OBJECTIVES

- Learn to identify metamorphic rocks by structure and mineralogy.
- Identify major minerals contained within a metamorphic rock.
- Distinguish between foliated and non-foliated metamorphic rocks.
- Distinguish between slaty, schistose, and gneissic foliations.
- Suggest possible parents for a given metamorphic rock.

INTRODUCTION

Most students have little trouble understanding the formation of igneous and sedimentary rocks, since the conditions under which each forms are (for the most part) apparent to us. If you haven’t actually seen a lava flow or a volcanic eruption up close, you’ve probably seen them in photographs or in videos. And we’ve all seen sediment being transported by wind and water. But metamorphic rocks form under conditions of high temperature and/or pressure no one has witnessed (certainly no one who is around to talk about it), so we can only understand metamorphic processes through observation, experimentation and inference.
Igneous rocks form from magma, which is not a rock (since it is a fluid) and sedimentary rocks lithify from loose sediment or precipitate from a solution. Metamorphic rocks form gradually from existing rocks in solid state, so they remain rocks throughout the process. Metamorphism occurs at varying depths in the Earth’s crust, where pressures and temperatures are much higher than those we experience at the surface. These conditions lead to the formation of new minerals, parallel alignment of mineral crystals, and the formation of bands or layers of like minerals.

**METAMORPHIC CONDITIONS**

Metamorphism occurs under a variety of conditions. First, the temperature at which metamorphism occurs, while much hotter than that at Earth’s surface, cannot exceed the temperature at which rocks will melt. We know from our igneous rocks lab that an increase in pressure also increases the melting temperature for a given rock so that metamorphism can still occur deep within the crust.

**Temperature**

Within the Earth the temperature increases with depth. The geothermal gradient (or geotherm, the rate of increase in temperature with depth) varies from place to place but the crustal average is approximately 20°C per kilometer. In the deepest mine shaft in the world (~3.5 km, in South Africa), the temperature of the rock is close to 60°C (140°F). The geothermal gradient is much higher in active volcanic regions (as high as 30-50°C/km), and lower in subduction zones (as low as 10°C/km).

Temperature by itself is not enough to alter rocks under these conditions, since we are not allowing the rocks to melt. But higher temperatures stretch and weaken bonds in minerals, allowing alteration and migration of atoms in combination with other conditions.

**Pressure**

Pressure refers to the weight of material that bears upon a surface. At the surface of the Earth we are subjected to atmospheric pressure, which is the weight of the atmosphere above your head. At the top of Mount Everest the air pressure is about ½ of the pressure you feel at sea level. 1 atmosphere of pressure is approximately the same as 1 Bar (short for barometer), or 1000 millibars.

The denser the medium the more rapidly the pressure changes with depth – water is 1000x denser than air at sea level, so diving ~ 10 meters or 33 feet beneath the ocean is equivalent to adding an extra atmosphere of pressure. The average rock is about 3x denser than water, so you gain an atmosphere of pressure with every 3 meters or 10 feet of rock.

In the atmosphere or underwater we refer to hydrostatic pressure, in which fluid is pressing on your body from all sides at once. You don’t feel the atmosphere pushing down on you, likewise when you go diving the increased pressure you feel is non-directional – your first sense of the increase in pressure is when it begins to push on your eardrums, and it feels the same no matter which way you position your head.
If pressure is *directed*, that is, if a body is being compressed in only one or two dimensions, it is called stress (*Figure 1*). If the stress is applied in one dimension but not in the other two, we call it compressive (imagine a ball of clay being squeezed into a pancake). If the stress is applied in two dimensions but not in the third it is called tensile (imagine the same ball of clay squeezed or pulled into a cigar). Rotational or shear stress occurs when a rock is located between zones that are moving in opposite directions (now the ball of clay is sitting on a table, beneath a flat board, and the board is moving parallel to the table).

*Figure 1*: Directed pressure, or stress. As rocks are squeezed they begin to fold. New metamorphic minerals will begin to form at right angles to the pressure creating foliations that are parallel to the fold axis. Note here that the foliation in the new rock will be very different from the original bedding plane of the sedimentary rock.

**Hydrothermal Fluids**

Water and other volatiles (such as carbon dioxide) are generally present during metamorphism, because they are contained within the rocks undergoing metamorphism or they are released during the process by metamorphic reactions. These fluids are capable of efficiently transferring free ions and radicals, thereby increasing the rate of reaction and the growth of new mineral crystals.

Around active volcanoes or igneous intrusions groundwater is heated and can dissolve minerals and transport ions and complexes that would not normally be soluble in water. This can lead to rapid alteration of minerals due to the flux of solutes, or to concentration of reduced compounds such as metals and metal sulfides (since there is very little free oxygen in the subsurface, common metals are obliged to combine instead with sulfur to produce minerals such as pyrite, galena, chalcopyrite, sphalerite, etc…).

**Metamorphic Zones**

*Figure 2* shows approximate upper and lower boundaries of metamorphism. This is a generalized diagram, as the conditions under which alteration occurs vary from mineral to mineral. Calcite for instance, will begin to recrystallize at very slightly elevated pressures and temperatures, while quartz and the feldspars will not begin to alter until they are well within the metamorphic zone.
Figure 2: Metamorphic facies, or environments. The texture and mineral composition of a metamorphic rock depends not only on the composition of the parent rock, but on the pressure and temperature conditions under which the rock experiences metamorphism.

**Contact Metamorphism** is the name given to the changes that take place when magma is injected into the surrounding solid rock (country rock). The changes that occur are greatest wherever the magma comes into contact with the rock because the temperatures are highest at this boundary and decrease with distance from it.

Around the igneous rock that forms from the cooling magma is a metamorphosed zone that resembles a “bull’s eye” pattern called a *contact metamorphism aureole*. Aureoles may show all degrees of metamorphism from the contact area to unmetamorphosed (unchanged) country rock some distance away.

*Hydrothermal metamorphism* is associated with contact zones as well, since heat forces fluids out and away from the zone of intrusion. Also, magmas typically release significant amounts of fluid that will accentuate changes, leading to the formation of important ore minerals at or near the contact zone.

**Regional Metamorphism** is the name given to changes in great masses of rock over a wide area, often within orogenic belts. These rocks are subjected to high pressures and temperatures associated with deep burial beneath the Earth’s surface. Pressures are
normally lithostatic, but tectonic plate motions, and differential movements within plates, can lead to directed stresses on a local level.

During regional metamorphism rocks subjected to higher pressures and temperatures are compressed and heated more those exposed to lesser conditions. As a result, a rock exposed to high-grade metamorphic conditions will differ from the same parent rock exposed to intermediate- or low-grade conditions in both texture and mineral content (though not necessarily in whole-rock chemistry). Slate, phyllite, schist, and gneiss are the products of progressively more intense pressure and temperature conditions.

**Dynamic Metamorphism** is a type of regional metamorphism that occurs in rocks subjected to high pressures, but at relatively low temperatures. Fault zones account for most dynamic metamorphism, as fault motions or pre-motions can generate significant shearing stresses without significantly changing the temperature.

At subduction zones extremely high pressures can be achieved at relatively low temperatures as plates are pushed against one another very near Earth’s surface.

Fault zones always produce directional pressures (called stresses) in which the rocks are simultaneously compressed in one or two dimensions but not in the other dimension(s). As a result, dynamic metamorphism will often produce rocks with distinct foliations.

**METAMORPHIC MINERALS**

Metamorphic rocks contain many of the same minerals found in igneous and sedimentary rocks, such as quartz, the feldspars, micas, amphiboles, and calcite. There are a number of minerals that occur almost exclusively in metamorphic rocks:

**Chlorite** is a green phyllosilicate (mica) mineral commonly occurring in low-grade metamorphic rocks; the common occurrence of green chlorite in low grade schists is the source of the name greenschist.

**Garnet** is a common mineral found in medium to high grade metamorphic rocks. It will almost always look out-of-place in foliated rocks as garnet crystals tend to be large and round and force the more platy minerals to form around them;

**Talc** is a hydrated magnesium silicate mineral that forms in hydrothermal zones from the metamorphism of ultramafic rocks such as greenstone or peridotite. It is soft, waxy to pearly, and is usually white to light green. It is very soft (1 on Mohs scale of hardness) and has a soapy feel;

**Serpentine** is a term that refers a group of iron and magnesium bearing phyllosilicate minerals that form under high pressures and at a variety of temperatures. There are approximately 20 different serpentine minerals, though since they can be difficult to differentiate in-situ we usually refer to them simply as serpentine. That said, there are three common varieties of serpentine minerals:
**Antigorite** is usually dark green to yellow to black in color, with a greasy luster. In pure form it often is translucent and olive green and is sometimes called “jadeite” (a misnomer as it is not true jade).

**Lizardite** is translucent and light green to yellow to white, with a waxy luster.

**Chrysotile** is an asbestos mineral, meaning that it grows in thin parallel fibers. It is generally white to green and will often appear in thin layers of short fibers between massive layers of other serpentine minerals;

**Glaucophane** is a blue-gray mineral that forms in rocks containing abundant sodium and metamorphosed at high pressures and low temperatures, as would be experienced in a subduction zone. The rocks in which it occurs are referred to as blueschists, due to the distinctive color;

In addition, some minerals only occur within restricted temperature and pressure ranges. **Kyanite, sillimanite, and andalusite** are polymorphs (different minerals with the same chemical formula: $\text{Al}_2\text{SiO}_5$). The three unique crystal structures of these minerals form under different pressure-temperature conditions, making these minerals useful for defining the conditions of metamorphism.

**METAMORPHIC ROCKS**

Metamorphic rocks are commonly divided into two groups: foliated and non-foliated. **Foliation** comes from the Latin word *folia* (meaning leaves) and refers to the arrangement or growth of mineral crystals in parallel or nearly parallel planes.

**Non-foliated rocks** lack minerals that tend to grow in preferred orientations. They are often mono-mineralic (dominated by a single mineral), like quartzite or marble. Both quartz and calcite form mineral crystals that do not have a distinctive orientation, thus these rocks are typically made of interlocking crystals of similar size.

**Quartzite** is a medium- to high-grade metamorphic rock that forms due to recrystallization of quartz sandstone. The granular texture of the original rock is generally retained while porosity is lost. Sedimentary structures may be lost as metamorphic grade increases.

**Marble** is a low- to medium-grade metamorphic rock that forms due to the recrystallization of limestone. Marbles are thus made almost exclusively of the mineral calcite. As limestone typically contains sedimentary structures and some silicate minerals such as clay and silt, higher grade metamorphism causes migration of silicates into distinctive bands within the rock. This layered texture is known as marbling.
Quartzite is identifiable by its granular texture and hardness (H = 7).

Marble has a coarsely crystalline texture, is quite soft (H = 3), and effervesces in HCl.

Serpentinite varies in color from black to green to yellow, has a waxy or greasy luster, is softer than glass and non-foliated.

Serpentinite with a vein of chrysotile (fibrous asbestos).

**Serpentinite** is a rock formed at high pressure and lower temperatures in the presence of hydrothermal fluids from mafic or ultramafic rocks such as gabbro or peridotite. It is composed of serpentine minerals, a group of similar minerals that are not always easy to distinguish, thus distinctions are usually not made. The process of forming these mineral types (and thus the rock) is known as serpentinization and is common on the ocean floor at plate boundaries. Serpentinite is the state rock of California.

**Foliated rocks** contain silicate mineral crystals of varying sizes that are aligned in parallel planes or (more rarely) in lines. This is usually associated with directed stresses, and favors minerals that have a preferred orientation, especially at low metamorphic grades.

Micas, which are plate-like, often form in rocks subjected to compressional or shear stress, growing perpendicular to the primary direction of stress. Hornblende, which typically grows in needle- or pencil-shaped crystals, often is found in rocks subjected to tensional or shear stress. Though minerals such as quartz and feldspar are usually present in all of these rocks they are not apparent until the crystals become large.

Four distinctive classifications of foliated rock are recognizable, and these are distinguished primarily on the basis of metamorphic grade or crystal size:
**Slate** refers to metamorphic rocks made of platy minerals that are aphanitic (too small to be seen with the naked eye). The foliation in slates looks similar to the fine laminations seen in shale (though in shale the laminations are bedding planes, where here they are due entirely to the pressure orientation). Rocks such as these readily split along flat, parallel planes described as slaty cleavage.

**Phyllite** represents a low to medium metamorphic grade between slate and schist. It is made of mineral crystals that are not quite large enough to be visible to the naked eye. These fine crystals give the rock a slightly glossy or silky appearance. Phyllites will cleave along parallel planes like slates, but the surfaces may be wrinkled to varying degrees.

*Slate has rock cleavage planes that are parallel and remarkably flat.*

*Phyllite has foliation that is not as perfectly flat as that found in slate, and its surface is shiny.*

**Schist** is a medium-grade metamorphic rock recognizable because it is composed of flaky (such as mica) or needle-like (such as hornblende) crystals large enough to be seen easily with the naked eye, giving it a glittery appearance. Schist has rock cleavage parallel to the foliation plane, but surfaces may have a bumpy or mottled texture due to grains of quartz and/or feldspar growing between the layers.

*Schist, though foliated, has a mottled surface and a glittery look due to large mica crystals.*

**Gneiss** is a high-grade metamorphic rock composed of coarse minerals arranged in banded layers in which several different types (and colors) of minerals alternate in parallel bands or layers. Platy minerals are present, but non-foliated layers containing feldspar and quartz are also common. Mineral crystals are coarse and can easily be identified with the naked eye. Gneiss has a look that is similar to granite or diorite, except for the banded texture.

*Gneiss has a banded appearance with dark and light minerals separated into layers.*
<table>
<thead>
<tr>
<th>Non-foliated rocks</th>
<th>Appearance, colors, properties</th>
<th>Rock name (mineralogy)</th>
<th>Parent rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translucent to opaque (colors vary)</td>
<td>Softer than glass, Reacts with dilute HCl</td>
<td>Marble (calcite)</td>
<td>Limestone</td>
</tr>
<tr>
<td></td>
<td>Softer than fingernail</td>
<td>Soapstone (talc)</td>
<td>Greenstone (basalt)</td>
</tr>
<tr>
<td></td>
<td>Harder than glass</td>
<td>Quartzite (quartz) may display original cross bedding or layering</td>
<td>Quartz sandstone</td>
</tr>
<tr>
<td>Opaque (black to green to yellow)</td>
<td>Harder than glass</td>
<td>Greenstone (chlorite, epidote, feldspar)</td>
<td>Hydrothermally altered gabbro or peridotite</td>
</tr>
<tr>
<td></td>
<td>Softer than glass</td>
<td>Serpentineite (serpentine) surface appears waxy or polished</td>
<td>Greenstone – peridotite, gabbro or other ultramafic rocks</td>
</tr>
<tr>
<td>Black, may be layered or jointed</td>
<td>Soft, low density</td>
<td>Bituminous coal</td>
<td>Peat or lignite</td>
</tr>
<tr>
<td>Black, shiny, often shows conchoidal fracture</td>
<td>Soft, low density</td>
<td>Anthracite coal</td>
<td>Bituminous coal</td>
</tr>
<tr>
<td>Foliated rocks</td>
<td>Fine grained: no visible crystals, dull surface</td>
<td>Slaty foliation</td>
<td>Slate (clays, micas: biotite, muscovite, chlorite)</td>
</tr>
<tr>
<td></td>
<td>Fine grained: tiny crystals may be visible with hand lens (shiny surface)</td>
<td>Phyllitic to schistose foliation</td>
<td>Phyllite (micas: biotite, muscovite, chlorite)</td>
</tr>
<tr>
<td></td>
<td>Fine-grained: shiny surface</td>
<td>Phyllitic to schistose foliation</td>
<td>Blueschist (micas, feldspars, glaucophane)</td>
</tr>
<tr>
<td>Coarse-grained: shiny, glittery surface</td>
<td>Schistose foliation</td>
<td>Schist (micas, minor feldspars, hornblende, quartz)</td>
<td>Phyllite, basalt, or granite</td>
</tr>
<tr>
<td>Coarse-grained: distinctive light and dark layers</td>
<td>Banded foliation</td>
<td>Gneiss (quartz and feldspars in light layers, hornblende and biotite in dark layers)</td>
<td>Schist or granite</td>
</tr>
</tbody>
</table>