CHAPTER 7

Metamorphism and Metamorphic Rocks

Contorted veins visible in a blueschist that formed under high-pressure conditions in a subduction zone. Sunol Regional Park, CA. *Photo by John A. Karachewski*

Metamorphism

Factors Controlling the Characteristics of Metamorphic Rocks
- Temperature
- Pressure
- Composition of the Parent Rock
- Fluids
- Time

Classification of Metamorphic Rocks
- Nonfoliated Rocks
- Foliated Rocks

Types of Metamorphism
- Contact Metamorphism
- Hydrothermal Metamorphism
- Regional Metamorphism

Metamorphic Grade
- Pressure and Temperature Paths in Time

Plate Tectonics and Metamorphism
- Foliation and Plate Tectonics
- Pressure-Temperature Regimes
- Hydrothermal Metamorphism and Plate Tectonics

Summary

LEARNING OBJECTIVES

- Using the rock cycle, compare metamorphic rocks to sedimentary and igneous rocks in terms of the conditions under which they form.
- Describe the factors that control the characteristics of metamorphic rocks.
- Distinguish between nonfoliated and foliated metamorphic rocks in terms of their appearance and the conditions under which they form.
- Outline the characteristics used to classify metamorphic rocks and describe the most common metamorphic rocks.
- Compare and contrast contact metamorphism and regional metamorphism.
- Relate the pressure-temperature conditions of metamorphism to plate-tectonic setting.
- Describe the importance of hydrothermal processes during metamorphism.

This chapter on metamorphic rocks, the third major category of rocks in the rock cycle (figure 7.1), completes our description of Earth materials (rocks and minerals). The information on igneous and sedimentary processes in previous chapters should help you understand metamorphic rocks, which form from *preexisting* rocks.

For example, look at the photo on the opening page of this chapter. This rock started out as basalt, erupting at a mid-oceanic ridge and forming part of the sea floor. Later, the oceanic crust was carried into a subduction zone and transported to great depths beneath the surface. Under these high-pressure conditions, the minerals forming the basalt recrystallized into new minerals, giving the new metamorphic rock its blue color and distinctive foliated texture.

Metamorphic rocks that form deep within Earth's crust provide geologists with many clues about conditions at depth. Therefore, understanding metamorphism will help you when we consider geologic processes involving Earth's internal forces. Metamorphic rocks are a feature of the oldest exposed rocks of the continents and of major mountain belts. They are especially important in providing evidence of what happens during subduction and plate convergence.

In this chapter we will explore the process of metamorphism and the factors that control the characteristics of metamorphic rocks before learning to describe and name metamorphic rocks. Following this we will explore some of the major types of metamorphism and the concept of metamorphic grade. We will conclude the chapter by exploring metamorphism and plate tectonics.

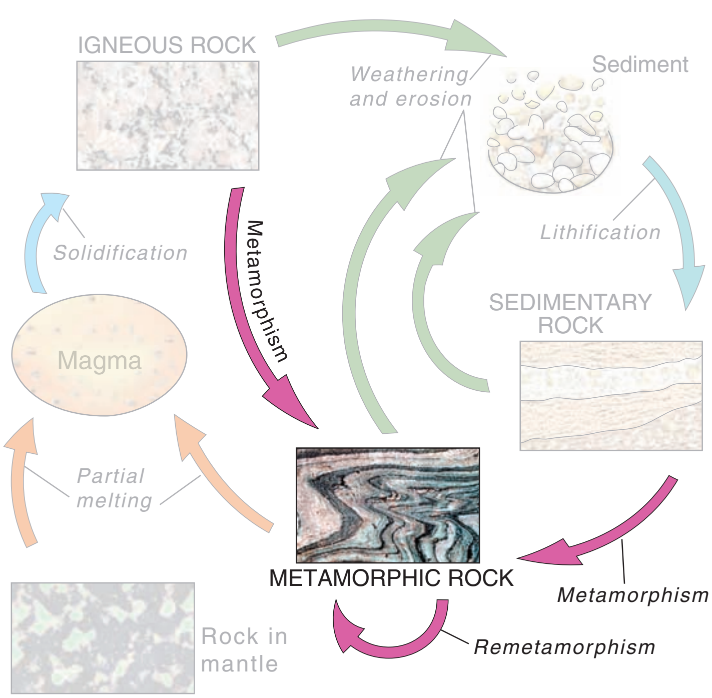


FIGURE 7.1

The rock cycle shows how igneous and sedimentary rocks undergo metamorphism to become metamorphic rocks. A metamorphic rock can also undergo remetamorphism to become a different metamorphic rock.

METAMORPHISM

From your study so far of Earth materials and the rock cycle, you know that rocks change, given enough time, when their physical environment changes radically. In chapter 6 you learned that as sediments are buried they undergo compaction and cementation, transforming them into sedimentary rocks. In chapter 3, you saw how deeply buried rocks melt (or partially melt) to form magma when temperatures are high enough.

What happens to rocks that are deeply buried but are not hot enough to melt? They become metamorphosed.

Metamorphism (a word from Latin and Greek that means literally "changing of form") refers to changes to rocks that take place in Earth's interior. The changes may be new textures, new mineral assemblages, or both. Transformations occur in the *solid state* (meaning the rock does not melt). The new rock is a **metamorphic rock.**

The conversion of a slice of bread to toast is a solid-state process analogous to metamorphism of rock. When the bread (think "sedimentary rock") is heated, it converts to toast (think "metamorphic rock"). The toast is texturally and compositionally different from its parent material, bread. Although the rock remains solid during metamorphism, it is important to recognize that fluids, notably water, often play a significant role in the metamorphic process.

In nearly all cases, a metamorphic rock has a texture clearly different from that of the original **parent rock** (or *protolith).* When limestone is metamorphosed to marble, for example, the fine grains of calcite coalesce and recrystallize into larger calcite crystals. The calcite crystals are interlocked in a mosaic pattern that gives marble a texture distinctly different from that of the parent limestone. If the limestone is composed entirely of calcite, then metamorphism into marble involves no new minerals, only a change in texture.

More commonly, the various elements of a parent rock react chemically and crystallize into new minerals, thus making the metamorphic rock distinct both mineralogically and texturally from the parent rock. This is because the parent rock is unstable in its new environment. The old minerals recrystallize into new ones that are at *equilibrium* in the new environment. For example, clay minerals form at Earth's surface (see chapter 5). Therefore, they are stable at the low temperature and pressure conditions both at and just below Earth's surface. When subjected to the temperatures and pressures deep within Earth's crust, the clay minerals of a shale can recrystallize into coarse-grained mica.

As most metamorphism takes place at moderate to great depths in Earth's crust, metamorphic rocks provide us with a window to processes that take place deep underground, beyond our direct observation. Metamorphic rocks are exposed over large regions because of erosion of mountain belts and the accompanying uplift due to isostatic adjustment (the vertical movement of a portion of Earth's crust to achieve balance, described in chapter 1). In fact, the stable cores of continents, known as *cratons,* are largely metamorphic rocks and granitic plutons. As described in chapter 20 (mountain belts and the continental crust), the North American craton is the central lowlands between the Appalachians and the Rocky Mountains. Very ancient (Precambrian) complexes of metamorphic and intrusive igneous rocks are exposed over much of Canada (known as the *Canadian Shield*). The inside front cover shows the Canadian Shield as the region underlain by Precambrian rocks. In the Great Plains of the United States, also part of the craton, similar rocks form the *basement* underlying a veneer of younger sedimentary rocks (see the tan area on the inside front cover map that the legend indicates is "Platform deposits on Precambrian basement"). Ancient metamorphic and plutonic rocks form the cratons of the other continental landmasses (e.g., Africa, Antarctica, Australia) as well.

No one has observed metamorphism taking place, just as no one has ever seen a granite pluton form. What, then, leads us to believe that metamorphic rocks form in a solid state (i.e., without melting) at high pressure and temperature? Many metamorphic rocks found on Earth's surface exhibit contorted layering (figure 7.2). The layering can be demonstrated to have been either caused by metamorphism or inherited from original, flat-lying sedimentary bedding (even though the rock has since recrystallized). These rocks, now hard and brittle, would shatter if smashed with a hammer. But they must have been **ductile** (or **plastic**), capable of being bent and molded under stress, to have been folded into such contorted patterns. In a laboratory, we can reproduce high pressure and temperature conditions and demonstrate such ductile behavior of rocks on a small scale. Therefore, a reasonable conclusion is that these rocks formed at considerable depth, where such conditions exist. Moreover, crystallization of a magma would not produce contorted layering.

FIGURE 7.2
Metamorphic rock from Greenland. Metamorphism took place 3,700 million years ago—it is one of the oldest rocks on Earth. *Photo by C. C. Plummer*

FACTORS CONTROLLING THE CHARACTERISTICS OF METAMORPHIC ROCKS

A metamorphic rock owes its characteristic texture and particular mineral content to several factors, the most important being (1) the conditions of metamorphism, such as temperature, pressure, and tectonic forces, (2) the composition of the parent rock before metamorphism, (3) the effects of fluids such as water, and (4) time.

Temperature

Heat, necessary for metamorphic reactions, comes primarily from the outward flow of geothermal energy from Earth's deep interior. Usually, the deeper a rock is beneath the surface, the hotter it will be. (An exception to this is the temperature distribution along convergent plate boundaries due to subduction of cold crust, described later in this chapter.) The particular temperature for rock at a given depth depends on the local *geothermal gradient* (described in chapter 3). Additional heat could be derived from magma if magma bodies are locally present.

A mineral is said to be *stable* if, given enough time, it does not react with another substance or convert to a new mineral or substance. Any mineral is stable only within a given temperature range. The stability temperature range of a mineral varies with factors such as pressure and the presence or absence of other substances. Some minerals are stable over a wide temperature range. Quartz, if not mixed with other minerals, is stable at atmospheric pressure (i.e., at Earth's surface) up to about 800°C. At higher pressures, quartz remains stable to even higher temperatures. Other minerals are stable over a temperature range of only 100° or 200°C.

By knowing (from results of laboratory experiments) the particular temperature range in which a mineral is stable, a geologist may be able to deduce the temperature of metamorphism for a rock that includes that mineral.

Minerals stable at higher temperatures tend to be less dense (or have a lower specific gravity) than chemically identical minerals (polymorphs) stable at lower temperatures. As temperature increases, the atoms vibrate more within their sites in the crystal structure. A more open (less tightly packed) crystal structure, such as high-temperature minerals tend to have, allows greater vibration of atoms. (If the heat and resulting vibrations become too great, the bonds between atoms in the crystal break and the substance becomes liquid.)

The upper limit on temperature in metamorphism overlaps the temperature of partial melting of a rock. If partial melting takes place, the component that melts becomes a magma; the solid residue (the part that doesn't melt) remains a metamorphic rock. Temperatures at which the igneous and metamorphic realms can coexist vary considerably. For an ultramafic rock (containing only ferromagnesian silicate minerals), the temperature will be over 1,200°C. For a metamorphosed shale under high water pressure, a granitic melt component can form in the metamorphic rock at temperatures as low as 650°C.

Pressure

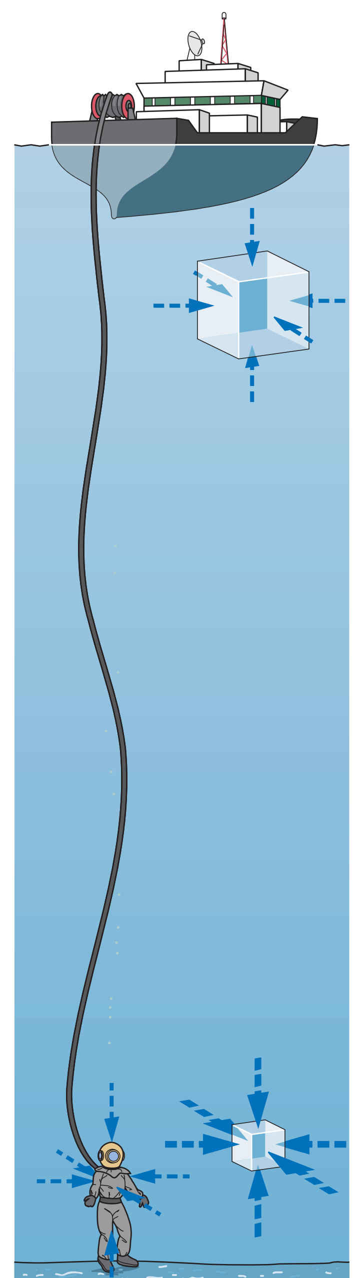
Usually, when we talk about pressure, we mean **confining pressure;** that is, pressure applied equally on all surfaces of a substance as a result of burial or submergence. A diver senses confining pressure (known as *hydrostatic pressure*) proportional to the weight of the overlying water (figure 7.3). The pressure uniformly squeezes the diver's entire body surface. Likewise, an object buried deeply within Earth's crust is compressed by strong confining pressure, called *lithostatic pressure,* which forces grains closer together and eliminates pore space. For metamorphism, pressure is usually given in *kilobars.* A kilobar is 1,000 bars. A *bar* is very close (0.99 atmospheres) to standard atmospheric pressure, so that, for all practical purposes, a kilobar is the pressure equivalent of a thousand times the pressure of the atmosphere at sea level. The *pressure gradient,* the increase in lithostatic pressure with depth, is approximately 1 kilobar for every 3.3 kilometers of burial in the crust.

Any new mineral that has crystallized under high-pressure conditions tends to occupy less space than did the mineral or minerals from which it formed. The new mineral is denser than its low-pressure counterparts because the pressure forces atoms closer together into a more closely packed crystal structure.

But what if pressure and temperature both increase, as is commonly the case with increasing depth into the Earth? If the effect of higher temperature is greater than the effect of higher pressure, the new mineral will likely be less dense. A denser new mineral is likely if increasing pressure effects are greater than increasing temperature effects.

Differential Stress

Most metamorphic rocks show the effects of tectonic forces. When forces are applied to an object, the object is under **stress,** force per unit area. If the forces on a body are stronger or weaker



A

B

FIGURE 7.3

Confining pressure. (*A*) The diver's suit is pressurized to counteract hydrostatic pressure. Object (cube) has a greater volume at low pressure than at high pressure. (*B*) These styrofoam cups were identical. The shrunken cup was carried to a depth of 2,250 meters by the submersible ALVIN in a biological sampling dive to the Juan de Fuca Ridge, off the coast of Washington state. *Photo courtesy of the National Science Foundation-funded REVEL Project, University of Washington* in different directions, a body is subjected to **differential stress.** Differential stress tends to deform objects into oblong or flattened forms. If you squeeze a rubber ball between your thumb and forefinger, the ball is under differential stress. If you squeeze a ball of dough (figure 7.4*A*), it will remain flattened after you stop squeezing, because dough is ductile (or plastic). To illustrate the difference between confining pressure and differential stress, visualize a drum filled with water. If you place a ball of putty underwater in the bottom of the drum, the ball will not change its shape (its volume will decrease slightly due to the weight of the overlying water). Now take the putty ball out of the water and place it under the drum. The putty will be flattened into the shape of a pancake due to the differential stress. In this case, the putty is subjected to *compressive differential stress* or, more simply, **compressive stress** (as is the dough ball shown in figure 7.4*A*).

Differential stress is also caused by **shearing,** which causes parts of a body to move or slide relative to one another across a plane. An example of shearing is when you spread out a deck of cards on a table with your hand moving parallel to the table. Shearing often takes place perpendicular to, or nearly perpendicular to, the direction of compressive stress. If you put a ball of putty between your hands and slide your hands while compressing the putty, as shown in figure 7.4*B*, the putty flattens parallel to the shearing (the moving hands) as well as perpendicular to the compressive stress.

Some rocks can be attributed exclusively to shearing during faulting (movement of bedrock along a fracture, described in chapter 15) in a process sometimes called *dynamic metamorphism.* Rocks in contact along the fault are broken and crushed when movement takes place. A *mylonite* is an unusual rock that is formed from pulverized rock in a fault zone. The rock is streaked out parallel to the fault in darker and lighter components due to shearing. Mylonites are believed to form at a depth of around a kilometer or so, where the rock is still cool and brittle (rather than ductile), but the pressure is sufficient to compress the pulverized rock into a compact, hard rock. Where found, they occupy zones that are only about a meter or so wide.

Foliation

Differential stress has a very important influence on the texture of a metamorphic rock because it forces the constituents of the rock to become parallel to one another. For instance, the pebbles in the metamorphosed conglomerate shown in figure 7.5 were originally more spherical but have been flattened by differential stress. When a rock has a planar texture, it is said to be *foliated.* **Foliation** is manifested in various ways. If a platy mineral (such as mica) is crystallizing within a rock that is undergoing differential stress, the mineral grows in such a way that it remains parallel to the direction of shearing or perpendicular to the direction of compressive stress (figure 7.6). Any platy mineral attempting to grow against shearing is either ground up or forced into alignment. Minerals that crystallize in

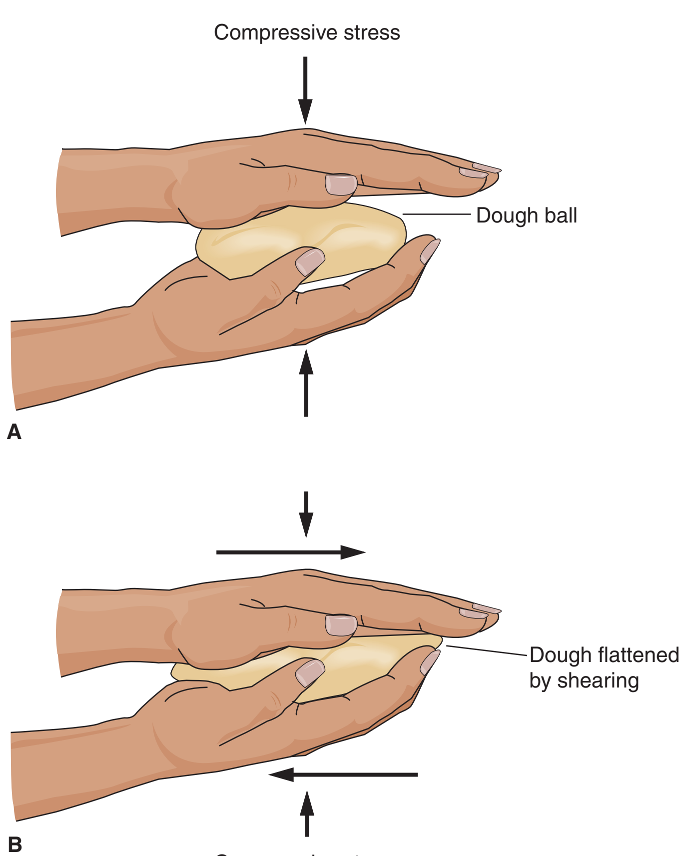


FIGURE 7.4

(*A*) Compressive stress exerted on a ball of dough by two hands. More force is exerted in the direction of arrows than elsewhere on the dough. (*B*) Shearing takes place as two hands move parallel to each other at the same time that some compressive force is exerted perpendicular to the flattening dough.

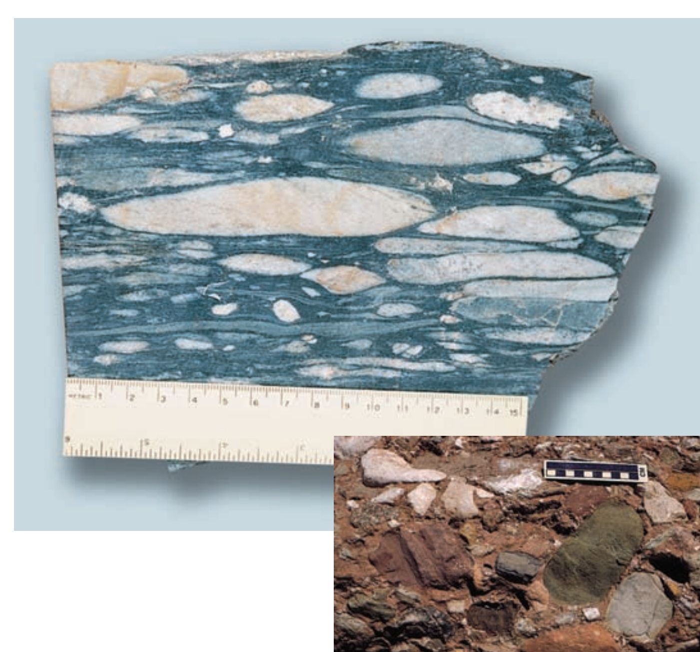


FIGURE 7.5

Metamorphosed conglomerate in which the pebbles have been flattened (sometimes called a stretched pebble conglomerate). Compare to the inset photo of a conglomerate (this is figure 6.7). *Background photo by C. C. Plummer; inset photo by David McGeary*

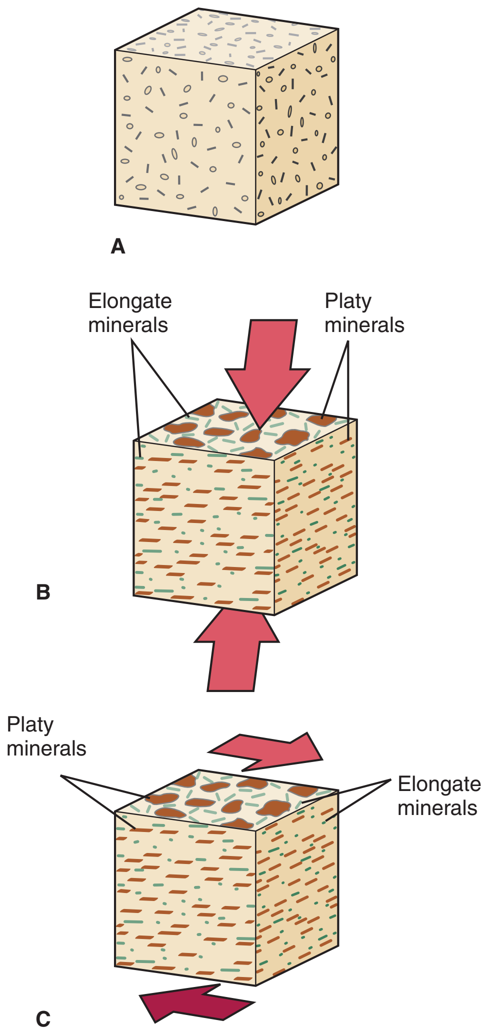


FIGURE 7.6

Orientation of platy and elongate minerals in metamorphic rock. (*A*) Platy minerals randomly oriented (e.g., clay minerals before metamorphism). No differential stress involved. (*B*) Platy minerals (e.g., mica) and elongate minerals (e.g., amphibole) have crystallized under the influence of compressive stress. (*C*) Platy and elongate minerals developed with shearing as the dominant stress.

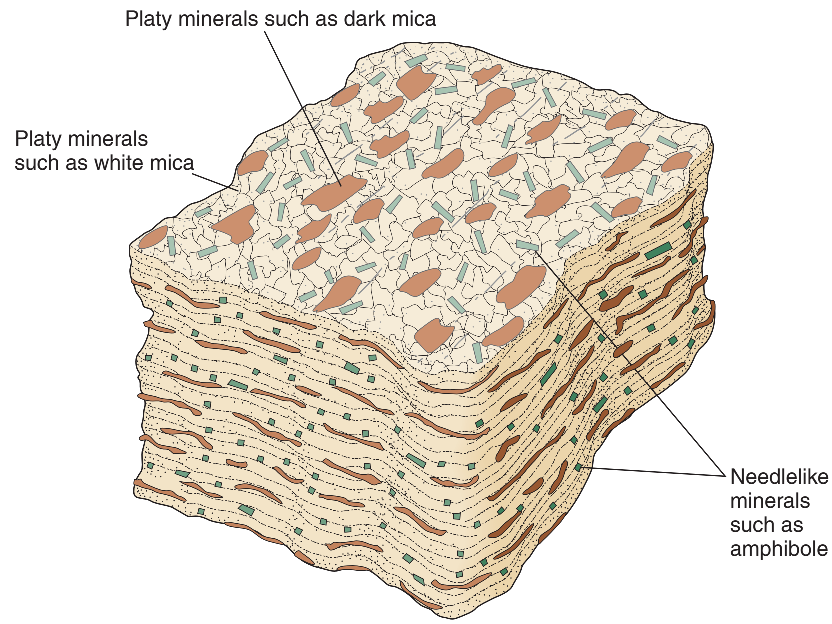


FIGURE 7.7

Schistose texture.

needlelike shapes (for example, hornblende) behave similarly, growing with their long axes parallel to the plane of foliation. The three very different textures described next (from lowest to highest degree of metamorphism) are all variations of foliation and are important in classifying metamorphic rocks:

1. If the rock splits easily along nearly flat and parallel planes, indicating that preexisting, microscopic, platy minerals were realigned during metamorphism, we say the rock is *slaty,* or that it possesses *slaty cleavage.*
2. If visible minerals that are platy or needle-shaped have grown essentially parallel to a plane due to differential stress, the rock is *schistose* (figure 7.7).
3. If the rock became very ductile and the new minerals separated into distinct (light and dark) layers or lenses, the rock has a layered or *gneissic* texture, such as in figure 7.14.

Composition of the Parent Rock

If no new elements or chemical compounds are added to the rock during metamorphism, the mineral content of the metamorphic rock will be the same as the chemical composition of the parent rock. For example, a quartz sandstone with a silica cement is composed entirely of silica (SiO_2). During metamorphism, the silica will recrystallize to form interlocking grains of quartz, and the new metamorphic rock would be called a quartzite. New metamorphic minerals can form if the parent rock contains the chemical compounds needed to form those minerals. For example, the mineral wollastonite can form during metamorphism of a limestone that contains some silica. The reaction that creates wollastonite is as follows:

$CaCO_3$	+	SiO_2	$\rightarrow$	$CaSiO_3$	+	CO_2
calcite		quartz		wollastonite (a mineral)		carbon dioxide

If fluids are involved in metamorphism, the composition of the parent rock, and thus the composition of the metamorphic rock, can be changed.

Fluids

Hot water (as vapor) is the most important fluid involved in metamorphic processes, although other gases, such as carbon dioxide, sometimes play a role. The water may have been trapped in a parent sedimentary rock or given off by a cooling pluton. Water may also be given off from minerals that have water in their crystal structure (e.g., clay, mica). As temperature rises during metamorphism and a mineral becomes unstable, its water is released.

Water is thought to help trigger metamorphic chemical reactions. Water, moving through fractures and along grain margins, is a sort of intrarock rapid transit for ions. Under high pressure, it moves between grains, dissolves ions from one mineral, and then carries these ions elsewhere in the rock where they can react with the ions of a second mineral. The new mineral that forms is stable under the existing conditions.

Fluids can also carry new ions into a rock, effectively changing its composition. This process, known as metasomatism, is discussed later in this section.

Time

The effect of time on metamorphism is hard to comprehend. Most metamorphic rocks are composed predominantly of silicate minerals, and silicate compounds are notorious for their sluggish chemical reaction rates. When garnet crystals taken from a metamorphic rock collected in Vermont were analyzed, scientists calculated a growth rate of 1.4 millimeters per million years. The garnets' growth was sustained over a 10.5-million-year period. Because the rate of metamorphic reactions can be so slow, it is possible to find metamorphic rocks with different mineral assemblages that formed under the same pressure and temperature conditions from identical parent rocks. This occurs when the duration of metamorphism varies from one location to another.

Many laboratory attempts to duplicate metamorphic reactions believed to occur in nature have been frustrated by the time element. The several million years during which a particular combination of temperature and pressure may have prevailed in nature are impossible to duplicate.

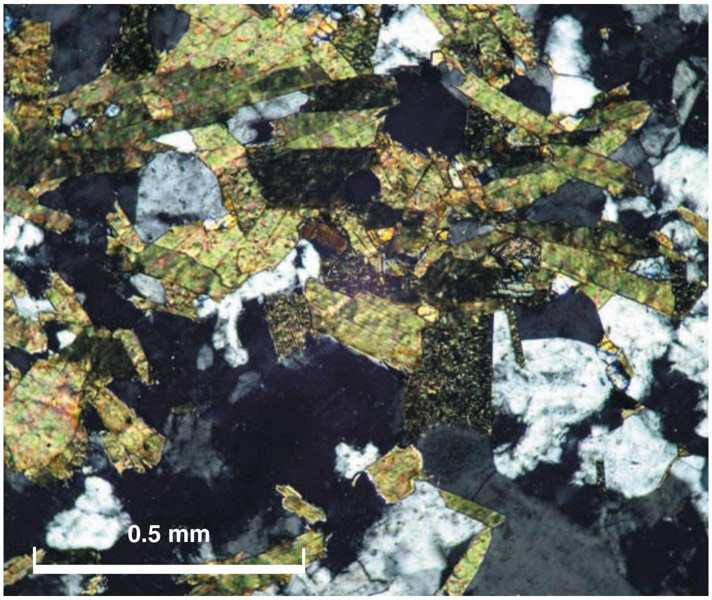
CLASSIFICATION OF METAMORPHIC ROCKS

As we noted before, the kind of metamorphic rock that forms is determined by the metamorphic environment (primarily the particular combination of pressure, stress, and temperature) and by the chemical constituents of the parent rock. Many kinds of metamorphic rocks exist because of the many possible combinations of these factors.

Metamorphic rocks, just like igneous and sedimentary rocks, are classified according to their texture and composition.

TABLE 7.1 Classification and Naming of Metamorphic Rocks (Based Primarily on Texture)

Nonfoliated			
Name Based on Mineral Content of Rock			
Usual Parent Rock	**Rock Name**	**Predominant Minerals**	**Identifying Characteristics**
Limestone	Marble	Calcite	Coarse interlocking grains of calcite (or, less commonly, dolomite).
Dolomite	Dolomite marble	Dolomite	Calcite (or dolomite) has rhombohedral cleavage; hardness intermediate between glass and fingernail. Calcite effervesces in weak acid.
Quartz sandstone	Quartzite	Quartz	Rock composed of interlocking small granules of quartz. Has a sugary appearance and vitreous luster; scratches glass.
Shale	Hornfels	Fine-grained micas	A fine-grained, dark rock that generally will scratch glass. May have a few coarser minerals present.
Basalt	Hornfels	Fine-grained ferromagnesian minerals, plagioclase	
Foliated			
Name Based Principally on Kind of Foliation Regardless of Parent Rock. Adjectives Describe the Composition (e.g., biotite-garnet schist)			
Texture	**Rock Name**	**Typical Characteristic Minerals**	**Identifying Characteristics**
Slaty	Slate	Clay and other sheet silicates	A very fine-grained rock with an earthy luster. Splits easily into thin, flat sheets.
Intermediate between slaty and schistose	Phyllite	Mica	Fine-grained rock with a silky luster. Generally splits along wavy surfaces.
Schistose	Schist	Biotite and muscovite amphibole	Composed of visible platy or elongated minerals that show planar alignment. A wide variety of minerals can be found in various types of schist (e.g., garnet-mica schist, hornblende schist, etc.).
Gneissic	Gneiss	Feldspar, quartz, amphibole, biotite	Light and dark minerals are found in separate, parallel layers or lenses. Commonly, the dark layers include biotite and hornblende; the light-colored layers are composed of feldspars and quartz. The layers may be folded or appear contorted.



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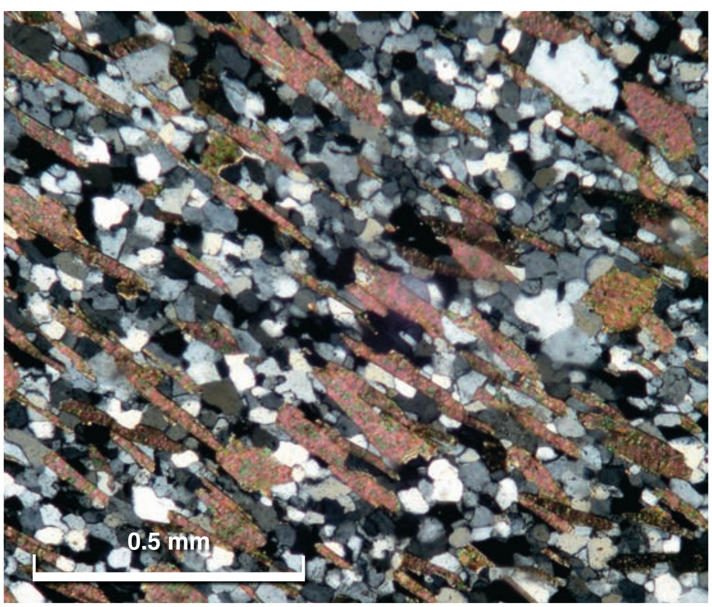


B

FIGURE 7.8

Photomicrographs taken through a polarizing microscope of metamorphic rocks. (*A*) Nonfoliated rock and (*B*) Foliated rock. Multicolored grains are biotite mica; gray and white are mostly quartz. *Photos by Lisa Hammersley*

(Appendix B contains a systematic procedure for identifying common metamorphic rocks.) Let us first consider texture. The relationship of texture to rock name is summarized in table 7.1. The first question to ask when looking at a metamorphic rock is, *is it foliated or nonfoliated* (figure 7.8)?

Nonfoliated Rocks

If the rock is nonfoliated, it is named on the basis of its composition. The two most common nonfoliated rocks are marble and quartzite, composed, respectively, of calcite and quartz.

Marble, a coarse-grained rock composed of interlocking calcite crystals (figure 7.9), forms when limestone recrystallizes during metamorphism. If the parent rock is dolomite, the recrystallized rock is a *dolomite marble.* Marble has long been valued as a building material and as a material for sculpture (figure 7.9*B*), partly because it is easily cut and polished and partly because it reflects light in a shimmering pattern, a result of the excellent cleavage of the individual calcite crystals. Marble is, however, highly susceptible to chemical weathering (see chapter 5).

Quartzite (figure 7.10) is produced when grains of quartz in sandstone are welded together while the rock is subjected to high temperature. This makes it as difficult to break along grain boundaries as through the grains. Therefore, quartzite, being as hard as a single quartz crystal, is difficult to crush or break. It is the most durable of common rocks used for construction, both because of its hardness and because quartz is not susceptible to chemical weathering.

Hornfels is a very fine-grained, nonfoliated, metamorphic rock whose parent rock is most commonly shale or basalt. If it forms from shale, characteristically only microscopically visible micas form from the shale's clay minerals. Sometimes a few minerals grow large enough to be seen with the naked eye; these are minerals that are especially capable of crystallizing under the particular temperature attained during metamorphism. If hornfels forms from basalt, amphibole, rather than mica, is the predominant fine-grained mineral produced.

Foliated Rocks

If the rock is foliated, you need to determine the type of foliation to name the rock. For example, a schistose rock is called a *schist.* But this name tells us nothing about what minerals are in this rock, so we add adjectives to describe the composition—for example, *garnet-mica schist.* The following are the most common foliated rocks progressing from lower grade (lower pressures and temperatures) to higher grade (higher pressures and temperatures):

Slate is a very fine-grained rock that splits easily along flat, parallel planes (figure 7.11). Although some slate forms from volcanic ash, the usual parent rock is shale. Slate develops under temperatures and pressures only slightly greater than those found in the sedimentary realm. The temperatures are not high enough for the rock to thoroughly recrystallize. The important controlling factor is differential stress. The original clay minerals partially recrystallize into equally fine-grained, platy minerals. Under differential stress, the old and new platy minerals are aligned, creating slaty cleavage in the rock. A slate indicates that a relatively cool and brittle rock has been subjected to intense tectonic activity.

Because of the ease with which it can be split into thin, flat sheets, slate is used for making chalkboards, pool tables, and roof tiles.

Phyllite is a rock in which the newly formed micas are larger than the platy minerals in slate but still cannot be seen with the naked eye. This requires a further increase in

FIGURE 7.9

(*A*) Hand specimen of marble. Inset is a photomicrograph showing interlocking crystals of calcite. (*B*) Close-up of *David* by Michelangelo at the piazza della Signoria, Italy. *Photo A by C. C. Plummer; photomicrograph by Lisa Hammersley; photo B © Eric Martin, photographer/Iconotec*

FIGURE 7.10

Quartzite. Inset shows photomicrograph taken using a polarizing microscope. *Photo by C. C. Plummer; photomicrograph by Lisa Hammersley.*

FIGURE 7.11

Slate outcrop in Antarctica. Inset is hand specimen of slate. *Background photo by P. D. Rowley, U.S. Geological Survey; Inset photo © Parvinder Sethi* temperature over that needed for slate to form. The very fine-grained mica imparts a satin sheen to the rock, which may otherwise closely resemble slate (figure 7.12). But the slaty cleavage may be crinkled in the process of conversion of slate to phyllite.

A **schist** is characterized by megascopically visible, approximately parallel-oriented minerals. Platy or elongate minerals that crystallize from the parent rock are clearly visible to the naked eye. Which minerals form depends on the particular combination of temperature and pressure prevailing during recrystallization as well as the composition of the parent rock. Two, of several, schists that form from shale are *mica schist* and *garnet-mica schist* (figure 7.13). Although they both have the same parent rock, they form under different combinations of temperature and pressure. If the parent rock is basalt, the schists that form are quite different. If the predominant ferromagnesian mineral that forms during metamorphism of basalt is amphibole, it is an *amphibole schist.* At a lower grade, the predominant mineral is chlorite, a green micaceous mineral, in a *chlorite schist.*

FIGURE 7.12

Phyllite, exhibiting a crinkled, silky-looking surface. *Photo by C. C. Plummer*

FIGURE 7.13

Garnet-mica schist. Small, subparallel flakes of muscovite mica reflect light. Garnet crystals give the rock a “fish-scale” appearance. *Photo by C. C. Plummer*

FIGURE 7.14

Gneiss. *Photo by C. C. Plummer*

Gneiss is a rock consisting of light and dark mineral layers or lenses. The highest temperatures and pressures have changed the rock so that minerals have separated into layers. Platy or elongate minerals (such as mica or amphibole) in dark layers alternate with layers of light-colored minerals of no particular shape. Usually, coarse feldspar and quartz are predominant within the light-colored layers. In composition, a gneiss may resemble granite or diorite, but it is distinguishable from those plutonic rocks by its foliation (figure 7.14).

Temperature conditions under which a gneiss develops approach those at which granite solidifies. It is not surprising, then, that the same minerals are found in gneiss and in granite. In fact, a previously solidified granite can be converted to a gneiss under appropriate pressure and temperature conditions and if the rock is under differential stress.

TYPES OF METAMORPHISM

Metamorphism can occur in a wide range of environments, each of which results in different pressure and temperature conditions. Metamorphism can be broadly classified into types based upon similarities in setting and metamorphic conditions. There are many types of metamorphism, including shock metamorphism, which occurs during meteorite impacts (box 7.1). Here we discuss three important types of metamorphism: contact metamorphism, hydrothermal metamorphism, and regional metamorphism.

Contact Metamorphism

Contact metamorphism (also known as *thermal* metamorphism) is metamorphism in which high temperature is the

PLANETARY GEOLOGY 7.1

Impact Craters and Shock Metamorphism

The spectacular collision of the comet Shoemaker-Levy with Jupiter in 1994 served to remind us that asteroids and comets occasionally collide with a planet. Earth is not exempt from collisions. Large meteorites have produced impact craters when they have collided with Earth's surface. One well-known meteorite crater is Meteor Crater in Arizona, which is a little more than a kilometer in diameter (box figure 1). Many much larger craters are known in Canada, Germany, Australia, and other places.

Impact craters display an unusual type of metamorphism called *shock metamorphism.* The sudden impact of a large extraterrestrial body results in brief but extremely high pressures. Quartz may recrystallize into the rare SiO_2 minerals coesite and stishovite. Quartz that is not as intensely impacted suffers damage (detectable under a microscope) to its crystal lattice.

The impact of a meteorite also may generate enough heat to locally melt rock. Molten blobs of rock are thrown into the air and become streamlined in the Earth's atmosphere before solidifying into what are called *tektites.* Tektites may be found hundreds of kilometers from the point of meteorite impact.

A large meteorite would blast large quantities of material high into the atmosphere. According to theory, the change in global climate due to a meteorite impact around 65 million years ago caused extinctions of many varieties of creatures (see box 8.2 on the extinction of dinosaurs). Evidence for this impact includes finding tiny fragments of shock metamorphosed quartz and tektites in sedimentary rock that is 65 million years old.

The intense shock caused by a meteorite creates large faults that can be filled with crushed and partially melted rocks. One of the largest such structures, at Sudbury, Ontario, is the host for very rich metallic ore deposits.

Shock metamorphosed rock fragments are much more common on the Moon than on Earth. There may be as many as 400,000 craters larger than a kilometer in diameter on the Moon.

BOX 7.1 ■ FIGURE 1
Meteor Crater in Arizona. Diameter of the crater is 1.2 kilometers. *Photo © Getty RF*

Mercury's surface is remarkably similar to that of the Moon. Our two neighboring planets, Venus and Mars, are not as extensively cratered as is the Moon. This is because these planets, like Earth, have been tectonically active since the time of greatest meteorite bombardment, about 4 billion years ago. If Earth had not been tectonically active and if we didn't have an atmosphere driving erosion, Earth would have around sixteen times the number of meteorite craters as the Moon and would appear just as pockmarked with craters.

Additional Resource

Meteor Crater

Website for Meteor Crater in Arizona

- www.meteorcrater.com/

dominant factor. Confining pressure may influence which new minerals crystallize; however, the confining pressure is usually relatively low. This is because contact metamorphism mostly takes place not too far beneath Earth's surface (less than 10 kilometers). Contact metamorphism occurs adjacent to a pluton when a body of magma intrudes relatively cool country rock (figure 7.15*A*). The process can be thought of as the "baking" of country rock adjacent to an intrusive contact; hence, the term *contact metamorphism.* The zone of contact metamorphism (also called an *aureole*) is usually quite narrow—generally from 1 to 100 meters wide. Differential stress is rarely significant. Therefore, the most common rocks found in an aureole are the nonfoliated rocks: marble when igneous rock intrudes limestone; quartzite when quartz sandstone is metamorphosed; hornfels when shale is baked.

Marble and quartzite also form under conditions of regional metamorphism. When grains of calcite or quartz recrystallize, they tend to be equidimensional, rather than elongate or platy. For this reason, marble and quartzite do not usually exhibit visible foliation, even though subjected to differential stress during metamorphism.

Hydrothermal Metamorphism

As described earlier, hot water is involved to some extent in most metamorphic processes. As shown in table 7.2, hydrothermal fluids can metamorphose an existing rock or deposit entirely new minerals in open spaces. Water is important during **hydrothermal metamorphism** because it can transport ions from one mineral to another and increase the rate of metamorphism.

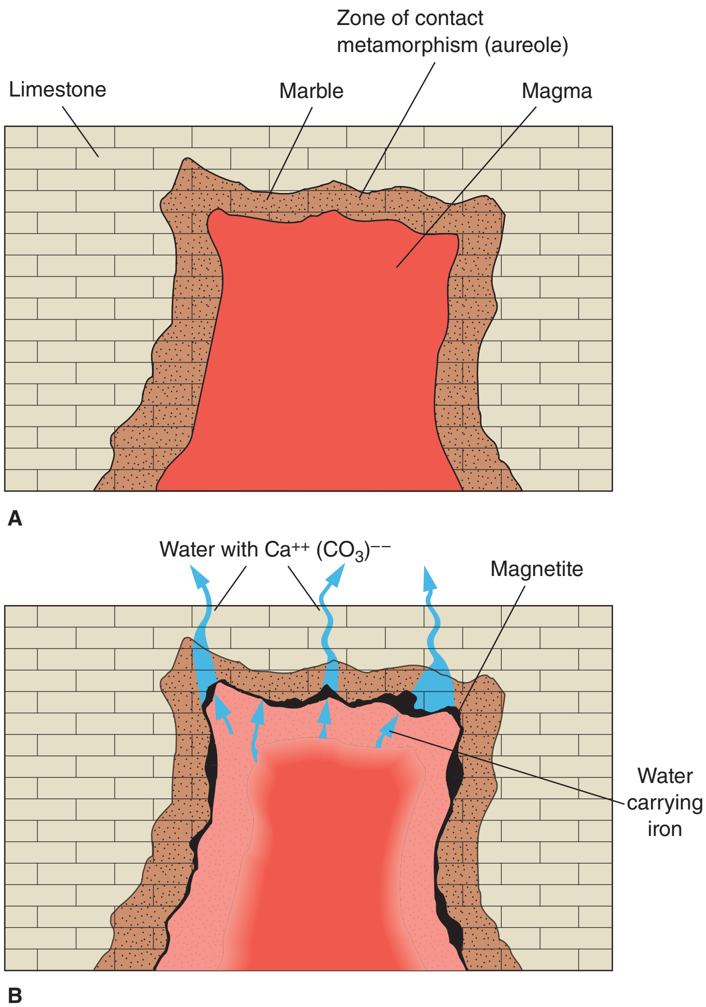


FIGURE 7.15

(*A*) Contact metamorphism. Magma intrudes country rock (limestone), and marble forms along contact. (*B*) Metasomatism. As magma solidifies, gases bearing ions of iron leave the magma, dissolve some of the marble, and deposit iron as magnetite.

TABLE 7.2 Hydrothermal Processes

Role of Water	Name of Process or Product
Water transports ions between grains in a rock. Some water may be incorporated into crystal structures.	Metamorphism
Water brings ions from outside the rock, and they are added to the rock during metamorphism. Other ions may be dissolved and removed.	Metasomatism
Water passes through cracks or pore spaces in rock and precipitates minerals on the walls of cracks and within pore spaces.	Hydrothermal veins and disseminated deposits

Metasomatism is metamorphism coupled with the introduction of *ions* from an external source. The ions are brought in by water from outside the immediate environment and are incorporated into the newly crystallizing minerals. Often, metasomatism involves ion exchange. Newly crystallizing minerals replace preexisting ones as water simultaneously dissolves and replaces ions.

If metasomatism is associated with contact metamorphism, the ions are introduced from a cooling magma. Some important commercially mined deposits of metals such as iron, tungsten, copper, lead, zinc, and silver are attributed to metasomatism. figure 7.15*B* shows how magnetite (iron oxide) ore bodies have formed through metasomatism. Ions of the metal are transported by water and react with minerals in the host rock. Elements within the host rock are simultaneously dissolved out of the host rock and replaced by the metal ions brought in by the fluid. Because of the solubility of calcite, marble commonly serves as a host for metasomatic ore deposits called skarns.

Hot water also plays an important role in creating new rocks and minerals. These form entirely by precipitation of ions derived from hydrothermal solutions. *Hydrothermal minerals* can form in void spaces or between the grains of a host rock. An aggregate of hydrothermal minerals may form within a preexisting fracture in a rock to form a hydrothermal **vein.**

Quartz veins are especially common where igneous activity has occurred (figure 7.16). Hot water can come from the cooling magma or from groundwater heated by a pluton and circulated by convection. Where the water is hottest, rock in contact with it is partially dissolved. As the hot water travels upward toward Earth's surface, temperature and pressure decrease. Fewer ions can be carried in solution, so minerals will precipitate onto the walls of the cracks. Most commonly, silica (SiO_2) dissolves in the very hot water, then will cake on the walls of cracks to form quartz veins.

Hydrothermal Processes and Ore Deposits

Hydrothermal veins are very important economically. In them, we find most of the world's great deposits of zinc, lead, silver, gold, tungsten, tin, mercury, and, to some extent, copper (see figure 7.17). Ore minerals containing these metals are usually found in quartz veins.

Some ore-bearing solutions percolate upward between the grains of the rock and deposit very fine grains of ore mineral throughout. These are called *disseminated ore deposits.* Usually, metallic sulfide ore minerals are distributed in very low concentration through large volumes of rock, both above and within a pluton. Most of the world's copper comes from disseminated deposits, also called *porphyry copper deposits,* because the associated pluton is usually porphyritic. Other metals, such as lead, zinc, molybdenum, silver, and gold may be deposited along with copper. Some very large gold mines are also in disseminated ore deposits.

Regional Metamorphism

The great majority of the metamorphic rocks found on Earth's surface are products of **regional metamorphism,** which is metamorphism that takes place over wide areas and generally at considerable depth in the crust. Regional metamorphism is commonly associated with mountain building at convergent

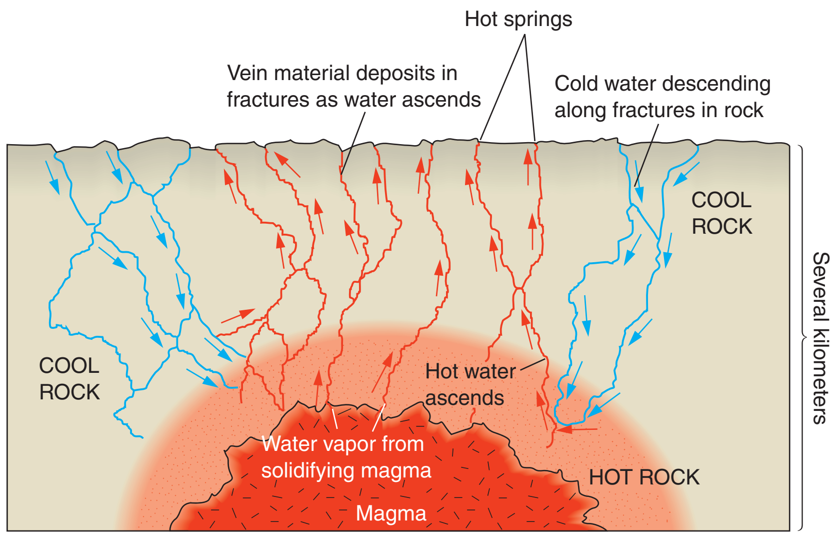


FIGURE 7.16

How veins form. Cold water descends, is heated, dissolves material, ascends, and deposits material as water cools and pressure drops upon ascending.

FIGURE 7.17

A wide vein that contains masses of sphalerite (dark), pyrite and chalcopyrite (both shiny yellow), as well as white quartz, in the Casapalca mine in Peru. It was mined for zinc and copper. *Photo © Brian Skinner*

plate boundaries, and regional metamorphic rocks are almost always foliated, indicating differential stress during recrystallization. Metamorphic rocks are prevalent in the most intensely deformed portions of mountain ranges. They are visible where once deeply buried cores of mountain ranges are exposed by erosion. Furthermore, large regions of the continents are underlain by metamorphic rocks, thought to be the roots of ancient mountains long since eroded down to plains or rolling hills.

Temperatures during regional metamorphism vary widely. Usually, the temperatures are in the range of 300 to 800°C. Temperature at a particular place depends to a large extent on depth of burial and the geothermal gradient of the region. Locally, temperature may also increase because of heat given off by nearby magma bodies. The high confining pressure is due to burial under 5 or more kilometers of rock. The differential stress is due to tectonism; that is, the constant movement and squeezing of the crust during mountain-building episodes.

Temperatures and pressures during metamorphism can be estimated through the results of laboratory experimental studies of minerals. In many cases, we can estimate temperature and pressure by determining the conditions under which an assemblage of several minerals can coexist. In some instances, a single mineral, or *index mineral,* suffices for determining the pressure and temperature combination under which a rock recrystallized (box 7.2).

Depending on the pressure and temperature conditions during metamorphism, a particular parent rock may recrystallize into one of several metamorphic rocks. For example, if basalt is metamorphosed at relatively low temperatures and pressures, it will recrystallize into a *greenschist,* a schistose rock containing chlorite (a green sheet-silicate), actinolite (a green amphibole), and sodium-rich plagioclase. Or it will recrystallize into a *greenstone,* a rock that has similar minerals but is not foliated. (A greenstone would indicate that the tectonic forces were not strong enough to induce foliation while the basalt was recrystallizing.) At higher temperatures and pressures, the same basalt would recrystallize into an *amphibolite,* a rock composed of hornblende, plagioclase feldspar, and, perhaps, garnet. Metamorphism of other parent rocks under conditions similar to those that produce amphibolite from basalt should produce the metamorphic rocks shown in table 7.3.

TABLE 7.3 Regional Metamorphic Rocks that Form Under Approximately Similar Pressure and Temperature Conditions

Parent Rock	Rock Name	Predominant Minerals
Basalt	Amphibolite	Hornblende, plagioclase, garnet
Shale	Mica schist	Biotite, muscovite, quartz, garnet
Quartz sandstone	Quartzite	Quartz
Limestone or dolomite	Marble	Calcite or dolomite

METAMORPHIC GRADE

The minerals present in a metamorphic rock indicate its *metamorphic grade.* Low-grade rocks formed under relatively cool temperatures and high-grade rocks at high temperatures, whereas medium-grade rocks recrystallized at around the middle of the range of metamorphic temperatures.

When a rock becomes buried to increasingly greater depths, it is subjected to increasingly greater temperatures and pressures and will undergo *prograde metamorphism*—that is, it recrystallizes into a higher-grade rock. As an example, consider figure 7.18, which shows what happens to a shale as it is progressively buried deeper in the Earth's crust during regional metamorphism.

Slate, which looks quite similar to the shale from which it forms, is the first metamorphic rock to form, and the lowest grade. Its slaty cleavage develops as a result of differential stress during incipient recrystallization of clay minerals to other platy minerals. As described earlier, phyllite is a rock that is transitional between slate and schist and, as such, we expect it to have formed at a depth between where slate and schist form.

Schist forms at higher temperatures and usually higher pressures than does phyllite. However, schist with shale as a parent rock forms over a wide range of temperatures and pressures. Figure 7.18 indicates the metamorphic setting for two varieties of schist (there are a number of others) that form from the same shale. For this particular composition of shale, *mica schist* indicates a grade of metamorphism slightly higher than that of phyllite. Garnet requires higher temperatures to crystallize in a schist, so the *garnet-mica schist* probably formed at a deeper level than that of mica schist.

If schist is subjected to high enough temperatures, its constituents become more mobile and the rock recrystallizes into gneiss. The constituents of feldspar migrate (probably as ions) into planes of weakness caused by differential stress where feldspars, along with quartz, crystallize to form light-colored layers. The ferromagnesian minerals remain behind as the dark layers.

If the temperature is high enough, partial melting of rock may take place, and a magma collects in layers within the foliation planes of the solid rock. After the magma solidifies, the rock becomes a **migmatite,** a mixed igneous and metamorphic rock (figure 7.19). A migmatite can be thought of as a "twilight zone" rock that is neither fully igneous nor entirely metamorphic.

The metamorphic rocks that we see usually have minerals that formed at or near the highest temperature reached during metamorphism. But why doesn't a rock recrystallize to one stable at lower temperature and pressure conditions during its long journey to the surface, where we now find it? The answer is that water is usually available during

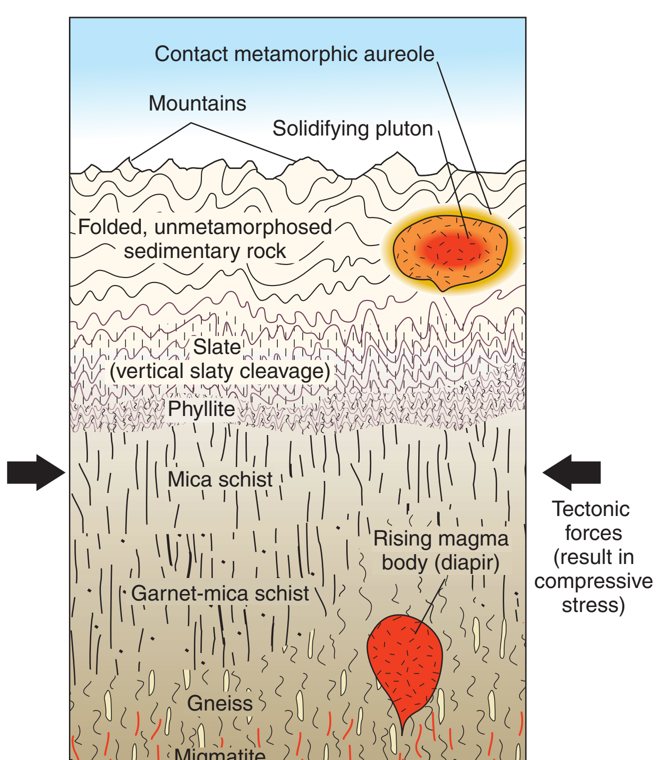


FIGURE 7.18

Schematic cross section representing an approximately 30-kilometer portion of Earth's crust during metamorphism. Rock names given are those produced from shale.

FIGURE 7.19

Migmatite in the Daniels Range, Antarctica. *Photo by C. C. Plummer*

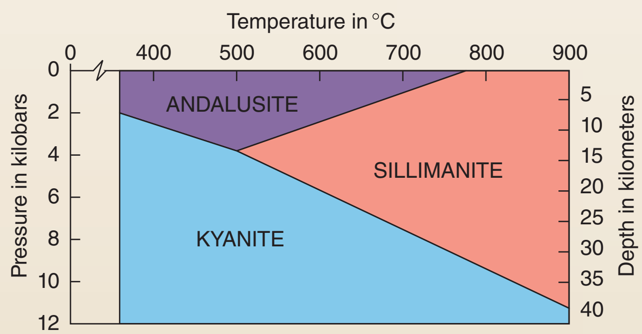
IN GREATER DEPTH 7.2

Index Minerals

Certain minerals can only form under a restricted range of pressure and temperature. Stability ranges of these minerals have been determined in laboratories. When found in metamorphic rocks, these minerals can help us infer, within limits, what the pressure and temperature conditions were during metamorphism. For this reason, they are known as *index minerals*. Among the best known are *andalusite, kyanite,* and *sillimanite*. All three have an identical chemical composition (Al_2SiO_5) but different crystal structures (they are *polymorphs*). They are found in metamorphosed shales that have an abundance of aluminum. Box figure 1 is a phase diagram showing the pressure-temperature fields in which each is stable. Box figure 2 is a map showing metamorphic patterns across the Grenville Province of the Canadian Shield. These patterns were established using the minerals andalusite-sillimanite-kyanite.

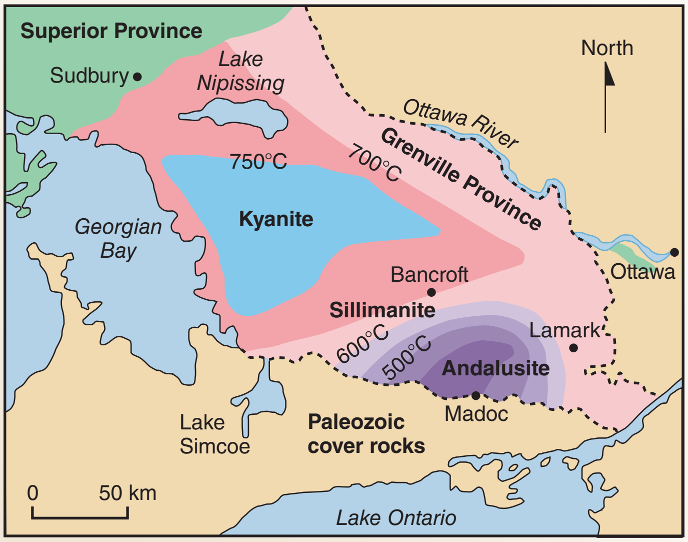
If andalusite is found in a rock, this indicates that pressures and temperatures were relatively low. Andalusite is often found in contact metamorphosed shales (hornfels). Kyanite, when found in schists, is regarded as an indicator of high pressure; but note that the higher the temperature of the rock, the greater the pressure needed for kyanite to form. Sillimanite is an indicator of high temperature and can be found in some contact metamorphic rocks adjacent to very hot intrusions as well as in regionally metamorphosed schists and gneisses that formed at considerable depths.

Note that if you found all three minerals in the same rock and could determine that they were mutually stable, you could infer that the temperature was close to 500°C and the confining pressure was almost 4 kilobars during metamorphism.



BOX 7.2 ■ FIGURE 1

Phase diagram showing the stability relationships for the Al_2SiO_5 minerals. *M. J. Holdaway, 1971, American Journal of Science,* v. 271. Reprinted by permission of *American Journal of Science* and Michael J. Holdaway



BOX 7.2 ■ FIGURE 2

Regional metamorphic patterns across the Grenville Province of the Canadian Shield. Colored bands represent reconstructed burial temperatures based on minerals present in the metamorphic rocks. Higher grades of metamorphism occur in the west of the Grenville Province and indicate deeper burial and higher temperatures in that area. *Courtesy of Nick Eyles*

prograde metamorphism, and the rock may be relatively dry after reaching its peak temperatures. The absence of water means that chemical reaction will be very slow at the cooler temperatures, limiting the degree to which the rock can adjust to its new, lower-grade conditions. Substantial *retrograde metamorphism* only occurs if additional water is introduced to the rock after peak metamorphism. Tectonic forces at work during the peak of metamorphism fracture the rock extensively and permit water to get to the mineral grains. After tectonic forces are relaxed, the rocks move upward as a large block as isostatic adjustment takes place. Rocks that do indicate retrograde metamorphism are those that recrystallized under lower temperature and pressure conditions than during the peak of metamorphism.

Pressure and Temperature Paths in Time

Index minerals (box 7.2) and mineral assemblages in a rock can be used to determine the approximate temperature and pressure conditions that prevailed during metamorphism. Precise determination of the chemical composition of some minerals can determine the temperature or pressure present during the growth of a particular mineral. The usual basis for determining temperature (*geothermometry*) or pressure (*geobarometry*) during mineral growth is the ratio of pairs of elements (e.g., Fe and Al) within the crystal structure of the mineral.

Modern techniques allow us to determine chemical compositional changes across a grain of a mineral in a rock. An *electron microprobe* is a microscope that allows the user to focus on a tiny portion of a mineral in a rock, then shoot a very narrow beam of electrons into that point in the mineral. The extent and manner in which the beam is absorbed by the mineral are translated, using specialized software, into the precise chemical composition of the mineral at that point. If the mineral is *zoned* (that is, the chemical composition changes within the mineral, as described in chapter 2), the electron microprobe will indicate the differing composition within the mineral grain.

A mineral grows from the center outward, adding layers of atoms as it becomes larger. If pressure and temperature conditions change as the mineral grows, the chemical composition of the outer layers will be different from that of the inner layers, reflecting those changes. Figure 7.20 shows the results of one such study. The diagram shows the changes of temperature and pressure experienced by a rock during burial, metamorphism, and subsequent uplift. The line represents the temperature-pressure-time path. If chemical analysis of the zones in the mineral indicates that pressure and temperature are both increasing, this indicates the rock is being buried deeper while becoming hotter. If temperature and pressure are both decreasing, the rock is cooling down at the same time that pressure is being reduced because of erosion at Earth's surface.

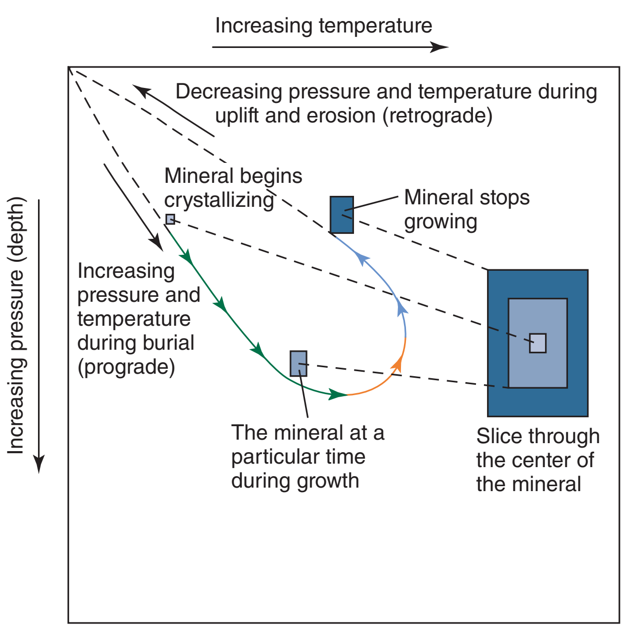


FIGURE 7.20

Pressure-temperature-time path for growth of a mineral during metamorphism. An electron microprobe is used to determine the precise chemical composition of the concentric zones of the mineral. The data are used to determine the pressure and temperature during the growth of the mineral. Three stages during the growth of the mineral are correlated to the graph—beginning of growth (center of crystal), an arbitrary point during its growth, and the end of crystallization (the outermost part of the crystal).

The green segment of the path indicates increasing pressure and temperature during metamorphism. The orange segment indicates that pressure was decreasing while temperature continued to rise. The blue segment indicates temperature and pressure were both decreasing. The decrease in pressure is likely to be the result of uplift and erosion at the surface. The dashed lines are inferred pressure and temperature paths before and after metamorphism.

PLATE TECTONICS AND METAMORPHISM

Studies of metamorphic rocks have provided important information on conditions and processes within the lithosphere and have aided our understanding of plate tectonics. Conversely, plate tectonic theory has provided models that allow us to explain many of the observed characteristics of metamorphic rocks.

Foliation and Plate Tectonics

Figure 7.21 shows an oceanic-continental boundary (oceanic lithosphere is subducted beneath continental lithosphere). One of the things the diagram shows is where differential stress that is responsible for foliation is taking place. Shearing takes place in the subduction zone where the oceanic crust slides beneath continental lithosphere. For here, we infer that the sedimentary rocks and some of the basalt becomes foliated, during metamorphism, roughly parallel to the subduction zone (parallel to the lines in the diagram).

Within the thickest part of the continental crust shown in figure 7.21, flowage of rock is indicated by the purple arrows. The crust is thickest here beneath a growing mountain belt. The thickening is due to the compression caused by the two colliding plates. Within this part of the crust, rocks flow downward and then outward (as indicated by the arrows) in a process (described in chapter 20 on mountains) of *gravitational collapse and spreading.* Under this concept, the central part of a mountain belt becomes too high after plate convergence and is gravitationally unstable. This forces the rock downward and outward. Regional metamorphism takes place throughout, and we expect foliation in the recrystallizing rocks to be approximately parallel to the arrows.

Pressure-Temperature Regimes

Before the advent of plate tectonics, geologists were hard-pressed to explain how some rocks apparently were metamorphosed at relatively cool temperatures yet high pressures. We expect rocks to be hotter as they become more deeply buried. How could rocks stay cool, yet be deeply buried?

Figure 7.22 shows experimentally determined stability fields for a few metamorphic minerals. Line *x* indicates

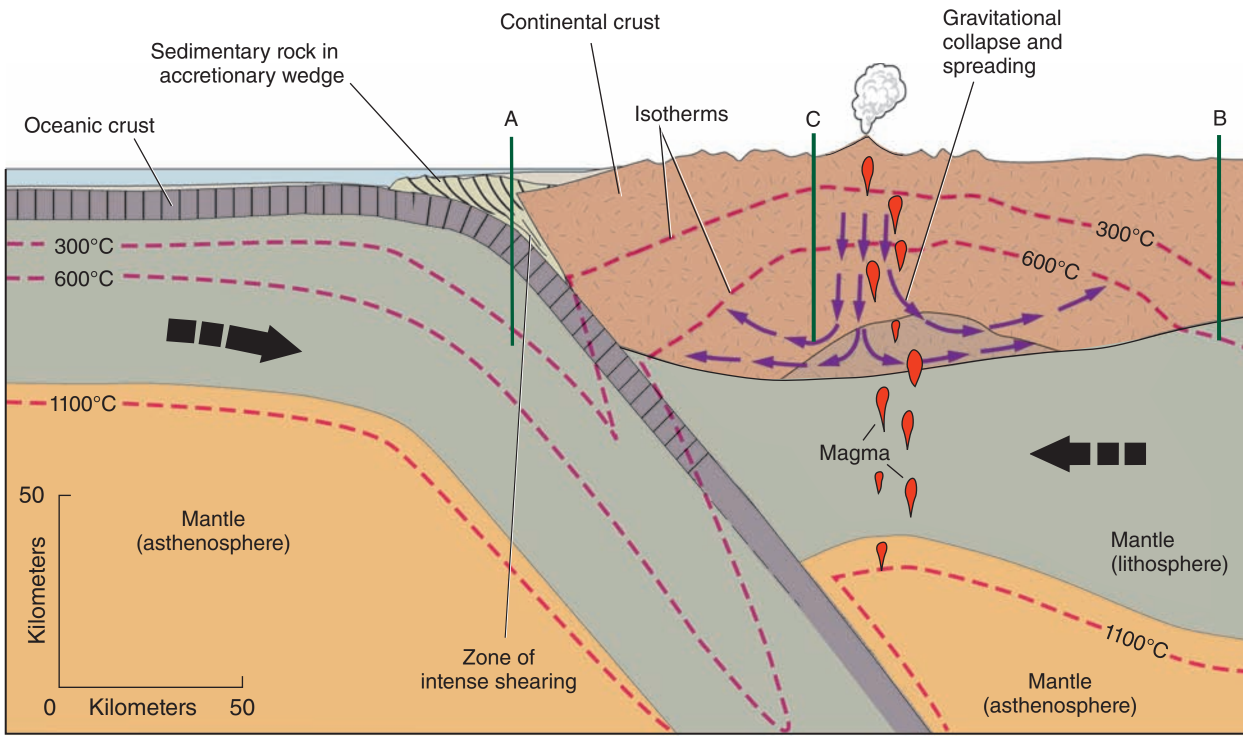


FIGURE 7.21

Metamorphism across a convergent plate boundary. All rock that is hotter than 300° or deeper than 5 kilometers is likely to be undergoing metamorphism. *Modified from W.G. Ernst, Metamorphism and Plate Tectonics Regimes. Stradsburg, PA: Dowden, Hutchinson & Ross, 1975, p. 425. Copyright © 1975 by W.G. Ernst. All rights reserved. Used with permission*

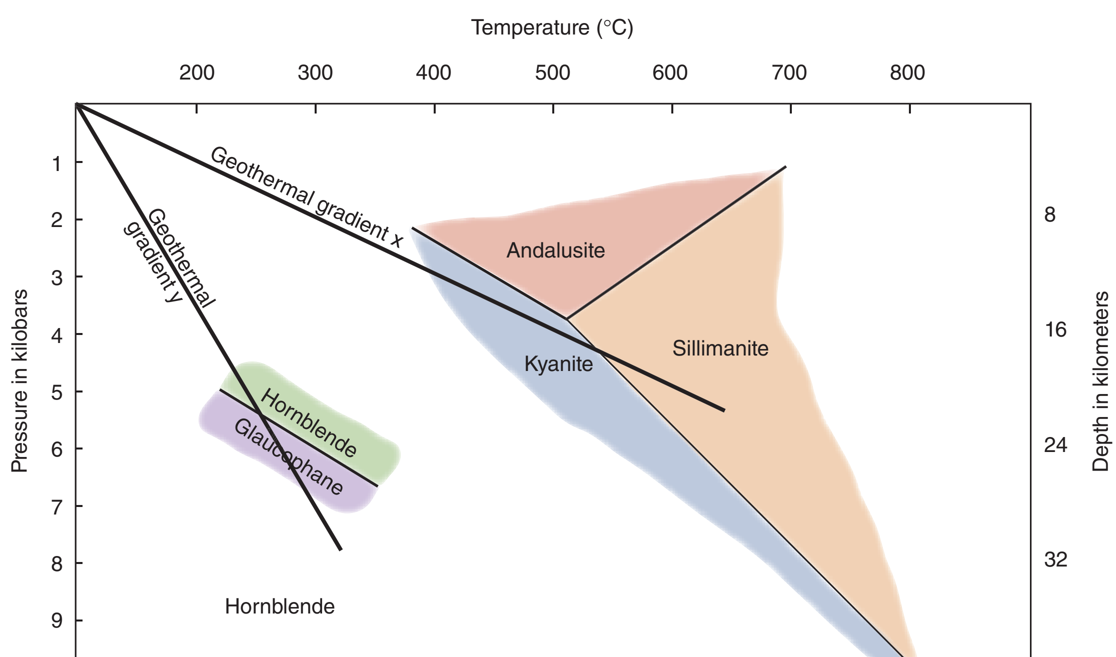


FIGURE 7.22

Stability fields for a few minerals. (Many more mineral stability fields can be used for increased accuracy.) The fields are based on laboratory research. Prograde metamorphism taking place with a geothermal gradient *x* involves a high temperature increase with increasing pressure. Prograde metamorphism under conditions of geothermal gradient *y* involves low temperature increase with increasing pressure. Hornblende is a calcium-bearing amphibole; glaucophane is a sodium-bearing amphibole.

a common geothermal gradient during metamorphism. At the appropriate pressure and temperature, kyanite begins to crystallize in the rock. If it were buried deeper, its pressure and temperature would change along line *x.* Eventually, it would cross the stability boundary and sillimanite would crystallize rather than kyanite. By contrast, if a rock contains glaucophane (sodium-rich amphibole), rather than calcium-rich hornblende, the rock must have formed under high pressure but abnormally low temperature for its depth of burial. Line *y* represents a possible geothermal gradient that must have been very low, and the increase in temperature was small with respect to the increase in pressure.

If we return to figure 7.21, we can use it to see how plate tectonics explains these very different pressure-temperature regimes at a convergent boundary. Confining pressure is directly related to depth. For this reason, we expect the same pressure at any given depth. For example, the pressure corresponding to 20 kilometers is the same under a hot volcanic area as it is within the relatively cool rocks of a plate's interior. Temperature, however, is quite variable as indicated by the dashed red lines. Each of these lines is an **isotherm,** a line connecting points of equal temperature.

Each of the three places (*A, B,* and *C*) in figure 7.21 would have a different geothermal gradient. If you were somehow able to push a thermometer through the lithosphere, you would find the rock is hotter at shallower depths in areas with higher geothermal gradients than at places where the geothermal gradient is low. As indicated in figure 7.21, the geothermal gradient is higher, progressing downward through an active volcanic-plutonic complex (for instance, the Cascade Mountains of Washington and Oregon) than it is in the interior of a plate (beneath the Great Plains of North America, for example). The isotherms are bowed upward in the region of the volcanic-plutonic complex because magma created at lower levels works its way upward and brings heat from the asthenosphere into the mantle and crust of the continental lithosphere. At point *C* we would expect the metamorphism that takes place to result in minerals that reflect the high temperature relative to pressure conditions such as those along line *x* in figure 7.22.

If we focus our attention at the line at *A* in figure 7.21, we can understand how minerals can form under high pressure but relatively low temperature conditions. You may observe that the bottom of line *A* is at a depth of about 50 kilometers, and if a hypothetical thermometer were here, it would read just over 300° because it would be just below the 300° isotherm. Compare this to vertical line *C* in the volcanic-plutonic complex. The confining pressure at the base of this line would be the same as at the base of line *A,* yet the temperature at the base of line *C* would be well over 600°. The minerals that could form at the base of line *A* would not be the same as those that could form at line *C*. Therefore, we would expect quite different metamorphic rocks in the two places, even if the parent rock had been the same (box 7.3).

So when we find high-pressure/low-temperature minerals (such as glaucophane) in a rock, we can infer that metamorphism took place while subduction carried basalt and overlying sedimentary rocks downward. Thus, plate tectonics accounts for the abnormally high-pressure/low-temperature geothermal gradients (such as line *y* in figure 7.22).

WEB BOX 7.3

Metamorphic Facies and Its Relationship to Plate Tectonics

Metamorphic rocks that contain the same set of pressure- or temperature-sensitive minerals are regarded as belonging to the same *metamorphic facies,* implying that they formed under broadly similar pressure and temperature conditions. Early in the twentieth century, geologists assigned metamorphosed basalts to a metamorphic facies based on the assemblage of minerals present in a rock. For instance, metabasalts that are mostly hornblende and plagioclase feldspar belong to the amphibolite facies (named after the rock). If a rock of the same chemical composition is composed largely of actinolite (an amphibole), chlorite (a green sheet silicate mineral) and sodium-rich feldspar, it belongs to the greenschist facies. Field relationships indicated that the greenschist facies represents metamorphism under lower pressure and temperature conditions than those of the amphibolite facies. Classifying rocks by assigning them to metamorphic facies evolved, after laboratory investigations, into a more quantitative system than the vaguely defined "grade" (low, intermediate, high).

To learn more, including how the various facies are used to infer the plate tectonic setting of metamorphism, go to the box in the website www.mhhe.com/plummer15e.

Hydrothermal Metamorphism and Plate Tectonics

As you have seen, water plays an important role in metamorphism. Hydrothermal processes are particularly important at mid-oceanic ridges. As shown in figure 7.23, cold seawater moves downward through cracks in the basaltic crust and is cycled upward by heat from magma beneath the ridge crest. Very hot water returns to the ocean at submarine hot springs (*hydrothermal vents*).

Hot water traveling through the basalt and gabbro of the oceanic lithosphere helps metamorphose these rocks while they are close to the divergent boundary. This is sometimes called *seafloor metamorphism.* During metamorphism, the ferromagnesian igneous minerals, olivine and pyroxene, become converted to *hydrous* (water-bearing) minerals such as amphibole. An important consequence of this is that the hydrous minerals may eventually contribute to magma generation at convergent boundaries.

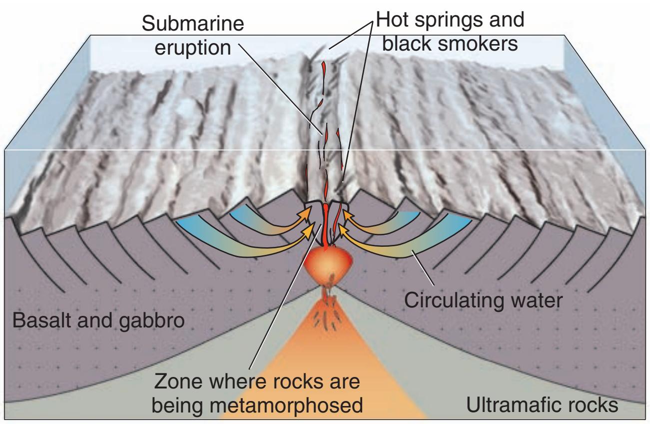


FIGURE 7.23

Cross section of a mid-oceanic ridge (divergent plate boundary). Water descends through fractures in the oceanic crust, is heated by magma and hot igneous rocks, and rises.

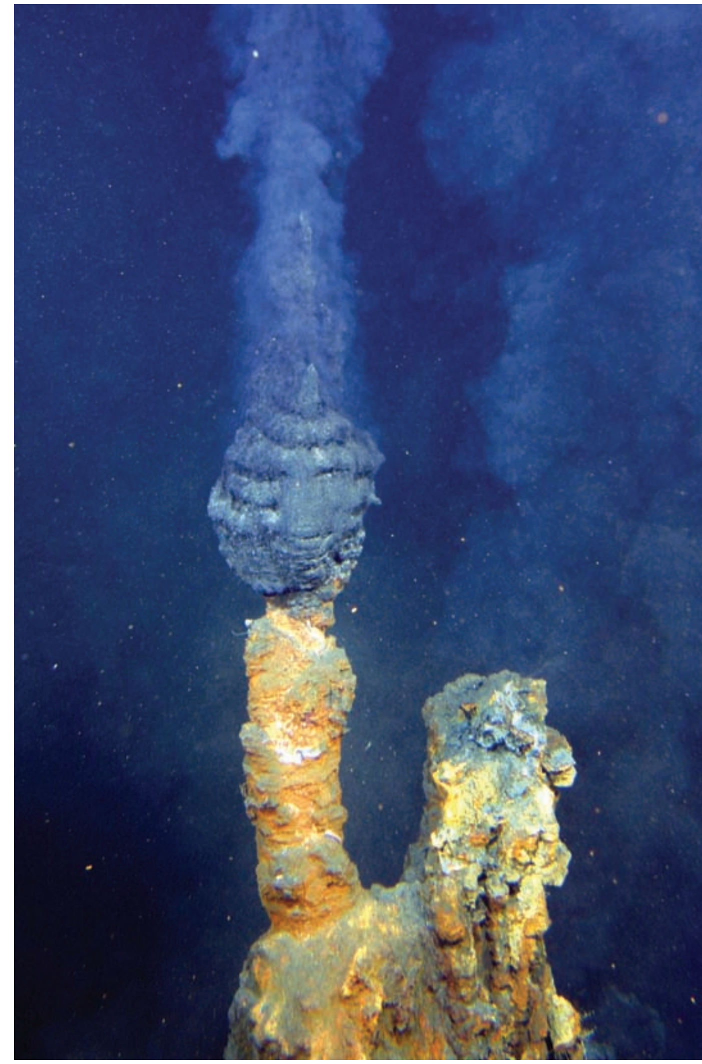


FIGURE 7.24

An example of a "black smoker" or hydrothermal vent. The "smoke" is a hot plume of metallic sulfide minerals being discharged into cold seawater from a chimney. *Image courtesy of New Zealand American Submarine Ring of Fire 2007 Exploration, NOAA Vents Program.*

As the seawater moves through the crust, it also dissolves metals and sulfur from the crustal rocks and magma. When the hot, metal-rich solutions contact cold seawater, metal sulfides are precipitated in a mound around the hydrothermal vent. This process has been filmed in the Pacific, where some springs spew clouds of fine-grained ore minerals that look like black smoke (figure 7.24). To learn more about seafloor hydrothermal vents, go to http://www.expeditions.udel.edu/extreme08/geology/index.php.

The metals in rift-valley hot springs are predominantly iron, copper, and zinc, with smaller amounts of manganese, gold, and silver. Although the mounds are nearly solid metal sulfide, they are usually small and widely scattered on the sea floor, so commercial mining of them may not be practical.

After oceanic crust is subducted, the minerals are dehydrated deep in a subduction zone (see figure 7.25). The water produced moves upward into the overlying asthenosphere and contributes to melting and magma generation, as described in chapter 3.

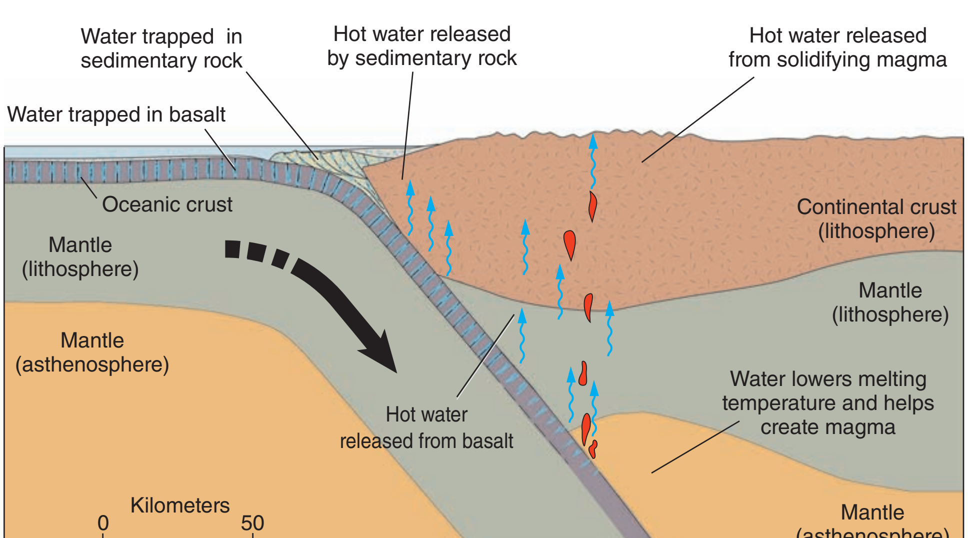


FIGURE 7.25

Water at a convergent boundary. Seawater trapped in the oceanic crust is carried downward and released upon heating at various depths within the subduction zone.

Summary

Metamorphic rocks form from other rocks that are subjected to high temperature, generally accompanied by high confining pressure. Although recrystallization takes place in the solid state, water, which is usually present, aids metamorphic reactions. Foliation in metamorphic rocks is due to *differential stress* (either *compressive stress* or *shearing*). Slate, phyllite, schist, and gneiss are foliated rocks that indicate increasing grade of regional metamorphism. They are distinguished from one another by the type of foliation.

Contact metamorphic rocks are produced during metamorphism usually without significant differential stress but with high temperature. Contact metamorphism occurs in rocks immediately adjacent to intruded magmas.

Regional metamorphism, which involves heat, confining pressure, and differential stress, has created most of the metamorphic rock of Earth's crust. Different parent rocks as well as widely varying combinations of pressure and temperature result in a large variety of metamorphic rocks. Combinations of minerals in a rock can indicate what the pressure and temperature conditions were during metamorphism. Extreme metamorphism, where the rock partially melts, can result in *migmatites.*

Hydrothermal veins form when hot water precipitates material that crystallizes into minerals. During *metasomatism,* hot water introduces ions into a rock being metamorphosed, changing the chemical composition of the metasomatized rock from that of the parent rock.

Plate tectonic theory accounts for the features observed in metamorphic rocks and relates their development to other activities in Earth. In particular, plate tectonics explains (1) the deep burial of rocks originally formed at or near Earth's surface; (2) the intense squeezing necessary for the differential stress, implied by foliated rocks; (3) the presence of water deep within the lithosphere; and (4) the wide variety of pressures and temperatures believed to be present during metamorphism.

Terms to Remember

compressive stress 161
confining pressure 160
contact metamorphism 166
differential stress 161
ductile (plastic) 159
foliation 161
gneiss 166
hornfels 164
hydrothermal metamorphism 167
isotherm 174
marble 164
metamorphic rock 158
metamorphism 158
metasomatism 168
migmatite 170
parent rock (protolith) 158
phyllite 164
quartzite 164
regional metamorphism 168
schist 166
shearing 161
slate 164
stress 160
vein 168

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. What are the effects on metamorphic minerals and textures of temperature, confining pressure, and differential stress?
2. Describe the role of fluids during metamorphism and metasomatism.
3. Compare the pressure and temperature conditions of regional and contact metamorphism. How do regional metamorphic rocks commonly differ in texture from contact metamorphic rocks?
4. What is metamorphic grade? Describe what happens to (a) a shale and (b) a basalt as they are subjected to increasingly high-grade metamorphism.
5. How would you distinguish between: (a) schist and gneiss? (b) slate and phyllite? (c) quartzite and marble? (d) granite and gneiss?
6. Why would a builder choose to construct a building from quartzite blocks? Why might the builder choose to use marble?
7. Compare the metamorphic conditions at a convergent plate boundary to those at a divergent plate boundary.
8. Another term for parent rock is
   a. starter.
   b. primer.
   c. protolith.
   d. sediment.
9. Which of these is regarded as a low-grade metamorphic rock?
   a. migmatite
   b. schist
   c. slate
   d. gneiss
10. Foliation forms as a result of
    a. confining pressure.
    b. lithostatic pressure.
    c. differential stress.
    d. contact metamorphism.
11. Metamorphic rocks are classified primarily on
    a. texture—the presence or absence of foliation.
    b. mineralogy—the presence or absence of quartz.
    c. environment of deposition.
    d. chemical composition.
12. Which is *not* a foliated metamorphic rock?
    a. gneiss
    b. schist
    c. phyllite
    d. hornfels
13. Limestone recrystallizes during metamorphism into
    a. hornfels.
    b. marble.
    c. quartzite.
    d. schist.