

11

Metamorphic Rocks

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11.1 INTRODUCTION

In any introductory textbook on physical geology, the reader will find the discussion on metamorphic rocks located after the chapters on igneous and sedimentary rocks, and for very good reason. Metamorphic rocks form by the physical and sometimes chemical alteration of a pre-existing rock, whether it is igneous or sedimentary. In some cases, even metamorphic rocks can be altered into a completely different metamorphic rock. With igneous rocks forming from the melt produced by any rock type and a sedimentary rock forming from the weathered product of any rock type, the alteration of any rock to produce a metamorphic one completes the components of what is known as the rock cycle. Basically, the rocks we encounter today that we classify as either igneous, metamorphic, or sedimentary, could have belonged to a different rock classification in the past, as rocks are recycled throughout geologic time, driven by the motion of the tectonic plates (see Chapter 4). It is easy to see that increasing the temperature of a rock can produce magma, and that rocks on the surface of the earth can break up into sediment that can ultimately lithify into a sedimentary rock. But how can we alter a solid rock into a new rock, without melting it or making it become sediment?

All rocks are formed at certain temperatures and pressures on or more commonly, beneath the earth's surface, and these rocks are the most stable at the conditions under which they form. Therefore, changing the temperature and/or pressure conditions may lead to a different rock, one that changed in order to be stable under new external conditions. This new rock that forms in response to changes in its physical and chemical environment is called a metamorphic rock; the word metamorphism means to change form, and for rocks this means a recrystallization of minerals (crystals) under subsolidus (temperatures too low for melt production) conditions. A metamorphic change can also occur if the rock's composition is altered by hot, chemically reactive fluids, causing a change in the mineral content of the rock. To distinguish between the pre-existing rock and the new metamorphic one, the term **protolith** or parent rock is used to describe the pre-existing rock,

and all metamorphic rocks have at least one protolith that has altered during metamorphism. In this chapter you will learn that all metamorphic rocks are identified by the mineral content and texture of the rock; for metamorphic rocks, texture refers to the orientation of the minerals in the rock, although crystal size does convey important information regarding the temperature conditions during metamorphism.

To summarize, metamorphism is the process by which a pre-existing rock (the protolith) is altered by a change in temperature, pressure, or by contact with chemically reactive fluids, or by any combination of these three parameters. The alteration process is a **recrystallization** event, where the initial rock's minerals (crystals) have changed size, shape, and/or composition in response to these new external conditions. The end result is a new (metamorphic) rock that has an altered appearance, sometimes strikingly different from what it used to look like before metamorphism occurred. What metamorphic rock you end up with is strongly dependent on what rock you started with before the metamorphic event. Of secondary importance is the agent of metamorphic change: was recrystallization due to increased temperature, pressure, or both, or were chemically reactive fluids involved? Also, one must consider how high the temperatures and pressures were, as metamorphism can occur in a range of temperature and pressure conditions. However, as mentioned in the preceding paragraph, metamorphism occurs under subsolidus conditions, meaning that elevated temperatures that promote the recrystallization of a rock are not high enough to cause melting.

11.1.1 Learning Outcomes

After completing this chapter, you should be able to:

- Correctly identify the metamorphic rocks and their distinguishing features
- Identify foliated metamorphic rocks, and the type of foliation
- Determine the grade of metamorphism based on foliation and possible index minerals
- Recognize metamorphic environments and types of metamorphism

11.1.2 Key Terms

Contact metamorphism	Lineation
Differential pressure	Lithostatic pressure
Dynamic (fault zone) metamorphism	Metamorphism
Foliation	Mylonite
Gneissic banding	Protolith
Hydrothermal Metamorphism	Recrystallization
	Regional metamorphism
Index mineral	Schistose foliation

- Regional metamorphism
 - Schistose foliation
 - Shock (impact) Metamorphism
- Slaty cleavage
 - Tektite
 - Thermodynamic metamorphism

11.2 AGENTS OF METAMORPHISM

11.2.1 Pressure

All rocks beneath the surface of the earth experience an increase in pressure due to the weight of the overlying sediment and rock layers, and with increasing depth there is a corresponding increase in pressure. This increased pressure does not necessarily cause a rock to become metamorphic, because this particular pressure is typically equal in all directions and is known as lithostatic pressure. Litho-static pressure is similar to hydrostatic pressure, such as the pressure on the eardrums a swimmer will experience as he or she dives deep in the water. Lithostatic pressure on rocks below the earth's surface may have a change in overall rock volume, but will not cause a change in the shape. An example of decreasing volume due to lithostatic pressure would be a closer packing of clasts and reduction of pore space within a clastic sedimentary rock. But what if the pressure on a rock is un-

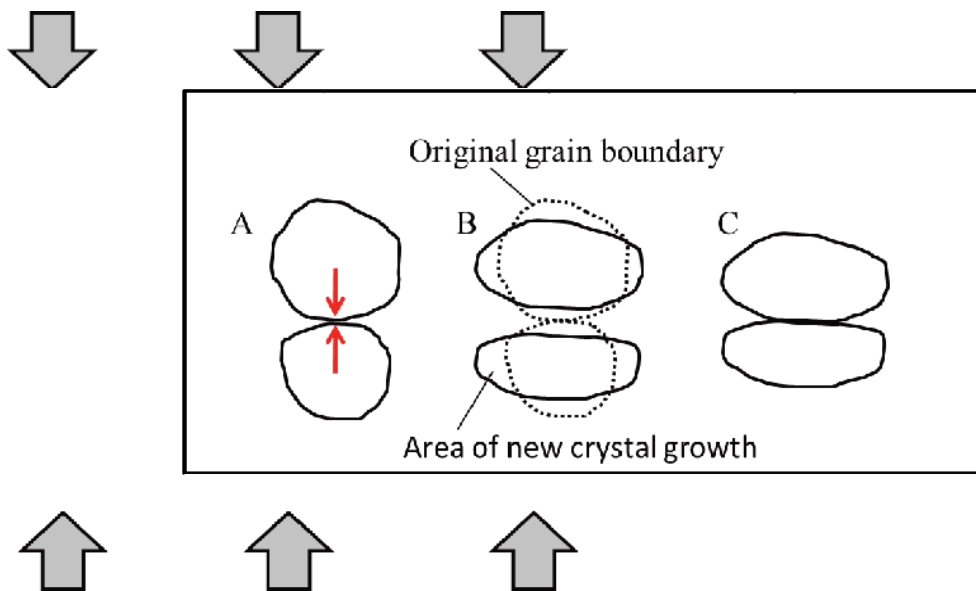


Figure 11.1 | Example of mineral grain deformation due to differential pressure: A) Rounded grains experience the greatest pressure at the contact between the two grains due to the greatest applied pressure as indicated by the large gray arrows. B) The grains change shape by bonds breaking in the high pressure areas, and atoms migrate laterally into the lower pressure areas (the area of new crystal growth). C) The final shape of these two grains. Note that the grains are flattened perpendicular to the direction of greatest pressure.

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equal, and the rocks become squeezed in one direction more than another direction? This is known as differential pressure, and it can result in a significant change in the appearance of a rock. Figure 11.1 demonstrates how a mineral can change shape due to differential pressure, in this case with the greatest pressures from the top and bottom (as demonstrated by the large gray arrows). Two initially rounded mineral grains (Figure 11.1A) within a sedimentary rock are experiencing the greatest amount of pressure at the contact between the grains (see red arrows in the figure), and the bonds linking the atoms in this grain will break. The atoms will migrate into the area of lesser pressure and reform a bond with other atoms in the mineral grain (Figure 11.1B). As a result, the grains have a flattened shape that is perpendicular to the direction of greatest pressure (Figure 11.1C).

Figure 11.1 only shows the deformation of two grains; imagine that this is happening to all of the grains in the sedimentary rock, or to all of the phenocrysts (crystals) in an igneous rock. In that case, you will end up with the entire rock having minerals aligned in a certain direction, all by the breaking of bonds between atoms in a mineral, and reforming (recrystallizing) in the lower pressure areas among the grains or crystals in the rock. The end result is a rock with a metamorphic pattern called a **foliation**. Metamorphic foliations are the patterns seen in a rock that has experienced differential pressure; these foliations may be fairly flat, or have a wavy appearance possibly due to more than one direction of greatest pressure. Some rocks may also develop what is called a **lineation**, which can be formed by an elongation of minerals that form a linear feature through the rock. To understand the difference between a foliation and a lineation, let us use some food analogies: a stack of pancakes demonstrates a foliation in your breakfast food, with each pancake layer representing flattened minerals. If you look at the top of the pancakes, you will not see a pattern, but if you view the stack of pancakes from the side, or cut through the stack with your knife in any orientation other than parallel to the pancake layers, you will see the layering or foliation. However, if within that pancake stack, there existed a slice of bacon (yum), the bacon would be the lineation in your breakfast “rock”, and you may or may not see it when you cut through the pancake stack. We will discuss foliations, and the different types of foliations, in a later section of this chapter.

11.2.2 Temperature

Probably the most common cause of metamorphism is a change in temperature. Often times metamorphism involves both an increase in temperature along with the pressure changes as described in the above section. Higher temperatures are often associated with metamorphism due to chemically reactive fluids (which we will discuss in the next section). The broad classification for metamorphism into low, medium and high grades of metamorphic change exists mainly due to temperature conditions; this will also be discussed in a later section.

Higher temperatures increase the vibrational energy between the bonds linking atoms in the mineral structure, making it easier for bonds to be broken in order

for the recrystallization of the minerals into new crystal shapes and sometimes the development of foliations and lineations as described in the previous section. However, recrystallization can be due to just temperature changes without any differential pressure conditions, and when temperatures are increased, there can be a corresponding increase in mineral sizes as initially small minerals become fused into larger crystals. This fusing of numerous smaller mineral sizes into fewer, yet larger, mineral sizes is known as annealing in metallurgy, but for metamorphic rocks it is still referred to as recrystallization.

In order to understand why increasing temperatures lead to increased grain sizes, we need to again address stability. In general, a mineral grain or crystal is most stable when it has a low surface area to volume ratio, therefore large grains are more stable than small grains, because increasing the grain size results in a greater increase in volume as opposed to a smaller increase in the surface area. Why does stability matter? Because that is why the rocks we are concerned with in this chapter are changing; rocks become unstable when their environment changes, and by a recrystallization processes

(metamorphism), they can return to a stable form once again. Figure 11.2 demonstrates the recrystallization process in a sedimentary rock in response to elevated temperature. In this example, the original grains are smaller and rounded, but recrystallization resulted in larger grains that are interlocking; the pore spaces are gone and instead larger crystals exist.

In addition to increased grain size with increased temperature, occasionally a new mineral forms during metamorphism. These new minerals form at certain temperatures and are called **index minerals**, which can be used to determine the temperature of metamorphism. Index minerals will be covered in more detail in a later section.

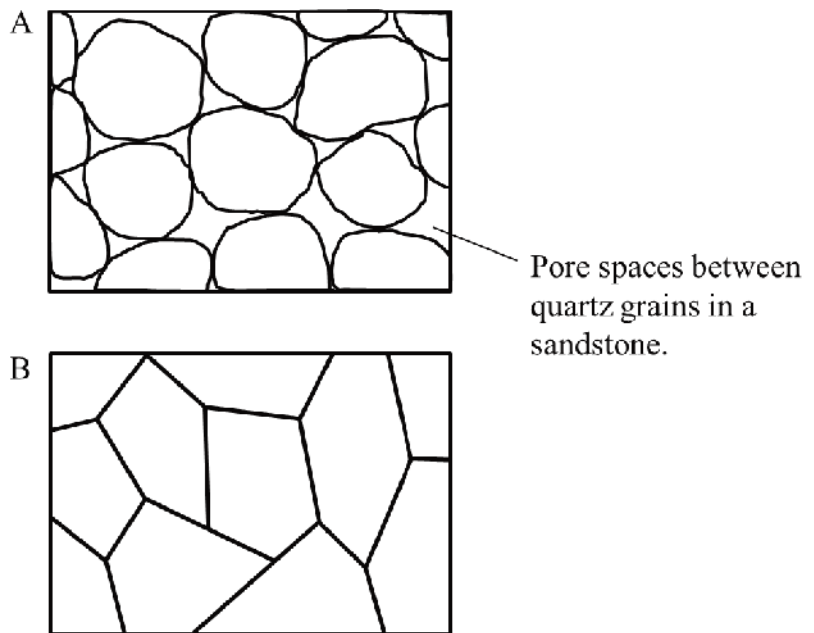


Figure 11.2 | An example of the recrystallization of crystals into larger sizes due to increased temperature: A) a sedimentary rock with rounded quartz grains, and pore spaces between the grains. B) a metamorphic rock with larger, interlocking quartz crystals due to increased temperature conditions. **Author:** Karen Tefend

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11.2.3 Chemically Reactive Fluids

The phrase chemically reactive refers to the dissolved ions in a fluid phase that may react with minerals in a rock; these ions may take the place of some of the atoms in the mineral's structure, which may lead to a significant change in the chemical composition of a rock. Sometimes these fluids are quite hot, especially if they are fluids released from a nearby magma body that is crystallizing while cooling. Metamorphism due to such fluids is known as **hydrothermal metamorphism**.

11.3 METAMORPHIC ROCK NAMES

11.3.1 Foliated Metamorphic Rocks

As mentioned previously, differential pressures can cause a foliation to develop in metamorphosed rocks. There are a few types of foliations that are commonly seen in metamorphic rocks, each foliation type is dependent on the minerals that define the foliation. One type is described as a layering of dark and light colored minerals, so that the foliation is defined as alternating dark and light mineral bands throughout the rock; such a foliation is called **gneissic banding** (Figure 11.3), and the metamorphic rock is called gneiss (pronounced “nice”, with a silent g). In Figure 11.3A, the layering in this gneiss is horizontal, and the greatest pressures were at right angles to the gneissic bands. Note that these bands are not always flat, but may be seen contorted as in Figure 11.3B; this rock still is considered to have gneissic banding even though the bands are not horizontal. The typical minerals seen in the dark colored bands are biotite micas and/or amphiboles, whereas the light colored bands are typically quartz or light-colored feldspars. The protoliths for gneiss can be any rock that contains more than one mineral, such as shale with its clay minerals and clay-sized quartz and feldspar, or an igneous rock with both dark-colored ferromagnesian minerals and light-colored non-ferromagnesian minerals (see Chapter 8 for review). In order for gneissic foliation to develop, temperatures

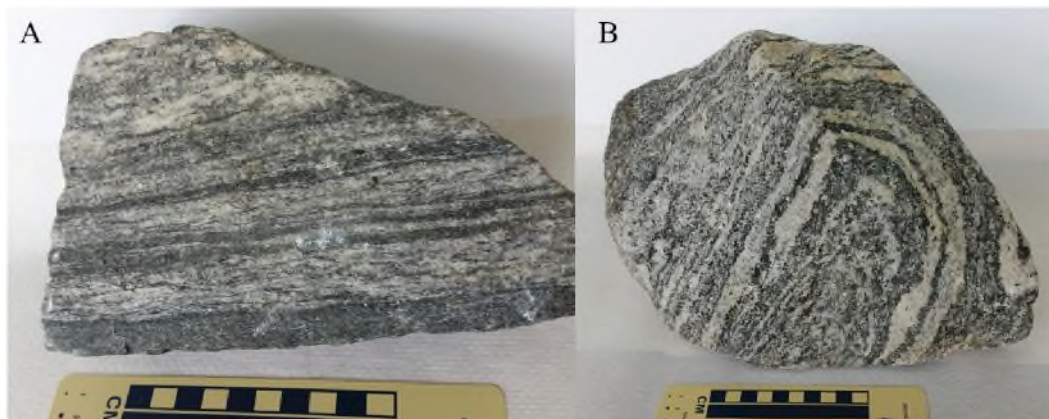


Figure 11.3 | Two examples of the metamorphic rock, gneiss. Each rock exhibits the alternating dark and light mineral bands throughout the rock.

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and pressures need to be quite high for this reason, gneiss rocks represent a high grade of metamorphism.

Sometimes a metamorphic rock is seen with mostly amphibole minerals that can define a foliation pattern as well, and is called an amphibolite (Figure 11.4). Occasionally amphibolites also have layers of light colored plagioclase minerals present, in that case, the rock may be called an amphibole gneiss. Amphibolites may not always have a foliation, however the rock picture in Figure 11.4 appears to have a parallel alignment of the amphiboles (see red arrows in figure) making this a foliated amphibolite. The protolith for an amphibolite must be a rock type with a large amount of dark ferromagnesian minerals, such as mafic or ultramafic igneous rock. Amphibolites require higher temperatures and pressures to form as well, and are considered to be high grade metamorphic rocks.

Another type of foliation is defined by the presence of flat or platy minerals such as muscovite or biotite micas. Metamorphic rocks with a foliation pattern defined by the layering of platy minerals are called schist; the rock name is commonly modified to indicate what mica is present. For example Figure 11.5 is a photo of a muscovite schist, however it also has garnet present, so the correct name for the rock pictured in Figure 11.5 is a garnet muscovite schist. By convention, when naming a metamorphic rock the mineral in the lowest quantity (garnet, in this case) is mentioned first. Notice that the muscovite micas



Figure 11.4 | Example of a foliated amphibolite. Notice the alignment of the amphibole minerals, best seen where the red arrows are indicating. The lighter colored minerals in this rock are plagioclase feldspars.

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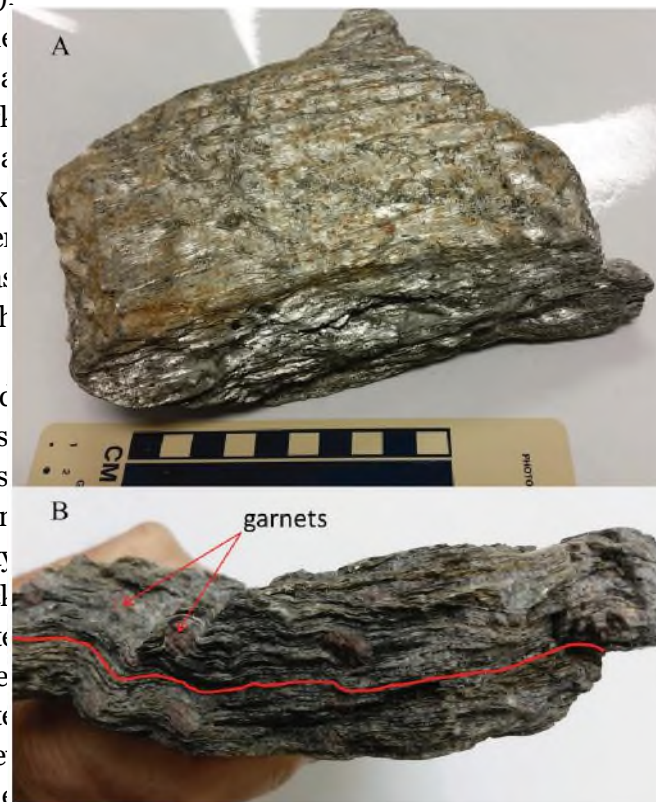


Figure 11.5 | Photo of a garnet muscovite schist. A) The muscovite micas are large enough to be seen as very shiny minerals in the top photograph. B) Side view of the schist shows the distinctive wavy foliation made by the platy micas. This metamorphic rock also contains the index mineral, garnet.

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define a very wavy foliation in the rock; this textural pattern of wavy micas is called a **schistose foliation** (Figure 11.5B). The sedimentary rock shale is usually the protolith for schist; during metamorphism, the very tiny clay minerals in shale recrystallize into micas that are large enough to see unaided. Temperatures and pressures necessary for schistose foliation are not as high as those for gneiss and amphibolite; therefore schists represent an intermediate grade of metamorphism.

There is one foliation type that is defined by the alignment of minerals that are too small to see, yet the foliation can still be visible. This type of foliation is only seen in the metamorphic rock called slate; slate forms by the low temperature and low pressure alteration of a shale protolith. The clay sized minerals in the shale recrystallize into very tiny micas which are larger than the clay minerals, but still too small to be visible. However, because these tiny micas are aligned, they control how the metamorphic rock (slate) breaks, and the rock tends to break parallel to the mica alignment. Therefore, even though we cannot see the aligned minerals that define the foliation, we can use the alignment of the rock fracture pattern, as the rock is cleaved or split. For this reason, the foliation is called a **slaty cleavage**, and a rock displaying this type of foliation is called a slate. Figure 11.6 is an example of the foliated slate displaying slaty cleavage; notice that this rock has retained its original sedimentary layering (depositional beds), which in this case is quite different from the foliation direction. The only protolith for slate is shale, and the fact that original sedimentary features and even some fossils in shale may be preserved and visible in slate is due to the low temperatures and pressures that barely alter the shale protolith, making slate an example of a low grade metamorphic rock. Slate has great economic value in the construction industry; due to its ability to break into thin layers and impermeability to water, slate is used as roofing tiles and flooring.

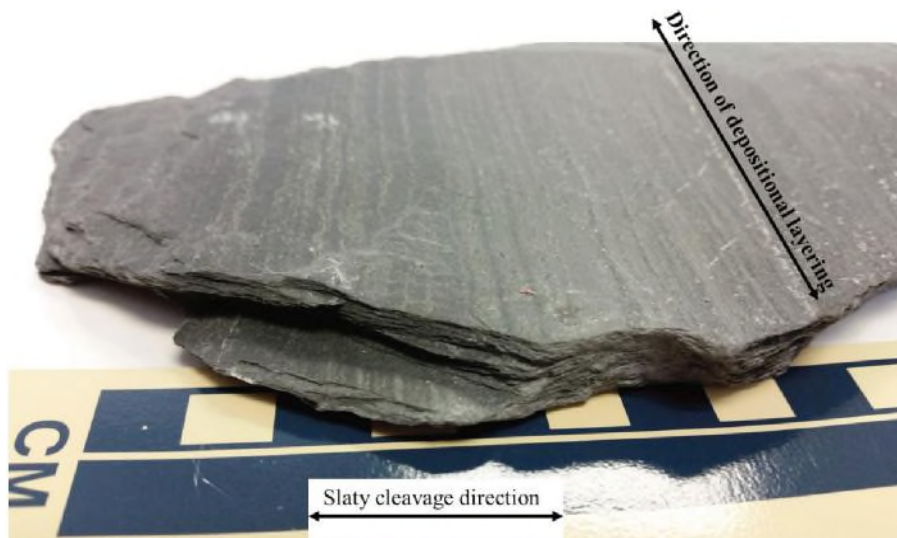


Figure 11.6 | Slaty cleavage in the metamorphic rock, slate. The alignment of very tiny micas controls how this rock breaks or cleaves. Note the banded appearance on the top of this rock, which is the depositional layering of the original rock, shale.

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11.3.2 Non-Foliated Metamorphic Rocks

The other class of metamorphic rocks is non-foliated; the lack of foliation may be due to a lack of differential pressure involved in the metamorphic process, however this is not necessarily the case for all non-foliated metamorphic rocks. If the protolith rock is monomineralic (composed of one mineral type), such as limestone, dolostone, or a sandstone with only quartz sands, then a foliation will not develop even with differential pressure. Why? The calcite mineral in limestone, the dolomite mineral in dolostone, and the quartz sands in sandstone are neither platy minerals, nor are there different colored minerals in these rocks. These minerals (calcite, dolomite, and quartz) recrystallize into equigranular, coarse crystals (see Figure 11.2B), and the metamorphic rocks that they make are named by their composition, not by foliation type. For example, Figure 11.7 is quartzite, a metamorphosed quartz-rich sandstone. Figure 11.8 shows two examples of marble; note that color can vary for marble, as well as for the quartzite. As a result, quartzites and marbles may be hard to identify based on appearance, therefore you must rely on the properties of the minerals that comprise these rocks; you may recall that quartz is harder than glass, while limestone and dolomite are softer than glass. Also, marble will react (effervesce) to acid, but quartz will not react. If you zoom in for a close view of the marble in Figure 11.8, you will see the calcite crystals are fairly large compared to the quartz crystals in the quartzite in Figure 11.7; this can be attributed to the temperature of metamorphism, as higher temperatures result in larger crystals. These rocks are also of economic importance; marble and quartzite are used for dimension stone in buildings and for countertops in many homes. Furthermore, marble is commonly used for statues and sometimes grave markers.



Figure 11.7 | An example of quartzite; a non-foliated metamorphic rock. Quartzite can appear in a variety of colors, but most are fairly light in color. **Author:** Karen Tefend **Source:** Original Work **License:** CC BY-SA 3.0



Figure 11.8 | Examples of the non-foliated rock, marble. The pink and white colors are common, however some marbles are darker in color, and others may be white with dark gray markings like the famous Carrara marble from Italy). **Author:** Karen Tefend **Source:** Original Work **License:** CC BY-SA 3.0

One final non-foliated rock type that should be mentioned is anthracite coal (Figure 11.9). As you may recall, coal is a sedimentary rock composed of fossilized plant remains. This sedimentary coal is called bituminous coal; under higher temperatures and pressures bituminous coal can lose more of the volatiles typical of coal (water vapor, for example), but the carbon content is enriched, making metamorphic coal (anthracite coal) a hotter burning coal due to the higher carbon content. Anthracite coal can be distinguished from sedimentary coal by the shinier appearance, and is somewhat harder than bituminous coal, although both coal types are of low density due to their carbon content. Note that this particular metamorphism is not a recrystallization event, per se, as coal is mostly organic remains. However, bonds are still being broken and reforming due to changes in temperature and pressure.

In order to identify and name metamorphic rocks, a logical first step would be to examine the rock for evidence of any pattern or foliation, and if present, identify what mineral or minerals are making the foliation pattern. Non-foliated metamorphic rocks can be identified by the properties defined by their mineral composition. Below is a table summarizing the metamorphic rock types, foliation names, and protolith rock types (Table 11.1).



Figure 11.9 | Anthracite coal. Note the shiny appearance of this metamorphosed coal.

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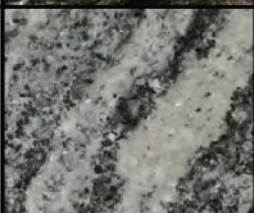




Texture	Characteristics	Protolith	Metamorphic Rock Name	
Foliated ↓ Increasing Temperature & Pressure	Fine-grained rock, tends to split in parallel fragments (known as slaty cleavage)	Shale	Slate	
	Contains shiny muscovite (light) or biotite (dark) micas, may see other minerals. Has schistose pattern of foliation	Shale	Schist	
	Contains alternating bands of light- and dark-colored minerals (usually biotite or amphibole), called gneissic banding.	Shale or Igneous Rock	Gneiss	
Possibly Foliated	Most of the minerals in this rock are amphiboles, which may be aligned to form a foliation.	Mafic or Ultramafic Rock	Amphibolite	
Non-foliated	Equigranular grains of quartz, which has a hardness of 7	Sandstone or Siltstone	Quartzite	
	Equigranular grains of calcite or dolomite, which has a hardness of 4, and reacts to acid	Limestone or Dolostone	Marble	
	Contains mostly carbon, is a low density rock, and has a shiny appearance.	Bituminous Coal	Anthracite Coal	

Table 11.1 | Summary chart of metamorphic rocks discussed in this chapter, including the names of some of the possible sedimentary rock and igneous rock protoliths for each metamorphic rock. A metamorphic rock can also be a protolith: for example, a slate can be a protolith for a schist.

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11.4 LAB EXERCISE

Part A - Metamorphic Rock Identification

In order to answer the questions in this lab, you will need the rock samples from your HOL rock kit that are labeled M1 through M7 (located in the metamorphic rock bag). A photo of these samples is given in Figure 11.10. You will also need your hand lens, glass plate, and the HCl bottle.

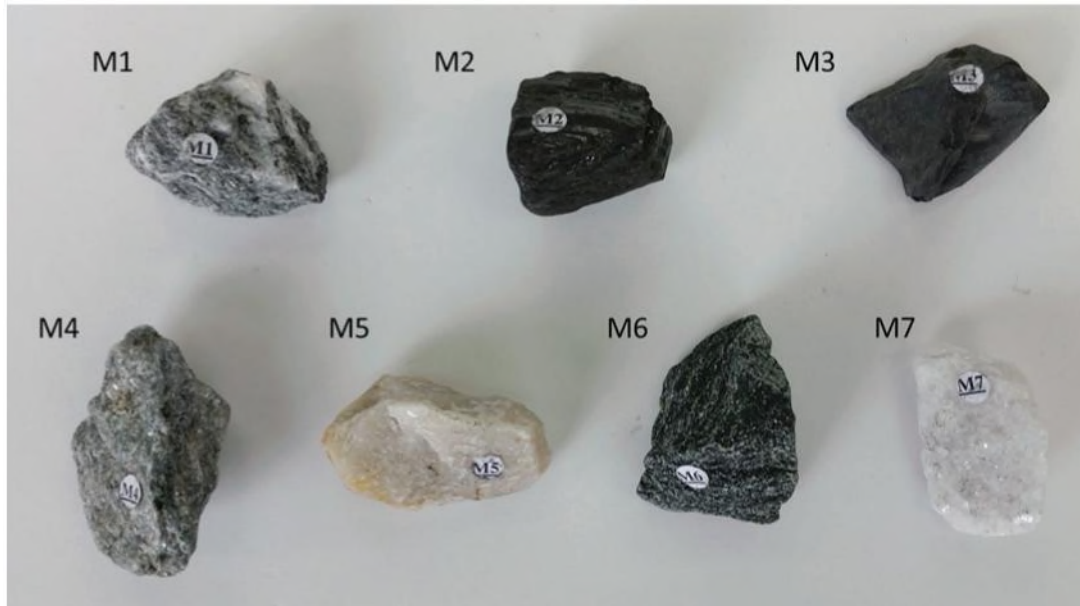


Figure 11.10 | Metamorphic rocks M1 through M7.

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1. Sample M1 has the following texture:
 - a. slaty cleavage
 - b. schistose foliation
 - c. gneissic banding
 - d. lineation
 - e. non-foliated

2. Sample M1 is called:
 - a. marble
 - b. quartzite
 - c. schist
 - d. gneiss
 - e. slate
 - f. anthracite coal
 - g. amphibolite

3. The dark minerals in Sample M1 are:
 - a. flat biotite micas
 - b. tabular amphiboles
 - c. flat muscovite micas
 - d. tabular feldspars

4. A possible protolith for Sample M1 is:

- a. an ultramafic rock
- b. basalt
- c. limestone
- d. granite
- e. sandstone

5. Sample M2 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

6. Sample M2 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite coal
- g. amphibolite

7. Sample M3 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

8. Sample M3 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite coal
- g. amphibolite

9. A possible protolith for Sample M3 is:

- a. bituminous coal
- b. basalt
- c. shale
- d. clay
- e. rhyolite
- f. sandstone

10. Sample M3 is an example of:

- a. high grade of metamorphism
- b. intermediate grade of metamorphism
- c. low grade of metamorphism

11. Sample M3 is used for:

- a. road construction
- b. statues
- c. roof tiles
- d. barbequing

12. Sample M4 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

13. Sample M4 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

14. Sample M4 is mainly composed of this mineral:

- a. biotite mica
- b. amphibole
- c. muscovite mica
- d. calcite
- e. quartz

15. Sample M4 is an example of:

- a. high grade of metamorphism
- b. intermediate grade of metamorphism
- c. low grade of metamorphism

16. Sample M5 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

17. Sample M5 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

18. Sample M5 is mainly composed of this mineral:

- a. biotite mica
- b. amphibole
- c. muscovite mica
- d. calcite
- e. quartz

19. A possible protolith for Sample M5 is:

- a. diorite
- b. quartz
- c. limestone
- d. shale
- e. sandstone

20. Sample M6 is mainly composed of this dark mineral:

- a. biotite mica
- b. amphibole
- c. muscovite mica
- d. calcite
- e. quartz

21. Sample M6 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

22. A possible protolith for Sample M6 is:

- a. basalt
- b. granite
- c. sandstone
- d. limestone
- e. shale

23. Sample M6 is an example of:

- a. high grade of metamorphism
- b. intermediate grade of metamorphism
- c. low grade of metamorphism

24. Sample M7 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

25. Sample M7 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

26. A possible protolith for Sample M7 is:

- a. basalt
- b. granite
- c. sandstone
- d. limestone
- e. shale

11.5 TYPES OF METAMORPHISM

11.5.1 Regional Metamorphism

Metamorphism that affects entire rock bodies over a broad region is referred to as **regional metamorphism**. There is a wide range of conditions in temperature and pressure that produce a wide range of metamorphic rock types; for example, all of the foliated rocks fall into this metamorphic category and some non-foliated rocks as well. The main point is that a large area is affected by changes in temperature and/or pressure. One type of regional metamorphism occurs at convergent plate boundaries, where rocks are subjected to a variety of pressures and temperatures, resulting in a **thermodynamic metamorphism** (“thermo-” for increased temperature, and “dynamic” for increased pressure). Mountain ranges that form by the converging of tectonic plates are classic examples of thermodynamic metamorphism, such as the Himalayan Mountains located in Asia, or our Sierra Nevada Mountains in North America. These can be viewed if you type the mountain range name in the search bar in Google Earth. Regional metamorphism also occurs along plate boundaries where an oceanic plate descends (subducts) back into the mantle as a result of plate convergence (this was discussed in the plate tectonics chapter); oceanic plates that subduct into the mantle will form a deep ocean trench, such as the trench along the western margin of South America. With increased pressure in these regions metamorphic foliations can get quite pronounced, as we saw in the development of slate to schist to gneiss; with increased temperature we see increases in grain size as well as the introduction of new minerals in the metamorphosed rock. These new minerals are useful in that they define the temperature of metamorphism for both regional and contact metamorphism (next section).

Figure 11.11 is an example of the possible index minerals that form during the metamorphism of a shale protolith. Shale is a sedimentary rock that contains clay

minerals and clay-sized quartz and (sometimes) feldspars. With increased temperature, recrystallization involves the formation of new minerals, starting with chlorite at the lowest metamorphic temperature. High temperature metamorphism results in the formation of the mineral sillimanite. The metamorphic sections in this figure are called mineral zones, named for the appearance of each new mineral. For example, the garnet zone begins when garnet first appears in the rock, and the appearance of a new mineral, staurolite, marks the end of the garnet zone and the beginning of the staurolite zone. The study of such index mineral zones have importance in terms of economic exploration, as some of these index minerals have economic importance; for example garnet is used as an abrasive, and sometimes for decorative purposes as a gemstone.

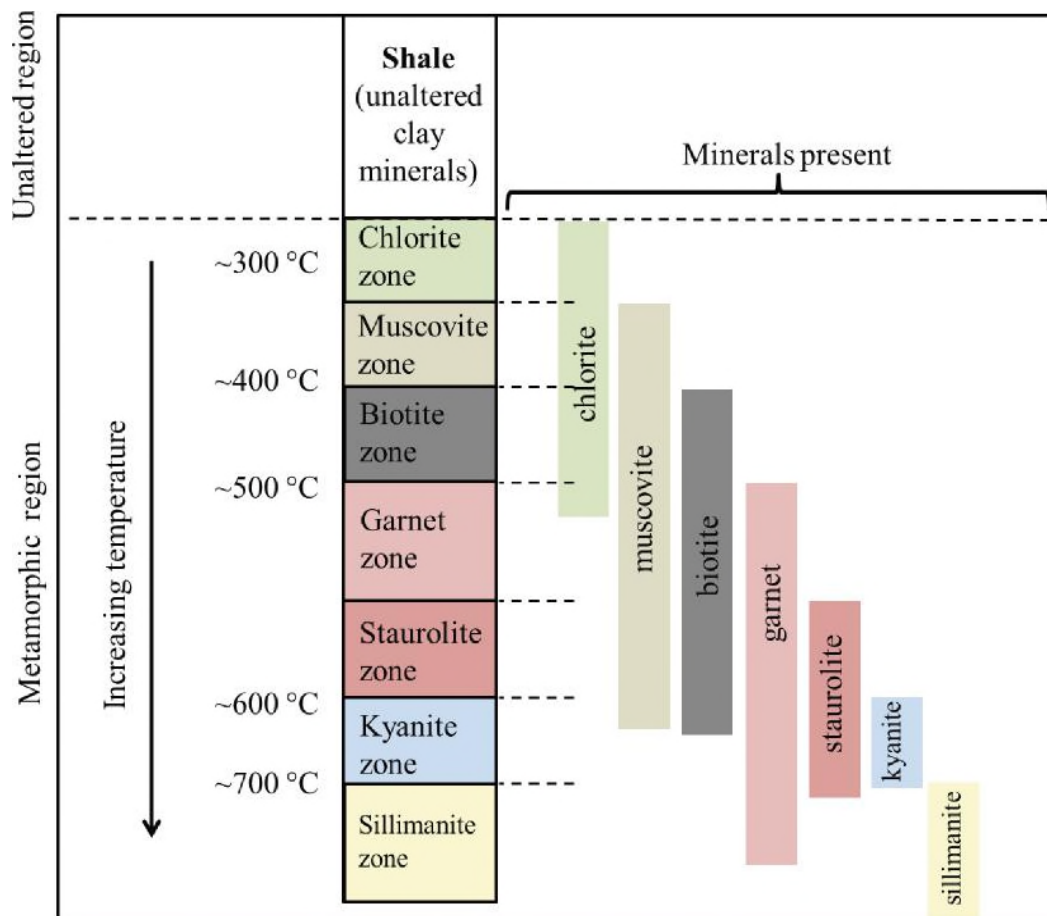


Figure 11.11 | Index mineral chart, showing possible minerals that can form from a shale protolith. The appearance of certain index minerals is also pressure dependent.

Author: Karen Tefend

Source: Original Work

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11.5.2 Contact Metamorphism

As mentioned previously, recrystallization due to increased temperature results in the formation of larger minerals, or sometimes in the formation of new

minerals (Figure 11.11). **Contact metamorphism** describes the type of metamorphism attributed to increased temperature, usually from proximity to a heat source such as an intrusive magma body or a lava flow, and the rock undergoes a **thermal metamorphism**. The rocks that are in closer contact to the magma will form larger crystals due to the higher heat, and may form high temperature index minerals such as garnet, staurolite, kyanite and sillimanite. Rocks that are in contact with hot chemically reactive fluids can also fall within the contact metamorphism category; recrystallization due to this type of contact is called **hydrothermal metamorphism**. Unlike the regional metamorphism described in the previous section, both types of contact metamorphism are confined to smaller areas near the heat source (magma, lava, or hydrothermal fluids). Since differential pressures are not involved, contact metamorphism results in the formation of non-foliated rocks. The non-foliated rock types that were covered previously included marble, quartzite, amphibolite, and anthracite coal. Other non-foliated rocks that have undergone contact metamorphism are broadly classified as horn-fels or granofels, to indicate that they are recrystallized rocks that lack foliation; for example, shale can be altered into a hornfels if it is recrystallized, but lacks slaty cleavage due to the lack of any developed foliation.

11.5.3 Shock (Impact) Metamorphism

This type of metamorphism is not as common as regional or contact metamorphism, and it differs from the other types in a spectacular way. Regional and contact metamorphism requires quite a bit of time (up to several hundred thousand years) for rocks to metamorphose; **shock metamorphism** takes place in a matter of seconds. This type of metamorphism occurs at the site of meteorite craters; rocks at the surface and near surface are subjected to extreme stresses upon impact, and sometimes portions of these surface rocks become tiny blobs of melt that cool to form a type of glass called a **tektite**. Age dating of these tektites has helped in the determination and even recognition of ancient meteorite impact sites worldwide. Shock or impact metamorphism is mainly due to the extreme stresses brought on by the impact, and for this reason shock metamorphism is considered to be a **dynamic metamorphism**, as opposed to dynamothermal (regional) metamorphism.

11.5.4 Fault Zone Metamorphism

Rocks along geologic faults are deformed due to pressures associated with shearing, compression, or extensional stresses, with minor changes due to heat. As with shock metamorphism, **fault zone metamorphism** is a type of dynamic metamorphism. Shallow faults (close to the earth's surface) may grind the nearby rocks into smaller, angular fragments called fault breccia, or you may see a fine clay powder called fault gouge; fault gouge forms by the chemical alteration of fault breccia. Fault breccia is a form of brittle deformation of rock; at greater depths, rocks along a fault will undergo

a more plastic type of deformation. The rocks that form adjacent to the fault in deeper sections are called **mylonite** (Figure 11.12). The minerals in mylonitic rocks are deformed due to shear stresses associated with movement along the fault.



Figure 11.12 | Example of a mylonite rock; note the deformed light-colored minerals (feldspars) that have developed a tail (red arrow). The direction of shearing can sometimes be determined by examining these minerals.

Author: Randa Harris

Source: Original Work

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11.6 LAB EXERCISE

Part B - Types of Metamorphism and Metamorphic Regions

For this portion of the lab, you will be using Google Earth, and Figure 11.11 in this chapter. You will also need your rock samples M1 and M7.

27. According to Figure 11.11, what mineral is unstable in the staurolite zone?
- a. chlorite b. muscovite c. biotite d. garnet
28. Refer again to Figure 11.11; which index minerals will not be found together in the same rock?
- a. chlorite and garnet b. chlorite and kyanite
- c. biotite and staurolite d. biotite and muscovite

29. Sample M1 from your rock kit is most likely an example of:
- a. hydrothermal metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. shock metamorphism
30. Sample M7 from your rock kit is most likely an example of:
- a. fault zone metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. shock metamorphism
31. Type 8 56 22.28N 126 55 54.33E in the search bar of Google Earth. Zoom out to an eye altitude of -1700 miles. What type of metamorphism is likely in this area?
- a. shock metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. dynamic metamorphism
32. The agents of metamorphism in this region, are most likely:
- a. chemically reactive fluids
 - b. temperature
 - c. pressure
 - d. both temperature and pressure
33. Type 35 06 53.42N 119 38 47.59W in the search bar of Google Earth. Zoom out to an eye altitude of -8500ft. What type of metamorphism is likely in this area?
- a. fault zone metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. shock metamorphism
34. Evidence of metamorphism at this location could be from the discovery of:
- a. gneiss
 - b. quartzite
 - c. tektites
 - d. mylonite
35. Type 35 01 38.93N 111 01 21.93W in the search bar of Google Earth. Zoom out to an eye altitude of -12,000ft. What type of metamorphism is likely in this area?
- a. fault zone metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. shock metamorphism
36. Evidence of metamorphism at this location could be from the discovery of:
- a. gneiss
 - b. quartzite
 - c. tektites
 - d. mylonite

11.7 STUDENT RESPONSES

1. Sample M1 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

2. Sample M1 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

3. The dark minerals in Sample M1 are:

- a. flat biotite micas
- b. tabular amphiboles
- c. flat muscovite micas
- d. tabular feldspars

4. A possible protolith for Sample M1 is:

- a. an ultramafic rock
- b. basalt
- c. limestone
- d. granite
- e. sandstone

5. Sample M2 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

6. Sample M2 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite coal
- g. amphibolite

7. Sample M3 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

8. Sample M3 is called:

- a. marble b. quartzite c. schist d. gneiss
e. ~~slate~~ f. ~~anthracite~~ g. ~~amphibolite~~

9. A possible protolith for Sample M3 is:

- a. bituminous coal b. basalt c. shale
d. clay e. rhyolite f. sandstone

10. Sample M3 is an example of:

- a. high grade of metamorphism
b. intermediate grade of metamorphism
c. low grade of metamorphism

11. Sample M3 is used for:

- a. road construction b. statues c. roof tiles d. barbequing

12. Sample M4 has the following texture:

- a. slaty cleavage b. schistose foliation
c. gneissic banding d. lineation
e. non-foliated

13. Sample M4 is called:

- a. marble b. quartzite c. schist d. gneiss
e. slate f. anthracite g. amphibolite

14. Sample M4 is mainly composed of this mineral:

- a. biotite mica b. amphibole c. muscovite mica
d. calcite e. quartz

15. Sample M4 is an example of:

- a. high grade of metamorphism
- b. intermediate grade of metamorphism
- c. low grade of metamorphism

16. Sample M5 has the following texture:

- a. slaty cleavage
- b. schistose foliation
- c. gneissic banding
- d. lineation
- e. non-foliated

17. Sample M5 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

18. Sample M5 is mainly composed of this mineral:

- a. biotite mica
- b. amphibole
- c. muscovite mica
- d. calcite
- e. quartz

19. A possible protolith for Sample M5 is:

- a. diorite
- b. quartz
- c. limestone
- d. shale
- e. sandstone

20. Sample M6 is mainly composed of this dark mineral:

- a. biotite mica
- b. amphibole
- c. muscovite mica
- d. calcite
- e. quartz

21. Sample M6 is called:

- a. marble
- b. quartzite
- c. schist
- d. gneiss
- e. slate
- f. anthracite
- g. amphibolite

30. Sample M7 from your rock kit is most likely an example of:
- a. fault zone metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
 - d. shock metamorphism
31. Type 8 56 22.28N 126 55 54.33E in the search bar of Google Earth. Zoom out to an eye altitude of -1700 miles. What type of metamorphism is likely in this area?
- a. shock metamorphism
 - b. contact metamorphism
 - c. regional metamorphism
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- a. gneiss
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 - c. tektites
 - d. mylonite
35. Type 35 01 38.93N 111 01 21.93W in the search bar of Google Earth. Zoom out to an eye altitude of -12,000ft. What type of metamorphism is likely in this area?
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 - c. regional metamorphism
 - d. shock metamorphism
36. Evidence of metamorphism at this location could be from the discovery of:
- a. gneiss
 - b. quartzite
 - c. tektites
 - d. mylonite