

LAB 6: METAMORPHIC ROCKS AND THE ROCK CYCLE

Lab Structure

Recommended additional work	Yes – review rock and mineral ID in preparation for Test 2
Required materials	Mineral ID kit, Rock Kits 1 and 2, hand lens, pencil

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.
- Recognize 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.
- Describe the rock cycle and the types of processes that lead to the formation of igneous, sedimentary, and metamorphic rocks.

Key Terms

-
- | | |
|---|--|
| <ul style="list-style-type: none">• Metamorphism• Metamorphic grade• Geothermal gradient• Index minerals• Protolith• Recrystallization | <ul style="list-style-type: none">• Foliation• Slaty• Schistose• Gneissic• Massive |
|---|--|
-

6.1 Metamorphism and Plate Tectonics

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, or **protoliths**, but they may have the same overall chemical composition.

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. 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.

The main factors that control metamorphic processes are:

- the mineral composition of the protolith,
- 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.

Protolith

The protolith, or “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 gneiss, the parent rock of the gneiss 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, while remaining in a solid state.

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 6.1.1).

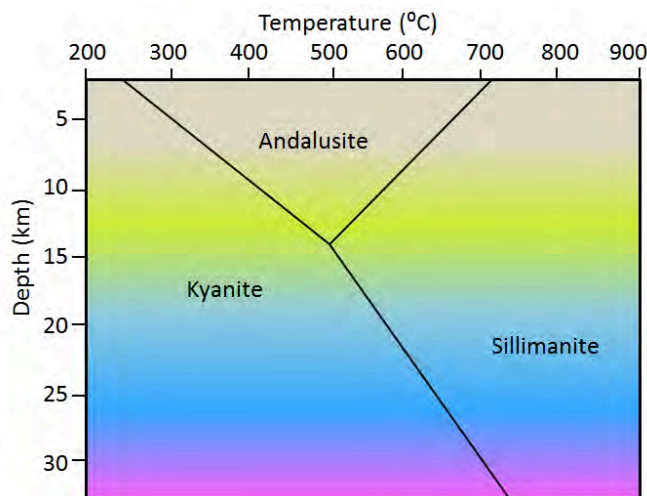


Figure 6.1.1: The temperature and pressure stability fields of the three polymorphs of Al_2SiO_5 (Pressure is equivalent to depth). Kyanite is stable at low to moderate temperatures and low to high pressures, andalusite at moderate temperatures and low pressures, and sillimanite at higher temperatures.)

Pressure

Pressure is important in metamorphic processes for two main reasons. First, it has implications for mineral stability (Figure 6.1.1). 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 6.1.2a), 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 6.1.2b). In situations where different blocks of the crust are being pushed in different directions, the rocks will likely be subjected to shear stress (Figure 6.1.2c).

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

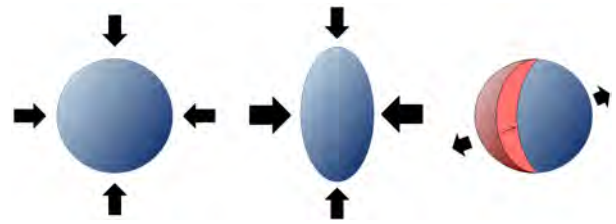


Figure 6.1.2: An illustration of different types of pressure on rocks. (a) confining pressure, where the pressure is essentially equal in all directions, (b) directed pressure, where the pressure from the sides is greater than that from the top and bottom, and (c) shear stress caused by different blocks 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, 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.

Practice Exercise 6.1

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 2 for Practice Exercise 6.1 answers.



Figure 6.1.3: Garnets in a schist. Euro coin (23 mm) is for scale.

Plate Tectonics and Metamorphism

All of the important processes of metamorphism can be understood in the context of geological processes related to plate tectonics. The relationships between plate tectonics and metamorphism are summarized in Figure 6.1.4. Two settings, continent–continent collisions and continental volcanic arcs are also shown in more detail in Figure 6.1.5.

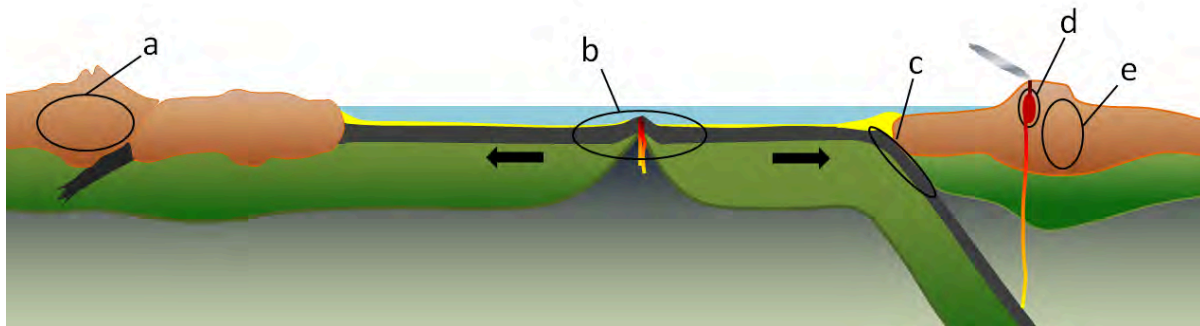


Figure 6.1.4: Environments of metamorphism in the context of plate tectonics: (a) regional metamorphism related to mountain building at a continent–continent convergent boundary, (b) regional metamorphism of oceanic crust in the area on either side of a spreading ridge, (c) regional metamorphism of oceanic 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 6.1.5. 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.

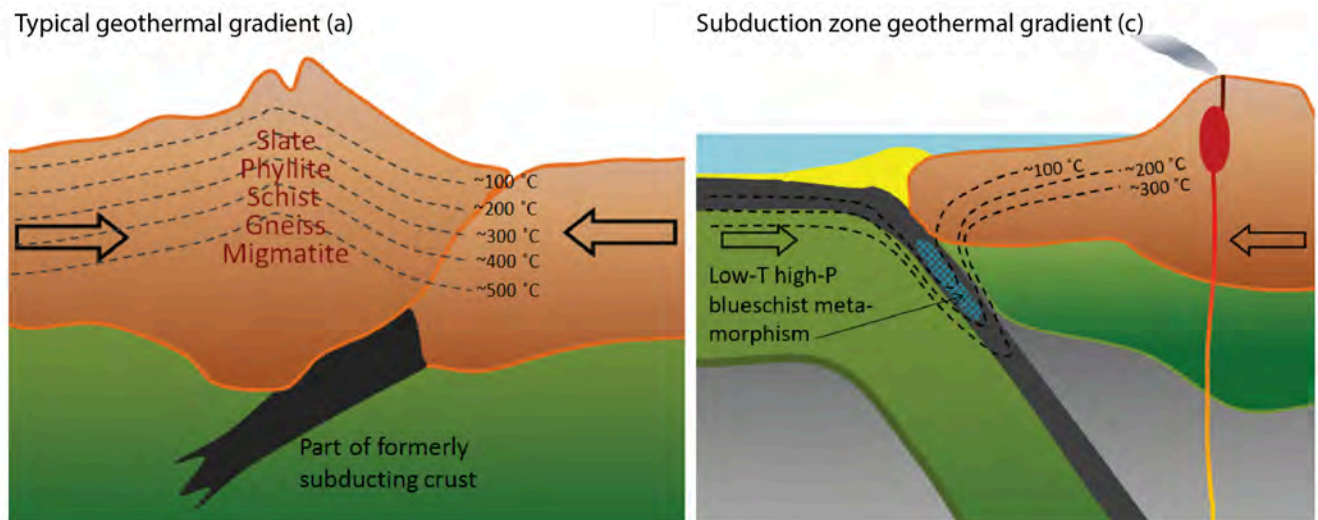


Figure 6.15: (left) Regional metamorphism beneath a mountain range related to continent-continent collision (typical geothermal gradient). Example: Himalayan Range. (right) Regional metamorphism of oceanic crust at a subduction zone forming a continental volcanic arc. (Example: Cascadia subduction zone. Rock of this type is exposed in the San Francisco area.)

Metamorphism also occurs at subduction zones, where oceanic crust is forced down into the hot mantle. Because the oceanic crust is typically relatively cool by the time it reaches the subduction zone, 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 6.1.5 right). A special type of metamorphism takes place under these very high-pressure but relatively low-temperature conditions, producing an amphibole mineral known as **glaucofan** ($\text{Na}_2(\text{Mg}_3\text{Al}_2)\text{Si}_8\text{O}_{22}(\text{OH})_2$), 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.

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 6.1.6). 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 6.1.6. 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 6.1.6 with the same letters (a through e) used in Figures 6.1.4 and 6.1.5.

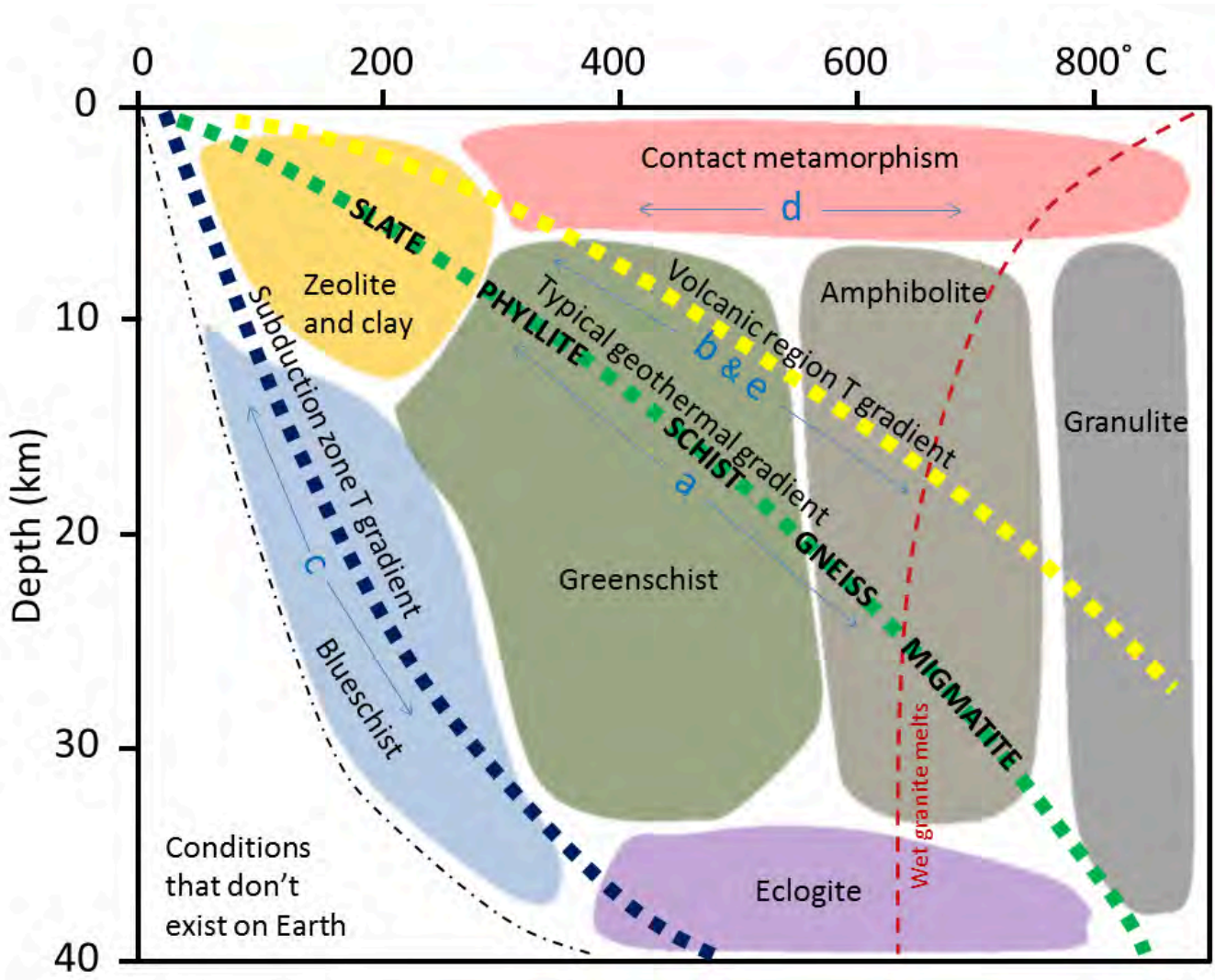


Figure 6.1.6: Types of metamorphism shown in the context of depth and temperature under different conditions. The metamorphic rocks formed from mudrock under regional metamorphism with a typical geothermal gradient are listed. The letters a through e correspond with those shown in Figures 6.1.4 and 6.1.5.

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 clay mineral zone (see Figure 6.1.6), 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.

Practice Exercise 6.2 Metamorphic rocks in areas with higher geothermal gradients

Figure 6.1.6 shows the types of rock that might form from a mudrock protolith at various points along the curve of the “typical” geothermal gradient (dotted green line). Looking at the geothermal gradient for volcanic regions (dot-

ted yellow line in Figure 6.1.6), estimate the depths at which you would expect to find the same types of rock forming from a mudrock protolith.

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

See Appendix 2 for Practice Exercise 6.2 answers.

Media Attributions

- Figures 6.1.1, 6.1.2, 6.1.4, 6.1.5, 6.1.6: © Steven Earle. CC BY.
- Figure 6.1.3: Garnet Mica Schist Syros Greece © Graeme Churchard. CC BY.

6.2 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 **massive** (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, tend to be massive because their minerals (quartz and calcite respectively) do not tend to show alignment (see Figure 6.2.1).

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 6.2.1). This contributes to the formation of foliation.

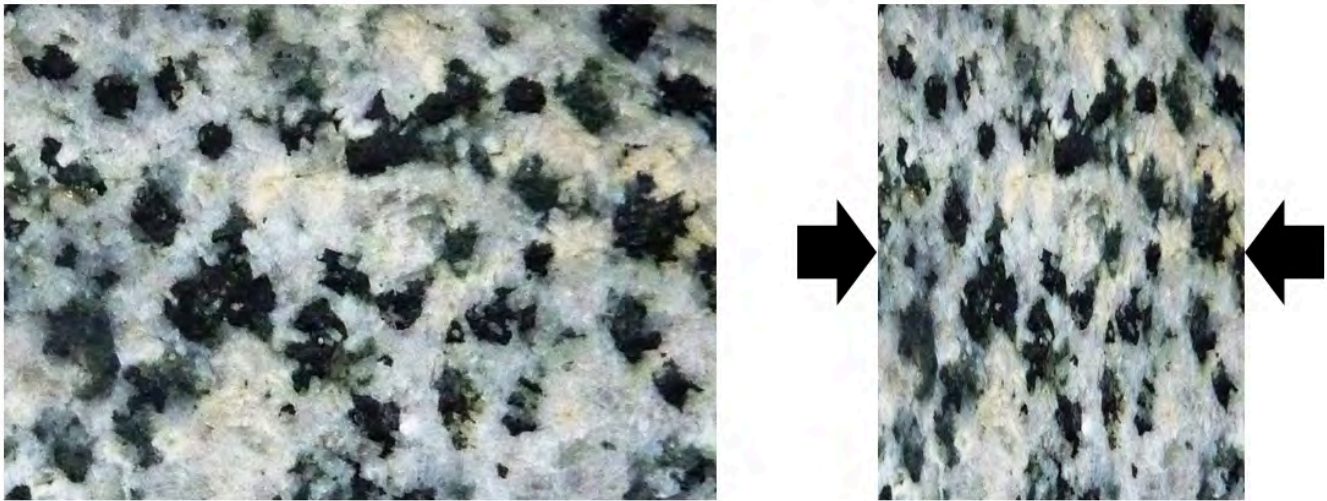


Figure 6.2.1: The textural effects of squeezing during metamorphism. In the original rock (left) there is no alignment of minerals. In the squeezed rock (right) the minerals have been elongated in the direction perpendicular to the squeezing.

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 6.2.2, 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.

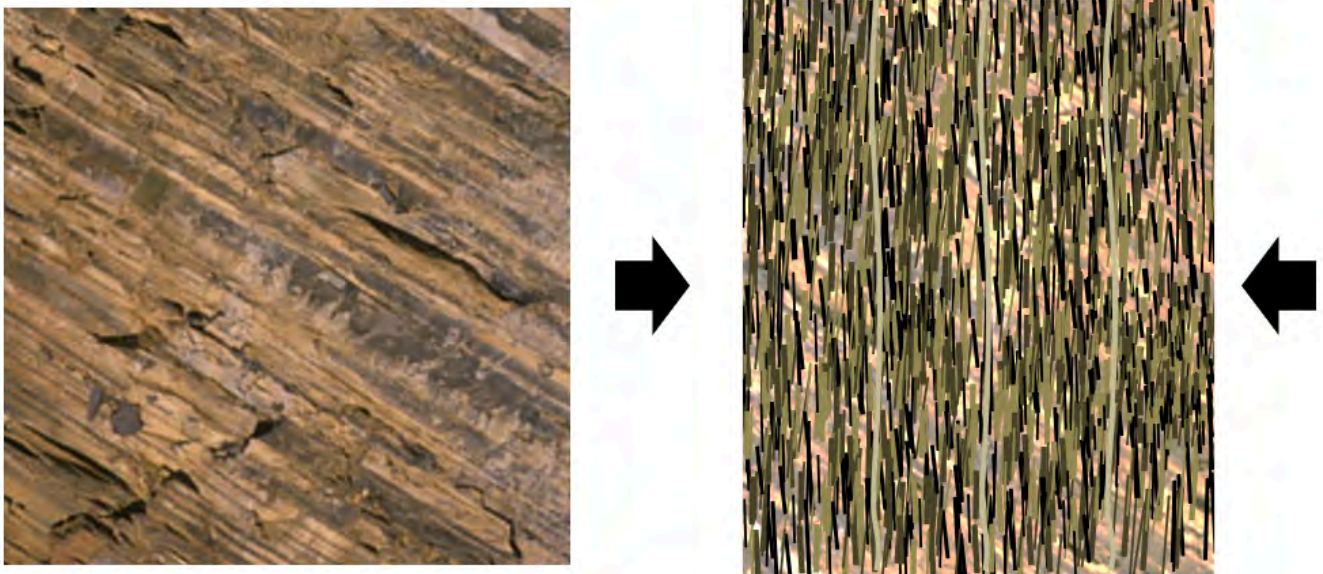


Figure 6.2.2: The textural effects of squeezing and mineral growth during regional metamorphism. The left diagram is shale with bedding slanting down to the right. The right diagram represents schist (derived from that shale), with mica crystals orientated perpendicular to the main stress direction and the original bedding no longer easily visible.

Figure 6.2.3 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 6.2.1) 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 6.2.2). 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 6.2.3: A slate boulder on the side of Mt. Wapta in the Rockies near Field, B.C. 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 **metamorphic grade** or intensity of metamorphism and the type of foliation are: **slaty**, **phyllitic**, **schistose**, and **gneissic** (Figure 6.2.4). 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 shiny sheen on the surface. Where slate is typically planar, phyllite can form in wavy layers. In the formation of a **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 a **gneiss**, the minerals may have separated into bands of different colours. In the example shown in Figure 6.2.4d, 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 or greenschist. 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 6.2.4: Examples of foliated metamorphic rocks: (A) Slate, (B) Phyllite, (C) Schist, (D) Gneiss.

Rather than focusing on just the metamorphic rock types (slate, schist, gneiss, etc.), geologists also tend to look at specific **index minerals** within the rocks that are indicative of different grades of metamorphism. Some common minerals in metamorphic rocks derived from a mudrock protolith are shown in Figure 6.2.5, 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.

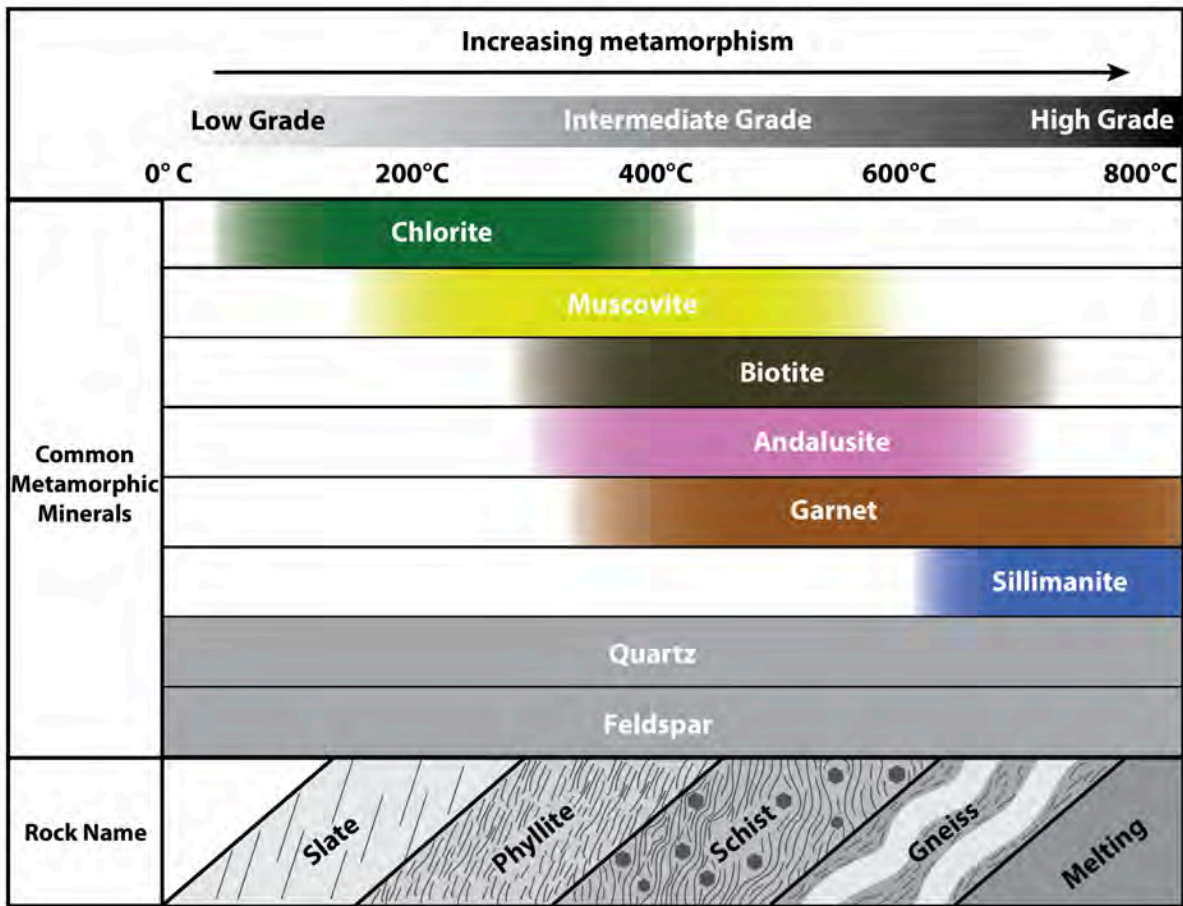


Figure 6.2.5: Metamorphic grades, common metamorphic index minerals, and corresponding rock names for a mudrock protolith under increasing metamorphism (increasing temperature and pressure). [Image description]

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 6.2.6).



Figure 6.2.6: 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 6.1. 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 6.1 A rough guide to the types of metamorphic rocks that form from different parent rocks at different grades of regional metamorphism. You are expected to know the rock names indicated in bold font.

Protolith	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	greenschist	greenschist	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, and their texture is described as **massive**. 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 **recrystallize** and 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 6.2.7), but if it had various impurities, such as clay, silica, or magnesium, the marble could be “marbled” in appearance.



Figure 6.2.7: Marble with visible calcite crystals (left) and an outcrop of banded marble (right).

Quartzite is metamorphosed sandstone (Figure 6.2.8). 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 6.2.8: 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.

Practice Exercise 6.3 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 2 for Practice Exercise 6.3 answers.

Image Descriptions

Figure 6.2.5 image description: Metamorphic index minerals for a mudrock protolith. As conditions change with increasing metamorphism, certain minerals become unstable and undergo solid-state changes to form new, stable minerals. For example, between ~300-400°C, the elements in chlorite will be re-ordered to form the mineral biotite. Note that while garnet, for example, is a common mineral in schist, it is not present in all schists! The new minerals that form in a metamorphic rock are dependent upon the composition of the protolith and a wide variety of minerals are possible. Approximate temperature range of metamorphic index minerals: Chlorite, 50 to 450°C. Muscovite, 175 to 625°C. Biotite, 300 to 725°C. Andalusite, 300 to 650°C. Garnet, 375 to 900°C. Sillimanite, 575 to 1000°C. Not all minerals in a metamorphic rock are indicative of

a particular metamorphic grade. Quartz, feldspar, and calcite (not shown), for example, are stable over the entire range of temperatures shown in Figure 6.3.1. [Return to Figure 6.2.5]

Media Attributions

- Figures 6.2.1, 6.2.2, 6.2.3, 6.2.4abd, 6.2.8: © Steven Earle. CC BY.
- Figure 6.2.4c: Schist detail © Michael C. Rygel. CC BY-SA.
- Figure 6.2.5: © Siobhan McGoldrick. CC BY.
- Figure 6.2.6: Migmatite in Geopark on Albertov © Chmee2. CC BY.
- Figure 6.2.7 (right): An outcrop of banded marble by the USGS. Public domain.

6.3 The Rock Cycle

Now that you have practiced identifying all three major categories of rock, let's examine how these rocks are slowly but constantly being changed from one form to another. The processes involved in the constant changing of these components of the Earth's crust are summarized in the **rock cycle** (Figure 6.3.1). The rock cycle is driven by two forces: (1) Earth's internal heat engine, which moves material around in the core and the mantle and leads to slow but significant changes within the crust, and (2) the hydrological cycle, which is the movement of water, ice, and air at the surface, and is powered by the sun.

The rock cycle is still active on Earth because our core is hot enough to keep the mantle moving, our atmosphere is relatively thick, and we have liquid water. On some other planets or their satellites, such as the Moon, the rock cycle is virtually dead because the core is no longer hot enough to drive mantle convection and there is no atmosphere or liquid water.

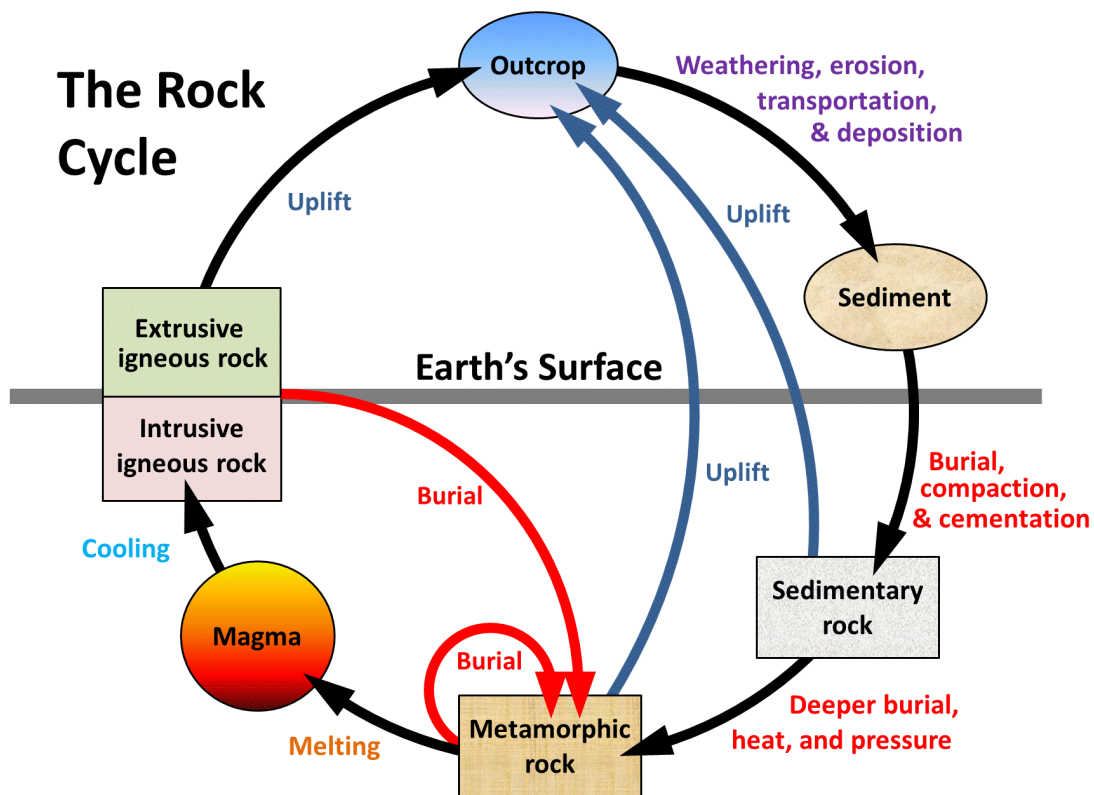


Figure 6.3.1: A schematic view of the rock cycle.

In describing the rock cycle, we can start anywhere we like, although it's convenient to start with magma. As you learned in Lab 4, magma is rock that is hot to the point of being entirely molten, with a temperature of between about 800° and 1300°C, depending on the composition and the pressure.

Magma can either cool slowly within the crust (over centuries to millions of years)—forming **intrusive igneous rocks**, or erupt onto the surface and cool quickly (within seconds to years)—forming **extrusive igneous rocks** (volcanic rocks). Intrusive igneous rocks typically crystallize at depths of hundreds of metres to tens of kilometres below the surface. To change its position in the rock cycle, intrusive igneous rock has to be uplifted and then exposed by the erosion of the overlying rocks.

Through the various plate tectonics-related processes of mountain building, all types of rocks are uplifted and exposed at the surface. Once exposed, they are weathered, both physically (by mechanical breaking of the rock) and chemically (by weathering of the minerals), and the weathering products—mostly small rock and mineral fragments—are eroded, transported, and then deposited as **sediments**. Transportation and deposition occur through the action of glaciers, streams, waves, wind, and other agents, and sediments are deposited in rivers, lakes, deserts, and the ocean.

Practice Exercise 6.4 Rock around the rock-cycle clock

Referring to the rock cycle (Figure 6.3.1), list the steps that are necessary to cycle some geological material starting with a sedimentary rock, which then gets converted into a metamorphic rock, and eventually a new sedimentary rock.

A *conservative* estimate is that each of these steps would take approximately 20 million years (some may be less, others would be more, and some could be much more). How long might it take for this entire process to be completed?

See Appendix 2 for Exercise 6.4 Answers.

Unless they are re-eroded and moved along, sediments will eventually be buried by more sediments. At depths of hundreds of metres or more, they become compressed and cemented into **sedimentary rocks**. Again through various means, largely resulting from plate-tectonic forces, different kinds of rocks are either uplifted, to be re-eroded, or buried deeper within the crust where they are heated up, squeezed, and changed into **metamorphic rock**.

Media Attributions

- Figure 6.3.1: © Steven Earle. CC BY.

Lab 6 Exercises

Part I: Metamorphic Rocks

The exercises below will guide you through the metamorphic rock samples in Rock Kits 1 and 2. Review the background information presented in Chapters 6.1 and 6.2 before you begin these exercises. You may wish to consult the Rock Classification Tables at the back of this manual as you complete the exercises below.

Tips for Classifying Metamorphic Rocks

- Your first step when examining a metamorphic rock is to determine if its texture is **foliated** or **massive**.
- If the rock is foliated, next determine the type of foliation:
 - **Slaty** foliations are flat, smooth surfaces along which a slate breaks. They might have a slightly shinier lustre than a shale.
 - Larger crystals of micas that define a **schistose** foliation give it a shiny, wavy appearance and any sheet-like or elongate minerals will be aligned in a preferred orientation.
 - **Gneissic** foliation, or gneissic banding, is defined by segregated bands of light-coloured quartz and feldspars and dark-coloured **ferromagnesian** minerals.
- If the texture is massive, test the sample with a drop of dilute HCl. **Marble** reacts with HCl just like its protolith – limestone!
- If the sample is massive and does not react with HCl, try testing the hardness. **Quartzite** is composed predominantly of quartz, giving it a hardness ~7.
- Lastly, if the metamorphic rock is foliated but has a distinctly green-colour to it, and contains abundant ferromagnesian minerals chlorite and green amphibole, it is called a **greenschist**.
- Figure E and Table D in the Rock Classification Tables appendix may be helpful resources as you complete these lab exercises.

1. The best way to really appreciate the metamorphic changes to a rock is to meet its parent! Examine each of the sample pairs listed below. Each pair contains a metamorphic rock and its **protolith** (parent rock). Identify which of the two samples is the metamorphic rock, and then carefully compare the two. In what ways are the metamorphic rock and its protolith similar? In what ways do they differ? Record your observations in the table below.

- Pair A: R221 and R361
- Pair B: R301 and R181
- Pair C: R1 and R331
- Pair D: R351 and R161

	Name of protolith	Name of metamorphic rock	Observations (how does the metamorphic rock differ from its protolith?)
Pair A			
Pair B			
Pair C			
Pair D			

2. Examine samples R181, R301, R321, R331, and R332. These samples show the progression of changes from a protolith (shale) to a high grade metamorphic rock (gneiss). Complete the table below by recording the changes you observe in mineralogy and texture with increasing metamorphism. For the changes in mineralogy, record what new minerals you see and note any minerals that have disappeared. For the changes in texture, look for changes in grain size or the development of a foliation.

	Changes in mineralogy	Changes in texture
<p>Shale to slate (R181 to R301/R302)</p>		
<p>Slate to schist (R301/R302 to R321)</p>		
<p>Schist to gneiss (R321 to R331/R332)</p>		

3. This progression of foliated metamorphic rocks from slate to gneiss is typical of mudrocks that are metamorphosed during **regional metamorphism** with a typical **geothermal gradient**. Using Figure 6.1.6 and Figure E in the Rock Classification Tables as a guide, complete the table below to summarize the range of temperatures and depths (pressure) responsible for the metamorphism of samples R301, R321, and R332.

Sample #	Approx. temperature (°C)	Approx. Depth (km)	Metamorphic Grade (low, intermediate, high)
R301			
R321			
R332			

4. Which two samples in your Rock Kits 1 and 2 represent non-foliated (or **massive**) metamorphic rocks? _____

5. Do these two samples exhibit crystalline or clastic textures? _____

6. Examine sample R351. Try to scratch this sample with the tools from your mineral ID kit. How hard is this sample? _____

7. Based on your answer above, and any other physical properties you observe, name the main mineral(s) present in this rock: _____

8. Examine sample R361. Try to scratch this sample with the tools from your mineral ID kit. How hard is this sample? _____

9. Place a small drop of HCl on a fresh surface of the sample. What happens? _____

10. On the basis of these two tests name the main mineral present in this rock: _____

11. Metamorphism may affect the texture or the mineral composition or both of these properties of the protolith. Do samples R351 and R361 have the same mineral composition as their respective sedimentary protoliths? Do they have the same texture? Explain your answers.

Part II: The Rock Cycle

The exercises below are a review of the rock cycle processes by which one type of rock is transformed into another over geological time. You will review all the rock samples in Rock Kits 1 and 2 that you have examined to date in preparation for Test 2. Review the background information presented in Chapter 6.3 before you begin these exercises. To benefit the most from these review exercises, remove all your rock samples from the Rock Kits and set the empty kits aside, so that you cannot see the names of the rocks.

All rocks are connected through the rock cycle. Any rock that you see today will at some point in the future be transformed into a different rock through the rock cycle (see Figure 6.3.1). This exercise focuses on the **processes** that are responsible for the transformation of one rock type into another. As a starting point, summarize the main processes involved in the formation of the three main categories of rock:

- Igneous:
- Sedimentary:
- Metamorphic:

The example presented below illustrates how you should complete question 12, by explaining the processes that formed the rocks in the second column. This example begins with granite, and the processes responsible for the formation of the granite are explained first. Then, the processes that explain how granite is transformed into quartz sandstone are outlined, and so on.

Order	Rock Name	Sample #	Rock Cycle Processes Responsible
1	Granite	R1	Partial melting of pre-existing rock to generate magma. Felsic magma cools and crystallizes at depth to form granite, a felsic intrusive igneous rock.
2	Quartz sandstone	R161	Granite is uplifted to surface, chemically and mechanically weathered, and eroded. Sand-sized grains of quartz, feldspar and some ferromagnesian minerals are transported. Feldspars and ferromagnesian minerals chemically weather to form clay minerals and ions in solution. Quartz grains become more rounded and better sorted with transport. Eventually quartz grains are deposited in a moderate to high energy environment (depending on grain size). Grains of quartz are lithified into sandstone through burial by other sediments, compaction, and cementation by mineral(s) precipitated from a fluid.
3	Quartzite	R351	Quartz sandstone is metamorphosed through regional or contact metamorphism. Grains of quartz recrystallize into coarser grains to form a crystalline texture.

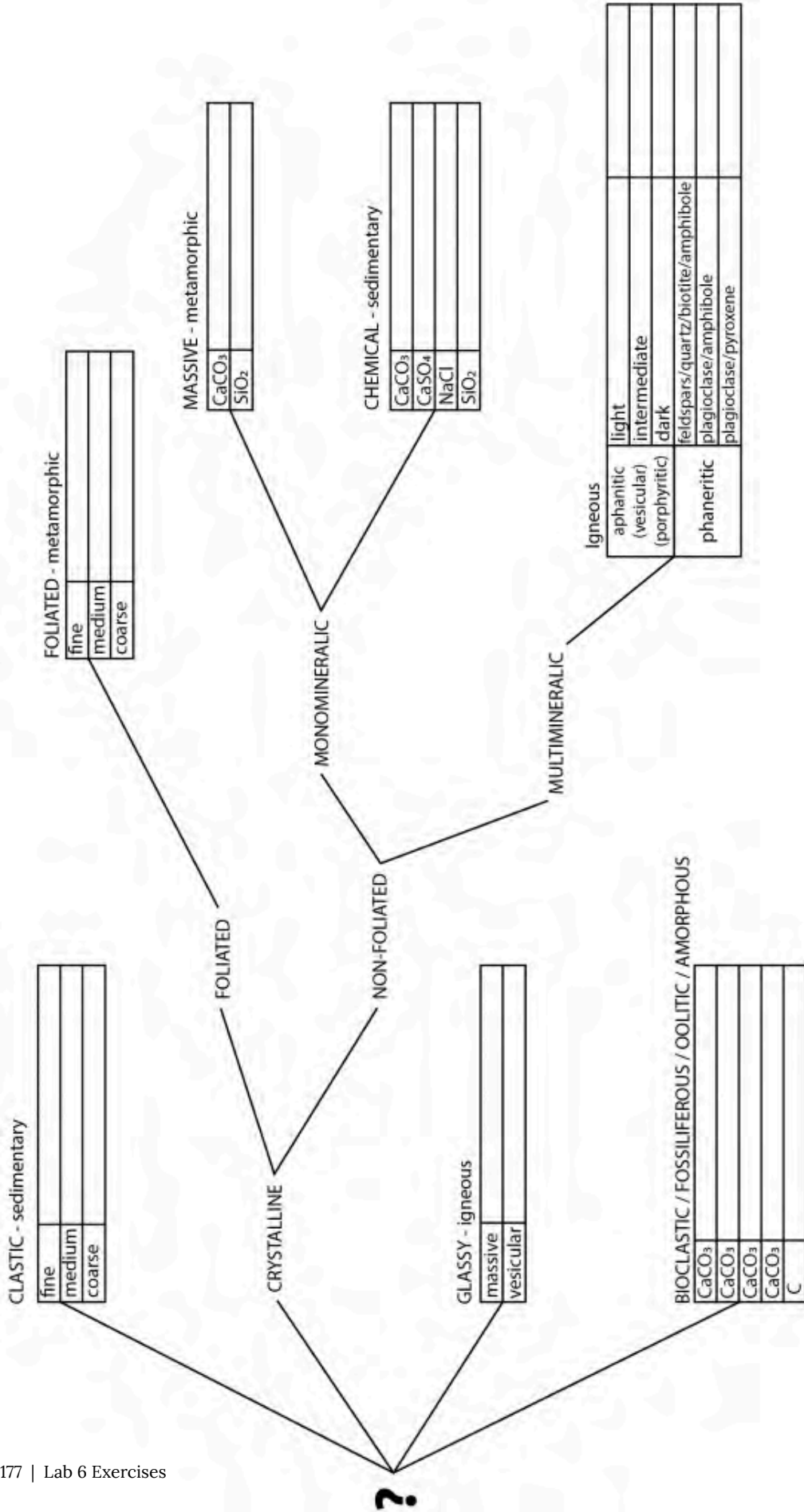
12. For each of the rocks specified below, find the corresponding rock sample from your collection of rocks. Remember, for this to be an effective review activity, do this without looking at the rock names in the kit! Complete the table with the appropriate sample number, and explain the processes from the rock cycle that have transformed the previous sample into the present sample. Begin by explaining how pebble-sized clasts of basalt formed, and then how shale could form from those basalt pebbles, and so on.

Order	Rock Name	Sample #	Rock Cycle Processes Responsible
1	Basalt pebbles (sediment)	N/A	
2	Shale		
3	Garnet gneiss		
4	Diorite		

Part III: Rock Review

13. Use the flow chart below to review igneous, sedimentary, and metamorphic rocks from Labs 4-6. This review will help you prepare for Test 2. The words “fine”, “medium”, and “coarse” on the flow chart refer to grain size. Chemical formulae are listed for any **monomineralic** rocks. The words “light”, “inter-

mediate”, and “dark” refer to the colour (and therefore composition) of aphanitic igneous rocks.



Summary

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

Section	Summary
6.1 Metamorphism and Plate Tectonics	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. Almost all metamorphism can be explained by plate tectonic processes. Most 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.
6.2 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 that do not tend to be foliated, even if formed under directed pressure, include marble and quartzite. Geologists also classify metamorphic rocks based on some key minerals—such as chlorite, garnet, andalusite, and sillimanite—that form at specific temperatures and pressures.
6.3 The Rock Cycle	The three types of rocks are <u>igneous</u> : formed from magma; <u>sedimentary</u> : formed from fragments of other rocks or precipitation from solution; and <u>metamorphic</u> : formed when existing rocks are altered by heat, pressure, and/or chemical action. The rock cycle summarizes the processes that contribute to cycling of rock material among these three types. The rock cycle is driven by Earth's internal heat, and by processes happening at the surface, which are driven by solar energy.
Lab 6 Exercises	Metamorphic rocks are classified according to their mineral composition, and texture (foliated or massive). Knowing the diagnostic properties of the common metamorphic minerals like chlorite, muscovite, biotite, and garnet will help you estimate the metamorphic grade of the rock (low, intermediate, or high grade). Just as with mineral samples, different samples of the same rock may not always look exactly the same, but they can always be identified by closely examining the mineral composition and texture. For example, schist can contain a wide variety of new metamorphic minerals with different colours and shapes, but all schists are characterized by schistose foliation.

Review of Minerals and Rocks

Mineral and Rock Review

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 (massive) metamorphic*). If the rock is metamorphic, list its protolith. The answers can be found 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		