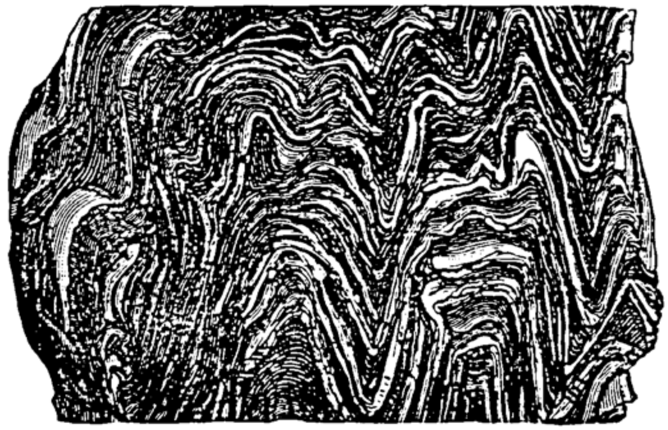

Chapter 4

Metamorphic Rocks

Metamorphic rocks are rocks that have undergone a change in texture and/or mineralogy due to high temperature or pressure, or through the action of chemical alteration induced by very hot and chemically aggressive, pore water. The process of alteration is termed **metamorphism**, and it generally occurs along active plate tectonic boundaries or deep within the Earth's crust (some 10 to 30 km below the surface). In these areas, temperatures can exceed 800 °C and pressures can build up to 6 kbars (6000 times atmospheric pressure). Although extreme, these conditions are not quite enough to actually melt rock. Nevertheless, the effects of metamorphism can be dramatic and frequently result in the total **overprinting** or destruction of the rock's original mineralogy and texture.

4.1 Types of Metamorphism

Geologists recognize several kinds of metamorphism, however, in the GY 111 laboratory component, we can restrict ourselves to the three major types: 1) **regional**, 2) **contact** and 3) **cataclastic**.

Figure shows a detailed sketch of deformed and folded rock layers that are typical in regionally metamorphosed areas. From: LeConte, J., 1905. Elements of Geology. D. Appleton and Co., New York, NY, 667p.

4.1-1. Regional Metamorphism

The most widespread and easily recognizable metamorphic rocks are those that form through regional metamorphism. This is a large scale process involving both heat and directed pressure, and generally occurs as part of the mountain building process. It is important to recognize that regionally metamorphosed rocks are important elements of all major mountain chains, including the Rockies and the Appalachians.

Rocks generally undergo changes in their texture when they experience regional metamorphism. Most of the time, this is a completely destructive process and little remains of the rock's original texture. **Marble**, which was originally limestone, is composed of crystalline calcite. The exact variety of limestone from which the marble formed (e.g., oolitic, micritic, fossiliferous), is usually impossible to tell because nothing was preserved of the original texture following metamorphism. In rare cases, regional metamorphism may not be so pervasive, and some of the original texture of a rock may be preserved. Metamorphosed sedimentary rocks containing bedding can retain vestiges of sedimentary structures. Look for evidence of preserved bedding or cross-stratification in some of the samples in your specimen tray.

4.1-2. Contact Metamorphism

This type of metamorphism, as the name implies, involves localized alterations induced by contact with an igneous intrusion. The major agent of contact metamorphism is heat. Temperatures in excess of 800 °C can occur when magma intrudes into **country rock**. However, unlike regional metamorphism, alteration associated with intrusions only affects a very thin rind or **halo** of country rock, surrounding the magma body. Original rock textures can be altered, but they are seldom destroyed like that which occurs in regional metamorphism. Contact metamorphism occurs adjacent to volcanoes in mountain belts and hot spots, and along divergent plate boundaries. The most common type of contact metamorphic rock is **hornfels** which is a pretty non-descript gray-black rock. Because it has few, if any, readily distinguishable characteristics, you will probably come to hate this rock if your instructor sees fit to put one in your metamorphic rock tray.

4.1-3. Cataclastic Metamorphism

This type of metamorphism involves **shear force** and results when rock bodies slide past one another along faults. Tectonic movements build up tremendous pressure (but temperature remains low) causing the rocks to grind and pulverize one another into small bits and pieces. Cataclastic metamorphic rocks are usually found in mountain belts where they are associated with regional metamorphism. One of the most important types of rock produced through this type of metamorphism is **mylonite**.

4.2 Metamorphic Textures

Metamorphic textures are distinguished on the basis of the size, shape and orientation of the crystals that comprise the rock. Each kind of metamorphism produces its own unique texture (or textures). Regional metamorphism generally produces rocks that display fine layering or partings collectively termed **foliations.** Foliated rocks contain an abundance of aligned platy constituents such as the mica minerals biotite and muscovite. Some foliated rocks also contain large relatively well-formed crystals that grew during metamorphism (e.g., garnet or staurolite). These crystals are called **porphroblasts** (they are somewhat analogous to phenocrysts in igneous rocks), and the rock's texture is said to be **porphroblastic**. Porphroblasts can form during any of the three types of metamorphism, but you will encounter them most commonly in the foliated rocks.

Contact metamorphism, and regional metamorphism of rocks that contain few platy minerals (e.g., quartz sandstone or limestone), produces rocks that are characterized by fine or coarse interlocking crystals that do not display foliation. These are known as **non-foliated** or **granular** metamorphic rocks and they typically contain an abundance of "equidimensional" grains such as quartz or calcite. Cataclastic metamorphism produces rocks with a **porphroclastic** texture, one dominated by large fragments set in a fine matrix of crushed minerals. A complete listing of the metamorphic rocks that you are responsible for in the laboratory component of GY 111 appears in Table 4.1.

4.2-1. Foliated Rocks

When minerals are exposed to stress (e.g., directed pressure), they tend to re-orient themselves perpendicular to the direction of stress to offer least resistance to the force (Figure 4.1). Platy minerals such as muscovite, biotite and chlorite are particularly susceptible to re-orientation, but pencil-like minerals (e.g., amphibole) can also be affected. In general, the more of these minerals that you have in a rock, the better the foliation that develops; however, chemical changes can occur as metamorphism proceeds, and it is possible for micas and other minerals to grow at the expense of other,

Table 4.1. The metamorphic rocks classified according to texture and metamorphic grade.

TEXTURE	ROCK NAME	DIAGNOSTIC FEATURES	*Minerals*	*Rock name*
Foliated (mostly products of regional metamorphism)	Slate	Dense, variably colored (black to red) rock composed of microscopic grains and crystals. May display rock cleavage and a subtle sheen along partings		
	Phyllite	Fine-grained rock characterized by prominent glossy sheen. Variably colored.		
	Schist	Fine to medium grained rock displaying a distinctive and frequently wavy layering of platy mica minerals (schistose texture). Schists are named after the dominant minerals comprising them. See adjacent column for <u>most</u> of the names that you are responsible for in GY 111L. There are many other possible combinations.	chlorite	chlorite schist
			garnet and chlorite	garnet chlorite schist
			muscovite & biotite	mica schist
			talc	talc schist
			graphite	graphite schist
			garnet & mica	garnet mica schist
			amphibole	amphibole schist (amphibolite)
			kyanite	kyanite schist
			staurolite	staurolite schist
			sillimanite	sillimanite schist
			calcite\limestone	schistose marble
	Gneiss	Coarse-grained rock characterized by layering of light (quartz and feldspar) and dark (biotite) minerals.		
	Augen gneiss	Coarse-grained rock characterized by layering of light (quartz and feldspar) and dark (biotite) minerals with larger "eye"-shaped crystals of garnet, quartz feldspar etc.		
Non-Foliated (products of contact and regional metamorphism)	Quartzite	Crystalline, hard (H=7) rock of variable color (white, green, grey, yellow, red etc.). May display conchoidal fracture. Called schistosic if there is a weak foliation.		
	Marble	Crystalline, soft (H=3) rock of variable color (white, green, grey, yellow, red etc.). Fizzes with HCl. Called schistosic marble if there is a weak foliation.		
	Dolomitic marble	Crystalline, soft (H=3) rock, generally white or pink in color. Does <u>not</u> fizz with HCl unless powdered. Called schistosic marble if there is a weak foliation.		
	Metaconglomerate	Texture of conglomerate, but breaks through pebbles. Pebbles may be deformed.		
	Hornfels	Light gray to black to green, massive rock that has been baked due to contact with a pluton. Resembles basalt.		
Cataclastic	Mylonite	Fine to coarse grained rock consisting of several types of angular to sub-rounded clasts set in a fine-grained foliated matrix		

less stable minerals. Mineral replacement occurs in a specific order which can be related to the intensity of metamorphism or **metamorphic grade** of a rock (see Section 4.3).

Foliated rock is classified on the basis of intensity of foliation, degree of mineral separation and crystal size. The lowest grade of foliated metamorphic rocks are called **slate**. Slates are metamorphosed shales, and like their precursor sedimentary rock, they are fine-grained. There is a foliation present in slate, but the platy minerals are so fine, that it is not normally obvious. Occasionally you will notice a slight sheen on the surface of a hand specimen. More often, you will notice that the slate breaks apart along nearly parallel planes. This is known as **rock cleavage** (or **fracture cleavage**) to distinguish it from the mineral variety, and it is a property of slate that makes it a useful building material (e.g., roof tiles, floor tiles, pool tables etc.). Slates come in various colors (red, green, black). In most cases, the color is simply inherited from the parent shale (black shale → black slate etc.). If metamorphism is more intense or prolonged, platy crystals may have the opportunity to grow larger, eventually dominating the mineralogy of the rock. **Phyllites** are metamorphic rocks of slightly higher grade than slates that are characterized by a distinctive foliation and "glossy sheen". The sheen is caused by the alignment of platy minerals that develops a

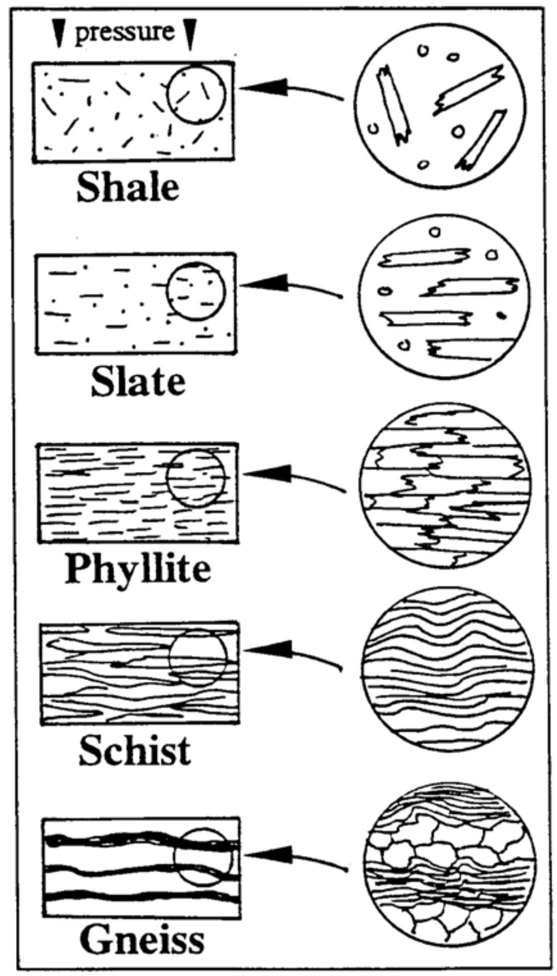

Figure 4.1. Effects of stress (pressure) on platy minerals in a shale. Mica minerals are first aligned perpendicular to the direction of pressure, and then grow larger with increasing grade of metamorphism. Eventually, complete mineral separation occurs giving the diagnostic layering found in gneiss.

"pearly" surface on the phyllite. Phyllites are dominated by platy minerals, but individual crystals are still hard to resolve even with the assistance of a hand lens. The glossy sheen is the best means to distinguish a phyllite from a schist. WARNING: you may have to rotate any suspected specimens of phyllite to see the sheen in our laboratory room because fluorescent lights dull the effect. Like slate, phyllite comes in a variety of colors depending upon the mineral composition. The two most common colors, green and gold, contain respectively, the minerals chlorite and muscovite.

If metamorphism is more intense or prolonged, platy crystals may have the opportunity to grow larger, eventually dominating the mineralogy of the rock. **Phyllites** are metamorphic rocks of slightly higher grade than slates characterized by a distinctive foliation and "glossy sheen". The sheen is caused by the alignment of platy minerals that develops a "pearly" surface on the phyllite. Phyllites are dominated by platy minerals, but individual crystals are still not visible even with the assistance of a hand lens. The glossy sheen is the best means to distinguish a phyllite from a schist, however, you may have to rotate any suspected specimens of phyllite to see the sheen in our laboratory room because fluorescent lights dull the effect. Like slate, phyllite comes in a variety of colors depending upon the mineral composition. The two most common colors, green and gold, contain respectively, the minerals chlorite and muscovite.

Schists are intermediate to high grade metamorphic rocks containing large crystals that are distinguishable by the naked eye. At least 50% of these minerals are platy in nature (i.e., muscovite and biotite) resulting in a distinctive foliated texture called **schistosity.** Because of the mica content, most schists split apart relatively easily, but splits are "wavy" rather than flat as seen in slates.

Schists are extremely abundant metamorphic rocks and come in many different "flavors". Because the crystals are large enough to identify, schists are named on the basis of their dominant mineral or minerals. A schist containing only muscovite and biotite is usually called a **mica schist.** One dominated by chlorite is called a **chlorite schist**, one dominated by garnet is called a **garnet schist**, one dominated by talc is a **talc schist**, one dominated by graphite is a **graphite schist** ... well you probably get the idea. The most common types of schist are listed in Table 4.1. A word of warning is necessary for a couple of these “schisty terms” (sorry; I couldn’t resist). **Greenschist** is commonly used to name medium-high grade metamorphic rock possessing a distinctive green color (primarily due to the minerals chlorite and amphibole). Unfortunately this term is also used to identify a specific suite of metamorphic rocks. The **greenschist facies** includes all slates and phyllites, and many of the schists as well. To avoid confusion, do not use the term greenschist to name a particular type of schist. It is far better to call it a **chlorite schist** or an **amphibole schist**. Amphibole schists are also known as **amphibolites.**

Two additional schists are worthy of special mention because they contain blue minerals that only form under conditions of high pressure and relatively low temperature (e.g., along convergent plate boundaries). **Kyanite schist** contains kyanite, a blue-gray tabular mineral notable for having two different hardnesses paralleling the long and short axes of the crystal (refer to Table 1.5 in Chapter 1).

Another blue mineral formed under conditions of high pressure is glaucophane ($Na_2(Mg,Fe)_3Al_2Si_8O_{22}(OH)_2$). You will not see a **glaucophane schist** in GY 111L, but along with kyanite schist (which you will see), they comprise another very important metamorphic facies; **blueschist.** The blueschist facies only occurs under conditions of high-pressure and low-temperature.

The highest grade of regional metamorphic rock is called **gneiss** (pronounced nice). The temperatures and pressures required to produce gneiss are so high that many of the platy minerals (chlorite, muscovite, biotite etc.), have been replaced through chemical reactions by more equidimensional minerals like quartz and feldspar. Gneisses look crystalline just like igneous rocks, but they possess a prominent **layering** due to the separation of minerals into light and dark bands. Many gneisses have the same overall mineral composition as granite and it seems likely that these **granite gneisses** formed through the high-grade metamorphism of granitic rocks. However, a high-grade metamorphosed shale could also give rise to a granite gneiss due to mineral alteration and replacement.

Augen gneiss is a particular variety of gneiss containing large porphroblasts of quartz, feldspar and/or garnet. The pressure that formed the gneiss flattened these mineral inclusions into "eye-shaped" agglomerates called **augen**, a German word meaning eye (it is pronounced ow-gan). They make very attractive building materials when polished, and are often used on the exteriors of office buildings.

4.2-2. Non-foliated Rocks

As previously mentioned, non-foliated metamorphic rocks are primarily composed of equidimensional grains that display little or no preferential orientation of platy minerals. They are formed primarily as a result of high temperatures such as that accompanying contact metamorphism. The major varieties of non-foliated metamorphic rocks that you are responsible for in GY 111 are **quartzite, marble** and **hornfels** (Table 4.1).

Quartzite is a metamorphosed quartz-rich sandstone (quartz arenite). Because of the lack of foliation, quartzites can superficially be confused with quartz arenite, but close examination with a hand lens will reveal obvious differences between the two types of rocks. Quartzites contain quartz grains that have been "fused" or "welded" by heat into an interlocking mosaic of crystals. Unlike a quartz-rich sandstone, you will not be able to distinguish any rounded grains in a quartzite. The fusing of quartz grains in quartzites also makes them harder than quartz-rich sandstones where sand grains are less-well held together by cement.

Marbles are metamorphosed carbonate rocks. The majority of marbles are derived through the metamorphism of limestone, but dolomite and dolostone will also produce marble if metamorphosed. We call these rocks **dolomitic marbles** to distinguish them from their limestone counterparts.

Marbles and dolomitic marbles, like quartzite, are characterized by recrystallized, interlocking crystals of roughly equal size. They vary in color from white to green and red and are highly sought after as building stones. Dolomitic marble is distinguished from marble by its slightly pink color and its lack of reaction with dilute hydrochloric acid. Some marble is less pure than others because the carbonate rocks that they formed from contained high concentrations of siliciclastic silt and clay. These “impure” substances frequently develop a weak foliation or schistosity upon metamorphism. These rocks are called **schistose marbles** to distinguish them from their more pure cousins.

As previously mentioned, hornfels are ugly rocks. They are non-foliated and generally gray-black in color because they were essentially baked due to direct contact with a pluton or other reservoir of magma. In many ways they resemble basalt with the exception that they are devoid of phenocrysts. Pray that you don’t get a hornfels in your metamorphic rock practical exam.

4.2-3. Cataclastic Rocks

Some metamorphic rocks contain very large grains set in a finer grained matrix. In some cases, the larger grains grew during the shearing or faulting event responsible for the rock's alteration (they would be classified as porphroblasts). In other cases, shearing has produced large grains derived from the original rock. These are called **porphroclasts**. In GY 111, we recognize only one cataclastic metamorphic rock: **mylonite**.

Mylonites are complex cataclastic rocks that are produced by high pressure and stress along faults and shear zones. They contain a wide assortment of angular and subangular rock clasts and porphroclasts that have been broken up from the adjacent bedrock all set in a fine-grained, foliated matrix. Owing to variability in clast size (a few millimetres up to several metres) and clast density, mylonites are much easier to recognize in large outcrops than they are in hand specimens. They can easily be confused with sedimentary rocks like breccias and siltstones. Most GY 111 instructors do not expect you to be able to identify mylonites in GY 111L, but if you have to, look for the characteristic foliation in mylonites. That is the best way to distinguish them from their sedimentary look-a-likes.

4.2-4. Other Metamorphic Rocks

Some rocks that have undergone metamorphism still retain much of their original texture, fabric or structure. These rocks are difficult to classify because they have been converted into slate or schist or marble etc. In some situations it is desirable to retain the name of the parent rock. The prefix "meta" is added to indicate that the rock has been altered due to metamorphism, but that the original fabric/texture/structure is still identifiable. For example, **metaconglomerates** are metamorphosed conglomerates. They look very much like conglomerates with the exception that the pebbles are stretched or deformed due to pressure. Metaconglomerates usually break across pebbles rather than around pebbles and this is the best way to distinguish them from conglomerates. Other common "meta" rocks include **metabasalt** (recognizable phenocrysts frequently overprinted by chlorite) and **metasandstone** (not quite a quartzite).

4.3 Metamorphic Grade

As regional metamorphism intensifies, new minerals form within a rock, often at the expense of pre-existing minerals. Chlorite is the first of the metamorphic minerals to form, generally from the replacement of clay minerals in rocks like shale. If the pressure and temperature increase, muscovite and biotite grow again at the expense of clay minerals. These are the two main minerals comprising schists. Eventually, minerals such as garnet, staurolite, kyanite and sillimanite (Al_2SiO_5) form, but only after metamorphism has become intense. Each of these minerals form under specific conditions of pressure and temperature. In fact, by determining the mineralogy of a metamorphic rock, it becomes possible to bracket the temperature and pressure at which the rock formed. For this reason, chlorite, muscovite, biotite, garnet, kyanite and other metamorphic products are considered to be **index minerals.** Each index mineral defines a specific metamorphic zone characterized by unique combinations of pressure and temperature (Figure 4.2).

The **metamorphic grade** of a rock is defined by the presence of certain index minerals. Low grade metamorphic rocks (including slates and phyllites), are characterized by an abundance of chlorite and/or muscovite. Intermediate grade metamorphic rocks (many schists) contain chlorite, muscovite, biotite and even some garnet and kyanite. The highest grade rocks (other schists and the gneisses), contain garnets and other metamorphic minerals discussed in your textbook. You are advised to consult your text book regarding metamorphic grade and index minerals such as staurolite and sillimanite. You may not see these minerals in the laboratory component of GY 111, but you are still responsible for understanding the circumstances of their formation for tests.

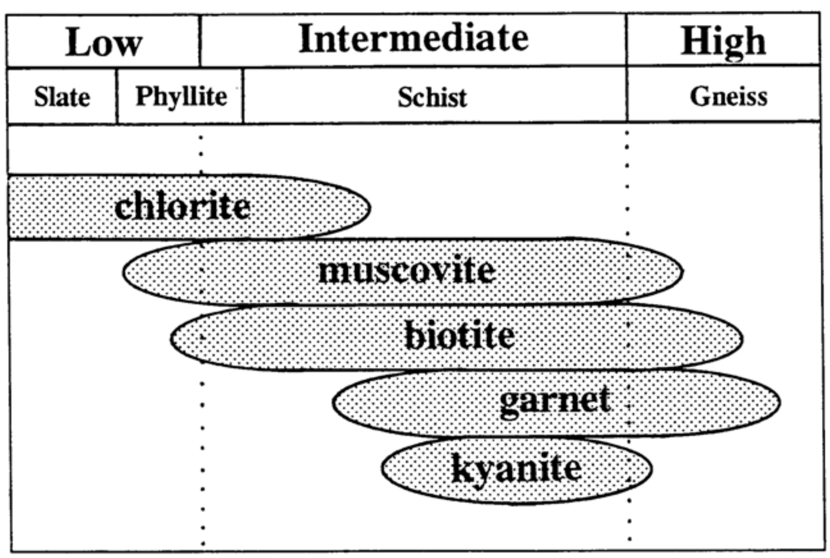

Figure 4.2. Metamorphic grade and index minerals associated with progressive regional metamorphism of a shale.

4.4. Exercises

As with the igneous and sedimentary components of this lab, in this section, you will be provided with a variety of metamorphic rocks all nicely packaged in a tray or drawer. To be totally honest, the metamorphic rocks are the easiest of all the rock types to identify. But don't skimp on your examination of them! If you see any foliation (e.g., an alignment of platy minerals), or obvious metamorphic minerals (chlorite, garnet, kyanite etc.), you know that you are dealing with a metamorphosed rock. Name the rocks according to their texture and mineral content.

Check with your lab instructor to determine which of the optional exercises (if any) that you are responsible for in this lab component of GY 111. Regardless of these exercises, all students should be able to identify metamorphic rocks and minerals rocks like those provided in the rock tray. For the exam, you should be able to identify the following attributes of each metamorphic rock specimen:

(a) their texture (foliated, non-foliated, cataclastic)
(b) the presence or absence of fracture cleavage
(c) grain size permitting, their mineral composition
(d) their name (Table 4.1).
(e) their metamorphic grade (Figure 4.2)
(f) possible source or parent rock (only for some specimens)

Optional Exercises

You may wish to refer to your lecture notes and/or textbook for assistance in answering some of these questions.

1) What types of metamorphic rocks would you expect to find in the following tectonic settings:
   a) 10 km below the Earth's surface at a convergent plate boundary
   b) 100 km below the Earth's surface at a convergent plate boundary
   c) 700 km below the Earth's surface at a convergent plate boundary

2) What are the chemical reactions responsible for the following conversions:
   a) kaolinite to muscovite
   b) limestone to garnet
   c) muscovite to orthoclase

3) What are the parent rocks of the following metamorphic rocks
   a) amphibolite; b) graphite schist

4) How would you distinguish between a quartzite and a marble?

5) How would you distinguish between a marble and a recrystallized limestone (tricky).

6) What are the major metamorphic facies? What are the factors that regulate them?

7) What kind of metamorphic rocks are found in the Appalachian mountain chain in northeastern Alabama?

8) What kind of rocks would result if a mixed sedimentary sequence of limestone and shale were metamorphosed? Assume a high grade of metamorphism.

9) Explain the relationship between the metamorphic minerals andalucite, sillimanite and staurolite. What variables control their formation?

10) What exactly are aureoles and how do minerals vary within these curious metamorphic features?