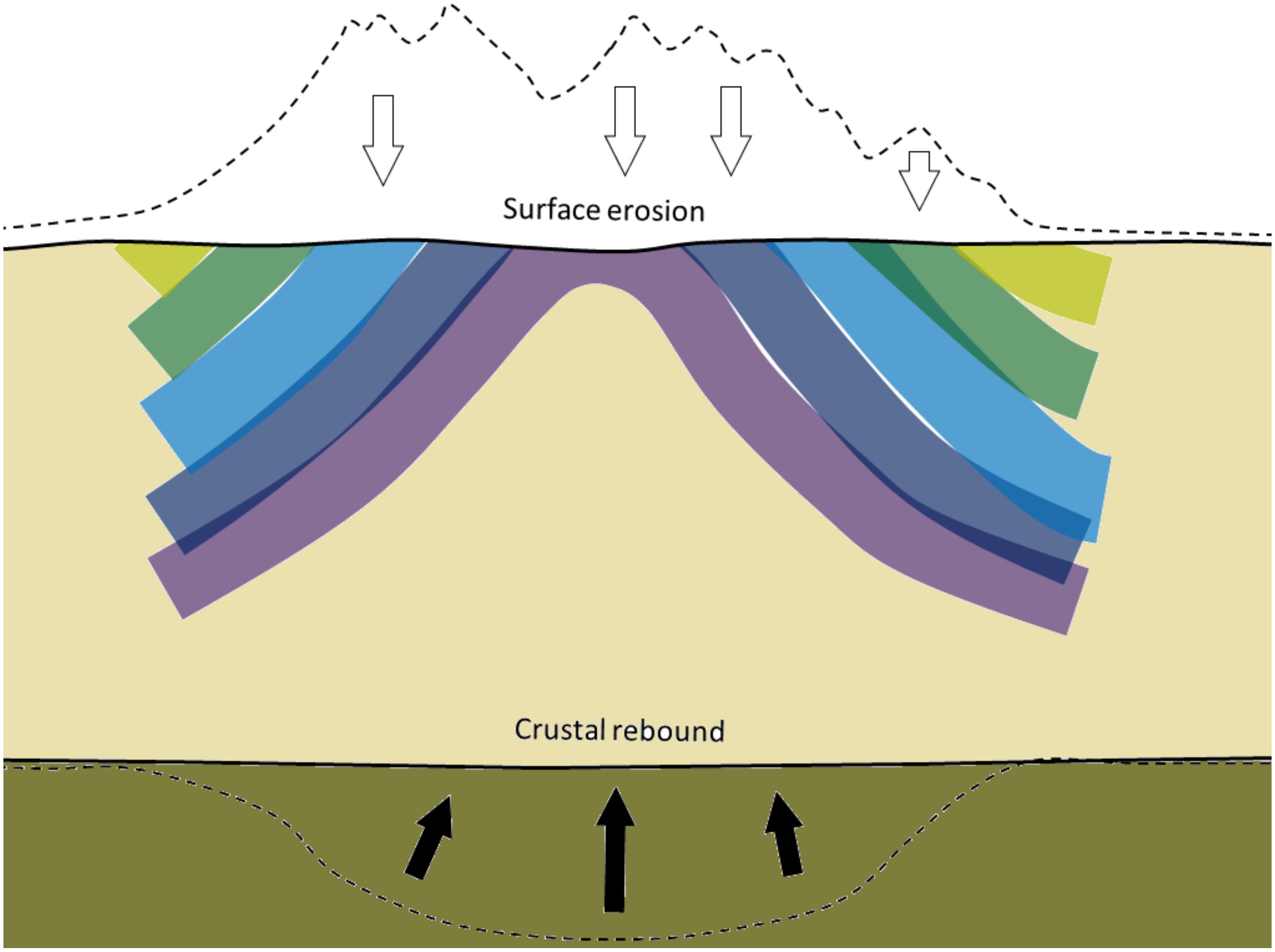

Figure 7.4.3b Schematic present-day cross-section through the Meguma Terrane. The mountains have been eroded. As they lost mass the base of the crust gradually rebounded, pushing up the core of the metamorphosed region so that the once deeply buried metamorphic zones are now exposed at surface.

The metamorphism in Nova Scotia's Meguma Terrane is just one example of the nature of regional metamorphism. Obviously many different patterns of regional metamorphism exist, depending on the parent rocks, the geothermal gradient, the depth of burial, the pressure regime, and the amount of time available. The important point is that regional metamorphism happens only at significant depths. The greatest likelihood of attaining those depths, and then having the once-buried rocks eventually exposed at the surface, is where mountain ranges existed and have since been largely eroded away. As this happens typically at convergent plate boundaries, directed pressures can be strong, and regionally metamorphosed rocks are almost always foliated.

Exercise 7.4 Scottish metamorphic zones

The map shown here represents the part of western Scotland between the Great Glen Fault and the Highland Boundary Fault. The shaded areas are metamorphic rock, and the three metamorphic zones represented are garnet, chlorite, and biotite.

Label the three coloured areas of the map with the appropriate zone names (garnet, chlorite, and biotite). Hint: refer to Figure 7.4.1 above to work out which of these zones might represent the peripheral area of low-grade metamorphism, and which might represent the core area of higher-grade metamorphism.

Indicate which part of the region was likely to have been buried the deepest during metamorphism.

British geologist George Barrow studied this area in the 1890s and was the first person anywhere to map metamorphic zones based on their mineral assemblages. This pattern of metamorphism is sometimes referred to as "Barrovian."

See Appendix 3 for Exercise 7.4 answers.

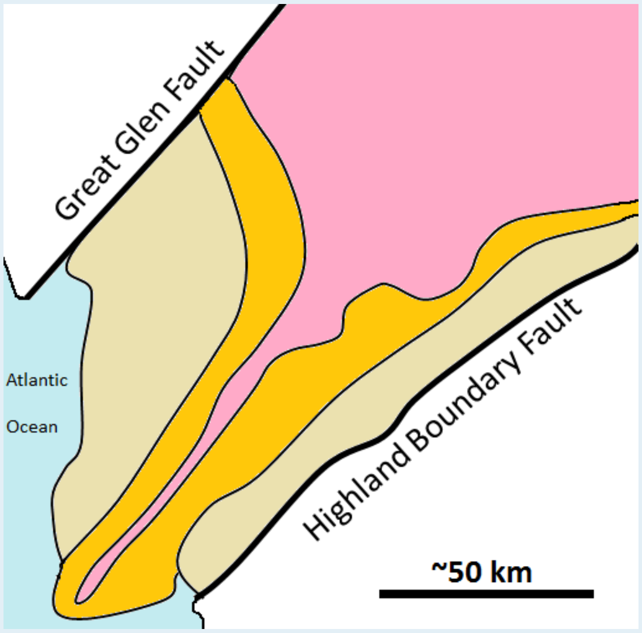

Figure 7.4.4

Image Descriptions

Figure 7.4.1 image description: Approximate temperature range of metamorphic minerals: Chlorite, 50 to 450°C. Muscovite, 175 to 625°C. Biotite, 350 to 725°C. Garnet, 375 to 900°C. Andalusite, 400 to 850°C. Sillimanite, 575 to 1000°C. [Return to Figure 7.4.1]

Media Attributions

- Figure 7.4.1, 7.4.3ab, 7.4.4: © Steven Earle. CC BY.
- Figure 7.4.2: Image edited by Steven Earle, after Keppie, D, and Muecke, G, 1979, Metamorphic map of Nova Scotia, N.S. Dept. of Mines and Energy, Map 1979-006., and from White, C and Barr, S., 2012, Meguma Terrane revisted, Stratigraphy, metamorphism, paleontology and provenance, Geoscience Canada, V. 39, No.1.

7.5 Contact Metamorphism and Hydrothermal Processes

Contact metamorphism takes place where a body of magma intrudes into the upper part of the crust. Any type of magma body can lead to contact metamorphism, from a thin dyke to a large stock. The type and intensity of the metamorphism, and width of the metamorphic **aureole** will depend on a number of factors, including the type of country rock, the temperature of the intruding body and the size of the body (Figure 7.5.1). A large intrusion will contain more thermal energy and will cool much more slowly than a small one, and therefore will provide a longer time and more heat for metamorphism. That will allow the heat to extend farther into the country rock, creating a larger aureole.

Contact metamorphic aureoles are typically quite small, from just a few centimetres around small dykes and sills, to several 10s of metres around a large stock. As was shown in Figure 7.3.7, contact metamorphism can take place over a wide range of temperatures—from around 300° to over 800°C—and of course the type of metamorphism, and new minerals formed, will vary accordingly. The nature of the country rock (or parent rock) is also important.

A hot body of magma in the upper crust can create a very dynamic situation that may have geologically interesting and economically important implications. In the simplest cases, water does not play a big role, and the main process is transfer of heat from the pluton to the surrounding rock, creating a zone of contact metamorphism (Figure 7.5.2a). In that situation mudrock or volcanic rock will likely be metamorphosed to hornfels (Figure 7.2.9), limestone will be metamorphosed to marble (Figure 7.2.6), and sandstone to quartzite (Figure 7.2.7). (But don't forget that marble and quartzite can also form during regional metamorphism!)

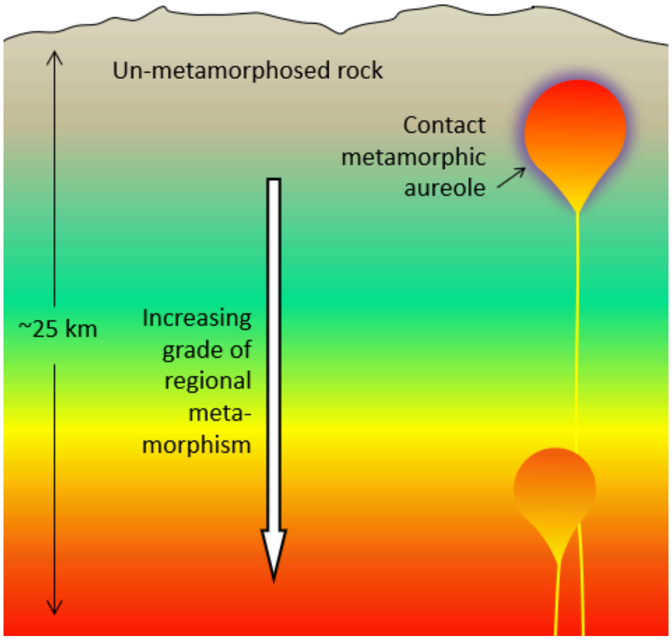

Figure 7.5.1 Schematic cross-section of the middle and upper crust showing two magma bodies. The upper body has intruded into cool unmetamorphosed rock near to the surface and has created a zone of contact metamorphism. The lower body is surrounded by rock that is already hot (and probably already metamorphosed), and so it does not have a significant metamorphic aureole.

In many cases, however, water is released from the magma body as crystallization takes place, and this water is dispersed along fractures in the country rock (Figure 7.5.2b). The water released from a magma chamber is typically rich in dissolved minerals. As this water cools, is chemically changed by the surrounding rocks, or boils because of a drop in pressure, minerals are deposited, forming veins within the fractures in the country rock. Quartz veins are common in this situation, and they might also include pyrite, hematite, calcite, and even silver and gold.

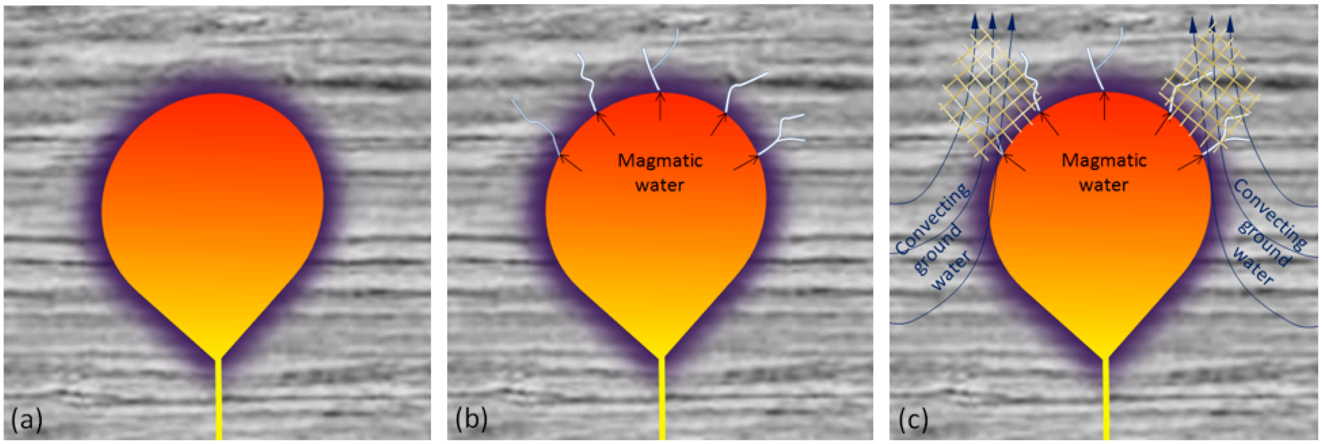

Figure 7.5.2 Depiction of metamorphism and alteration around a pluton in the upper crust. (a) Thermal metamorphism only (within the purple zone). (b) Thermal metamorphism plus veining (white) related to dispersal of magmatic fluids into the overlying rock. (c) Thermal metamorphism plus veining from magmatic fluids plus alteration and possible formation of metallic minerals (hatched yellow areas) from convection of groundwater.

Heat from the magma body will heat the surrounding groundwater, causing it to expand and then rise toward the surface. In some cases, this may initiate a convection system where groundwater circulates past the pluton. Such a system could operate for many thousands of years, resulting in the circulation of billions of litres of groundwater from the surrounding region past the pluton. Hot water circulating through the rocks can lead to significant changes in the mineralogy of the rock, including alteration of feldspars to clays, and deposition of quartz, calcite, and other minerals in fractures and other open spaces (Figure 7.5.3). As with the magmatic fluids, the nature of this circulating groundwater can also change adjacent to, or above, the pluton, resulting in deposition of other minerals, including ore minerals. Metamorphism in which much of the change is derived from fluids passing through the rock is known as **metasomatism**. When hot water contributes to changes in rocks, including mineral alteration and formation of veins, it is known as **hydrothermal alteration**.

Figure 7.5.3 Calcite veins in limestone of the Comox Formation, Nanaimo, B.C

A special type of metasomatism can take place where a hot pluton intrudes into carbonate rock such as limestone. When magmatic fluids rich in silica, calcium, magnesium, iron, and other elements flow through the carbonate rock, their chemistry can change dramatically, resulting in the deposition of minerals that would not normally exist in either the igneous rock or limestone. These include garnet, epidote (another silicate), magnetite, pyroxene, and a variety of copper and other minerals (Figure 7.5.4). This type of metamorphism is known as **skarn**, and again, some important types of mineral deposits can form this way.

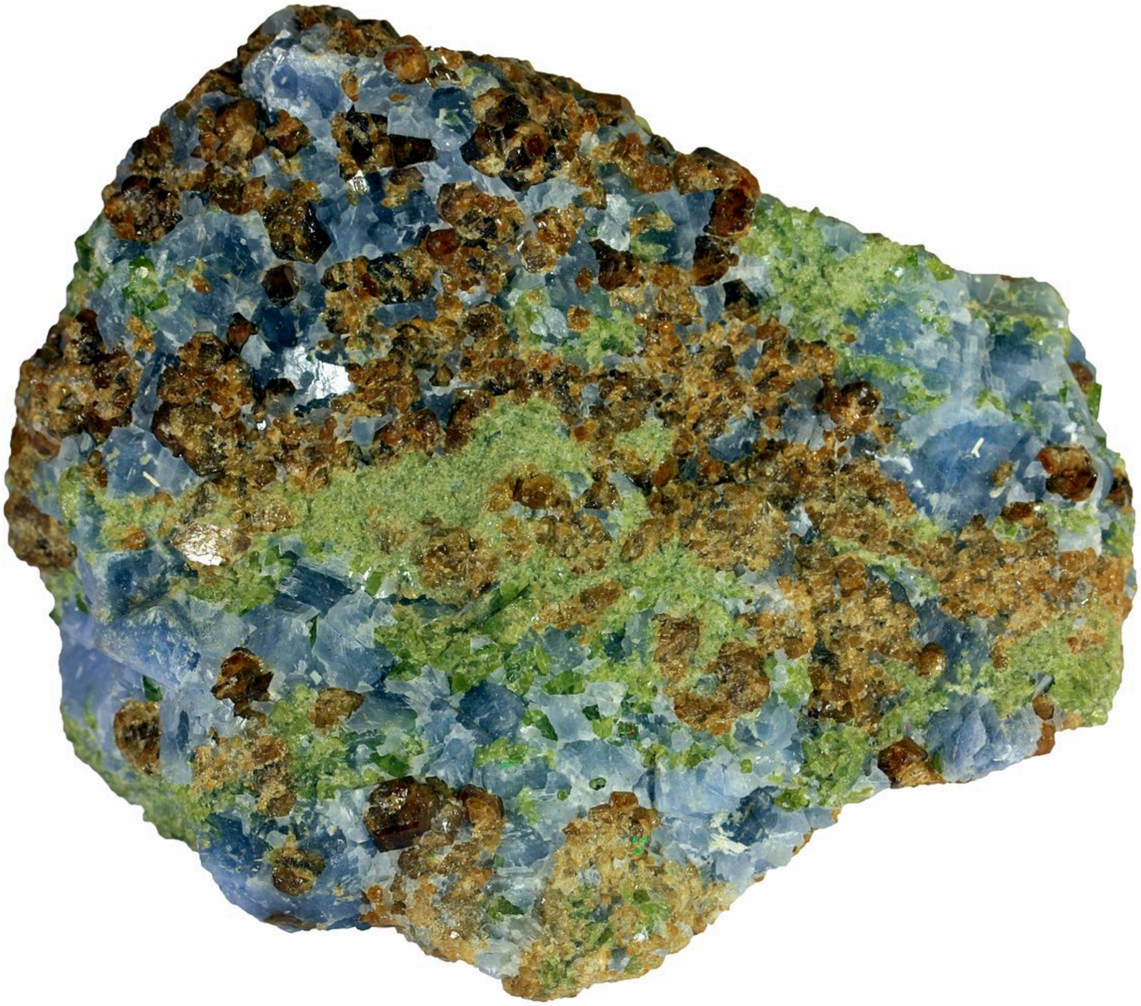

Figure 7.5.4 A skarn rock from Mount Monzoni, Northern Italy, with recrystallized calcite (blue), garnet (brown), and pyroxene (green). The rock is 6 centimetres across.

Exercise 7.5 Contact metamorphism and metasomatism

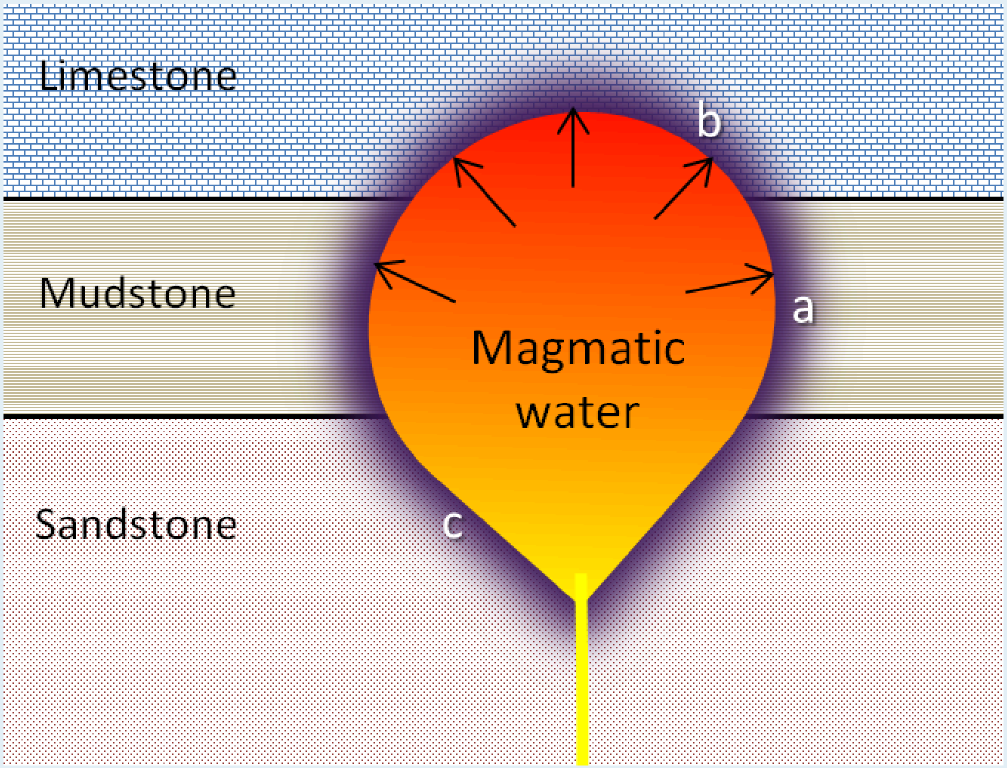

Figure 7.5.5

This diagram shows a pluton that has intruded into a series of sedimentary rocks. What type of metamorphic rock would you expect to see at locations:

a) Mudstone? ______________________

b) Limestone? ______________________

c) Sandstone? ______________________

See Appendix 3 for Exercise 7.5 answers.

Media Attributions

- Figures 7.5.1, 7.5.2, 7.5.3, 7.5.5: © Steven Earle. CC BY.
- Figure 7.5.4: 00031 6 cm grossular calcite augite skarn © Siim. CC BY SA.

Summary

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

Section	Summary
7.1 Controls Over Metamorphic Processes	Metamorphism is controlled by five main factors: the composition of the parent rock, the temperature to which the rock is heated, the amount and type of pressure, the volumes and compositions of aqueous fluids that are present, and the amount of time available for metamorphic reactions to take place.
7.2 Classification of Metamorphic Rocks	Metamorphic rocks are classified on the basis of texture and mineral composition. Foliation is a key feature of metamorphic rocks formed under directed pressure. Foliated metamorphic rocks include slate, phyllite, schist, and gneiss. Metamorphic rocks formed in environments without strong directed pressure include hornfels, marble, and quartzite, although the latter two may form in high-pressure situations but not develop obvious foliated textures.
7.3 Plate Tectonics and Metamorphism	Almost all metamorphism can be explained by plate-tectonic processes. Oceanic crustal rock can be metamorphosed near the spreading ridge where it was formed, but most other regional metamorphism takes place in areas where mountain ranges have been created, which are most common at convergent boundaries. Contact metamorphism takes place around magma bodies in the upper part of the crust, which are also most common above convergent boundaries.
7.4 Regional Metamorphism	Geologists classify metamorphic rocks based on some key minerals—such as chlorite, garnet, andalusite, and sillimanite—that form at specific temperatures and pressures. Most regional metamorphism takes place beneath mountain ranges because the crust becomes thickened and rocks are pushed down to great depths because of the isostatic relationship between the crust and mantle. When mountains erode, those metamorphic rocks are uplifted by crustal rebound.
7.5 Contact Metamorphism and Hydrothermal Processes	Contact metamorphism takes place around magma bodies that have intruded into cool rocks at high levels in the crust. Heat from the magma is transferred to the surrounding country rock, resulting in mineralogical and textural changes. Water from a cooling body of magma, or from convection of groundwater produced by the heat of the pluton, can also lead to metasomatism, hydrothermal alteration, and accumulation of valuable minerals in the surrounding rocks.

Questions for Review

Answers to Review Questions can be found in Appendix 2.

1. What are the two main agents of metamorphism, and what are their respective roles in producing metamorphic rocks?
2. Into what metamorphic rocks will a mudrock be transformed at very low, low, medium, and high metamorphic grades?
3. Why doesn't granite change very much at lower metamorphic grades?

4. Describe the main process of foliation development in a metamorphic rock such as schist.
5. What process contributes to metamorphism of oceanic crust at a spreading ridge?
6. How do variations in the geothermal gradient affect the depth at which different metamorphic rocks form?
7. Blueschist metamorphism takes place within subduction zones. What are the unique temperature and pressure characteristics of this geological setting?
8. Rearrange the following minerals in order of increasing metamorphic grade: biotite, garnet, sillimanite, chlorite.
9. Why does contact metamorphism not normally take place at significant depth in the crust?
10. What is the role of magmatic fluids in metamorphism that takes place adjacent to a pluton?
11. How does metasomatism differ from regional metamorphism?
12. How does the presence of a hot pluton contribute to the circulation of groundwater that facilitates metasomatism and hydrothermal processes?
13. What must be present in the country rock to produce a skarn?
14. Two things that a geologist first considers when looking at a metamorphic rock are what the parent rock might have been, and what type of metamorphism has taken place. This can be difficult to do, even if you have the actual rock in your hand, but give it a try for the following metamorphic rocks:
    a. Chlorite schist
    b. Slate
    c. Mica-garnet schist
    d. Amphibolite
    e. Marble

Review of Minerals and Rocks

Mineral and rock review

Steven Earle

Mineral and Rock Review

Crystals of the mineral native sulphur growing on the rock basalt at an outlet of volcanic gases, Kilauea volcano, Hawaii

Now that we've covered minerals and all three types of rocks it's important for you to convince yourself that you've got them straight in your mind. As already noted, one of the most common mistakes that geology students make on assignments, tests and exams is to confuse minerals with rocks and then give a wrong answer when asked to name one or the other based on information provided.

In this exercise you are given a list of names of minerals and rocks and asked to determine which ones are minerals and which are rocks. For those that you think are minerals you should then indicate which mineral group it belongs to (e.g., *oxide, sulphate, silicate, carbonate, halide* etc.). For those that you think are rocks, you should describe what type of rock it is (e.g., *intrusive igneous, extrusive igneous, clastic sedimentary, chemical sedimentary, foliated metamorphic* and *non-foliated metamorphic)*. The answers can be found in Rock and mineral review exercise answers in Appendix 3.

Mineral or rock name	**Rock or mineral?**	**If it's a mineral, which group does it belong to? If it's a rock, what type is it?**
Feldspar		
Calcite		
Slate		
Hematite		
Rhyolite		
Sandstone		
Diorite		
Olivine		
Pyrite		
Quartzite		
Granite		
Amphibole		
Conglomerate		
Chert		
Halite		
Gneiss		
Mica		
Pyroxene		
Chlorite		
Limestone		
Andesite		

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