**Metamorphic Rocks**

Recall from the discussion of the rock cycle that metamorphism is the transformation of one rock type into another. Metamorphic rocks are produced from preexisting igneous, sedimentary, or even other metamorphic rocks. Thus, every metamorphic rock has a parent rock—the rock from which it was formed. Metamorphism, which means to “change form,” is a process that leads to changes in the mineral content, texture, and sometimes the chemical composition of rocks. Metamorphism takes place where preexisting rock is subjected to new conditions, usually elevated temperatures and pressures,That are significantly different from those in which it initially formed. In response to these new conditions, the rock gradually changes until a state of equilibrium with the new environment is achieved. The intensity of metamorphism can vary substantially from one environment to another. For example, in low-grade metamorphic environments, the common sedimentary rock shale becomes the more compact metamorphic rock slate. Hand samples of these rocks are sometimes difficult to distinguish, illustrating that the transition from sedimentary to metamorphic is often gradual and the changes can be subtle. In more extreme environments, metamorphism causes a transformation so complete that the identity of the parent rock cannot be determined. In high-grade metamorphism, such features as bedding planes, fossils, and vesicles that existed in the parent rock are obliterated. Further, when rocks deep in the crust (where temperatures are high) are subjected to directed pressure, the entire mass may deform, producing large-scale structures, mainly folds. In the most extreme metamorphic environments, the temperatures approach **The agents** of metamorphism include heat, pressure (stress), and chemically active fluids. During metamorphism, rocks are usually subjected to all three metamorphic agents simultaneously. However, the degree of metamorphism and the contribution of each agent vary greatly from one environment to another.

**Heat as a Metamorphic Agent** The most important factor driving metamorphism is heat because it provides the energy needed to drive the chemical reactions that result in the recrystallization of existing minerals and/or the formation of new minerals. Recall from the discussion of igneous rocks that an increase in temperature causes the ions within a mineral to vibrate more rapidly. Even in a crystalline solid, where ions are strongly bonded, this elevated level of activity allows individual atoms to migrate more freely between sites in the crystalline structure. **CHANGES CAUSED BY HEAT**. When Earth materials are heated, especially those that form in low-temperature environments, they are affected in two ways. First, heating promotes recrystallization of mineral grains. This is particularly true of sedimentary and volcanic rocks that are composed of fine grained clay and silt sized particles. Higher temperatures promote crystal growth in which fine particles join together to form larger grains with the same mineral composition. Second, when rocks are heated, they eventually reach a temperature at which one or more minerals become chemically unstable. When this occurs, the constituent atoms begin to arrange themselves into crystalline structures that are more stable in the new high-temperature environment. These chemical reactions create new minerals with stable configurations that have an overall composition roughly equivalent to that of the original rock. (In some environments ions may actually migrate into or out of a rock, thereby changing its overall chemical composition.).

**WHAT IS THE SOURCE OF HEAT**? Earth’s internal heat comes mainly from energy that is continually being released by radioactive decay and thermal energy that remains from the time when our planet was forming. Recall that temperatures increase with depth at a rate known as the geothermal gradient. In the upper crust, this increase in temperature averages about 25 °C per kilometer (FIGURE 7.2). Thus, rocks that formed at Earth’s surface will experience a gradual increase in temperature if they are transported to greater depths. When buried to a depth of about 8 kilometers (5 miles), where temperatures are about 200 °C, clay minerals tend to become unstable and begin to recrystallize into new minerals, such as chlorite and muscovite, that are stable in this environment. Chlorite is a micalike mineral formed by the metamorphism of dark (iron and magnesium rich) silicate minerals. However, many silicate minerals, particularly those found in crystalline igneous rocks—quartz and feldspar for example— remain stable at these temperatures. Thus, metamorphic changes in these minerals generally occur at much greater depths. Environments where rocks may be carried to great depths and heated include convergent plate boundaries where slabs of sediment-laden oceanic crust are being subducted. Rocks may also become deeply buried in large basins where gradual subsidence results in very thick accumulations of **sediment.**

**Confining Pressure and Differential Stress Pressure,** like temperature, also increases with depth as the thickness of the overlying rock increases. Buried rocks are subjected to confining pressure, which is analogous to water pressure, in which the forces are applied equally in all directions (FIGURE Below). The deeper you go in the ocean, the greater the confining pressure. The same is true for buried rock. Confining pressure causes the spaces between mineral grains to close, producing a more compact rock having a greater density. Furthermore, as confining pressure increases some minerals recrystallize into new minerals that have the same chemical composition but a more compact crystalline form. In addition to confining pressure, rocks may be subjected to directed pressure. This occurs, for example, at convergent plate boundaries where slabs of lithosphere collide. Here the forces that deform rock are unequal in different directions and are referred to as differential stress (Figure belowB). Unlike confining pressure, which “squeezes” rock equally in all directions, differential stresses are greater in one direction than in others. As shown in Figure below B, rocks subjected to differential stress are shortened in the direction of greatest stress and elongated, or lengthened, in the direction perpendicular to that stress. As a result, the rocks involved are often folded or flattened (similar to when you step on a rubber ball). Along convergent plate boundaries the greatest differential stress is directed roughly horizontal in the direction of plate motion, and the least pressure is in the vertical direction. Consequently, in these settings the crust is greatly shortened (horizontally) and thickened (vertically). Although, differential stresses are generally small when compared to confining pressure, they are important in creating the various large scale structures and textures exhibited by metamorphic rocks.



**Chemically Active Fluids** Many minerals, including clays, micas, and amphiboles, are hydrated—meaning they contain water in their crystalline structures. Elevated temperatures and pressures cause the dehydration of these minerals. Once expelled, these hot fluids promote recrystallization by enhancing the migration of mineral matter. As discussed earlier, the metamorphism of shale to slate involves clay minerals that recrystallize to form mica and chlorite minerals. Hot fluids enhance this process by dissolving and transporting ions from one site in the crystal structure to another. In increasingly hotter environments these fluids become correspondingly more reactive. In some metamorphic environments, hot fluids transport mineral matter over considerable distances. This occurs, for example, when hot, mineral-rich fluids are expelled from a magma body as it cools and solidifies. If the rocks that surround the pluton differ markedly in composition from the invading fluids, there may be an exchange of ions between the fluids and host rocks. When this occurs, the overall chemical composition of the surrounding rock changes. When substantial chemical change accompanies metamorphism the process is called metasomatism.

**The Importance of Parent Rock** Most metamorphic rocks have the same overall chemical composition as the parent rock from which they formed, except for the possible loss or acquisition of volatiles such as water (H2O) and carbon dioxide (CO2). Therefore, when trying to establish the parent material from which metamorphic rocks were derived, the most important clue comes from their chemical composition. Consider the large exposures of the metamorphic rock marble found high in the Alps of southern Europe. Because marble and the common sedimentary rock limestone have the same mineral content (calcite, CaCO3), it seems reasonable to conclude that limestone is the parent rock of marble. Furthermore, because limestone usually forms in warm, shallow marine environments we can surmise that considerable deformation must have occurred to convert limy deposits in a shallow sea into marble crags in the lofty Alps. The mineral makeup of the parent rock also largely determines the degree to which each metamorphic agent will cause change. For example, when magma forces its way into surrounding rock, high temperatures and hot fluids may alter the host rock. If the host rock is composed of minerals that are comparatively unreactive, such as quartz grains in sandstone, any alterations that may occur will be confined to a narrow zone next to the pluton. However, when the host rock is limestone, which is highly reactive, the zone of metamorphism may extend far from the intrusion

**Metamorphic Textures**

 Recall that the term texture is used to describe the size, shape, and arrangement of grains within a rock. Most igneous and many sedimentary rocks consist of mineral grains that have a random orientation and thus appear the same when viewed from any direction. By contrast, deformed metamorphic rocks that contain platy minerals (micas) and/or elongated minerals (amphiboles), typically display some kind of preferred orientation in which the mineral grains exhibit a parallel to subparallel alignment. Like a fistful of pencils, rocks containing elongated minerals that are oriented parallel to each other will appear different when viewed from the side than when they are viewed head-on. A rock that exhibits a preferred orientation of its minerals is said to possess foliation.

**Foliation** The term foliation refers to any planar (nearly flat) arrangement of mineral grains or structural features within a rock. Although foliation may occur in some sedimentary and even a few types of igneous rocks, it is a fundamental characteristic of regionally metamorphosed rocks—that is, rock units that have been strongly deformed, mainly by folding. In metamorphic environments, foliation is ultimately driven by compressional stresses that shorten rock units, causing mineral grains in preexisting rocks to develop parallel, or nearly parallel, alignments. Examples of foliation include the parallel alignment of platy minerals; the parallel alignment of flattened pebbles; compositional banding in which the separation of dark and light minerals generates a layered appearance; and rock cleavage where rocks can be easily split into tabular slabs. These diverse types of foliation can form in many different ways, including:

 1. Rotation of platy and/or elongated mineral grains into a parallel or nearly parallel orientation.

 2. Recrystallization that produces new minerals with grains that exhibit a preferred orientation.

3. Mechanisms that change spherically shaped grains into elongated shapes that are aligned in a preferred orientation. The rotation of existing mineral grains is the easiest of these mechanisms to envision. illustrates the mechanics by which platy or elongated minerals are rotated. Note that the new alignment is roughly perpendicular to the direction of maximum shortening. Although physical rotation of platy minerals contributes to the development of foliation in low-grade metamorphism, other mechanisms dominate in more extreme environments. Recall that recrystallization is the creation of new mineral grains out of old ones. When recrystallization occurs as rock is being subjected to differential stresses, any elongated and platy minerals that form tend to recrystallize perpendicular to the direction of maximum stress. Thus, the newly formed mineral grains will possess a parallel alignment and the metamorphic rock containing them will exhibit foliation. Mechanisms that change the shapes of existing grains are especially important for

**Foliated Textures** Various types of foliation exist, depending largely upon the grade of metamorphism and the mineral content of the parent rock. We will look at three: rock or slaty cleavage, schistosity, and gneissic texture.

**ROCK OR SLATY CLEAVAGE**. Rock cleavage refers to closely spaced, flat surfaces along which rocks split into thin slabs when hit with a hammer. Rock cleavage develops in various metamorphic rocks but is best displayed in slates, which exhibit an excellent splitting property called slaty cleavage. Depending on the metamorphic environment and the composition of the parent rock, rock cleavage develops in a number of ways. In a low-grade metamorphic environment, rock cleavage is known to develop where beds of shale (and related sedimentary rocks) are strongly folded and metamorphosed to form slate. The process begins as platy grains are kinked and bent—generating microscopic folds having limbs (sides) that are roughly aligned . With further deformation, this new alignment is enhanced as old grains break down and recrystallize preferentially in the direction of the newly developed orientation. In this manner the rock develops narrow parallel zones where mica flakes are concentrated. These features alternate with zones containing quartz and other mineral grains that do not exhibit a pronounced linear orientation. It is along these very thin zones of platy mineral that slate splits.

**Other Metamorphic Textures** Not all metamorphic rocks exhibit a foliated texture. Those that do not are referred to as nonfoliated. Nonfoliated metamorphic rocks typically develop in environments where deformation is minimal and the parent rocks are composed of minerals that exhibit equidimensional crystals, such as quartz or calcite. For example, when a fine-grained limestone (made of calcite) is metamorphosed by the intrusion of a hot magma body, the small calcite grains recrystallize to form larger interlocking crystals. The resulting rock, marble, exhibits large, equidimensional grains that are randomly oriented, similar to those in a coarse-grained igneous rock. Another texture common to metamorphic rocks consists of unusually large grains, called porphyroblasts, that are surrounded by a fine-grained matrix of other minerals. Porphyroblastic textures develop in a wide range of rock types and metamorphic environments when minerals in the parent rock recrystallize to form new minerals. During recrystallization certain metamorphic minerals, including garnet, staurolite, and andalusite, often develop a small number of very large crystals. By contrast, minerals such as muscovite, biotite, and quartz typically form a large number of very small grains. As a result, when metamorphism generates the minerals garnet, biotite, and muscovite in the same setting, the rock will contain large crystals (porphyroblasts) of garnet embedded in a finergrained matrix of biotite and muscovite.

**Nonfoliated Rocks MARBLE**. Marble is a coarse, crystalline metamorphic rock whose parent was limestone or dolostone .Pure marble is white and composed essentially of the mineral calcite. Because of its relative softness (hardness of 3), marble is easy to cut and shape. Unfortunately, marble’s composition of calcium carbonate causes it to weather when exposed to acid rain. The parent rocks from which most marbles form contain impurities that color the stone. Thus, marble can be pink, gray, green, or even black and may contain a variety of accessory minerals (chlorite, mica, garnet, and wollastonite). When marble forms from limestone interbedded with shales, it will appear banded and exhibit visible foliation. When deformed, these banded marbles may develop highly contorted mica-rich folds that give the rock a rather artistic design. Hence, these decorative marbles have been used as a building stone since prehistoric times.

 **QUARTZITE**. Quartzite is a very hard metamorphic rock formed from quartz sandstone. Under moderateto high-grade metamorphism, the quartz grains in sandstone fuse together. The recrystallization is often so complete that when broken, quartzite will split through the quartz grains rather than along their boundaries. In some instances, sedimentary features such as cross-bedding are preserved and give the rock a banded appearance. Pure quartzite is white, but iron oxide may produce reddish or pinkish stains, while dark mineral grains may impart a gray color.

**Metamorphic Environments** There are many environments in which metamorphism occurs. Most are in the vicinity of plate margins, and several are associated with igneous activity. We will consider the following types of metamorphism: (1) contact or thermal metamorphism; (2) hydrothermal metamorphism; (3) burial and subduction zone metamorphism; (4) regional metamorphism; (5) metamorphism along faults; (6) impact metamorphism and with the exception of impact metamorphism, there is considerable overlap among the types.

**Contact or Thermal Metamorphism** Contact or thermal metamorphism occurs when rocks immediately surrounding a molten igneous body are “baked” and therefore altered from their original state. The altered rocks occur in a zone called a metamorphic aureole . The emplacement of small intrusions such as dikes and sills typically form aureoles only a few centimeters thick, while large igneous plutons that generate batholiths can produce aureoles extending outward for several kilometers. In addition to the size of the magma body, the mineral composition of the host rock and the availability of water greatly affect the size of the aureole produced. In chemically active rock such as limestone, the zone of alteration can be 10 kilometers (6 miles) thick. These large aureoles often consist of distinct zones of metamorphism. Near the magma body, high-temperature minerals such as garnet may form, whereas farther away low-grade minerals such as chlorite are produced. Although contact metamorphism is not entirely restricted to shallow crustal depths, it is most easily recognized when it occurs in this setting. Here, the temperature contrast between the molten body and the surrounding host rock is large. Because contact metamorphism does not involve directed pressure, rocks found within a metamorphic aureole are usually not foliated.

**Hydrothermal Metamorphism** When hot, ion-rich fluids circulate through fissures and cracks in rock, a chemical alteration called hydrothermal metamorphism occurs. This type of metamorphism is often closely associated with the emplacement of magma. As large magma bodies cool and solidify, silica-rich fluids (mainly water) are driven into the host rocks. When the host rock is highly fractured, mineral matter contained in these hydrothermal solutions may precipitate to form a variety of minerals, some of which are economically important. If the host rocks are permeable and highly reactive, such as the carbonate rock limestone, silicaterich hydrothermal solutions react to produce a variety of calcium-rich silicate minerals. Recall that a metamorphic process that alters the overall chemical composition of a rock unit is called metasomatism. As our understanding of plate tectonics grew, it became clear that the most widespread occurrence of hydrothermal metamorphism is along the axis of the mid-ocean ridge system. As plates move apart, upwelling magma from the mantle generates new seafloor. As seawater percolates through the young, hot oceanic crust, it is heated and chemically reacts with the newly formed basaltic rocks. The result is the conversion of ferromagnesian minerals, such as olivine and pyroxene, into hydrated silicates, such as serpentine, chlorite, and talc. In addition, calciumrich plagioclase feldspars in basalt become increasingly sodium enriched as the salt (NaCl) in seawater exchanges Na ions for Ca ions.

**Burial and Subduction Zone Metamorphism** Burial metamorphism tends to occur where massive amounts of sedimentary or volcanic material accumulates in a subsiding basin (see Figure 7.2). Here, low-grade metamorphic conditions may be attained within the deepest layers. Confining pressure and geothermal heat drive the recrystallization of the constituent minerals—changing the texture and/or mineral content of the rock without appreciable deformation. The depth required for burial metamorphism varies from one location to another, depending mainly on the prevailing geothermal gradient. Metamorphism typically begins at depths of about 8 kilometers (5 miles), where temperatures are about 200 °C. However, in areas that exhibit large geothermal gradients and where molten rock has been emplaced near the surface, such as near the Salton Sea in California and in northern New Zealand, drilling operations have collected metamorphic minerals from depths of only a few kilometers. Rocks and sediments can also be carried to great depths along convergent boundaries where oceanic lithosphere is being subducted. This phenomenon, called subduction zone metamorphism, differs from burial metamorphism in that differential stresses play a major role in deforming rock as it is metamorphosed. Furthermore, metamorphic rocks that form along subduction zones are often further metamorphosed by the collision of two continental block.

**Regional Metamorphism** Most metamorphic rock is produced by regional metamorphism during mountain building when large segments of Earth’s crust are intensely deformed along convergent plate boundaries. This activity occurs most often during continental collisions. Sediments and crustal rocks that form the margins of the colliding continental blocks are folded and faulted, causing them to shorten and thicken like a rumpled carpet. Continental collisions also involve crystalline continental basement rocks, as well as slices of oceanic crust that once floored the intervening ocean basin. The general thickening of the crust that occurs during mountain building results in buoyant lifting, in which deformed rocks are elevated high above sea level. Crustal thickening also results in the deep burial of large quantities of rock as crustal blocks are thrust one beneath another. Deep in the roots of mountains, elevated temperatures caused by deep burial are responsible for the most productive and intense metamorphic activity within a mountain belt. Often, these deeply buried rocks become heated to their melting point. As a result, magma collects until it forms bodies large enough to rise buoyan and intrude the overlying metamorphic and sedimentary rocks. Consequently, the cores of many mountain ranges consist of folded and faulted metamorphic rocks, often intertwined with igneous bodies. Over time, these deformed rock masses are uplifted, and erosion removes the overlying material to expose the igneous and metamorphic rocks that comprise the central core of the mountain range.