CHAPTER 5

METAMORPHIC ROCKS

MATERIALS NEEDED

- **Pencil**
- **Hand lens**
- Dilute hydrochloric acid
- Glass or knife to test hardness
- Samples of metamorphic rocks to be identified

INTRODUCTION

A rock that is subjected to heat and pressure may change because its mineralogy and texture change. The characteristics of the original rock, and the type and intensity of metamorphism, determine how drastic the change is. This chapter will introduce some of the common varieties of metamorphic rocks, illustrate their typical textural and mineralogic features, show how they relate to the original or parent rock, and introduce the idea of metamorphic zones.

In some ways, metamorphic rocks are the most mysterious of the three major types of rocks. We can observe volcanoes and see how some igneous rocks form, and watch as sediment accumulates on the Earth's surface. But metamorphic rocks typically form well below the surface where we can't see what happens. To understand them, we must infer what goes on, or run experiments in the lab at high temperatures and pressures. We now think we understand how and under what conditions they form and can, in turn, use actual metamorphic rocks to understand what happens deep beneath the Earth's surface, especially in the cores of mountain belts and underneath volcanic regions, and to unravel the geologic past represented by metamorphic rocks found around our planet.

Metamorphic rocks are crystalline rocks that form from other rocks. **Metamorphism** takes place at varying depths within the Earth's crust, where both temperature and pressure are higher than at the surface. The results of metamorphism include the creation of new minerals, the development of bands or layers of like minerals (for example, layers of quartz or mica), and the parallel alignment of new and old mineral crystals.

CONDITIONS OF METAMORPHISM

Metamorphism takes place at temperatures and pressures that fall between those in which sediments are lithified and those in which rocks begin to melt to form magmas. Figure 5.1 shows approximate lower and upper boundaries of metamorphism. A rock will be metamorphosed if it is heated and buried deeply enough to fall within the areas labeled *metamorphism* on Figure 5.1. Some rocks, such as granite or quartz sandstone, are not affected much by metamorphism until temperatures and pressures are well within the field of metamorphism on Figure 5.1; others, such as porous tuffs consisting of shards of volcanic glass, are highly reactive and undergo changes at temperatures and pressures near those of the field labeled *lithification of sediment.* Similarly, melting begins at different temperature-pressure conditions for different rocks.

Water and such fluids as carbon dioxide are generally present during metamorphism, because they are either contained in the rocks undergoing metamorphism or are released by metamorphic reactions. These fluids are important in the metamorphic process. Among other things, they allow ions to move about more readily, thereby speeding up the chemical reactions that enable the recrystallization and growth of mineral crystals.

TYPES OF METAMORPHISM

There are two common types of metamorphism: regional and contact.

Regional metamorphism occurs over areas of hundreds or thousands of square kilometers. Regionally metamorphosed rocks were buried beneath thick accumulations of other rocks at some

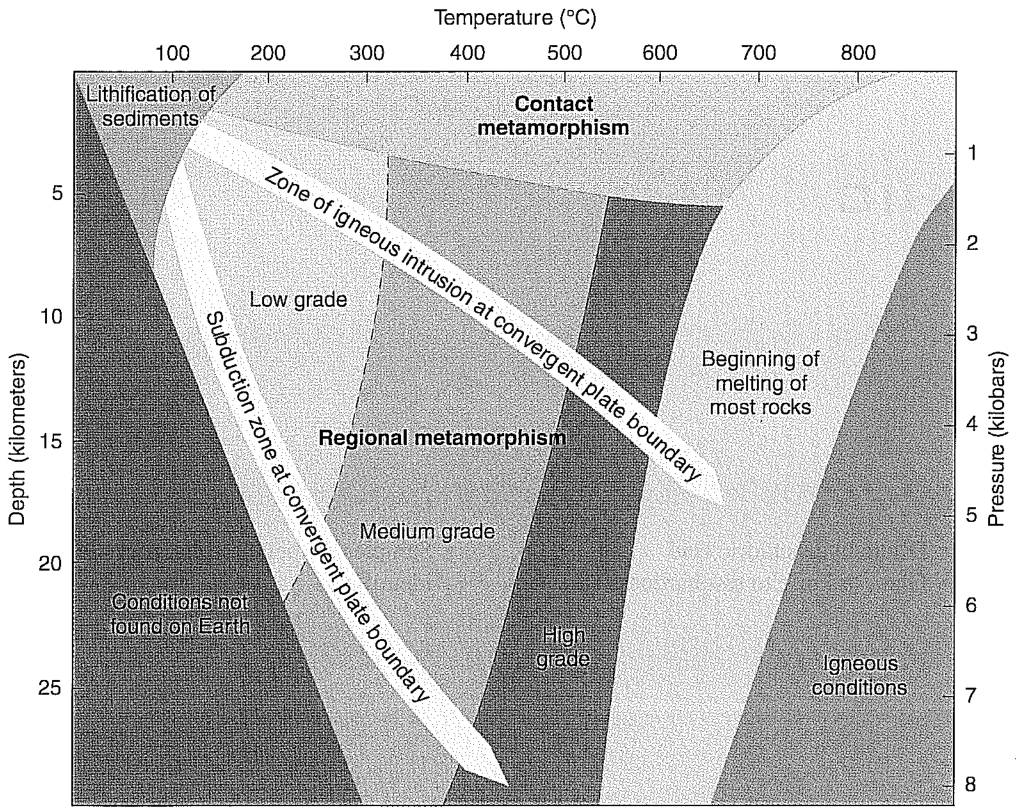


FIGURE 5.1
Temperature and depth (or pressure) conditions for lithification, contact metamorphism, grades of regional metamorphism, and melting. Arrows show how temperature changes with depth at convergent plate boundaries.

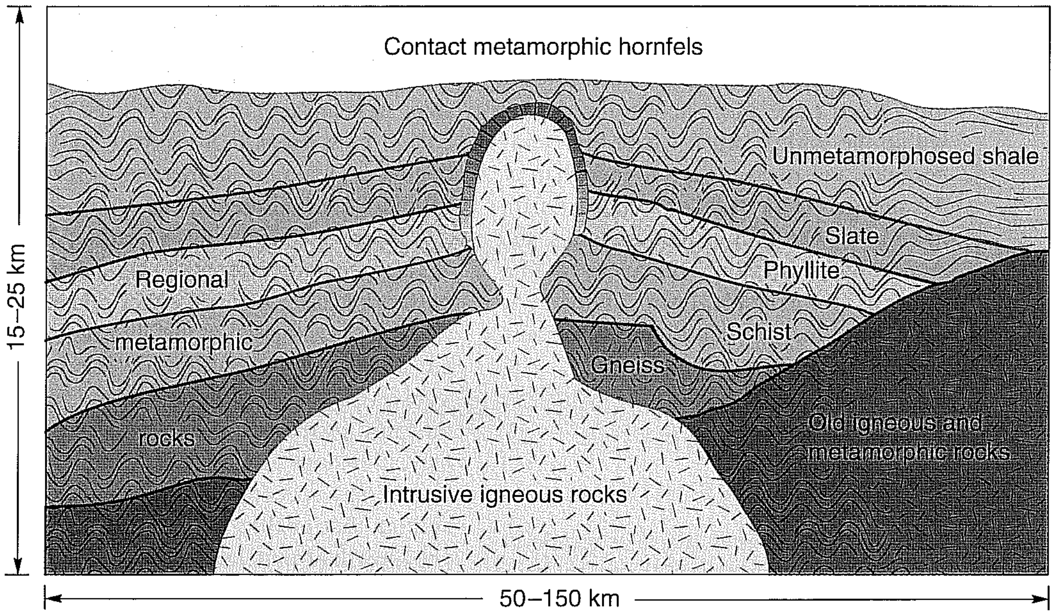
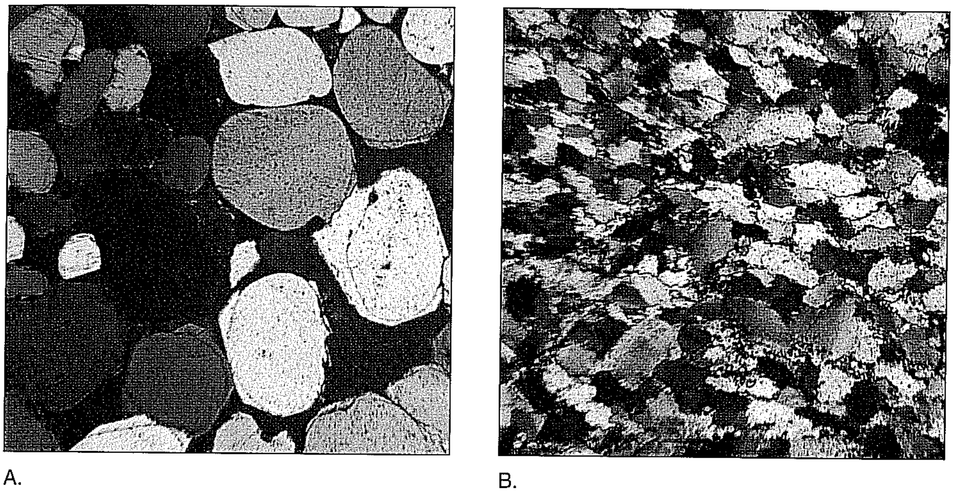


FIGURE 5.2
Cross section illustrating possible setting for regional and contact metamorphism. The metamorphic rocks shown are those that would form from a shale parent.

time during their history (Fig. 5.2). During this period of burial, they were subjected to the higher temperatures and pressures found beneath the surface (Fig. 5.1). The weight of the overlying rocks provided most of the pressure, but collisions between tectonic plates, such as occurs at convergent boundaries, can also create pressure directed from the side.

Heat from an intruding body of magma causes **contact metamorphism** of the surrounding rocks (Fig. 5.2). Fluids released from the magma or the surrounding rocks may accentuate the changes. As suggested in Figures 5.1 and 5.2, contact metamorphism is most evident around igneous intrusions that formed within a few kilometers of the surface. Because temperature increases with depth, it becomes increasingly difficult below a few kilometers to distinguish contact and regional metamorphism.


A.

B.

FIGURE 5.3
These photomicrographs (×10; polarized light) compare (A) quartz sandstone and (B) quartzite. The original sand grains are evident in the sandstone, but recrystallization has removed traces of them in the quartzite.

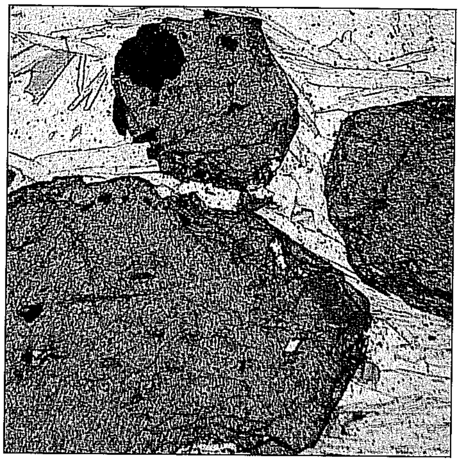


FIGURE 5.4
A new mineral, garnet (brown in photograph), formed during metamorphism, as seen in this photomicrograph of garnet in schist (×10).

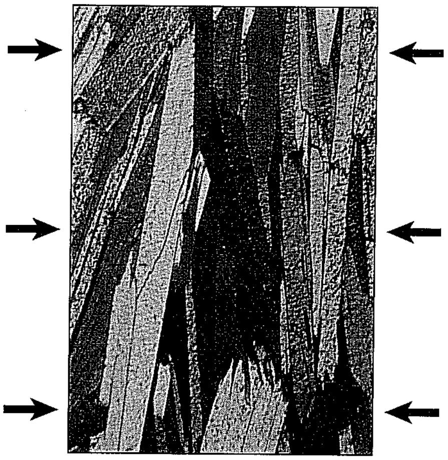


FIGURE 5.5
This photomicrograph of schist shows the distinctive orientation of the mica crystals caused by directed pressure during metamorphism. The black arrows show the sense of squeezing. Examination of similar foliations in ancient rocks helps geologists work out the history of tectonic plate collisions. The photograph was taken in polarized light, which changes the natural mineral colors.

CHANGES DURING METAMORPHISM

The important changes that may take place during metamorphism are:

1. Recrystallization of existing minerals, especially into larger crystals (Fig. 5.3);
2. Development of new minerals and disappearance of some old ones (Fig. 5.4); and
3. Deformation and reorientation of existing mineral crystals and growth of new ones with a distinctive orientation (Fig. 5.5).

The net result is a rock with a different texture and, commonly, a different mineral content.

Recrystallization and development of new minerals (and disappearance of old ones) take place during both contact and regional metamorphism. In general, the crystal size and kinds of minerals in metamorphic rocks indicate the intensity, or **grade,** of metamorphism (see Fig. 5.1). **High-grade metamorphic rocks** are the most intensely metamorphosed. They are characteristically coarsely crystalline and contain minerals that are stable under higher temperatures and pressures. **Low-grade metamorphic rocks** are the least intensely metamorphosed; they are generally finely crystalline (although crystal size also depends on the size of the grains or crystals in the rock prior to metamorphism) and contain minerals that are stable under lower temperatures and pressures.

Minerals are deformed and reoriented primarily as the result of **directed pressure,** pressure that is greater in one direction than in others. Directed pressure is created at convergent boundaries as the tectonic plates collide and compress each other. A subducting oceanic slab pushes hard against the overriding plate, and the collision of two continental plates can create huge mountain belts such as the ancient Appalachians and modern Himalayas.

Simple deep burial of rocks causes only **lithostatic pressure,** which is a pressure felt equally in all directions. If you were in a deeply buried barrel, the weight of overlying rocks would cause the rocks along the side of the barrel to push in with the same force as the rocks above and below the barrel. Since the pressure during contact metamorphism is usually lithostatic, it normally results in little deformation or reorientation of metamorphic minerals.

METAMORPHIC TEXTURES

Metamorphic rocks have crystalline textures and are further subdivided into two main textural groups: **nonfoliated** and **foliated. Foliation** is the arrangement of mineral crystals in parallel or nearly parallel planes. An example is shown in Figure 5.5, where the flat crystals of mica are aligned in the same direction.

Nonfoliated metamorphic rocks lack flat mineral crystals with parallel alignment. Instead, crystals typically are all about the same size and are interlocked in a crystalline texture (see Fig. 5.3B). Quartz, feldspar, and calcite commonly produce nonfoliated textures.

Foliated metamorphic rocks contain minerals that are aligned in parallel planes (Figs. 5.6 through 5.9). The **foliated texture** commonly results from the parallelism of micas, but crystals of other flat or elongate metamorphic minerals, such as chlorite or hornblende, also can form parallel planes. Foliated rocks commonly appear to be layered or banded. In addition to the parallel arrangement of minerals, the crystals also are grown together in an interlocking fashion, as in other rocks with crystalline textures. Foliation results from directed pressures usually present during regional metamorphism; the pressures were perpendicular to the planes of foliation (Fig. 5.5).

Warning: Some metamorphic rocks preserve banding that is not considered foliation. Metamorphosed sandstones can preserve cross-bedding and metamorphosed limestones can display banding that reflects layered impurities in the original rock. In both cases, the rocks are dominated by interlocking mineral grains that are all about the same size (they are nonfoliated), and the banding is defined only by color or traces of tiny mineral grains. Foliation requires a substantial fraction of the rock to consist of aligned mineral grains.

Four distinct types of foliation are recognized primarily on the basis of crystal size. The following list is arranged from low (slaty) to high (gneissic) grade metamorphism.

Slaty (Fig. 5.6): a foliation in metamorphic rocks made of platy (flat) minerals too small to be seen without a microscope. Such rocks readily split or cleave along almost perfectly parallel planes and are said to have a **slaty cleavage.**

Phyllitic (Fig. 5.7): a foliation in metamorphic rocks made of platy mineral ranging in size from visible with a 10-power hand lens to just barely visible to the unaided eye. Phyllitic rocks have a shiny or glossy luster. The rock cleavage is along nearly parallel surfaces, but these surfaces may be wrinkled to varying degrees. This type of foliation represents a state of textural development intermediate between slaty and schistose.

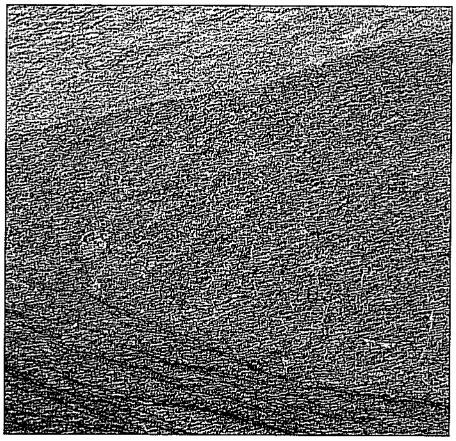


FIGURE 5.6
Slaty cleavage is the most distinctive feature of slate. Slate is so finely crystalline—mineral crystals are indistinguishable—and breaks along such flat surfaces that the really good slate was used for blackboards before about 1945. It makes a durable roof too, and is still used for that purpose. Slate comes in a variety of colors, but is commonly black, bluish black ("slate blue"), gray-green, purple, or dull red. Slate forms from metamorphism of shale and is usually distinguishable from it by its slightly shinier luster.

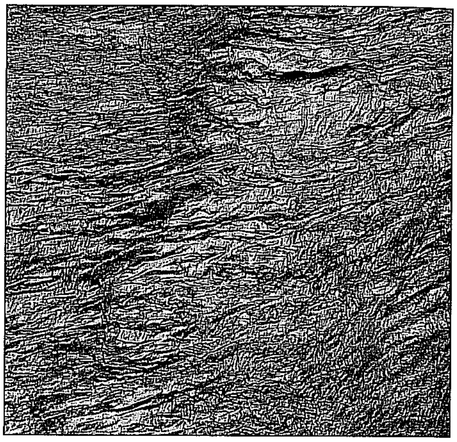
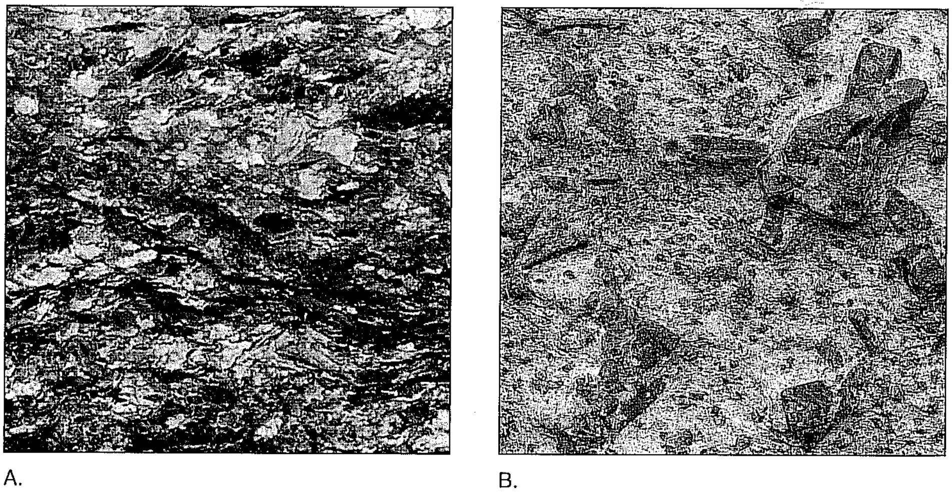


FIGURE 5.7
Metamorphic intensity slightly higher than that required to form slate turns shale into phyllite, a rock characterized by its phyllitic foliation. On the low-metamorphic-grade side, phyllite is distinguished from slate by a shinier, more satin-like luster and by crystals that are large enough to give just a hint of their presence. On the high-grade side, phyllite is distinguished from schist by crystals that are almost, but not quite, large enough to identify. Phyllite has a good rock cleavage, but the cleavage surfaces are commonly wrinkled and the cleavage is not as good as slate's.



A.

B.

FIGURE 5.8
Schists have crystals that are large enough for individual minerals to be identified. Their distinctive schistose foliation is caused by the presence of platy minerals such as talc, chlorite, biotite, and muscovite. The larger crystal size and the presence of other minerals, such as quartz and feldspar, cause schists to split along rough, irregular surfaces that more or less parallel the foliation. Schists derived from the metamorphism of shale may contain typically metamorphic minerals such as garnet, staurolite, kyanite, or even sillimanite, depending on the metamorphic grade. Schists derived from other parent rocks contain other minerals, such as blue, green, or black amphibole. Because the mineral content of schists is variable, the characterizing minerals are used in the rock name: (A) quartz-biotite schist, and (B) garnet-muscovite-staurolite schist are examples. More intensely metamorphosed schists may be somewhat banded due to segregation of dark and light minerals. Commercially valuable minerals such as talc and kyanite are obtained from schists in which these minerals are sufficiently concentrated.

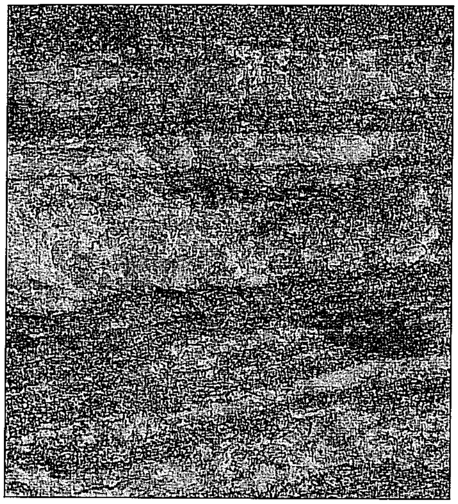


FIGURE 5.9
Gneissic foliation, or banding, characterizes gneiss. For example, *granitic gneiss* has light-colored layers of quartz and feldspar that alternate with dark layers of biotite and/or hornblende. Other minerals such as garnet or sillimanite may be present as well. Layers are a few millimeters to a few centimeters thick. Some gneisses and migmatites are beautiful when cut and polished and are used extensively for monuments and decorative building stones.

Schistose (Fig. 5.8): a foliation in rocks composed of mineral crystals large enough to be seen with the unaided eye. Rock cleavage is parallel to the foliation, but cleavage surfaces are usually irregular. Platy minerals commonly predominate, but other minerals, such as quartz, are also present.

Gneissic (Fig. 5.9): a coarse foliation in which like minerals are more or less segregated into roughly parallel bands or layers. A common example is a rock in which nonfoliated layers made of quartz and feldspar alternate with foliated layers made of biotite. Mineral crystals are coarse and can be identified with the unaided eye.

During very high-grade metamorphism, local partial melting of quartz and feldspar may result in the formation of a **migmatite,** a mixed igneous-metamorphic rock with enlarged pods of quartz and feldspar in the midst of swirling light and dark bands. With further melting, the foliation would be destroyed and an igneous rock formed.

TABLE 5.1
RECOGNIZING MINERALS IN METAMORPHIC ROCKS

Mineral	*Properties*
K-feldspar	Usually white or pink Two cleavages at 90° Equidimensional to ovoid crystals
Plagioclase	Usually white (Na-plagioclase) or gray (Ca-plagioclase) Two cleavages at 90° Elongate to equidimensional crystals Striations may or may not be present
Quartz	Colorless to gray Glassy with conchoidal fracture Irregular crystals or lens-shaped masses
Biotite	Shiny and black One perfect cleavage Thin crystals parallel to foliation
Muscovite	Shiny and silvery white One perfect cleavage Thin crystals parallel to foliation
Hornblende (amphibole)	Black with shiny, splintery appearance Two cleavages at 56° and 124° Elongate, commonly parallel, crystals
Garnet	Pink, red, reddish brown Vitreous to resinous luster Equidimensional, twelve-sided crystals with diamond-shaped faces are common
Staurolite	Brown, red-brown to brownish black Vitreous to dull luster Prismatic and X- or cross-shaped crystals
Kyanite	Light blue to greenish blue Vitreous luster Blade-shaped crystals
Talc	White, gray, apple green Pearly luster Soft (H = 1), with greasy feel
Chlorite	Green to blackish green One good cleavage Crystals commonly small, flaky, and parallel to foliation
Serpentine	Multicolored black, green, grey Hardness = 3 to 5 Dull to greasy luster, with a slightly greasy feel Commonly dominates composition of rock (serpentinite)

METAMORPHIC MINERALS

Metamorphic rocks contain many of the same minerals found in igneous and sedimentary rocks. Certain minerals, however, form almost exclusively in metamorphic rocks. In addition, some minerals of metamorphic rocks are present only in rocks of a specific metamorphic grade. Table 5.1 summarizes the properties of common metamorphic minerals, and Figure 5.10 shows the metamorphic grades at which they occur.

PARENT ROCK

Metamorphic rocks are formed by the effects of temperature and pressure on a preexisting rock, the *parent.* It is always helpful in working out the geologic history of a metamorphic area to determine what the parent rock was, although this is not always possible. Common parent rocks and their metamorphic derivatives are listed in Table 5.2.

CLASSIFICATION AND IDENTIFICATION OF METAMORPHIC ROCKS

Metamorphic rocks are classified on the basis of texture and the kinds and proportions of minerals present. However, microscopic examination may be necessary to determine the mineralogic content. Therefore, the primary basis of the classification to be used here is texture, as shown in Table 5.2.

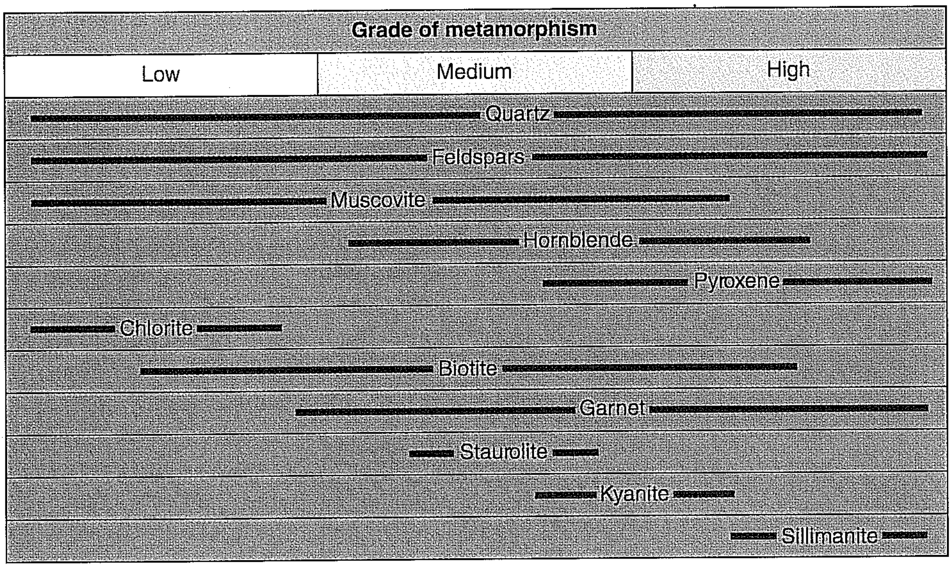


FIGURE 5.10
Most of the common minerals of metamorphic rocks form at different metamorphic grades. Thick lines indicate the range of metamorphic grade through which each mineral is possible.

TABLE 5.2
CLASSIFICATION OF METAMORPHIC ROCKS

Foliated Metamorphic Rocks		
Parent rock	*Comments*	*Rock name*
Shale or mudstone	Low metamorphic grade. Slaty cleavage, cleavage surfaces dull to slightly shiny. Very fine grained. Generally dark (e.g., black, green, red).	Slate
	Low metamorphic grade. Phyllitic foliation. Fine grained. Silky, shiny luster.	Phyllite
	Intermediate metamorphic grade. Schistose foliation. Medium to coarse grained. Name modified by mineral name (e.g., quartz-biotite schist).	Schist
Shale, mudstone, granite	High metamorphic grade. Gneissic foliation. Medium to coarse grained. Light and dark layers common. Name modified by mineral names.	Gneiss
	Border between igneous and metamorphic rock. Pods of feldspar or quartz in midst of swirling light and dark bands.	Migmatite
Nonfoliated or Weakly Foliated Metamorphic Rocks		
Limestone or dolostone	Variable metamorphic grade. Chiefly calcite or dolomite; H = 3–4; effervesces in dilute HCl. Commonly coarsely crystalline.	Marble
Quartz sandstone	Variable metamorphic grade. Chiefly quartz; H = 7. Crystalline.	Quartzite
Basalt or gabbro	Low to medium metamorphic grade. Chlorite, green amphibole, epidote, and Na-plagioclase. Greenish gray or black.	Greenstone
Basalt or gabbro	Medium to high metamorphic grade. Hornblende, Na-Ca plagioclase, ± garnet. Dark gray to black. May be foliated.	Amphibolite
Peridotite	Low to medium metamorphic grade. Chiefly talc. Gray to dark greenish gray. Soft; can be carved (see Fig. 2.6).	Soapstone
	Variable metamorphic grade. Mostly fine-grained serpentine; some may be fibrous. Greenish; commonly mottled or streaked.	Serpentinite
Coal	Low to medium metamorphic grade. Shiny, dark gray to black. Conchoidal fracture.	Anthracite coal
Conglomerate, graywacke, chert	Low to medium metamorphic grade. Parent rock easily recognizable.	Metaconglomerate, metagraywacke, metachert
Various	A low-grade, contact-metamorphic rock. Commonly fine grained and dark color.	Hornfels

To identify a metamorphic rock, first identify the texture:

A. If the rock is foliated, use a name consistent with the type of foliation: *slate* (Fig. 5.6), *phyllite* (Fig. 5.7), *schist* (Fig. 5.8), or *gneiss* (Fig. 5.9). This name is then modified by mineral names when possible, as in quartz-biotite schist. Some geologists use igneous-rock names to describe gneisses with similar mineral compositions (e.g., granitic gneiss).

B. If the rock is nonfoliated, its name is determined by mineral content when possible or by recognition of parent rock textures. Rocks named by mineral content include *quartzite* (Fig. 5.11), *marble,* (Fig. 5.12), *soapstone* (Fig. 2.6), *serpentinite* (made of serpentine), and *anthracite* (hard coal recognized by vitreous luster and conchoidal fracture). *Greenstone* is a low-grade rock formed by the metamorphism of basalt, gabbro, or andesite. Greenstones are identified by their greenish gray or greenish black color, which comes from tiny (frequently microscopic) chlorite or epidote crystals, and the preservation of parent rock textures. *Amphibolites* result from higher grade metamorphism of these same igneous rocks. They have lost the parent rock textures but may show slight foliation and are dominated by hornblende, plagioclase, and garnet.

Metaconglomerate, metagraywacke, and metachert are metamorphosed equivalents of the sedimentary rocks conglomerate, graywacke, and chert; they are usually recognized by the preserved sedimentary textures.

Hornfels is a general name used for contact-metamorphic rocks that are nonfoliated and too fine grained for individual minerals to be readily recognized.

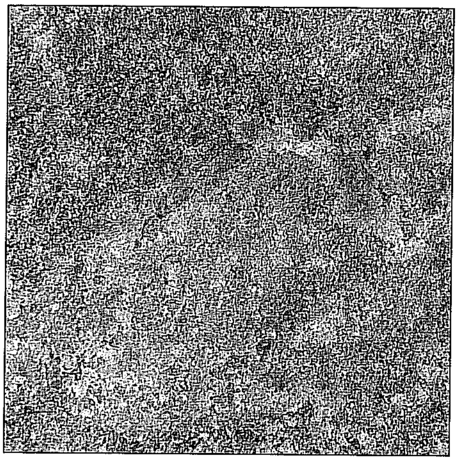


FIGURE 5.11
Quartzite is a nonfoliated rock made mostly of quartz. It may be white to various shades of purple, green, gray, or pink. Its crystalline texture is evident in hand specimen, but a microscopic view (Fig. 5.3) better illustrates how the original grains of quartz sand have become intergrown. Impure quartzites contain minerals other than quartz, such as muscovite or kyanite. In many quartzites, original sedimentary features, such as bedding, cross-bedding or ripple marks, are still evident, having survived metamorphism.

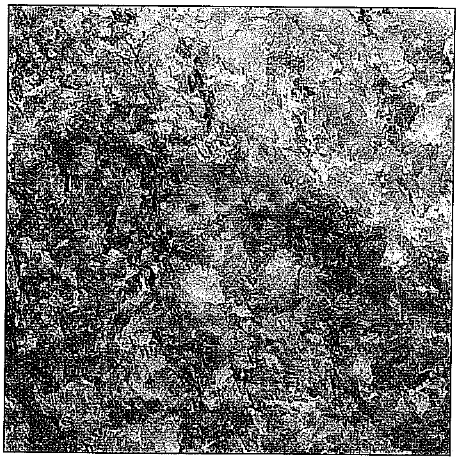


FIGURE 5.12
Marble, a nonfoliated rock made mostly of calcite or dolomite, has a variety of colors and textural patterns. It has long been used for decorative purposes, but because of its susceptibility to acidic rain, it does much better in an interior setting. Its hardness (3 to 3.5), reaction with acid, and commonly coarse crystalline texture aid in identification. Some impure marbles, especially those formed by contact metamorphism, contain spectacular crystals of unusual minerals.

ZONES OF METAMORPHISM

During regional metamorphism, rocks subjected to higher temperatures and pressures are squeezed and cooked more than those exposed to less intense conditions. The result is that high-grade metamorphic rocks differ from intermediate- and low-grade rocks in texture and mineral content. For example, slate, phyllite, schist, and gneiss are the metamorphic products of progressively more intense temperature and pressure conditions.

One way to learn how varying intensities of metamorphism affect rocks is to find a place where erosion has stripped away the overlying rocks to expose a sequence of metamorphic rocks ranging from low to high grade. It is then possible to study the entire sequence in the field and the laboratory to see exactly what textural and mineralogic changes have occurred, as illustrated by the following hypothetical example.

Figure 5.13A is a map of an imaginary area showing rock *outcrops,* places where the bedrock is not covered by soil (circled and lettered areas). Most of the rocks in this area are metamorphosed to varying degrees, but the *parent rock* for all of them was shale. Furthermore, the whole area was tilted to the northeast before it was eroded to a nearly flat surface. Thus, the rocks that were most deeply buried during metamorphism are now exposed in the southwest part of the area. Unmetamorphosed shale, which was closest to the surface during metamorphism, is present only in the northeast corner. In between are rocks that were buried to intermediate depths. Note that the texture changes from northeast to southwest, with more coarsely crystalline rocks reflecting more intense metamorphism.

The minerals present in rocks from localities A through J are given in the box in Figure 5.13A. Those that are underlined have special significance, because they formed by chemical reactions that take place only under certain temperature and pressure conditions. Figure 5.10 shows that some minerals are restricted to a narrow range of metamorphic conditions whereas others form over wider ranges. Thus, the presence or absence of these *index minerals* in a rock formed by the metamorphism of a shale indicates whether or not certain temperatures and pressures were attained during metamorphism (see "Metamorphic Reactions" box, on p. 83).

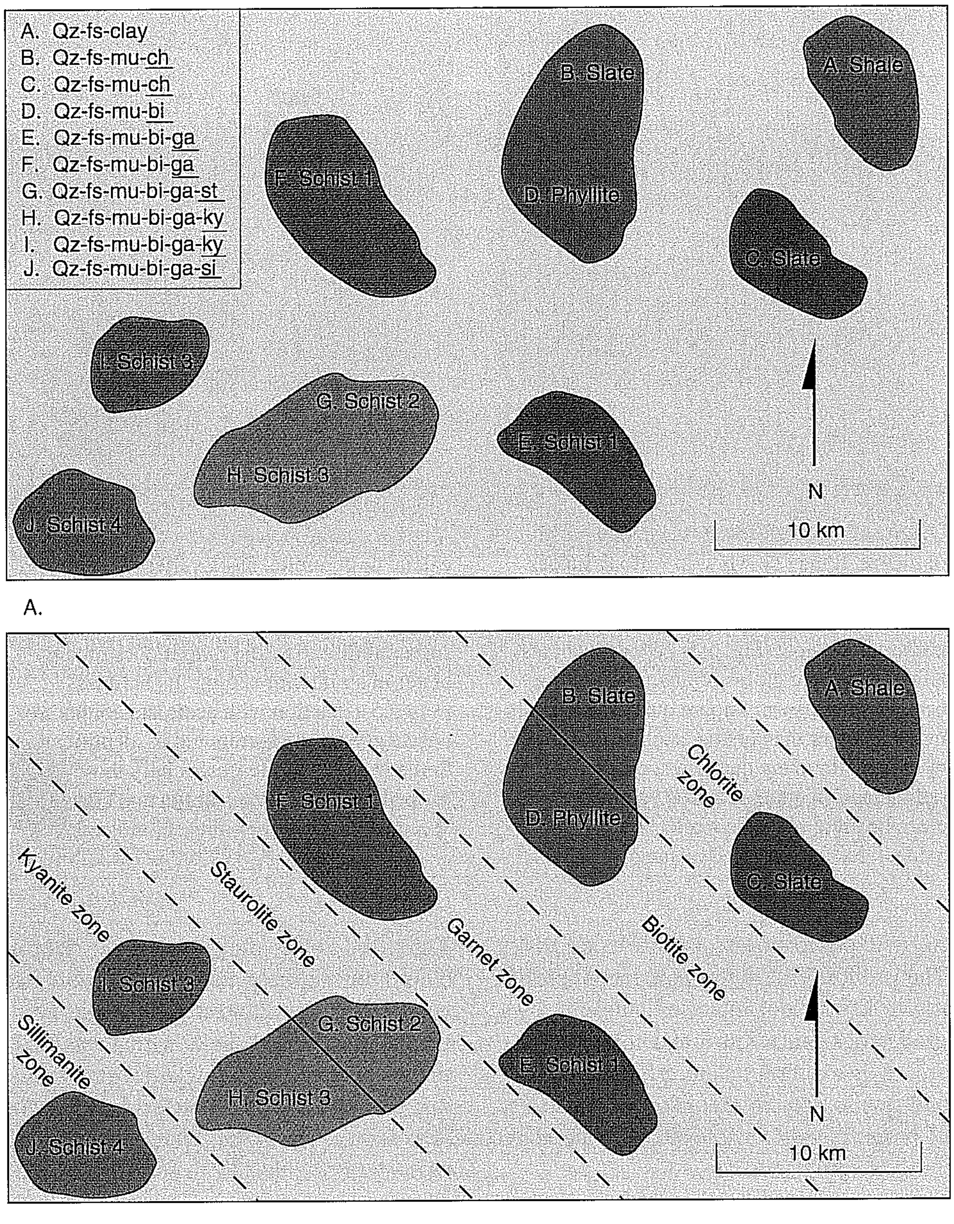


FIGURE 5.13
A. Map of outcrops indicating rock types and mineral assemblages. *Qz* = quartz; *fs* = feldspar; *mu* = muscovite; *ch* = chlorite; *bi* = biotite; *ga* = garnet; *st* = staurolite; *ky* = kyanite; *si* = sillimanite. Index minerals are underlined. B. Same map showing isograds and mineral zones.

In Figure 5.13B, lines are drawn to outline zones based on the appearance of the index minerals. Because these lines approximate the same metamorphic grade, they are called **isograds.** This metamorphic map gives a clearer picture of the metamorphism of the shale. For example, it is easy to see at a glance that the metamorphic grade increases from northeast to southwest, and the index minerals indicate just how intense the metamorphism was.

DISTINGUISHING AMONG IGNEOUS, SEDIMENTARY, AND METAMORPHIC ROCKS

After finishing this lab, you will have looked at a number of specific examples of igneous, sedimentary, and metamorphic rocks. What if you were handed a rock and simply asked to tell whether it was igneous, sedimentary, or metamorphic? Could you do it? This seems like an easy thing, yet there are times when it is very difficult. Let's first review some of the major characteristics of each rock type, then consider some specific cases.

Most igneous rocks have nonfoliated, crystalline textures and are composed of several of the common minerals—feldspar, quartz, olivine, augite, hornblende, biotite, or muscovite—in varying proportions. Most common sedimentary rocks have clastic textures. They may contain some of the same minerals as igneous rocks (quartz and feldspar are the most common), but they also may contain non-igneous minerals such as clay or calcite. Sedimentary rocks with crystalline textures are composed of minerals, such as calcite, dolomite, gypsum, or halite, not usually found in igneous rocks. Foliated metamorphic rocks are distinguished from igneous and sedimentary rocks by foliation. Some contain typically metamorphic minerals like garnet, staurolite, or kyanite. Nonfoliated metamorphic rocks usually consist mostly of one mineral, such as quartz or calcite.

Some specific "problem rocks" are the following:

Shale vs. slate. Because a slate forms by low-grade metamorphism of a shale, these two rocks are very similar. In general, a slate is shinier and a bit harder and tougher than a fissile shale. Thin pieces of slate tend to "ring" when dropped on a table, whereas shale tends to "thunk."

Quartz sandstone vs. quartzite. Like shale and slate, a complete range, or gradation, can be seen from sandstone to quartzite, depending on the degree of metamorphism. One way to distinguish the two is based on the way the rock breaks. If the break cuts through individual quartz grains, the rock generally is quartzite; if it breaks around grains, it is quartz sandstone.

Limestone or dolostone vs. marble. Again, a complete range exists from limestone/dolostone to marble, depending on the degree of metamorphism. Marbles have readily distinguishable crystalline textures, with individual crystals large enough to see rather easily. Although some limestones have crystalline textures, the crystal size generally is quite small. Sometimes, however, it is nearly impossible to distinguish limestones from marbles in hand specimens. They usually can be distinguished in the field by looking at the surrounding rocks; if they are sedimentary, it is likely a limestone; if they are metamorphic, it is likely a marble. Marbles are *not* harder than limestones; they are equally hard. Why?

Graywacke vs. basalt. A dark gray, fine-grained graywacke may be difficult to distinguish from basalt. However, with a hand lens, you generally can see the clastic texture in graywacke and the crystalline texture in basalt. Graywackes may contain quartz, whereas basalts do not.

Mudstone vs. tuff. Some tuffs are so fine grained that they look like mudstones. Tuffs are commonly lighter in color and weight than mudstones, but examination with a microscope may be necessary to distinguish the two.

Conglomerate or sedimentary breccias vs. volcanic breccia. Volcanic breccias or tuffs with pyroclastic fragments may look like conglomerate or sedimentary breccia. The volcanic rocks usually contain only fragments of other volcanic rocks, whereas the particles in conglomerate and sedimentary breccia may be any rock type or a mixture of rock types. Tuffs commonly contain small crystals of common igneous minerals and almost always contain tiny bits of broken volcanic glass or shards (these may be difficult to see). Many tuffs and some volcanic breccias are lighter weight than conglomerates.

METAMORPHIC REACTIONS

An example of a metamorphic reaction is illustrated in Figure 5.14. That figure shows the temperature and depth (or pressure) conditions at which the reaction *muscovite + quartz = potassium feldspar + sillimanite +* H_2O can occur. Muscovite and quartz can occur together without reacting, as long as the combination of temperature and depth is to the left of the reaction curve; for example, at 500° and 10 km. If the temperature at that depth were higher, so that it was to the right of the reaction curve (for example, 700°), then muscovite and quartz could not occur together without reacting to form potassium feldspar, sillimanite, and water. When the rock cools again, the reverse reaction (forming muscovite + quartz) generally does not take place in nature, because the water necessary for the reaction has escaped. Because water and other fluids are driven off during metamorphism, the minerals present in metamorphic rocks generally are those formed at the highest temperature and pressure conditions that were attained.

It is sometimes possible to find rocks that contain both products and reactants. For the reaction shown in Figure 5.14, that rock would contain quartz, muscovite, potassium feldspar, and sillimanite. Such a rock would have been subjected to conditions right on the reaction curve (for example, 625° at a depth of 10 km). If a series of outcrops with the same products and reactants could be located, they would all represent the same metamorphic grade. A line on a map connecting them would be an isograd, a line of equal metamorphic grade, generally defined by a specific reaction or the appearance of a specific mineral.

By using numerous reactions like the one shown in Figure 5.14, it is possible to determine the temperature and pressure conditions that must have existed at the time of metamorphism. Because pressure, especially, can be related approximately to depth (see Fig. 5.1), it is also possible to figure out how deep the rocks must have been when they were metamorphosed.

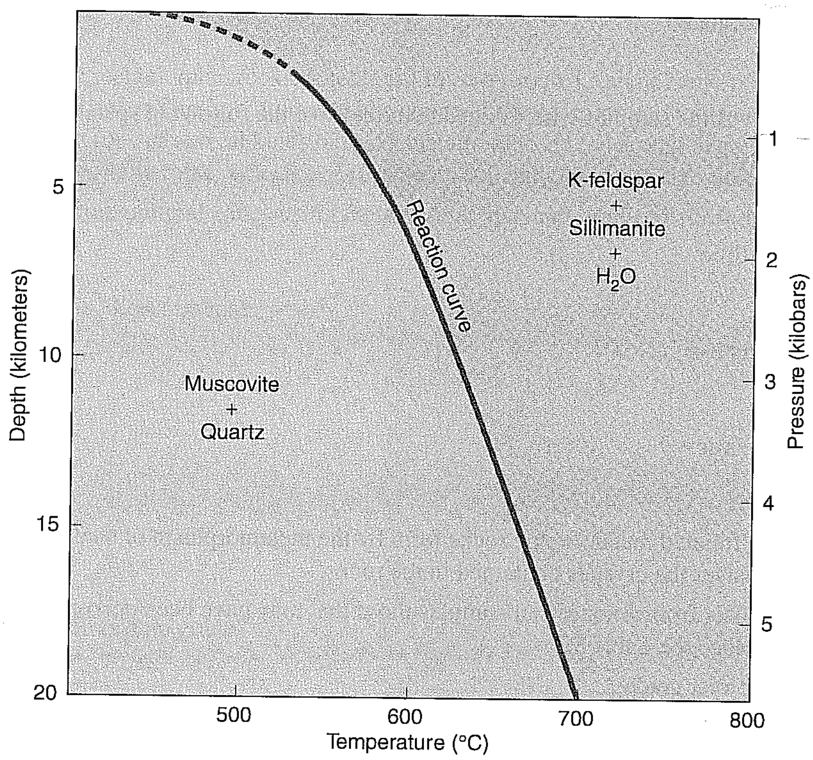


FIGURE 5.14
The reaction *muscovite + quartz = K-feldspar + sillimanite +* H_2O occurs when the combination of temperature and depth (pressure) fall on the reaction curve. If temperature and depth are left of the curve, muscovite and quartz are present; if they are right of the curve, K-feldspar, sillimanite and H_2O are present.