



## 6 Metamorphic Rocks

Most of the rocks exposed in the continental shields and in the cores of mountain belts show evidence that their original igneous or sedimentary textures and compositions have changed. At the same time, many were ductilely deformed, as shown by contorted parallel bands of minerals resembling the swirled colors in marble cake. Other rocks recrystallized and developed large mineral grains, and the constituent minerals of many have strong fabrics with planar orientations called foliation. These are the hallmarks of recrystallization in the solid state, a process we call metamorphism. The result is a new rock type with a distinctive texture and fabric and, in some cases, new mineral compositions.

In the photograph above, metamorphic rocks are exposed in the sheer walls of Arizona's Grand Canyon. Here, near Phantom Ranch, metamorphic rocks dominate the inner gorge of the canyon. The high vertical cliff exposes younger sedimentary formations. The minerals in the metamorphic rocks did not crystallize from a magma, but they are stable only at high temperatures and pressures found deep in the crust. Light-colored dikes and sills of igneous rock cut the metamorphic rocks. Note the strong vertical fabric of the canyon wall. This planar fabric is characteristic of many metamorphic rocks. Complex folds and contortions in





the rock units show the degree to which these rocks have been deformed at high temperature. In this area, we are looking at the roots of mountains built long before the continents split to form the Atlantic Ocean or even before life had evolved that could survive on land. In fact, most of the rocks originally formed as horizontal beds of sedimentary and volcanic rocks more than 1.6 billion years ago. Later, the collision of two tectonic plates pushed them to great depths in the crust, and there they recrystallized without melting at high temperature and under immense pressure. The rocks were folded and contorted; the bedding was destroyed; even their microscopic grain-to-grain textures changed. The change was as complete and striking as the metamorphosis of a caterpillar to a butterfly. Meanwhile, a folded mountain belt formed above the metamorphic zone, and was then slowly eroded away eventually exposing the rocks of the deep mountain roots. All of this history can be read by a simple realization of the metamorphic character of the rock.

Events such as these formed the very foundation of each of the continents. The rocks of the shields and those in the deep parts of the stable platforms are mostly of this type. Every aspect of metamorphic rock, from the small grain to the regional fabric of a shield, points toward the same theme: metamorphic rocks dramatically show the mobility of a dynamic crust.





## MAJOR CONCEPTS

1. Metamorphic rocks can be formed from igneous, sedimentary, or previously metamorphosed rocks by recrystallization in the solid state. The driving forces for metamorphism are changes in temperature, pressure, and composition of pore fluids.
2. These changes produce new minerals, new textures, and new structures within the rock body. Careful study of metamorphic rocks reveals the thermal and deformation history of Earth's crust.
3. During metamorphism, new platy mineral grains grow in the direction of least stress, producing a planar texture called foliation. Rocks with only one mineral (such as limestone) or those that recrystallize in the absence of deforming stresses do not develop strong foliation but instead develop a granular texture. Mylonite develops where shearing along a fracture forms small grains by ductile destruction of larger grains.
4. The major types of foliated metamorphic rocks include slate, schist, gneiss, and mylonite; important nonfoliated (or granular) rocks include quartzite, marble, hornfels, greenstone, and granulite. They are distinguished by their textures and secondarily by their compositions.
5. Contact metamorphism is a local phenomenon associated with thermal and chemical changes near the contacts of igneous intrusions. Regional metamorphism is best developed in the roots of mountain belts along convergent plate boundaries.
6. Mineral zones are produced where temperature, pressure, or fluid compositions varied systematically across metamorphic belts or around igneous intrusions.
7. Distinctive sequences of metamorphic rocks are produced in each of the major plate tectonic settings.

## THE NATURE OF METAMORPHIC ROCKS

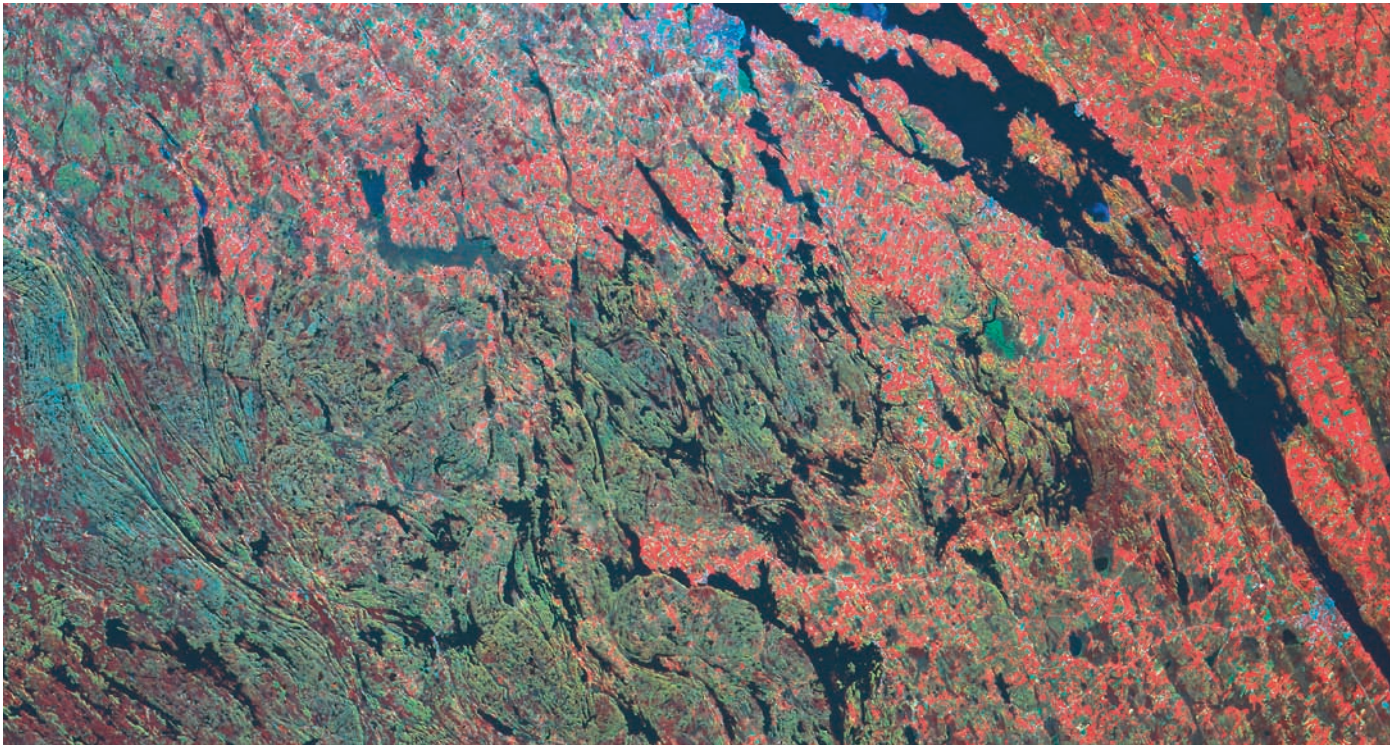
Metamorphic rocks form by recrystallization in the solid state because of changes in temperature, pressure, or the composition of pore fluids. New minerals form that are in equilibrium with the new environment, and a new rock texture develops in response to the growth of new minerals.

Many igneous and sedimentary rocks have recrystallized in the solid state—without melting—to such an extent that the diagnostic features of the original rock have been greatly modified or obliterated. Recrystallization occurs because of changes in temperature, pressure, and the chemical composition of the fluids that flow through them. We call these solid-state processes **metamorphism** (Greek, “changed form”). These solid state reactions are akin to those that a potter uses to convert soft clay into hard ceramic. When a soft clay pot is placed in a kiln at a temperature near 1200°C, the clay minerals change into other minerals that are stable under those conditions. In other words the clay is metamorphosed. The recrystallization occurs without melting, but is sufficient to create a new material radically different than its precursor.

During metamorphism of rocks, most structural and textural features in the original rock—such as stratification, graded bedding, vesicles, and porphyritic textures—are destroyed. New minerals replaced those originally in the rock to create a new rock texture. These are **metamorphic rocks**, a major group of rocks that results largely from the constant motion of tectonic plates (Figure 6.1). Metamorphic rocks can be formed from igneous, sedimentary, or even previously metamorphosed rocks.

Many people know something about various igneous and sedimentary rocks but only vaguely understand the nature of metamorphic rocks. All of us have

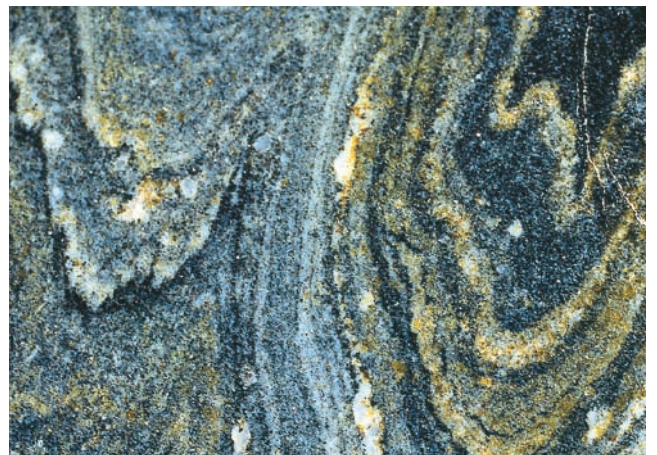




(A) Satellite image of metamorphic rocks in the Canadian Shield. Note the complex folds and fractures resulting from extensive crustal deformation while the rocks were at high temperature and pressure. (Courtesy of National Air Photo Library, Department of Energy, Mines, and Resources, Canada)



(B) Outcrop of metamorphic rocks at 5500-m level of Mount Everest in Tibet. The foliation in this rock formed by shear during the collision of India and Asia.



(C) Hand sample of a highly metamorphosed rock. Note that recrystallization in the solid state has concentrated light and dark minerals into layers which were then deformed and folded.

**FIGURE 6.1** The characteristics of metamorphic rocks are shown on three different scales. Each shows features resulting from strong deformation and solid-state recrystallization caused by changes in temperature, pressure, or fluid composition.

seen many environments where new sedimentary rocks are forming; most have also seen a few igneous rocks form—when volcanoes erupt, for example. But the formation of metamorphic rocks takes place so deep within the crust that we are not familiar with these processes. Perhaps the best way to become acquainted with this group of rocks, and to appreciate their significance, is to study carefully Figure 6.1. The satellite image of part of the Canadian Shield (Figure 6.1A) shows that the rocks have been distorted and compressed. Originally, these were sedimentary, and volcanic layers deposited horizontally. They have been deformed so intensely, however, that it is difficult to determine the original bottom or top of the rock sequence.





**FIGURE 6.2** A stretched pebble formed during metamorphism of a conglomerate. The pebble was once nearly spherical and about the same size as the specimen shown to the side, but it was deformed at high confining pressure and temperature and stretched to six times its original length. (Photograph by Stan Macbean)

Figure 6.1B shows a more detailed view of metamorphic rocks. The alteration and deformation of the rock are evident in the alternating layers of light and dark minerals. These rocks were intensely sheared along almost horizontal planes while it was in a plastic or semiplastic state. The degree of **plastic deformation** possible during metamorphism is best seen by comparing the shapes of pebbles in a conglomerate with the shapes of pebbles in metamorphosed rock. In a metamorphosed rock, the original spherical pebbles in the conglomerate have been stretched into long, ellipsoidal blades (the long axis is as much as 30 times the original diameter, Figure 6.2). A definite preferred orientation of the grains shows that they recrystallized either under unequal stress (force applied to an area) or by flowing as a plastic.

The typical texture of metamorphic rocks does not show a sequence of formation of the individual minerals like that evident in igneous rocks. All grains in metamorphic rocks apparently recrystallize at roughly the same time, and they have to compete for space in an already solid rock body. As a result, the new minerals grow in the direction of lowest stress. Most metamorphic rocks thus have a layered, or planar, structure, resulting from recrystallization.

Metamorphic rocks make up a large part of the continental crust. Extensive exposures (Figure 6.3) are found in the vast shield areas of the continents. Deep drilling in the stable platform shows that the bulk of the continental crust is also made up of metamorphic rocks. In addition to those beneath the stable platforms of the continents and exposed in the shields, metamorphic rocks are also found in the cores of eroded mountain ranges, such as the Appalachian and Rocky Mountain chains. The widespread distribution of metamorphic rocks in the continental crust, especially among the older rocks, is evidence that Earth's crust has been deformed repeatedly. Large parts of the oceanic crust are also metamorphosed. Even the mantle is made mostly of a type of metamorphic rock.

## ORIGIN OF METAMORPHIC ROCKS

The driving forces for metamorphism are changes in temperature, pressure, and composition of the environment or strong deformation. These changes cause recrystallization in the solid state as the rock changes toward equilibrium with the new environment.

Metamorphism causes a series of changes in the texture and composition of a rock. The changes occur to restore equilibrium to rocks subjected to an environment different from the one in which they originally formed (Figure 6.4). Several agents of change act in combination and create distinctive metamorphic environments depending upon which factors are most important.

### Temperature Changes

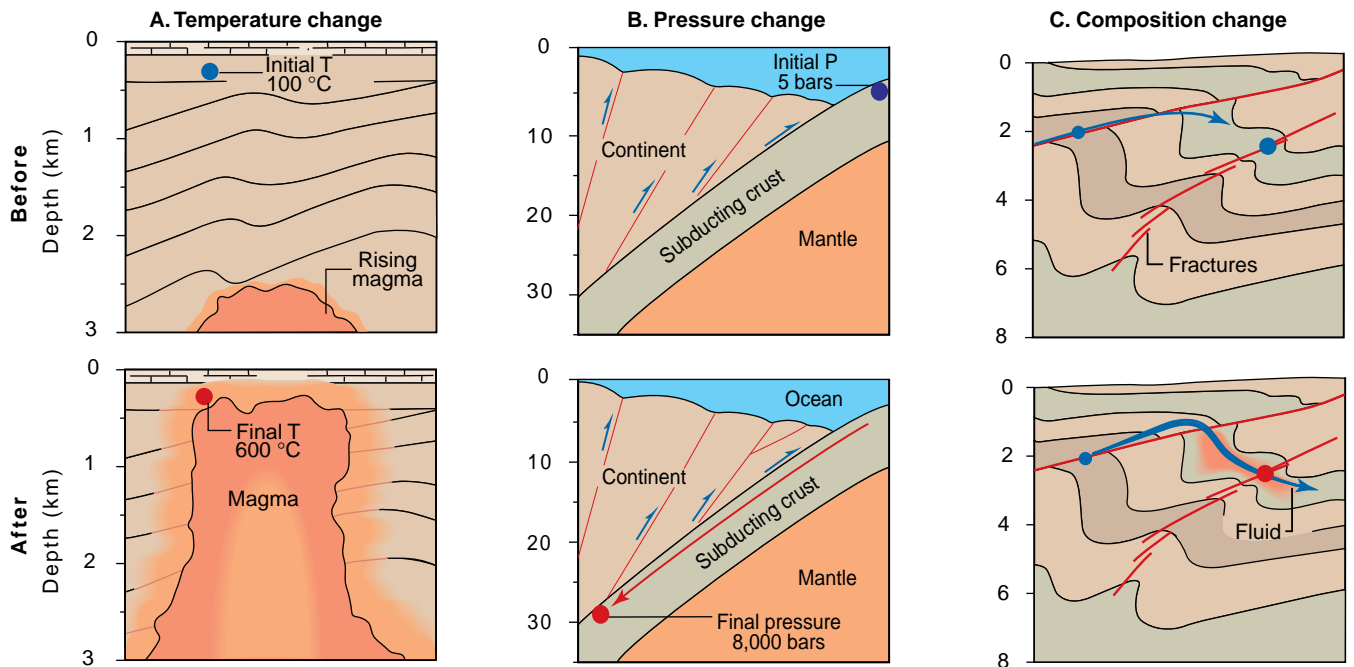
Heat is one of the most important factors in metamorphism. For example, as a rock's temperature increases, its minerals may become unstable and react with other minerals to form new mineral assemblages that are stable under the new conditions (Figure 6.4A). Below 200°C, reaction rates are low, and most minerals will remain unchanged for millions of years. As the temperature rises, however, chemical reactions become more vigorous. Crystal lattices are broken down and re-created using different combinations of ions and different atomic structures. As a result, new minerals appear. For example, if pressure is held constant at 2 kb and temperature increases, the mineral andalusite recrystallizes to sillimanite at about 600°C (Figure 6.5). When the sillimanite crystallizes, the bonding of atoms in the mineral is rearranged and new crystal forms result. If temperature continues to increase, the rock becomes partially molten at about 700°C, and layers of solid material mixed with layers of magma might form. The critical idea here is



#### Solid State Recrystallization



**FIGURE 6.3** Metamorphic rocks are widely distributed in the Canadian Shield and in the cores of folded mountain belts such as the Appalachians of eastern North America. A blanket of sedimentary rocks covers the metamorphic rocks in the stable platform.



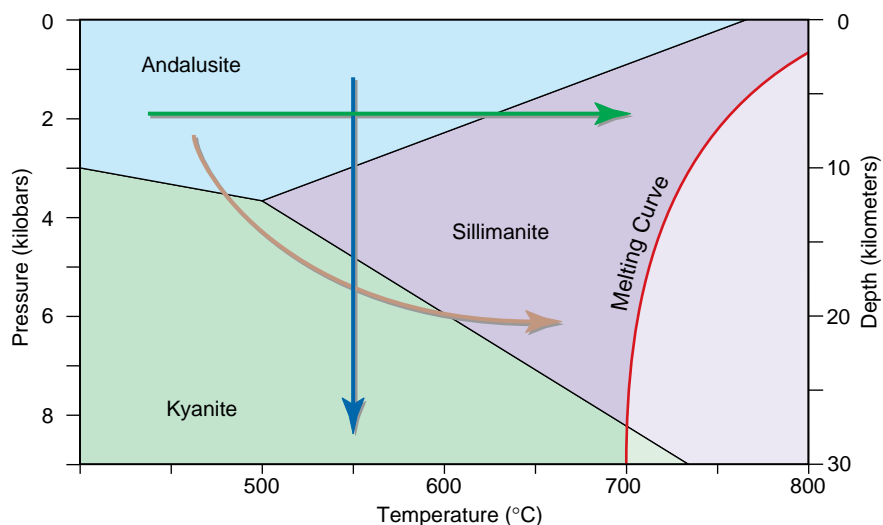
**(A)** Temperature changes when a magmatic body intrudes the shallow crust and causes recrystallization around the intrusion (region in light orange).

**(B)** Pressure changes can be caused by the collision of two plates, where minerals at low pressure (blue dot) are dragged to high pressure (red dot) in a subducting plate.

**(C)** Fluids carrying dissolved ions may flow from one spot (blue dot) to another (red dot), causing minerals along the flow path to recrystallize as they equilibrate with the fluid.

**FIGURE 6.4** Metamorphic changes can occur as the result of changes in temperature, pressure, and in the composition of pore fluids, as the rocks attempt to reach equilibrium with the new conditions. These cross sections illustrate some of the changes.

**FIGURE 6.5** The stable form of  $\text{Al}_2\text{SiO}_5$  varies at different temperatures and pressures. Andalusite is stable at low temperatures and changes to sillimanite during metamorphism at higher temperatures. Higher pressure produces kyanite. At even higher temperatures, a metasedimentary rock partially melts to make migmatite. The arrows show possible pressure-temperature paths during metamorphism.

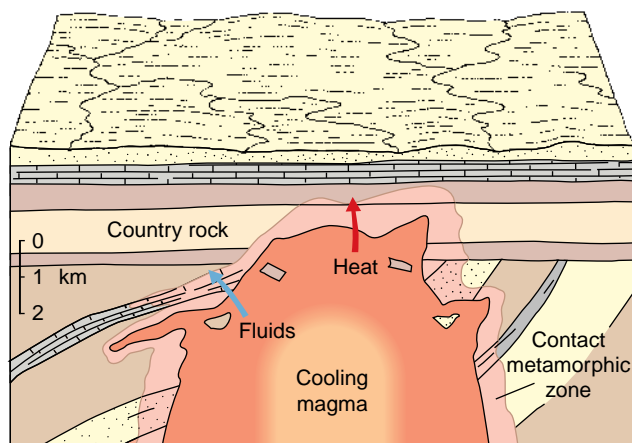


that different minerals are in equilibrium at different temperatures. The minerals in a rock, therefore, provide a key to the temperatures at which the rock was metamorphosed. This powerful interpretive tool is not without its problems, however. For example, with a decrease in temperature, the sillimanite becomes unstable; but, because reaction rates are lower at these lower temperatures, the sillimanite may persist for a long time without converting back to andalusite. In such cases, the mineral is said to be **metastable**.

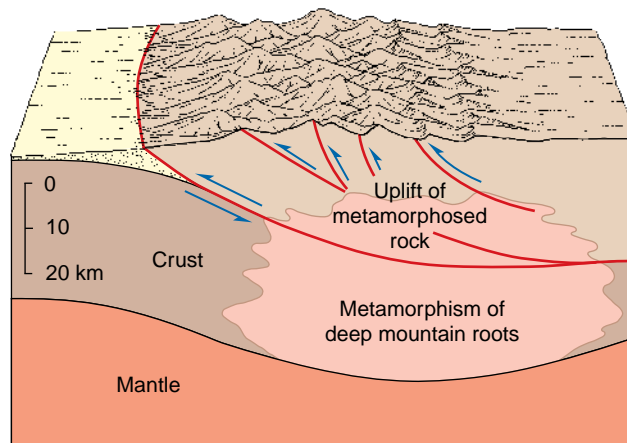
How is heat added to cause metamorphism? The two most important ways are intrusion of hot magma and deep burial (Figure 6.4). Recall that magmas have temperatures that range from about 700° to 1200°C depending on their compositions. The temperature of the country rocks around an intrusion increases as heat diffuses from the intrusion. Zones of different mineral assemblages in metamorphic rocks show that strong thermal gradients once existed around igneous intrusions. This kind of metamorphism is called **contact metamorphism** (Figure 6.6A).

Deep burial also increases a rock's temperature. Temperature increases about 15° to 30°C for each kilometer of depth in the crust. Even gradual burial in a sedimentary basin may take rocks formed at the surface to depths as great as several kilometers, where low-temperature metamorphism can occur. The tectonic processes that make folded mountain belts can bury rocks to even greater depths—

#### What is the difference between regional and contact metamorphism?



**(A)** Contact metamorphism occurs around hot igneous intrusions. Changes in temperature and composition of pore fluids cause preexisting minerals to change and reach equilibrium in the new environment. Narrow zones of altered rock extending from a few meters to a few hundred meters from the contact are produced.



**(B)** Regional metamorphism develops deep in the crust, usually as the result of subduction or continental collision. Wide areas are deformed, subjected to higher pressures, and intruded by igneous rocks. Hot fluids may also cause metamorphic recrystallization.

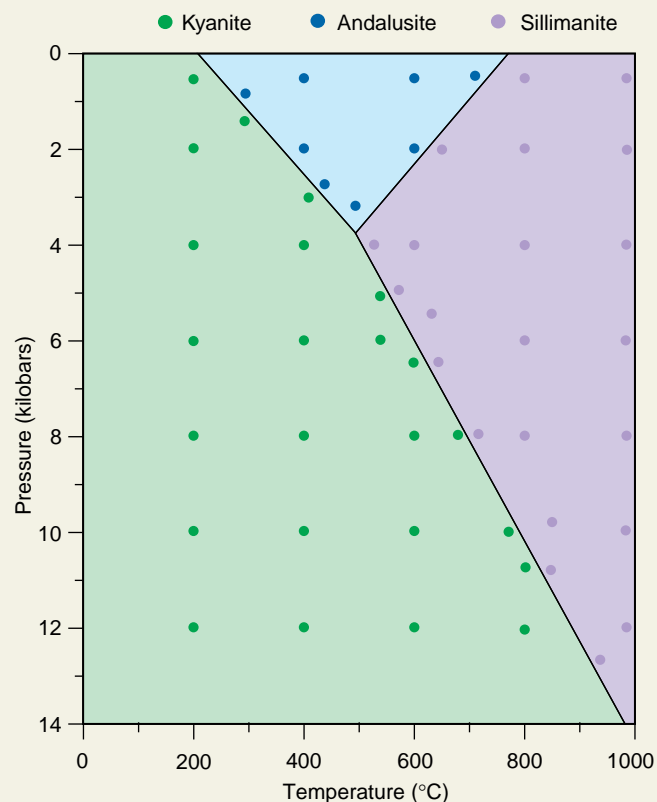
**FIGURE 6.6** Metamorphic environments are many and varied. Two major examples are shown here.

In this chapter, phase diagrams are used as graphical summaries of the stability fields of minerals. Phase diagrams tell us much about the origin of metamorphic rocks, which have all recrystallized because of changes in their physical or chemical environment. But how do we know that kyanite is not stable at pressures higher than about 4 kilobars (Figure 6.5) or that garnet is stable in many rocks at temperatures of about 500°C (Figure 6.14)? The answer is: we conduct laboratory experiments.

An important branch of geology involves the experimental determination of the stability ranges of minerals. One type of experimental apparatus is shown here. Small samples of pulverized rock are placed in a tiny metal capsule about the size of a vitamin pill. The capsule is usually made of gold or some other noble metal that remains stable at high temperature. This small capsule is then placed inside a “bottle” with strong metal walls and a screw top. A fluid is pumped inside the bottle to increase the confining pressure. Heating filaments are used to control the temperature. Once the capsule is safely inside the “bomb,” the pressure and temperature are brought up to the point of experimental interest, say 1 kilobar and 400°C, and maintained at that point for many hours. Some experiments last for weeks so that equilibrium can be achieved between the various solids and fluids in the capsule. At the end of the experiment, the capsule is rapidly cooled and the pressure is dropped back to normal conditions. If the temperature drop is rapid enough, the phases formed at high pressure and temperature will persist as metastable minerals (see Chapter 2). The capsule is carefully opened to see what minerals were stable under the experimental conditions. The results are plotted on a pressure-temperature grid like the one shown here. Each point represents one experiment.



(Courtesy of M. J. Rutherford)



The major problem with such experiments is ensuring that equilibrium between the mineral phases and their environment actually occurred. To test this, several experiments are usually done with different starting minerals. Other tests involve starting the experiment from a high temperature or from a lower temperature. If equilibrium is achieved, every experiment at a given pressure and temperature will produce the same minerals.

You can see that many time-consuming experiments are needed to establish the stability field of a mineral. The experiments clearly show that many minerals indicate the specific temperature and pressure at which they formed and can be used to determine the history of changes a certain natural rock has experienced. For example, if sillimanite is present in a metamorphic rock (with the same composition as the experiment), then we can conclude that the rock recrystallized at a temperature above about 600°C. On the other hand, if andalusite is present and sillimanite is absent, the rock must have recrystallized at a lower temperature and a pressure between 0 and 4 kb. Such interpretations give us a better understanding of how mountain belts form and then erode away, uplifting the metamorphic rocks to the surface.





## Metamorphism

tens of kilometers—where the temperature is much higher. In this case, metamorphism may occur over a large area. This is type of **regional metamorphism** (Figure 6.6B) contrasts with the much smaller volumes involved in contact metamorphism. Because it typically owes its origin to the construction of folded mountain belts, this type of metamorphism is sometimes called **orogenic metamorphism** (Greek *oro*, “high or elevated”)

### Pressure Changes

High pressure, deep within Earth, also causes significant changes in the properties of rocks that originally formed at the surface (Figure 6.4B). An increase in pressure can drive chemical reactions to produce new minerals with closer atomic packing and higher densities. The vertical blue arrow in Figure 6.5 shows a pressure increase at a constant temperature of 550°C. If a rock containing andalusite followed this pressure-temperature path, it would recrystallize to form sillimanite at 3 kb; kyanite would crystallize at about 5 kb (almost 20 km deep).

Pressure increases when rocks are buried deep beneath Earth’s surface. Burial may be caused by prolonged sedimentation in a basin. Metamorphic rocks are also caused by increasing pressure during the stacking of thrust sheets at convergent plate boundaries or as oceanic crust is thrust deep into the mantle. The **confining pressure** is equal to the weight of the overlying rocks and causes these kinds of mineral changes.

If a rock experienced progressively lower pressure during uplift, theoretically it would undergo metamorphic changes to bring it to equilibrium at the lower pressure (Figure 6.5). However, these changes may be so slow that the high-pressure minerals remain metastable at the new lower pressure. An extreme example is that of diamond, which is stable only at pressures that exceed 30 kb, reached at depths of more than 100 km. Soft graphite is the stable form of carbon at 1 bar (atmospheric pressure), but the change from diamond to graphite is infinitesimally slow.

Temperature and confining pressure increase together in most environments where metamorphic rocks form. Such a path is shown with the sloping orange arrow in Figure 6.5. Along this pressure-temperature path, andalusite recrystallizes to form kyanite at about 450°C and 3.5 kb. Further increases in temperature and pressure make kyanite recrystallize to form sillimanite at about 600°C and 6 kb. If the rock continues to follow the sloping path of the curve in Figure 6.5, partial melting could occur to form small bodies of magma. Obviously, metamorphism occurs under many different conditions. Metamorphism that takes place at low temperature and pressure is called **low-grade metamorphism**; high pressure and high temperature produce **high-grade metamorphism**.

### Movement of Fluids

Metamorphic recrystallization is often accompanied by some change in the chemical composition of the rock—that is, by a loss or gain of certain elements (Figure 6.4C). This process is **metasomatism**. Especially important is the movement of water and carbon dioxide. In metamorphic processes that involve an increase in temperature, many minerals that contain H<sub>2</sub>O or CO<sub>2</sub> eventually break down, providing a separate fluid that migrates from one place to another. For example, at high temperatures, calcite (CaCO<sub>3</sub>) and clay [Al<sub>2</sub>Si<sub>2</sub>O<sub>5</sub>(OH)<sub>4</sub>] break down to release CO<sub>2</sub> and H<sub>2</sub>O fluids and other ions (Figure 6.4C). Original crystals break down, and new crystal structures, which are stable under the new conditions, develop. If an ion becomes detached from a mineral’s crystal structure, it may move with the fluid to some other place. The fluids move through tiny pore spaces, fractures, and along the margins of grains. The small amount of pore fluid transports material through the rock and allows it to rearrange into new mineral structures.

Other metamorphic reactions occur by the addition of volatile fluid components such as water and carbon dioxide. This kind of metasomatism is commonly

**How can fluids cause metamorphic reactions?**



connected with the flow of hot water. For example, magmatic intrusions may release hot fluids that flow into the surrounding country rock. Consequently, minerals that are stable in the new chemical environment crystallize. Many types of metallic ore deposits are created by metasomatism. Because of the importance of hot water in the formation of such metasomatic rocks, the process is also known as **hydrothermal alteration**. Veins of white milky quartz are a common expression of the mobility of water in metamorphic rocks. The quartz crystallized from a fluid flowing through a fracture. Gold or other valuable minerals may also crystallize with the quartz.

The circulation of hot seawater through cold oceanic crust probably produces more metasomatic rocks than all other processes combined. **Ocean ridge metamorphism** converts olivine and pyroxene into hydrated silicates, including serpentine, chlorite, and talc (see Figure 6.19). This is the most characteristic kind of metamorphism in the oceanic crust. As much as one-fourth of the oceanic crust is metamorphosed in this way. This example shows that several different factors, in this case an increase in temperature and a change in fluids, may be involved in a single metamorphic environment (Figure 6.7).

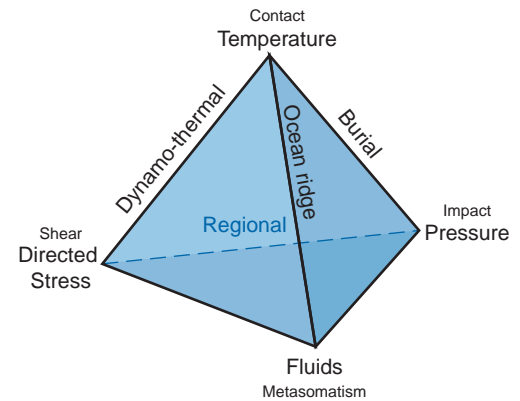
## Deformation

You have seen that changes in temperature, confining pressure, and fluid proportions can cause new minerals to crystallize while a rock is still in the solid state. In addition, deformation of rock can also cause metamorphism. The result is preserved in the grain-to-grain relationships—the texture. In many tectonic settings, there is directed or **differential stress** that acts to shorten and compress the rock, or, alternatively, to lengthen and extend the rock. In other words, the forces on the rock are not equal in all directions. Differential stress is usually the result of horizontal compression at zones of plate convergence or collision. At high temperature or confining pressure, a rock becomes **ductile** and may be deformed slowly if such a differential stress is applied. Mineral grains may move, rotate, or flatten, but more commonly new grains actually grow in new orientations. At low pressure or rapid rates of deformation, mineral grains may be strongly sheared. Deformation reorients mineral grains and forms a new rock texture.

**Differential Stress.** Perhaps the most obvious sign of differential pressure is the distinct orientation of grains of platy minerals such as mica and chlorite. An important result of metamorphic deformation is the alignment and elongation of minerals in the direction of least stress (Figure 6.8). Because many metamorphic rocks form during deformation where stresses are not uniformly oriented, they develop textures in which the mineral grains have strongly preferred orientations (Figure 6.9). This orientation may impart a distinctly planar element to the rock, known as **foliation** (Latin *folium*, “leaf,” hence “splitting into leaflike layers”). The planar structure can result from the alignment of platy minerals, such as mica and chlorite, or from alternating layers having different minerals (**gneissic foliation**).

Everything else being equal, the grain sizes in foliated rocks increase with the intensity of metamorphism; that is, they depend on the temperature and confining pressure. Grains range from microscopic to very coarse.

Foliation is a good record of rock deformation. It usually forms during recrystallization associated with regional horizontal compression. In most foliated metamorphic rocks, the mineral alignment is nearly perpendicular to the direction of compressional stress. The orientation of foliation, therefore, is closely related to the large folds and structural patterns of rocks. This relationship commonly extends from the largest folds down to microscopic structures. For instance, the foliation in slate is generally oriented parallel to the hinge planes of the folds, which can be many kilometers apart. A slice of the rock viewed under a microscope shows small wrinkles and folds having the same orientation as the larger structures mapped in the field.

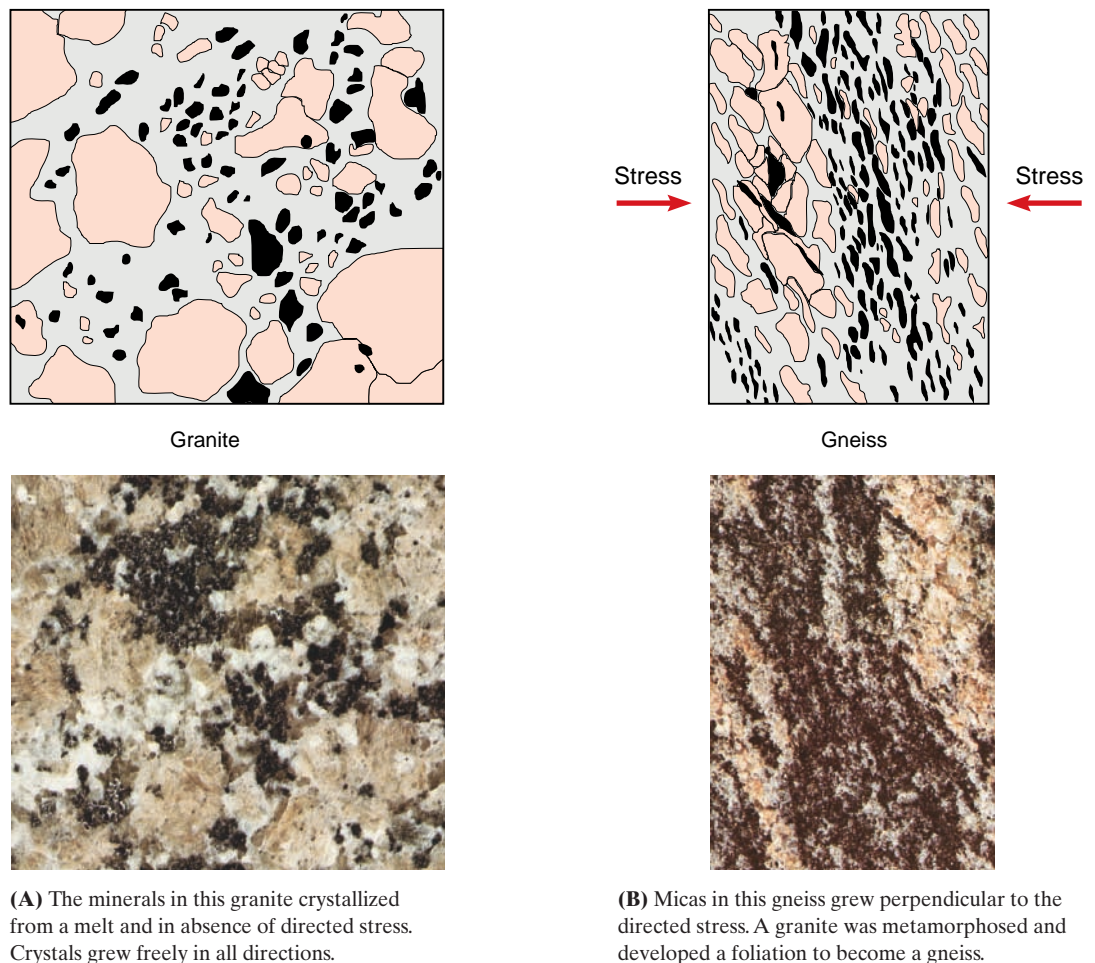


**FIGURE 6.7** Metamorphism is caused by changes in temperature, pressure, fluid composition, or strong deformation. Different metamorphic environments involve one or more of these factors. Regional metamorphism lies within the tetrahedron because all four factors are important. (Modified after M.G. Best, 2003)



## Development of Foliation





(A) The minerals in this granite crystallized from a melt and in absence of directed stress. Crystals grew freely in all directions.

(B) Micas in this gneiss grew perpendicular to the directed stress. A granite was metamorphosed and developed a foliation to become a gneiss.

**FIGURE 6.8 Foliation develops in metamorphic rocks** when platy minerals grow. Minerals such as mica grow perpendicular to the applied stress. For example, during compression, the foliation will be perpendicular to the directed stress. (Courtesy of Cold Spring Granite Company)

Foliation is actually caused by several different mechanisms. For example, during solid state recrystallization platy minerals grow to become elongate perpendicular to the directed stress—growth is enhanced where the pressure is lowest. Some grains are also rotated during deformation to become aligned, like logs floating in a stream. Some ductile grains are also flattened by compression.

Shear stress is a distinctive type of differential stress which causes one part of a material to move laterally past another part: you can shear a deck of cards on a table by moving your hand parallel to the table. Intense shearing forms a group of relatively rare metamorphic rocks with textures formed by the destruction of grains rather than their growth. This type of rock may form in a tectonic shear zone where two walls of a fracture grind past one another at very high confining pressure. The progressive destruction of grain shapes and reduction of grain sizes is characteristic of this type of deformation. The shearing dismembers and destroys preexisting mineral grains to make a very fine-grained rock called **mylonite** (Greek *mylon*, “to mill”). A microscope may be required to see the intensely strained individual grains (Figure 6.9B). Most mylonites form by pervasive ductile flow of solid rock (Greek *mylon*, “to mill”). During deformation, zones of slippage develop within individual grains to allow them to flow. At high temperature, the rock deforms much like soft taffy. At lower temperatures, at which the deformation is dominated by brittle breakage, mylonitic rocks grade into tectonic breccias that have fragments with angular margins.



**Uniform Stress.** Not all metamorphic rocks are foliated. Some metamorphic rocks form where the stress is fairly uniform in all directions and so no planar texture develops. The resulting texture is best described as granular, or, simply, **nonfoliated**. If the rocks have micas or other platy minerals, they are randomly oriented. For example, during contact metamorphism, there are no strong differential stresses and the metamorphic rocks are not strongly deformed.

The texture of nonfoliated metamorphic rocks reveals some of the results of crystallization in the solid state. Typical grains are polygonal, reflecting the mutual growth and competition for space. Grain boundaries are relatively straight, and triple junctions are common. The growth of quartz during the metamorphism of sandstone shows this kind of texture (Figure 6.9C). A familiar example of this process is the growth of bread rolls as they bake in an oven. The outlines of the rolls become polygonal as they expand against one another, and they have straight boundaries; triple junctions occur where three rolls meet.

## TYPES OF METAMORPHIC ROCKS

The two major groups of metamorphic rocks—foliated and nonfoliated—are further subdivided based on the basis of mineral composition. The major types of foliated rocks are slate, schist, gneiss, and mylonite. Important nonfoliated rocks are quartzite, marble, hornfels, greenstone, and granulite.

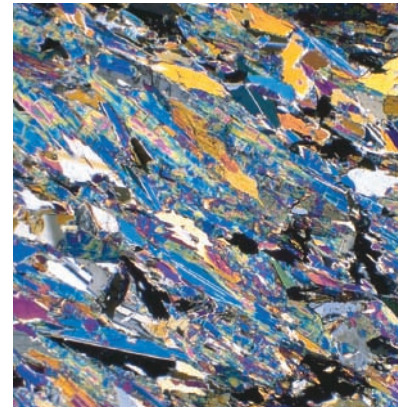
Because of the great variety of original rock types and the variation in the kinds and degrees of metamorphism, many types of metamorphic rocks have been recognized. A simple classification of metamorphic rocks, largely based on texture, is usually sufficient for beginning students. The major rock names can then be qualified by prefixes listing the important minerals.

### Foliated Rocks

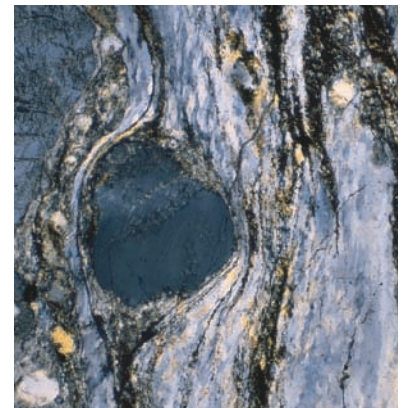
**Slate** is a very fine-grained metamorphic rock, generally produced by the low-grade metamorphism of shale. It is characterized by excellent foliation, known as **slaty cleavage**, in which the planar element of the rock is a series of surfaces along which the rock can be easily split (Figure 6.10A). Slaty cleavage is produced by the parallel alignment of minute flakes of platy minerals, such as mica, chlorite, and talc. Zeolites also form in these low-grade rocks. The mineral grains are too small to be obvious without a microscope, but the parallel arrangement of small grains develops innumerable parallel planes of weakness, so the rock can be split into smooth slabs. Because of this property, slate has been used for blackboards and as roof and floor tiles.

Slaty cleavage should not be confused with the bedding planes of the parent rock. It is completely independent of the original (relict) bedding and commonly cuts across the original planes of sedimentary stratification. Relict bedding can be rather obscure in slates, but it is often expressed by textural changes resulting from interbedded, thin layers of sand or silt. Excellent foliation can develop in the shale part of the sedimentary sequence, in which clay minerals are abundant and are easily altered to mica. In thick layers of quartz sandstone, however, the slaty cleavage plane is generally poorly developed. Metamorphism of some volcanic sequences also produces slate.

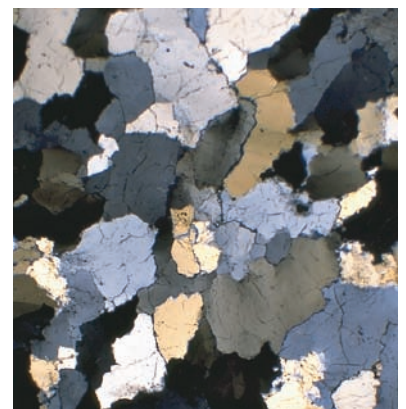
A **phyllite** is a metamorphic rock with essentially the same composition as a slate, but the micaceous minerals are larger and impart a definite luster to the rock's plane of foliation. The large mineral grains result from enhanced growth at higher temperature and pressure than for slate. Like slates, most phyllites form from rocks that were originally shales.



(A) Strongly foliated schist with aligned grains of chlorite that grew in a differential stress field during contraction.



(B) Mylonites have grains that reflect destruction by shearing. The fine grains formed by crushing and shearing of larger grains, such as the large quartz grain.



(C) Nonfoliated texture resulting from growth without deformation. Solid-state growth produces polygonal grains with abundant triple junctions.

**FIGURE 6.9** Metamorphic textures range widely, but all indicate crystallization in the solid state, as illustrated by these thin sections. Each view is 3 mm across.





**(A)** Slate is a fine-grained foliated rock. The foliation usually cuts across sedimentary bedding.



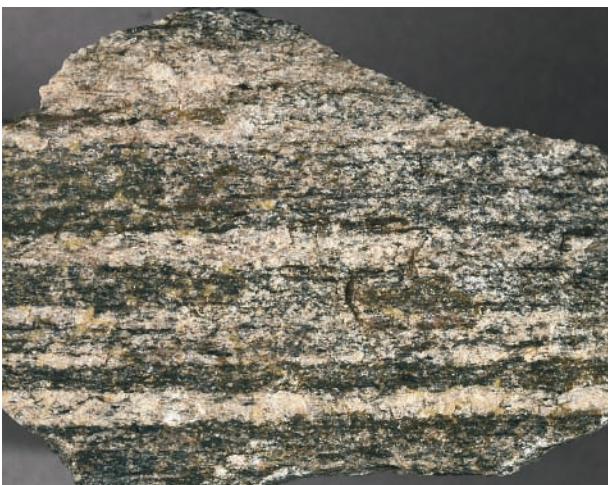
**(D)** Quartzite is a nonfoliated metamorphic rock derived from quartz-rich sandstone.



**(B)** Schist is a strongly foliated metamorphic rock with abundant platy minerals, usually muscovite or chlorite.



**(E)** Metaconglomerate often displays highly elongated clasts.



**(C)** Gneiss has a foliation defined by alternating layers of light (mostly feldspar and quartz) and dark (mafic silicates) layers. The layers do not conform to preexisting sedimentary beds.



**(F)** Marble is limestone that recrystallized during metamorphism. It consists of mostly calcite.

**FIGURE 6.10** The major metamorphic rocks include foliated (A–C) and nonfoliated (D–F) varieties shown in their actual sizes.



**Schist** is a strongly foliated rock ranging in texture from medium-grained to coarse-grained. Foliation results from the parallel arrangement of relatively large grains of platy minerals, such as mica, chlorite, talc, and hematite, and is called **schistosity**. The mineral grains are large enough to be identified with the unaided eye and produce an obvious planar structure because of their overlapping sub-parallel arrangement (Figure 6.10B). The foliation of schist differs from that of slate mainly in the size of the crystals. The term schistosity comes from the Greek *schistos*, meaning “divided” or “divisible.” As the name implies, rocks with this type of foliation break readily along the cleavage planes of the parallel platy minerals.

The mineral composition provides a basis for subdividing schists into many varieties, such as chlorite schist, mica schist, and amphibole schist. In addition to the platy minerals, significant quantities of quartz, feldspar, garnet, amphibole, sillimanite, graphite, and other minerals occur in schist. The mineral proportions are largely controlled by the original composition of the rock. Parent rock types include basalt, granite, shale, and tuff.

Schists result from a higher grade of regional metamorphism than the type that produces slates. Schists are one of the most abundant metamorphic rock types.

**Gneiss** is a coarse-grained, granular metamorphic rock in which foliation results from alternating layers of light and dark minerals, or gneissic layering (Figure 6.10C). The composition of most gneisses is similar to that of granite. The major minerals are quartz, feldspar, and mafic minerals such as biotite and amphibole. Feldspar commonly is abundant and, together with quartz, forms light-colored (white or pink) layers of polygonal grains. Mica, amphibole, and other mafic minerals form dark layers. Gneissic layering can be highly contorted because of deformation during recrystallization. When struck with a rock hammer, gneiss generally fractures across the layers, or planes of foliation, but where micas are abundant, it can break along the foliation.

Gneiss forms during high-grade metamorphism, and in some areas it grades into partially molten rock if the temperature of initial melting is reached (Figure 6.11). Such a rock that is partly igneous and partly metamorphic is known as **migmatite** (Greek *migma*, “mixed”). Migmatites are commonly deformed and have thin dikes or sills. The migmatites may even grade into completely igneous rocks, such as granite.

The mineral composition of gneisses is varied because the possible parent rocks are so different from one another. Gneiss can form as the highest grade of metamorphism of shales, but more commonly the parents were plutonic and volcanic igneous rocks such as granite and basalt. For example, biotite gneiss is commonly derived from granite. Metasedimentary gneisses typically have garnet and other aluminum-rich silicates. Metamorphism of basalt or gabbro produces **amphibolite** gneisses, coarse-grained mafic rocks composed chiefly of amphibole and plagioclase. Because of the abundance of basalt, amphibolite is a fairly common metamorphic rock. Most amphibolites have a distinctive lineation caused by the alignment of elongate grains of amphibole. Some amphibolites develop a true foliation if mica or other platy minerals are abundant, but many are more or less massive with little foliation.

**Mylonite** is the hard, fine-grained metamorphic rock with a streaked or weakly foliated texture formed by intense shearing. Less-deformed, larger grains may survive as relicts embedded in a sheared groundmass. Very fine-grained mylonite forms sheetlike bodies that appear to be as structureless as chert, but the streaked and lineated appearance hints at its true origin. Mylonites form in shear zones in folded mountain belts and along transform fault plate boundaries.

## Nonfoliated Rocks

Nonfoliated metamorphic rocks can form in two different ways. Some form by recrystallization in a uniform stress field. Others, probably most, lack a foliation

How does foliation differ from stratification?



Recrystallization and Melting



**FIGURE 6.11 Migmatite** is a mixed metamorphic and igneous rock. The light-colored pods and layers crystallized from granitic magma, and the darker zones consist of metamorphic rock rich in mafic minerals. Migmatite may form if the temperature and pressure are high enough to cause partial melting.

### Why are some strongly metamorphosed rocks not foliated?

because they are made of minerals that are equant in shape and not platy like micas and chlorite. For example, **quartzite** is a metamorphosed, quartz-rich sandstone (Figure 6.10D). It is not foliated because quartz grains, the principal constituents, do not form platy crystals. The individual grains commonly form a tight mass, so the rock breaks across the grains as easily as it breaks around them. Nonetheless, some sedimentary structures survive metamorphism, including cross-bedding and grain size variations. Pure quartzite is white or light-colored, but iron oxide and other minerals often impart various tones of red, brown, green, and other colors.

**Metaconglomerate** is not an abundant metamorphic rock. It is important in some areas, however, and illustrates the degree to which a rock can be deformed in the solid state. Under differential stress, individual pebbles are stretched into a mass that shows distinctive linear fabric (Figure 6.10E).

**Marble** is metamorphosed limestone or dolostone. Calcite, the major constituent of the parent rocks, is equidimensional, so marble is usually not foliated (Figure 6.10F). The grains are commonly large and compactly interlocked, forming a dense rock. The purest marbles are snow white, but many marbles contain a small percentage of minerals other than calcite that were present in the original sedimentary rock. These impurities result in streaks or bands and, when abundant, may impart a variety of colors to the marble. Thus, marbles may exhibit a range of colors including white, green, red, brown, and black. Because of its coloration and softness, marble is a popular building and monument stone. Most marbles occur in areas of regional metamorphism where metamorphosed sedimentary rocks include schists and phyllites. Impure marbles contain a wide variety of other minerals.

**Hornfels** is a fine-grained, nonfoliated metamorphic rock that is very hard and dense. A lack of differential stress is the main reason these rocks are not foliated. Platy minerals, such as mica, can be present but they have random orientations. Commonly, grains of high-temperature minerals are present. Hornfels are usually fine-grained and dark-colored and may resemble basalt, dark chert (flint), or even dark, fine-grained limestone. They result from thermal metamorphism of the wall rocks around igneous intrusions. The parent rock is usually shale.

Low-grade metamorphism converts the minerals in mafic igneous rocks (plagioclase, pyroxene, and olivine) to new minerals such as chlorite, epidote, and serpentine that are stable at low temperatures (about 200° to 450°C) and in the presence of water. Because these abundant minerals are characteristically green, metamorphosed mafic rocks such as basalt have come to be called **greenstones**. These fine-grained rocks commonly lack pronounced foliation because of the low grade of metamorphism. Moreover, most greenstones form where differential stresses are absent. For example, much of the oceanic crust is metamorphosed by the interaction of hot water circulating passively through basaltic lava flows at an ocean ridge. Ancient greenstone belts in the continental shields record the low-grade metamorphism of basaltic lavas or incorporation of slivers of oceanic crust into a deformed mountain belt.

### How are the different types of metamorphic rocks distinguished and classified?

On the opposite end of the metamorphic spectrum, high-grade metamorphism produces a distinctly granular rock called **granulite**. Minerals that lack water, such as pyroxene and garnet, are characteristic of granulites; other common minerals include feldspars and quartz. Their parent rocks range from sedimentary to many kinds of igneous rocks. The most important implication of granulites is the extremely intense metamorphism that is required in their formation. Such high temperatures and confining pressures are achieved only in the lowermost parts of the continental crust. They cause micas to break down; the replacement of platy micas with equigranular pyroxene, garnet, and feldspar creates the unique texture of granulite. Granulite may form at temperatures as high as 700° to 800°C.



## Parent Material for Metamorphic Rocks

The origin of metamorphic rocks is complicated and presents some challenging problems of interpretation. A single-parent rock can be changed into a variety of metamorphic rocks, depending on the grade of metamorphism and the type of deformation. For example, shale can be changed to a variety of metamorphic rock types, including slate, schist, gneiss (Figure 6.12) or even migmatite, if it gets hot enough. Contact metamorphism may also convert shale into hornfels. Alternatively, shale may be deformed to make mylonite if it is strongly sheared. Gneiss can form from many different kinds of rocks, such as shale, granite, or rhyolite. The chart in Figure 6.13, which relates parent rocks and metamorphic conditions to metamorphic rock types, gives a generalized picture of the origin of common metamorphic rocks.

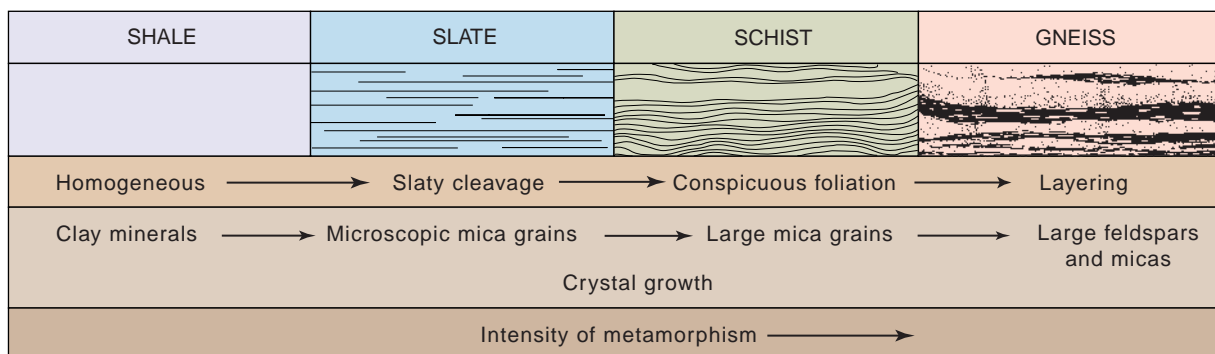
## REGIONAL METAMORPHIC ZONES

Regional metamorphism involves large-scale recrystallization. The metamorphosed rocks commonly show mineralogic zones that reflect the differences in metamorphic grade (temperature and pressure) across the region.

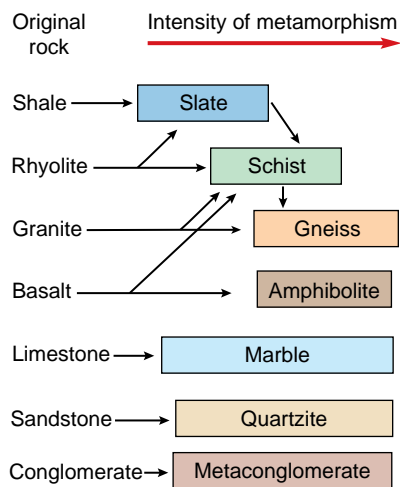
Regional metamorphism involves large-scale changes in thick masses of rock in which major recrystallization and structural adjustments occurred in ancient orogenic belts. Regional metamorphic rocks commonly show systematic changes from place to place—metamorphic zones—that reflect large gradients in temperature and confining pressure. These gradients are correlated with depth and distance from ancient heat sources. By mapping zones of differing grade, geologists can locate the central and marginal parts of ancient mountain belts and infer something about ancient interactions between tectonic plates.

One type of metamorphic zonation can be defined because of the occurrence of certain **index minerals**—a mineral that forms at a specific metamorphic grade. For the metamorphism of shale, a typical sequence of index minerals that reveals the transition from low-grade to high-grade metamorphism is chlorite, biotite, garnet, staurolite, kyanite, and sillimanite. Each index mineral is stable over a narrow range of temperature and pressure, thus characterizing a particular grade of metamorphism. Figure 6.14 is a phase diagram showing stability fields for the index minerals produced during metamorphism of shale. For example, with increasing metamorphic grade—chiefly an increase in temperature shown by the arrow—chlorite breaks down and is replaced by biotite, then garnet, staurolite, kyanite, and, ultimately, sillimanite appear. These changes in mineral composition may be accompanied by textural changes from phyllite to slate to schist to gneiss.

Index minerals are not as useful for indicating metamorphic grade if the com-



**FIGURE 6.12** The metamorphism of shale can involve a series of steps, depending on the intensity of temperature and pressure. Shale can change to slate, schist, or even gneiss.



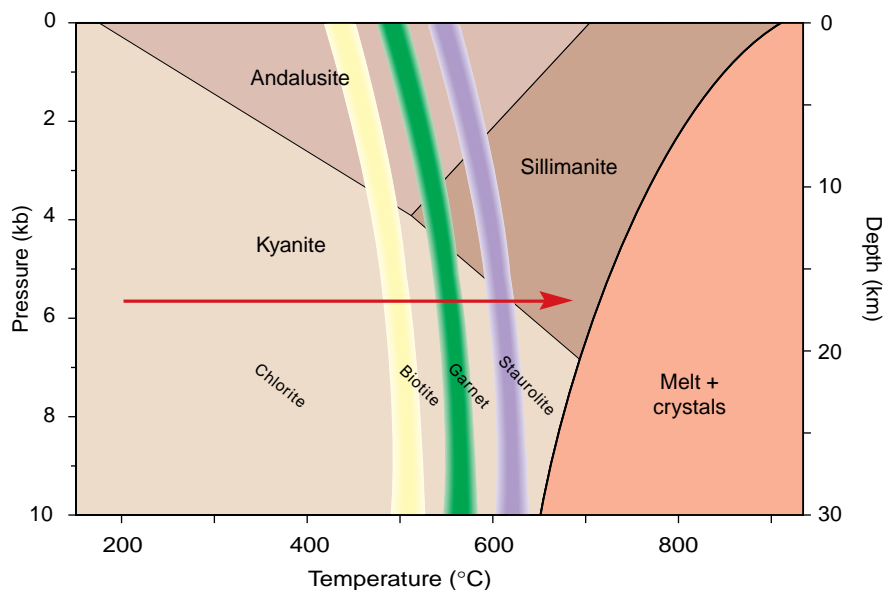
**FIGURE 6.13** The source rocks for common metamorphic rocks are varied. In some cases, such as quartzite, marble, and metaconglomerate, the nature of the original rock is easily determined. In other cases, such as schist and gneiss, it is difficult and sometimes impossible to determine the type of source rock. This simplified flowchart shows the origin of some of the common metamorphic rocks.

### What features of a rock indicate zones of different degrees of metamorphism?

position of the rocks varies across a region. For example, a limestone and a shale metamorphosed under exactly the same conditions would have different stable minerals. In this case, metamorphic zonation can be defined on the basis of a *group of associated minerals* formed under specific metamorphic conditions. The distinctive group of minerals, known as a **metamorphic facies**, is named after a characteristic rock or mineral type (Figure 6.15). Each metamorphic facies is defined by the assemblage of minerals found in rocks of diverse composition but of similar metamorphic grade. In this way, the metamorphosed limestone and the shale could be assigned to the same metamorphic facies by considering the whole range of minerals that could be produced under similar conditions of temperature and pressure.

Figure 6.16 shows the major metamorphic facies in relation to variations in confining pressure and temperature. The boundaries between the facies are gradational because of the complex nature of mineral reactions. The implications of each facies can be understood by tracing the metamorphic gradients shown by the arrows. For example, contact metamorphism around shallow intrusions follows the upper, low-pressure path.

Most metamorphic rocks formed in folded mountain belts, however, recrystallized along the middle path. The **zeolite facies** represents metamorphism at low temperature and pressure and is transitional from the changes in sediment resulting from compaction and cementation. The low temperature and pressure produce zeolite minerals. With a further increase in temperature and pressure, these minerals are soon altered as water is driven out of the mineral structure. The set of minerals characteristic of the **greenschist facies** then forms at moderate pressure and still fairly low temperature. This low-grade facies is typified by the minerals chlorite, talc, serpentine, muscovite, sodic plagioclase, and quartz (Figure 6.17). The rocks are characteristically green because they have abundant green minerals—chlorite, talc, and serpentine. If temperature increases further along the middle curve in Figure 6.16, the minerals of the **amphibolite facies** form: in many types of rocks hornblende (a type of amphibole) forms. With a further increase in temperature (above 650°C), the minerals of the **granulite facies** form. Pyroxene is an important mineral in this facies, along with sillimanite and garnet—depending on the original composition of the rock. The granulite facies represents the highest



**FIGURE 6.14** Metamorphic index minerals show the grade of metamorphism and are related to temperature and pressure. The arrow shows a typical change from lower to higher grades at a given depth. The sequence of index minerals for a metamorphosed shale will commonly be chlorite, biotite, garnet, staurolite, kyanite, and sillimanite.



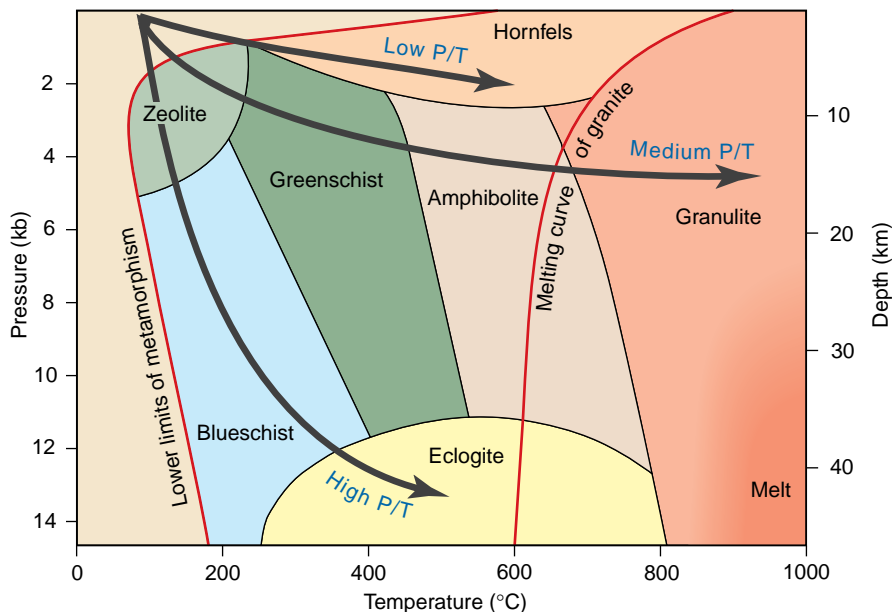
grade of metamorphism wherein most hydrous minerals like micas and amphiboles are not stable. Under these conditions, melting may occur and magma may be produced.

The pressure-temperature path traced by the lowermost arrow produces a different sequence of metamorphic facies. In this case, temperature rises slowly with depth (pressure) and rocks of the **blueschist facies** form, so called because of the characteristic blue amphiboles that form under these conditions (Figure 6.18). Distinctive blue-green pyroxenes also form. With further increase in temperature and pressure, the blueschist facies grades into the **eclogite facies**, consisting of feldspar-free rocks with pyroxene and garnet with granular textures. This high pressure-low temperature path is followed by cold oceanic crust as it is subducted deep within the mantle.

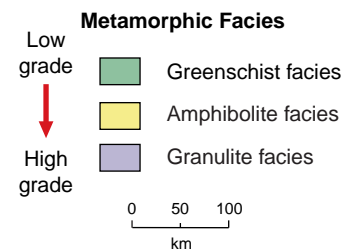
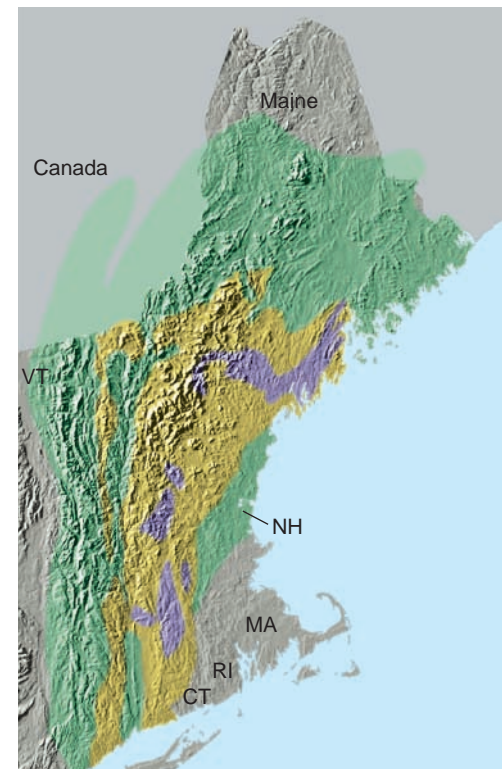
## METAMORPHIC ROCKS AND PLATE TECTONICS

Most metamorphic rocks develop because of plate collision deep in the roots of folded mountain belts. Subduction zone metamorphism occurs and high pressure but relatively low temperature. Ocean ridges, transform faults, and continental rift zones also develop distinctive types of metamorphic rocks.

We can never observe metamorphic processes in action because they occur deep within the crust. In the laboratory, however, we can study how minerals react to changes in temperature and pressure that simulate the conditions under which metamorphism occurs. These laboratory studies, together with field observations and studies of texture and composition, provide the rationale for interpreting metamorphic rocks in the framework of plate tectonics. Figure 6.19 summarizes some of the major ideas concerning the relationships of metamorphic rocks to plate



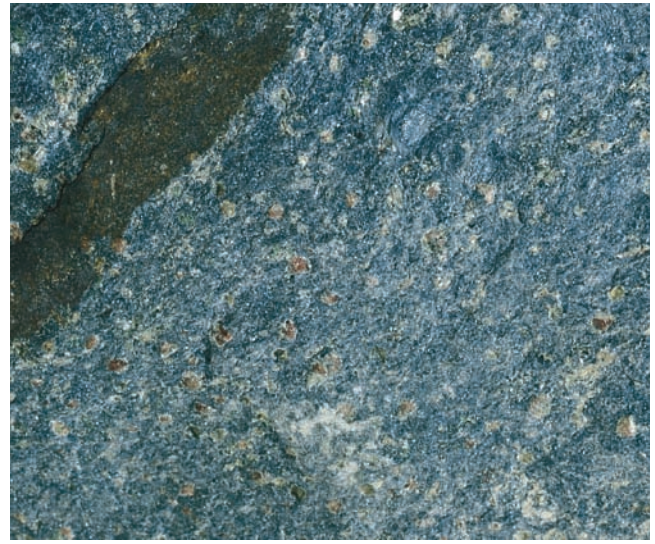
**FIGURE 6.16** Metamorphic facies are defined by a set of minerals stable at a certain temperature and pressure (depth) and independent of rock composition. The arrows show three possible paths of metamorphism. If temperature increased moderately with pressure, the sequence of facies would be zeolite, greenschist, amphibolite, and granulite (the middle arrow). If the increase in temperature with depth was slight, changes in metamorphic facies would follow the path indicated by the lower arrow, with the formation of blueschist and then eclogite. Contact metamorphism is limited to zones of low pressure around shallow igneous intrusions (the upper arrow).



**FIGURE 6.15** Regional metamorphic gradients are displayed across large areas, as shown in this map of New England. Distinctive groups of minerals (facies) with different stability ranges show the pressures and temperatures of peak metamorphism. Compare the zonation with the phase diagram shown in Figure 6.16. This region once formed the roots of an ancient mountain belt before uplift and erosion exposed it to the surface.



**FIGURE 6.17** Greenschist facies rocks are characteristic of low-grade metamorphism. The green color indicates an abundance of green minerals—chlorite, talc, serpentine, and epidote. Greenschist facies conditions are typical of ocean ridge metamorphism.



**FIGURE 6.18** Blueschist facies rocks are characteristic of metamorphism in subduction zones. The distinctive blue mineral is a type of amphibole that is stable at high pressure but relatively low temperature.

### Is there only one kind of metamorphism at convergent plate margins?

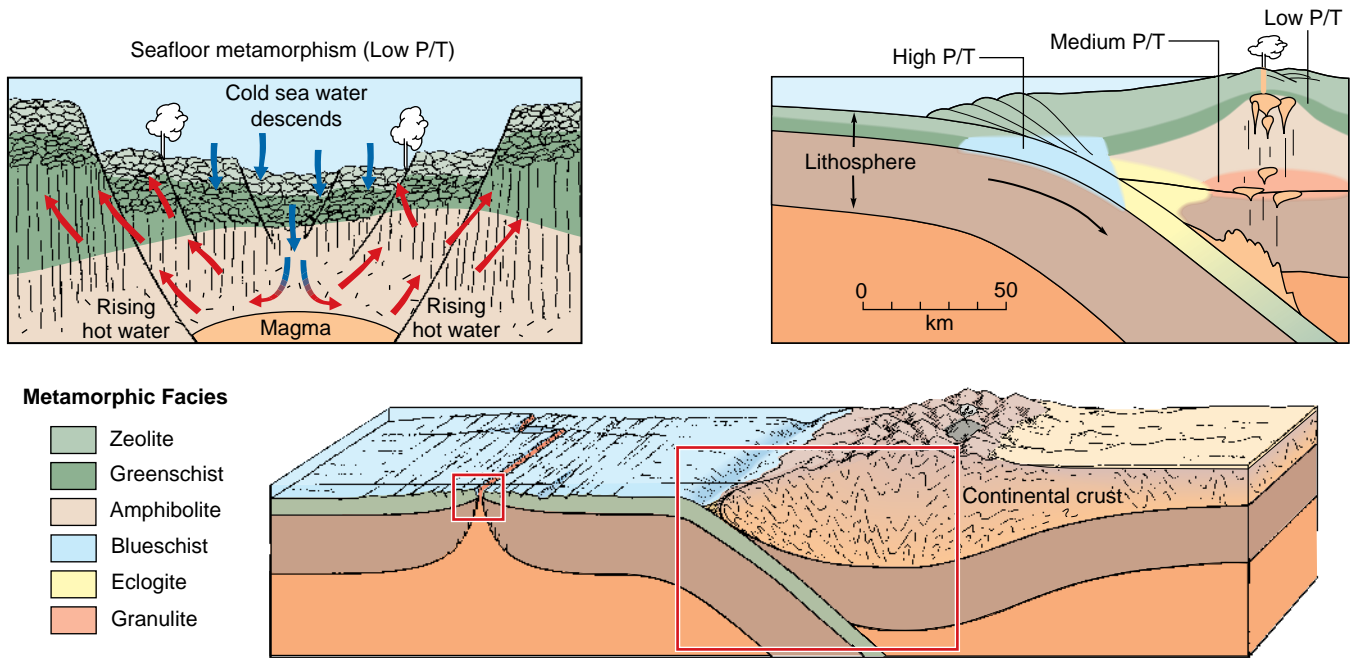
tectonics. According to the theory of plate tectonics, high confining pressures can be produced by tectonic burial at convergent plate boundaries. Temperatures are high near zones of magma intrusion or at great depth. Deformation and shearing occur where plates collide or where they slide past each other along fault zones and in deep subduction zones.

Regional metamorphism is best developed in the deep roots of folded mountain belts, which form at convergent plate boundaries. Recrystallization tends to produce nearly vertical foliations in a long belt parallel to the margins of the converging plates and perpendicular to the applied stress. Different kinds of metamorphic rocks are generated from different parent materials: sand, shale, and limestone along continental margins are converted into quartzite, schist or gneiss, and marble; volcanic sediments and lava flows in island arcs change into greenstones, gneisses and amphibolites; and mixtures of deep-marine sediments and oceanic basalt from the oceanic crust in the subduction zone are converted into schists, amphibolites, and gneisses.

After the stresses from the converging plates are spent, erosion of the mountain belt occurs, and the mountain roots rise because of isostasy. Ultimately, the deep roots and their complex metamorphic rocks are exposed at the surface, forming a new segment of continental crust. Although the return of the root to the surface involves changes in confining pressure and temperature, metamorphic reaction rates are low because the changes are toward lower temperatures. Therefore, many high-grade metamorphic rocks reach the surface as metastable relicts, little changed from the peak in metamorphic temperatures and pressures. The entire process takes several hundred million years. Repetition of this process causes the continents to grow larger with each mountain-building event. The belts of metamorphic rocks in the shields are thus considered to be the record of ancient continental collisions (see Figure 6.3).

Close to a subduction zone, sediments that have accumulated on the seafloor, together with fragments of basaltic oceanic crust, may be scraped off the descending plate. Locally, these rocks are crushed in a chaotic mass of deep-sea sediment, oceanic basalt, and other rock types. This jumbled association of rocks is called **mélange** (French for “mixture”). Slices of this material are apparently dragged to great depth by the relatively cold subducting slab, where they recrystallize along the high pressure-low temperature path in Figure 6.16. The basalt in deeply subducted oceanic crust may convert to dense garnet-bearing eclogite. These





**FIGURE 6.19** The origin of metamorphic rocks is strongly linked to plate tectonics. Oceanic crust is dragged deep into the mantle along a subduction zone to form blueschists. In the deep mountain roots, high temperatures and high pressures occur and develop schists and gneisses. Contact metamorphism develops around the margins of igneous intrusions. ocean ridge metamorphism is caused by the circulation of seawater through hot basaltic rocks of the ocean floor.

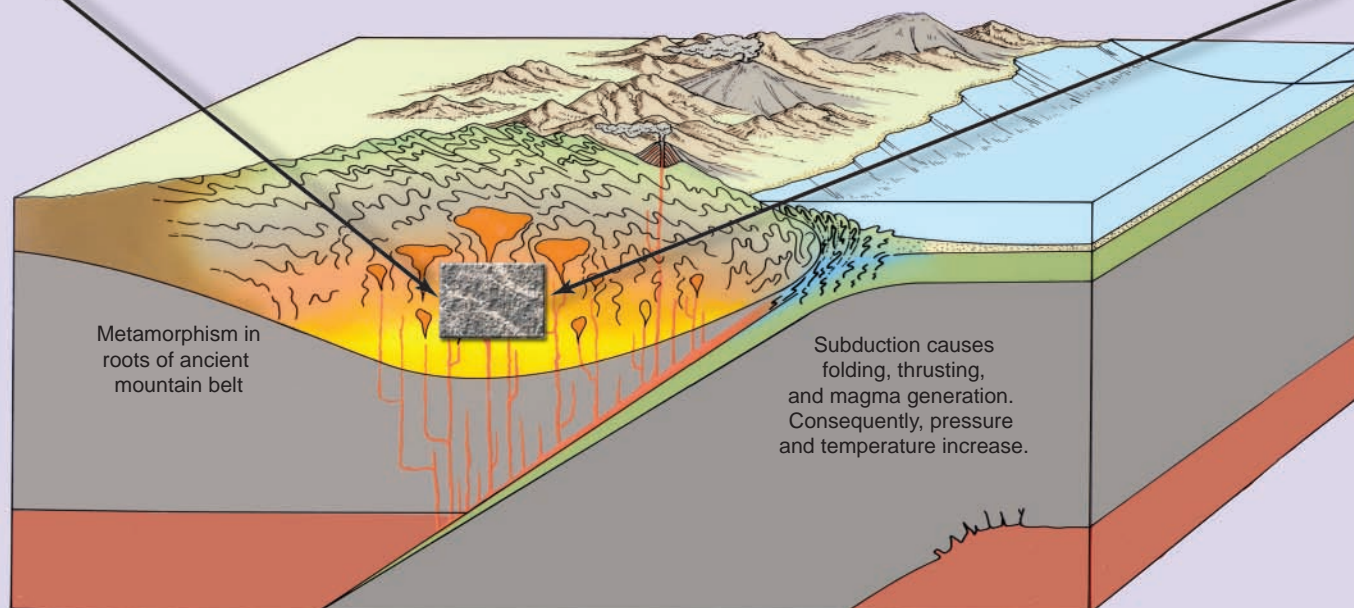
metamorphic rocks then return rapidly to the surface as a mixed broken up mass that includes blueschist facies metamorphic rocks in a *mélange*. Farther inland from the subduction zone, in the mountain root, moderate-pressure and high-temperature metamorphism occurs, forming rocks of the greenschist, amphibolite, and granulite facies (Figure 6.19).

Mylonites can be produced by shearing along fracture zones developed at convergent plate margins. Shear zones are common in the ancient shields of the continents, as well as along the transform faults that cut spreading ocean ridges.

Another metamorphic environment that has a distinctive plate tectonic setting is found at and near midoceanic ridges (Figure 6.19). Here, ocean ridge metamorphism produces low grade metamorphic rocks at low pressure, mostly of the zeolite and greenschist facies. Hot fluids form when cold seawater flows through the hot igneous rocks near the ridge crest. The basaltic lavas and other rocks of the crust reequilibrate to form new minerals stable in the hot fluid, and much of the oceanic crust becomes metamorphosed.

Much smaller volumes of metamorphic rock are probably formed in the lower part of the crust at continental rift zones and above mantle plumes (Figure 6.19). High temperatures may be produced by the intrusion of mantle-derived magmas into the crust and by the rise of hot mantle below the rift zone. In this way, a small fraction of the lowermost continental crust may become metamorphosed in divergent rather than convergent environments.

**What type of metamorphism dominates at divergent plate boundaries on the sea floor?**



A remarkable sequence of metamorphic rocks is exposed in the steep walls of the Black Canyon of the Gunnison River in Colorado. Here, the characteristics of metamorphic rocks are there for all to see.

### Observations

1. The canyon walls are made of high-grade metamorphic rock such as schist and gneiss.
2. The foliation of the metamorphic rocks results from aligned grains of muscovite and biotite in schist and by bands of different composition in gneiss.
3. Locally, beds of quartzite or layers with different grain size and texture reveal that these high grade metamorphic rocks were once beds of sedimentary rocks.
4. Careful mapping of the walls also shows that there are a multitude of folds and shear zones.
5. Radiometric dating shows that the metamorphic minerals crystallized about 1.7 billion years ago.
6. The metamorphic rocks are cut by thin light-colored granitic dikes.

### Interpretations

Even a beginning geologist can use these facts to make a logical interpretation of the ancient history. More than 1.7 billion years ago, sedimentary rocks were deposited in an ancient ocean basin. These rocks were gradually buried to a depth of perhaps 15 km where the temperature was about 600° to 700° C (indicated by the presence of garnet and staurolite, Figure 6.14). This dramatic change in pressure and temperature caused the minerals in the sedimentary rock to be unstable; they recrystallized to form new minerals and new foliated textures. Compression folded and deformed the hot rocks. Platy minerals grew perpendicular to the applied stress. Locally, the temperature was so high that the rocks melted and formed magma that rose and was injected into fractures and then cooled to become dikes.

What tectonic environment could produce such profound change? As we look into the Black Canyon are we seeing the roots of an ancient folded mountain belt formed billions of years ago at a convergent plate margin? Although the converging plates have long since disappeared, the evidence in the rocks remains to be seen today.



## KEY TERMS

amphibolite (p. 157)	granulite (p. 158)	metaconglomerate (p. 158)	orogenic metamorphism (p. 152)
amphibolite facies (p. 160)	granulite facies (p. 160)	metamorphic facies (p. 160)	phyllite (p. 155)
blueschist facies (p. 161)	greenschist facies (p. 160)	metamorphic rock (p. 146)	plastic deformation (p. 148)
confining pressure (p. 152)	greenstone (p. 158)	metamorphism (p. 146)	quartzite (p. 158)
contact metamorphism (p. 150)	high-grade (p. 152)	metasomatism (p. 152)	regional metamorphism (p. 152)
ductile (p. 153)	hornfels (p. 158)	metastable (p. 150)	schist (p. 157)
differential stress (p. 153)	hydrothermal alteration (p. 153)	migmatite (p. 157)	schistosity (p. 157)
eclogite facies (p. 161)	index mineral (p. 159)	mylonite (p. 154)	slate (p. 155)
foliation (p. 153)	low-grade (p. 152)	nonfoliated (p. 155)	slaty cleavage (p. 155)
gneiss (p. 157)	marble (p. 158)	ocean ridge metamorphism (p. 153)	zeolite facies (p. 160)
gneissic foliation (p. 153)	mélange (p. 162)		

## REVIEW QUESTIONS

1. What causes metamorphic reactions?
2. Compare and contrast the characteristics of metamorphic rocks with those of igneous and sedimentary rocks.
3. What important variables cause changes associated with regional metamorphism? With contact metamorphism? With ocean ridge metamorphism?
4. Make a series of sketches showing the changes in texture that occur with regional metamorphism of (a) slate, (b) sandstone, (c) conglomerate, and (d) marble.
5. Contrast the texture of a schist and a mylonite. What accounts for the textural differences?
6. Define foliation and explain the characteristics of (a) slaty cleavage, (b) schistosity, (c) gneissic layering, and (d) mylonitic texture.
7. Describe the major types of metamorphic rocks.
8. Make a generalized flowchart showing the origin of the common metamorphic rocks.
9. Draw an idealized diagram of converging plates to illustrate the origin of regional metamorphic rocks.
10. What type of metamorphic rock would result if zeolite facies rocks were subjected to temperatures of about 800°C at a depth of 15 km as a result of tectonic processes?
11. You find the mineral sillimanite in a regional (orogenic) metamorphic gneiss. To what metamorphic facies does it belong?
12. How does ocean ridge metamorphism change the composition of oceanic crust? What does this imply about the composition of subducted oceanic crust?
13. What evidence do you see that metamorphic crystallization takes place in the solid state without melting?

## ADDITIONAL READINGS

- Best, M. G. 2003. *Igneous and Metamorphic Petrology*. Boston: Blackwell.
- Blatt, H., and R. Tracy. 1996. *Petrology: Igneous, Sedimentary, and Metamorphic*, 2nd ed. New York: Freeman.
- Bucher, K., and M. Frey. 1994. *Petrogenesis of Metamorphic Rocks*, 6th ed. New York: Springer-Verlag.
- Kretz, R. 1994. *Metamorphic Crystallization*. New York: Wiley.
- Miyashiro, A. 1994. *Metamorphic Petrology*. New York: Oxford University Press.
- Philpotts, A. R. 1990. *Principles of Igneous and Metamorphic Petrology*. Englewood Cliffs, N.J.: Prentice Hall.
- Yardley, B. W. D., W. S. Mackenzie, and C. Guilford. 1990. *Atlas of Metamorphic Rocks and Their Textures*. New York: Wiley.

## MULTIMEDIA TOOLS



### Earth's Dynamic Systems Website

The Companion Website at [www.prenhall.com/hamblin](http://www.prenhall.com/hamblin) provides you with an on-line study guide and additional resources for each chapter, including:

- On-line Quizzes (Chapter Review, Visualizing Geology, Quick Review, Vocabulary Flash Cards) with instant feedback
- Quantitative Problems
- Critical Thinking Exercises
- Web Resources



### Earth's Dynamic Systems CD

Examine the CD that came with your text. It is designed to help you visualize and thus understand the concepts in this chapter. It includes:

- Animations of metamorphism
- Video clips of showing metamorphic recrystallization and eventual melting of simple metamorphic systems
- Slide shows with metamorphic rocks and structures
- A direct link to the Companion Website