

Metamorphic Rocks

A potter forms a delicate vase from moist clay. She places the soft piece in a kiln and slowly heats it to 1000°C. As temperature rises, the clay minerals decompose. Atoms from the clay then recombine to form new minerals that make the vase strong and hard. The breakdown of the clay minerals, growth of new minerals, and hardening of the vase all occur without melting. The reactions in a potter's kiln are called **solid-state reactions** because they occur in solid materials.

Chemical reactions occur more rapidly in liquid or gas than in a solid because atoms and molecules are more mobile in a fluid. However, with enough time and elevated temperature, atoms in solid rock also react. Small amounts of fluid, such as the water in the potter's clay, increase the mobility of atoms and speed the reactions, but the reactions take place in solid materials.

Metamorphism (from the Greek words for “changing form”) is the process by which rising temperature—and changes in other environmental conditions—transforms rocks and minerals. Metamorphism occurs in solid rock—like the transformations in the vase as the potter fires it in her kiln. Metamorphism can change any type of parent rock: sedimentary, igneous, or even another metamorphic rock.



Many metamorphic rocks show evidence of high temperature and plastic deformation. (J. M. Harrison/Geological Survey of Canada)



► 8.1 MINERAL STABILITY AND METAMORPHISM

A mineral that does not decompose or change in other ways, no matter how much time passes, is a **stable** mineral. Millions of years ago, weathering processes may have formed the clay minerals used by the potter to create her vase. They were stable and had remained unchanged since they formed. A stable mineral can become **unstable** when environmental conditions change. Three types of environmental change cause metamorphism: rising temperature, rising pressure, and changing chemical composition.

For example, when the potter put the clay in her kiln and raised the temperature, the clay minerals decomposed because they became unstable at the higher temperature. The atoms from the clay then recombined to form new minerals that were stable at the higher temperature. Like the clay, every mineral is stable only within a certain temperature range. In a similar manner, each mineral is stable only within a certain pressure range.

In addition, a mineral is stable only in a certain chemical environment. If fluids transport new chemicals to a rock, those chemicals may react with the original minerals to form new ones that are stable in the altered chemical environment. If fluids remove chemical components from a rock, new minerals may form for the same reason.

Metamorphism occurs because each mineral is stable only within a certain range of temperature, pressure, and chemical environment. If temperature or pressure rises above that range, or if chemicals are added to or removed from the rock, the rock's original minerals may decompose and their components recombine to form new minerals that are stable under the new conditions.

► 8.2 METAMORPHIC CHANGES

Metamorphism commonly alters both the texture and mineral content of a rock.

TEXTURAL CHANGES

As a rock undergoes metamorphism, some mineral grains grow larger and others shrink. The shapes of the grains may also change. For example, fossils give fossiliferous limestone its texture (Fig. 8–1). Both the fossils and the cement between them are made of small calcite crystals. If the limestone is buried and heated, some of the calcite grains grow larger at the expense of others. In the process, the fossiliferous texture is destroyed.



Figure 8–1 Fossils give this limestone its fossiliferous texture.

Metamorphism transforms limestone into a metamorphic rock called **marble** (Fig. 8–2). Like the fossiliferous limestone, the marble is composed of calcite, but the texture is now one of large interlocking grains, and the fossils have vanished.

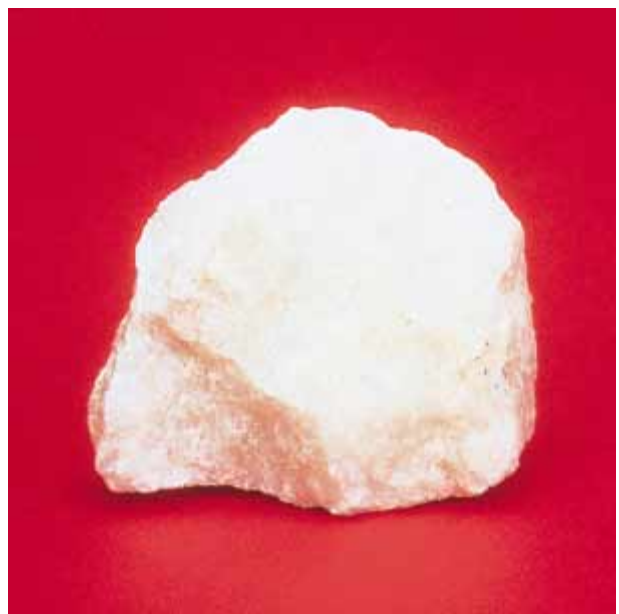


Figure 8–2 Metamorphism has destroyed the fossiliferous texture of the limestone in Figure 8–1 and replaced it with the large, interlocking calcite grains of marble.



Figure 8-3 Shale is a very fine-grained sedimentary rock, containing clay, quartz, and feldspar.



Figure 8-4 Hornfels forms by metamorphism of shale. The white spots are metamorphic minerals. (Geoffrey Sutton)

MINERALOGICAL CHANGES

As a general rule, when a parent rock (the original rock) contains only one mineral, metamorphism transforms the rock into one composed of the same mineral but with a coarser texture. The mineral content does not change because no other chemical components are available during metamorphism. Limestone converting to marble is one example of this generalization. Another is the metamorphism of quartz sandstone to **quartzite**, a rock composed of recrystallized quartz grains.

In contrast, metamorphism of a parent rock containing several minerals usually forms a rock with new and different minerals *and* a new texture. For example, a typical shale contains large amounts of clay, as well as quartz and feldspar (Fig. 8-3). When heated, some of those minerals decompose, and their atoms recombine to form new minerals such as mica, garnet, and a different kind of feldspar. Figure 8-4 shows a rock called **hornfels** that formed when metamorphism altered both the texture and minerals of shale.

If migrating fluids change the chemical composition of a rock, new minerals invariably form. These effects are discussed further in Section 8.3.

DEFORMATION AND FOLIATION

Changes in temperature, pressure, or the chemical environment alter a rock's texture during metamorphism. But another factor also causes profound textural changes. Metamorphic rocks commonly form in large regions of the Earth's crust near a subduction zone, where two tectonic plates converge. The tectonic forces crush, break, and bend rocks in this environment as the rocks are undergoing metamorphism. This combination of metamorphism and **deformation** creates layering in the rocks.

Micas are common metamorphic minerals; they form as many different parent rocks undergo metamorphism. Recall from Chapter 3 that micas are shaped like pie plates. When metamorphism occurs without deformation, the micas grow with random orientations, like pie plates flying through the air (Fig. 8-5). However, when metamorphism and deformation occur together, the

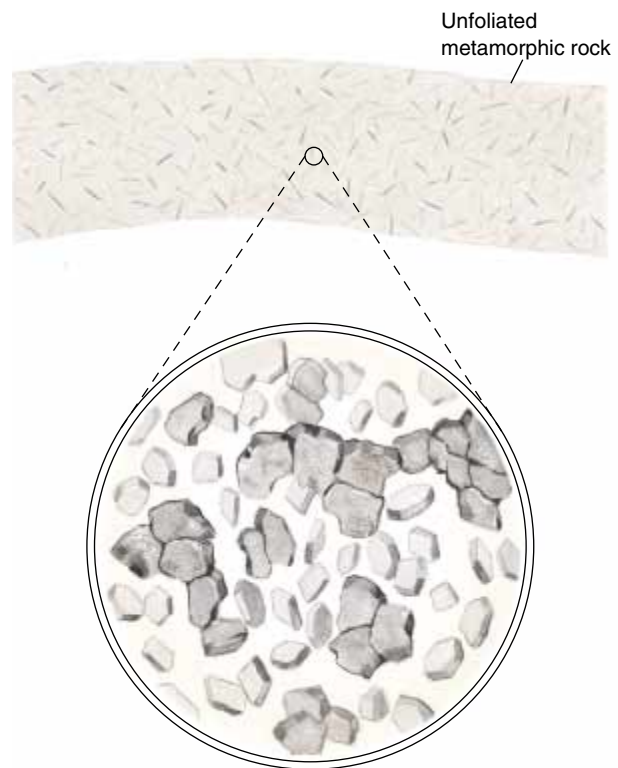


Figure 8-5 When metamorphism occurs without deformation, platy micas grow with random orientations.

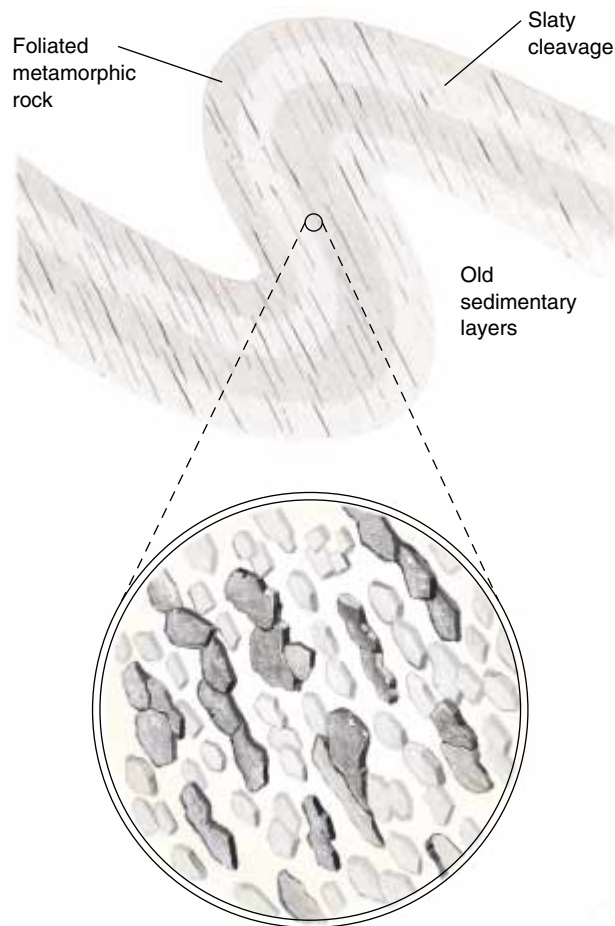


Figure 8-6 When deformation accompanies metamorphism, platy micas orient in a parallel manner to produce metamorphic layering called foliation.

micas develop a parallel orientation. This parallel alignment of micas (and other minerals) produces the metamorphic layering called **foliation** (Fig. 8-6). The layers range from a fraction of a millimeter to a meter or more in thickness. Metamorphic foliation can resemble sedimentary bedding but is different in origin.

Micas and other platy minerals orient at right angles to the tectonic force squeezing the rocks. Pencil-shaped minerals such as amphiboles align in a similar manner. When horizontal forces deform shale into folds during metamorphism, the clays decompose and micas grow with their flat surfaces perpendicular to the direction of squeezing. As a result, the rock develops vertical foliation—perpendicular to the horizontal force. Many metamorphic rocks break easily along the foliation planes. This parallel fracture pattern is called **slaty cleavage** (Fig. 8-7). In most cases, slaty cleavage cuts across the original sedimentary bedding.



Figure 8-7 Horizontal compression formed this tight fold in interbedded shale and sandstone. Slaty cleavage developed in the shale but not in the sandstone. (Karl Mueller)

METAMORPHIC GRADE

Metamorphic grade expresses the intensity of metamorphism that affected a rock. Because temperature is the most important factor in metamorphism, metamorphic grade closely reflects the highest temperature attained during metamorphism. Geologists can interpret the metamorphic grade of most rocks because many metamorphic minerals form only within certain temperature ranges.

The temperature in shallow parts of the Earth's crust rises by an average of 30°C for each kilometer of depth. It continues to rise in deeper parts of the crust and in the mantle, but at a lesser rate. The rate at which temperature increases with depth is called the **geothermal gradient**. Consequently, the metamorphic grade of many rocks is related to the depth to which they were buried (Fig. 8-8). Low-grade metamorphism occurs at shallow depths, less than 10 to 12 kilometers beneath the surface, where temperature is below 350°C. High-grade conditions are found deep within continental crust and in the upper mantle, 40 or more kilometers below the Earth's surface. The temperature in these regions is 600°C or hotter and is near the melting point of rock. High-grade metamorphism can occur at shallower depths, where magma rises to a shallow level of the Earth's crust.

THE RATE OF METAMORPHISM

A rule of thumb among laboratory chemists is that the speed of a chemical reaction doubles with every 10°C

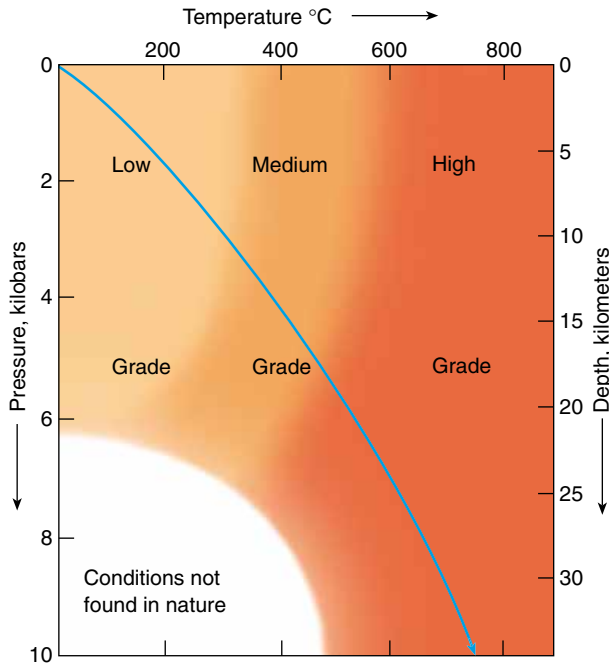


Figure 8-8 Metamorphic grade commonly increases with depth because the Earth becomes hotter with increasing depth. The blue line traces an average geothermal gradient: the path of temperature and pressure in an average part of continental crust.

rise in temperature. Thus, reactions occur slowly in a cold environment, but rapidly in a hot one. For the same reason, metamorphic changes occur slowly at low temperature, but much faster at high temperature. For example, clay minerals in 20-million-year-old shale buried to a depth of 2 to 3 kilometers in the Mississippi River delta show mineralogical changes at 50°C, about the temperature of a cup of hot coffee. Elsewhere, similar clays at the same temperature, but only 1 million years old, show no changes. Thus, metamorphism can occur at temperatures as low as 50°C, but the reactions require millions of years.¹ In contrast, geologists routinely produce metamorphic reactions in the laboratory at temperatures above 500°C in a few days.

The upper limit of metamorphism is the point at which rocks melt to form magma. That temperature varies depending on rock composition, pressure, and amount of water present, but it is between 600° and 1200°C for most rocks. A rock heated to its melting point creates magma, which forms igneous rocks when it solidifies.

¹Many geologists call mineral reactions that occur between 50°C and 250°C *diagenesis* and reserve the term *metamorphism* for changes that occur at temperatures above about 250°C.

Metamorphism refers only to changes that occur *without* melting.

8.3 TYPES OF METAMORPHISM AND METAMORPHIC ROCKS

Recall that three conditions cause metamorphism: rising temperature, rising pressure, and changing chemical environment. In addition, tectonic deformation develops foliation and thus strongly affects the texture of a metamorphic rock. These conditions occur in four geologic environments.

CONTACT METAMORPHISM

Contact metamorphism occurs where hot magma intrudes cooler country rock. The country rock may be of any type—sedimentary, metamorphic, or igneous. The highest-grade metamorphic rocks form at the contact, closest to the magma. Lower-grade rocks develop farther out (Fig. 8-9). A metamorphic halo around a pluton can range in width from less than a meter to hundreds of meters, depending on the size and temperature of the intrusion and the effects of water or other fluids.

Contact metamorphism commonly occurs without deformation. As a result, the metamorphic minerals grow with random orientations—like the pie plates flying through the air—and the rocks develop no metamorphic layering.

Common Contact Metamorphic Rocks

The hornfels shown in Figure 8-4 is a hard, dark, fine-grained rock usually formed by contact metamorphism of shale. Mica and chlorite are common in the cooler, outer parts of a hornfels halo. Hornblende and other amphiboles occur in the middle of the halo, and pyroxenes can form next to the pluton, in the highest-temperature zone. Quartz and feldspar are common throughout the halo, because they are stable over a wide temperature range.

BURIAL METAMORPHISM

Burial metamorphism results from deep burial of rocks in a sedimentary basin. A large river carries massive amounts of sediment to the ocean every year, where it accumulates on a delta. Over tens or even hundreds of millions of years, the weight of the sediment becomes so great that the entire region sinks isostatically, just as a canoe sinks when you climb into it. Younger sediment may bury the oldest layers to a depth of more than 10 kilometers in a large basin.

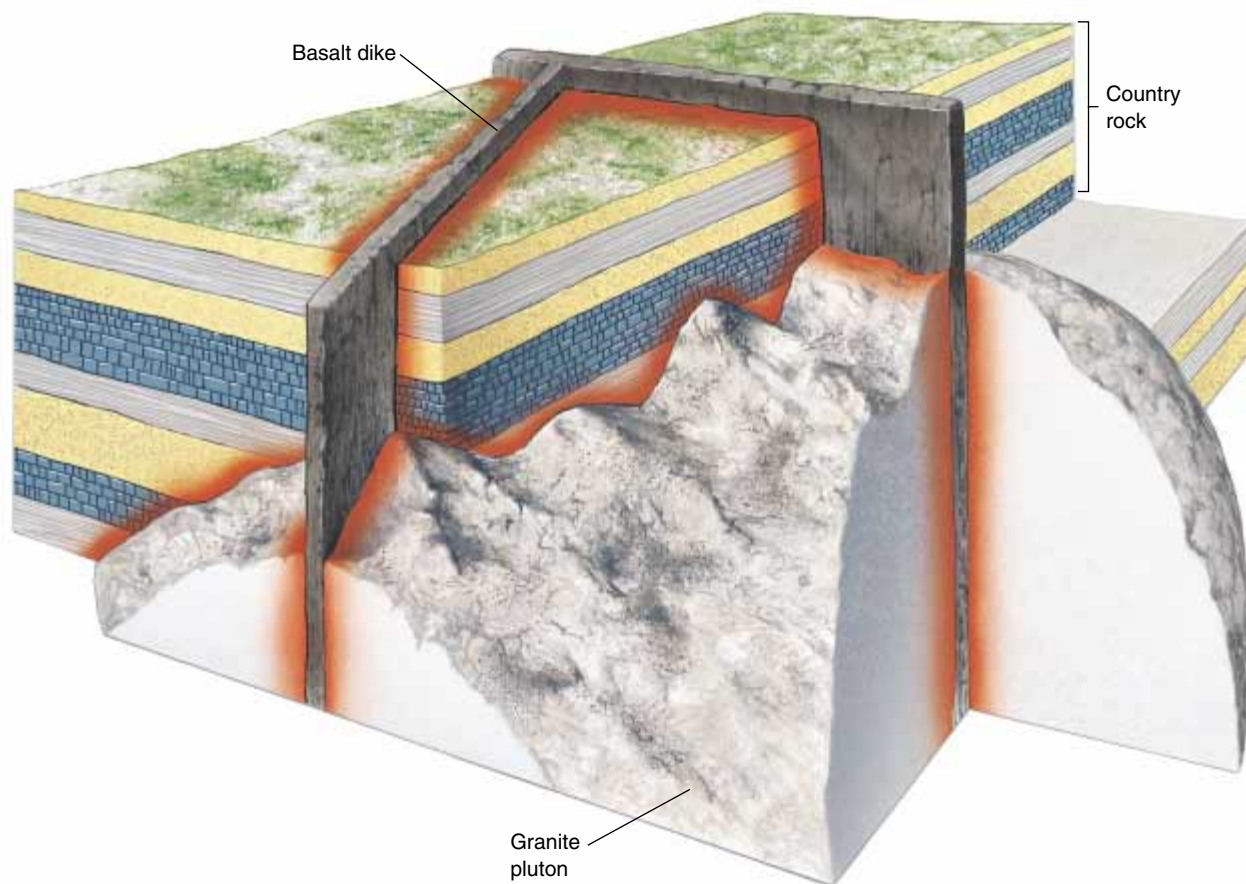


Figure 8–9 A halo of contact metamorphism in red surrounds a pluton. The later intrusion of the basalt dike metamorphosed both the pluton and the sedimentary rock.

Pressure is commonly expressed in kilobars. One kilobar is approximately equal to 1000 times the pressure of the atmosphere at sea level.² Because rocks are heavy, pressure within the Earth increases rapidly with depth, at a rate of about 0.3 kilobar per kilometer. Over time, temperature and pressure increase within the deeper layers until burial metamorphism begins.

Geologists have studied sedimentary basins in detail because most of the world's oil and gas form in them. Thousands of wells have been drilled into the Mississippi River basin, where burial metamorphism is occurring today. Temperature measurements made in the wells (the deepest of which reaches a depth of about 8 kilometers), combined with rock samples recovered as the wells were drilled, allow geologists to identify the mineralogical changes that occur with increasing depth and temperature.

²By international agreement, geologists now express pressure in units of *gigapascals* (Gpa). One Gpa is equal to 10 kilobars. We continue to use kilobars in this text because it is a more familiar unit of pressure.

No metamorphic changes occur in the upper 2 kilometers of the Mississippi delta sediment. In this zone, pressure compacts the clay-rich mud and squeezes most of the water from the sediment. The water rises and returns to the ocean.

At about 2 kilometers, however, where the temperature reaches 50°C,³ the original clay minerals decompose, and their components recombine to form new, different clays. At greater depths and higher temperatures, the clays continue to react and change character. At the greatest depths attained in the basin, corresponding to temperatures of about 250° to 300°C, the clay minerals have completely transformed to mica and chlorite. Similar metamorphic reactions are occurring today in the sediments underlying many large deltas, including the Amazon Basin on the east coast of South America and the Niger River delta on the west coast of Africa.

³50°C does not correspond to a depth of 2 kilometers in a region with a normal geothermal gradient. The gradient in these sediments is abnormally low because shallow parts of the delta are filled with young, cold sediment.



Figure 8–10 Argillite forms this cliff in western Montana.

Burial metamorphism occurs without tectonic deformation. Consequently, metamorphic minerals grow with random orientations and, like contact metamorphic rocks, burial metamorphic rocks are unfoliated.

Common Burial Metamorphic Rocks

Because of the lack of deformation, rocks formed by burial metamorphism often retain sedimentary structures. Shale and siltstone become harder and better lithified to form **argillite** (Fig. 8–10), which looks like the parent rock although new minerals have replaced the original ones. Quartz sandstone becomes quartzite. When sandstone is broken, the fractures occur in the cement *between* the sand grains. In contrast, quartzite becomes so firmly cemented during metamorphism that the rock fractures *through* the grains. Burial metamorphism converts limestone and dolomite to marble.

REGIONAL METAMORPHISM

Regional metamorphism occurs in and near a subduction zone, where tectonic forces build mountains and deform rocks. It is the most common and widespread type of metamorphism and affects broad regions of the Earth's crust.

Figure 8–11 shows magma forming in a subduction zone, where oceanic lithosphere is sinking beneath a continent. As the magma rises, it heats large regions of the crust. The high temperatures cause new metamorphic minerals to form throughout the region. At the same time, the tectonic forces squeeze and deform rocks. The

rising magma further deforms the hot, plastic country rock as it forces its way upward. As a result of all of these processes acting together, regionally metamorphosed rocks are strongly foliated and are typically associated with mountains and igneous rocks. Regional metamorphism produces zones of foliated metamorphic rock tens to hundreds of kilometers across.

Common Rocks Formed by Regional Metamorphism

Shale consists of clay minerals, quartz, and feldspar and is the most abundant sedimentary rock. The mineral grains are too small to be seen with the naked eye and can barely be seen with a microscope. Shale undergoes a sequence of changes as metamorphic grade increases.

Figure 8–12 shows the temperatures at which certain metamorphic minerals are stable. Thus, it shows the sequence in which minerals appear, and then decompose, as metamorphic grade increases. As regional metamorphism begins, the clay minerals break down and are replaced by mica and chlorite. These new, platy minerals grow perpendicular to the direction of tectonic squeezing. As a result, the rock develops slaty cleavage and is called **slate** (Fig. 8–13b). With rising temperature and continued deformation, the micas and chlorite grow larger, and wavy or wrinkled surfaces replace the flat, slaty cleavage, giving **phyllite** a silky appearance (Fig. 8–13c).

As temperature continues to rise, the mica and chlorite grow large enough to be seen by the naked eye, and foliation becomes very well developed. Rock of this type is called **schist** (Fig. 8–13d). Schist forms approximately

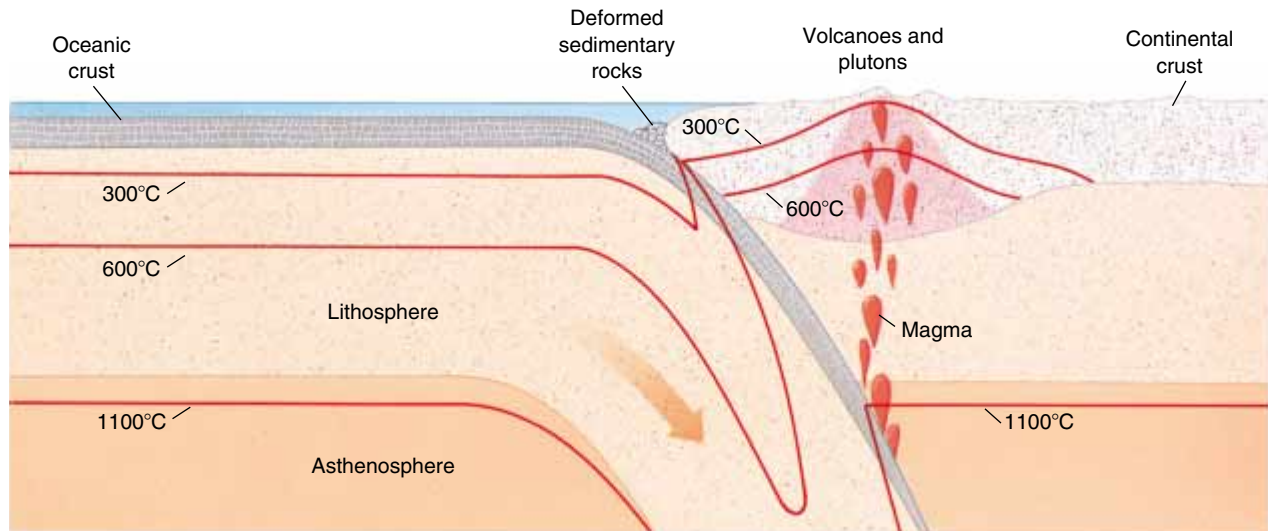


Figure 8-11 Regional metamorphism is common near a subduction zone. The pink shaded area is a zone where rising magma and tectonic force cause abnormally high temperatures and regional metamorphism. The red lines connect points of equal temperature and are called isotherms.

at the transition from low to intermediate metamorphic grades. In some schists, crystals of nonplaty minerals such as garnet, quartz, and feldspar give the rock a knotty appearance.

At high metamorphic grades, light- and dark-colored minerals often separate into bands that are thicker than the layers of schist to form a rock called **gneiss** (pronounced “nice”) (Fig. 8-13e). At the highest metamorphic grade, the rock begins to melt, forming small veins of granitic magma. When metamorphism wanes and the rock cools, the magma veins solidify to form **migmatite**, a mixture of igneous and metamorphic rock (Fig. 8-13f).

Under conditions of regional metamorphism, quartz sandstone and limestone transform to foliated quartzite and foliated marble, respectively.

HYDROTHERMAL METAMORPHISM

Water is a chemically active fluid; it attacks and dissolves many minerals. If the water is hot, it attacks minerals even more rapidly. **Hydrothermal metamorphism** (also called *hydrothermal alteration* and *metasomatism*) occurs when hot water and ions dissolved in the hot water react with a rock to change its chemical composition and minerals. In some hydrothermal environments, water reacts with sulfur minerals to form sulfuric acid, making the solution even more corrosive.

The water responsible for hydrothermal metamorphism can originate from three sources. **Magmatic water** is given off by a cooling magma. **Metamorphic water**

is released from rocks during metamorphism. Most hydrothermal alteration, however, is caused by circulating ground water—the water that saturates soil and bedrock. Cold ground water sinks through bedrock fractures to depths of a few kilometers, where it is heated by the hotter rocks at depth or, in some cases, by a hot, shallow pluton. Upon heating, the water expands and rises back toward the surface through other fractures (Fig. 8-14). As it rises, it alters the country rock through which it flows.

Rocks Formed by Hydrothermal Metamorphism

Hydrothermal metamorphism is like an accelerated form of weathering. As in weathering, feldspars and many other minerals of the parent rock dissolve. The hot water carries away soluble components, such as potassium, sodium, calcium, and magnesium. Aluminum and silicon remain because they have low solubilities. They combine with oxygen and water to form clay minerals. Hydrothermally metamorphosed rocks often have a white, bleached appearance and a soft consistency because the clays are white and soft.

Most rocks and magma contain low concentrations of metals such as copper, gold, lead, zinc, and silver. For example, gold makes up 0.0000002 percent of average crustal rock, while copper makes up 0.0058 percent and lead 0.0001 percent. Although the metals are present in very low concentrations, hydrothermal solutions sweep slowly through vast volumes of country rock, dissolving

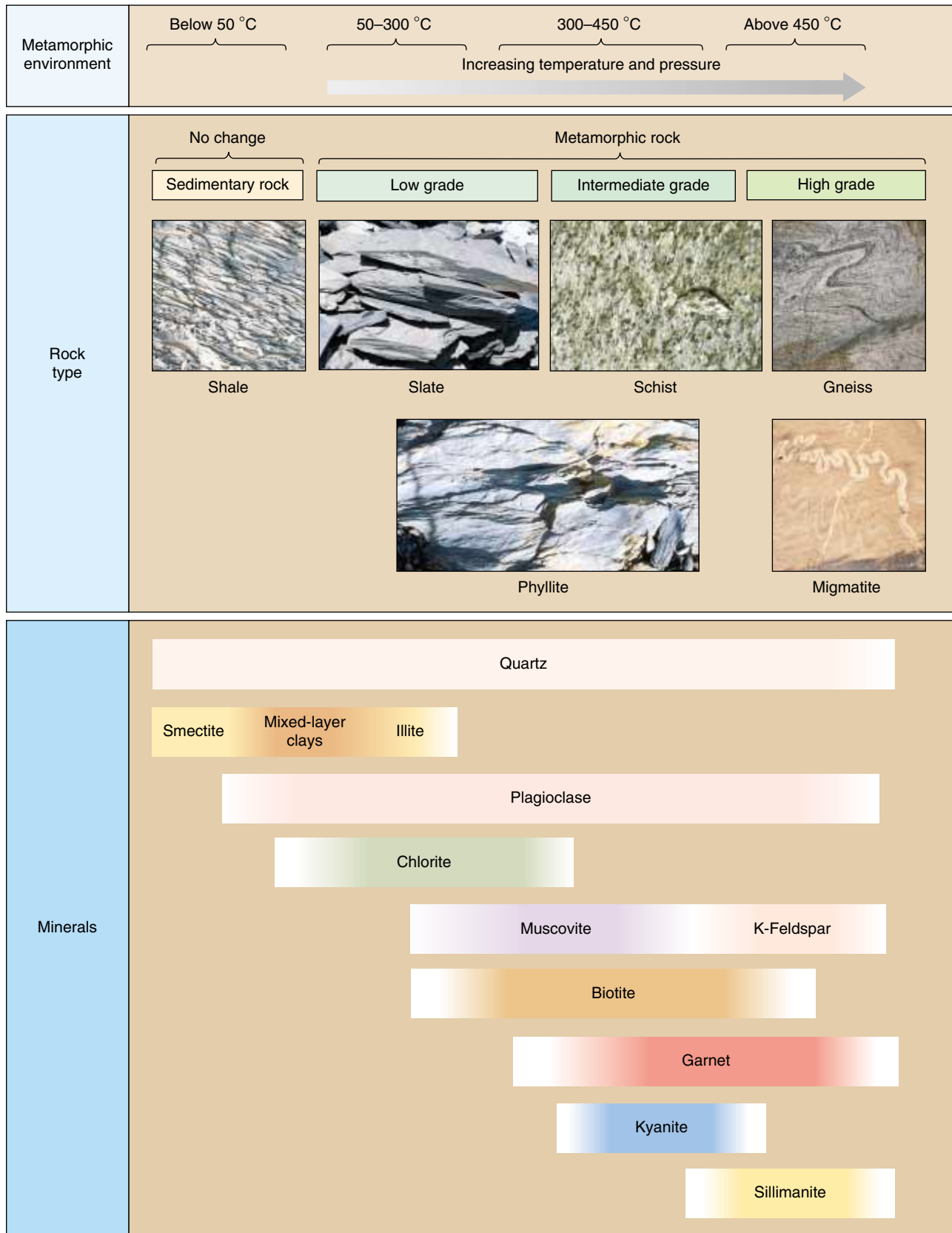


Figure 8–12 Shale changes in both texture and minerals as metamorphic grade increases. The lower part of the figure shows the stability ranges of common metamorphic minerals.



(a)



(b)



(c)



(d)



(e)



(f)

Figure 8–13 (a) Shale is the most common sedimentary rock. Regional metamorphism progressively converts shale to slate (b), phyllite (c), schist (d), and gneiss (e). Migmatite (f) forms when gneiss begins to melt.

and accumulating the metals as they go. The solutions then deposit the dissolved metals when they encounter changes in temperature, pressure, or chemical environment (Fig. 8–15). In this way, hydrothermal solutions

scavenge and concentrate metals from average crustal rocks and then deposit them locally to form ore. Hydrothermal ore deposits are discussed further in Chapter 19.

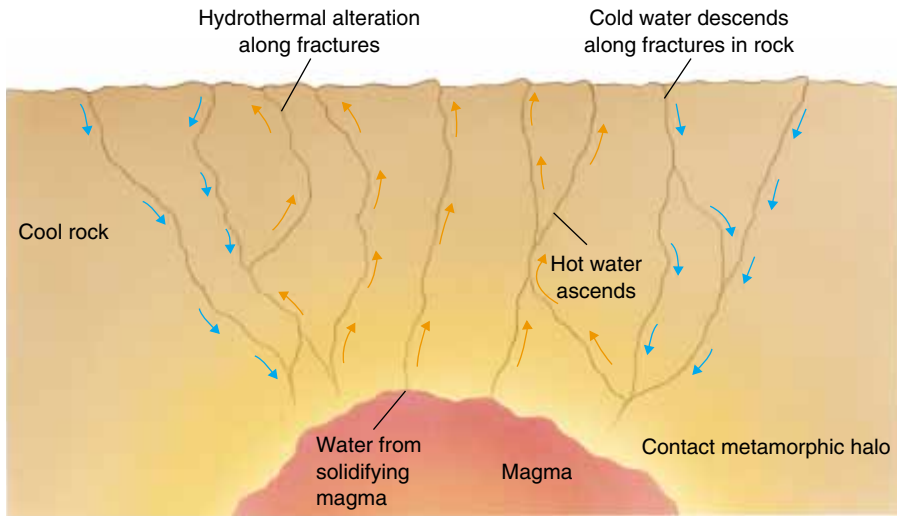


Figure 8-14 Ground water descending through fractured rock is heated by magma and rises through other cracks, causing hydrothermal metamorphism in nearby rock.

► 8.4 MEASURING METAMORPHIC GRADE

If you are studying a metamorphic rock exposed on the Earth's surface, it is impossible to measure the temperature and pressure at which it formed because the rock may have formed several kilometers beneath the surface and millions or even a few billion years ago. However, scientists estimate the temperature and pressure at which the rock formed using an experimental approach. They heat and apply pressure to chemical compounds similar to the composition of the rock until new minerals form. They then repeat the experiment at different temperatures and pressures until they duplicate the mineral con-

tent of the real rock. Thus, by comparing natural rocks with experimental results, scientists determine the temperature and pressure of metamorphism within 10° or 20°C and a fraction of a kilobar. This experimental approach is not reliable for the slow reactions that form low-grade metamorphic rocks, but it works well for determining the temperature and pressure at which higher-grade rocks formed.

METAMORPHIC FACIES

Imagine that you are studying the outcrop of metamorphic rock shown in Figure 8-16. One striking feature of this outcrop is that it contains two very different rocks,

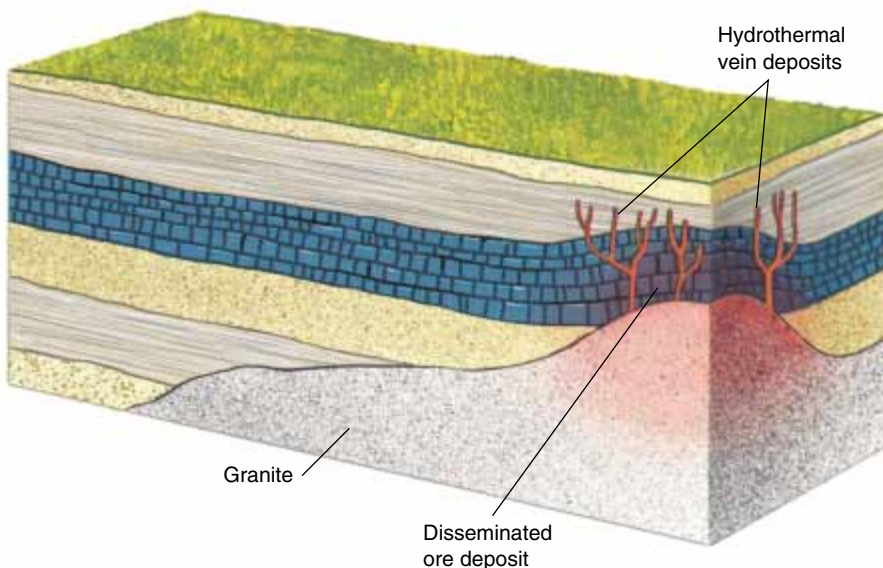


Figure 8-15 Hydrothermal ore deposits form when hot water deposits metals in fractures and surrounding country rock.



Figure 8-16 The same metamorphic conditions have converted limestone to white marble and shale to dark schist in this outcrop in Connecticut.

one consisting mostly of black minerals and the other of white ones. Recall that temperature, pressure, and composition control the mineral content of a metamorphic rock. You know that the metamorphic temperature and pressure must have been identical for the two rocks because they are so close together. Therefore, the difference in mineral content must result from a compositional contrast between the two rocks.

Ideally, all metamorphic rocks that formed under identical temperature and pressure conditions are grouped together into a single category called a **metamorphic facies**. Each rock differs from others in the same facies by having a different chemical composition and therefore a different mineral assemblage. Metamorphic facies differ from one another in that they form under different

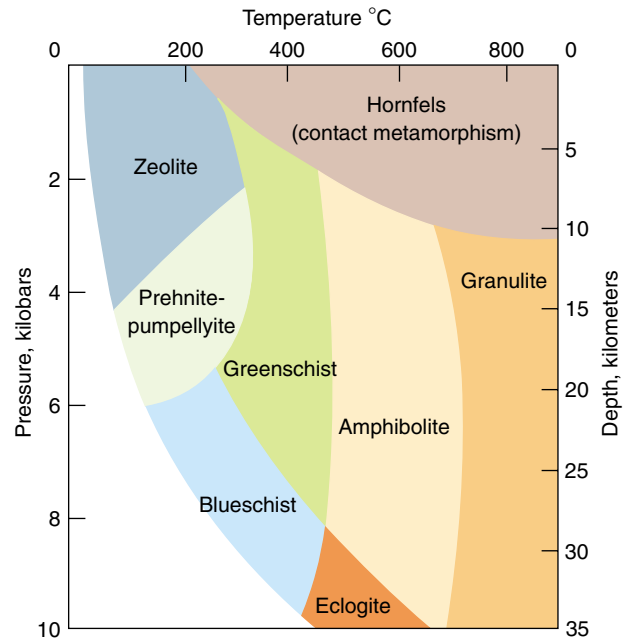


Figure 8-17 The names and metamorphic conditions of the metamorphic facies.

conditions of temperature and pressure. Each facies is given a name derived from a mineral and/or texture commonly found in rocks of that facies (Fig. 8-17).

Think of the white and black rocks shown in Figure 8-16. Initially, the white rock layers were limestone, and the black layers were shale. Limestone has a different composition from that of shale. Both rocks were metamorphosed at the temperature and pressure of the amphibolite facies. The limestone became marble. The shale converted to schist. Each contains different minerals because of their different original compositions. Both rocks, however different they may be, belong to the amphibolite facies because they both formed under the same temperature and pressure conditions.

SUMMARY

Metamorphism is the process by which solid rocks and minerals change in response to changing environmental conditions.

Most metamorphic reactions occur because each mineral is stable only within a certain range of temperature, pressure, and chemical environment. If temperature or pressure rises above that range, or if the chemical environment changes, the mineral decomposes and its components recombine to form a new mineral that is stable at the new conditions. Deformation creates **foliation**.

Both the texture and the minerals can change as a rock is metamorphosed. The mineralogy of a metamorphic rock reflects its **metamorphic grade**, the temperature and pressure at which it formed. Metamorphic grade is often expressed by the relative terms **low-**, **medium-**, and **high-grade metamorphism**.

Contact metamorphism occurs when an igneous intrusion heats nearby country rock. **Burial metamorphism** results from increasing temperature and pressure caused by burial of rocks, commonly within a sinking sedimen-

tary basin. Both types of metamorphism produce **nonfoliated** metamorphic rocks. **Regional metamorphism** forms **foliated** rocks. It is the most common type of metamorphism and is caused by rising temperature and pressure accompanied by tectonic deformation, commonly near a subduction zone. **Hydrothermal meta-**

morphism occurs when hot, migrating fluids change the chemical composition of country rock.

All metamorphic rocks that formed under identical temperature and pressure are grouped into a **metamorphic facies**.

Important Metamorphic Rocks

Marble Phyllite	Quartzite Schist	Hornfels Gneiss	Argillite Migmatite	Slate
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REVIEW QUESTIONS

- Describe the two general kinds of changes that a rock undergoes during metamorphism.
- Describe four main factors that cause and control metamorphism.
- How does the nature of parent rock affect the products of metamorphism?
- What is the approximate temperature range over which metamorphism occurs? What factors define the upper and lower temperatures of metamorphism?
- Explain how deformation produces foliated textures in metamorphic rocks.
- Name and briefly describe each of the different types of metamorphism.
- Describe and name a rock that might result from contact metamorphism of a shale.
- What rock types might form by contact metamorphism of limestone?
- Describe and name the succession of metamorphic rocks that form as shale experiences progressively higher grades of regional dynamothermal metamorphism.
- Where does the water responsible for hydrothermal alteration originate?
- How does contact metamorphism differ from regional metamorphism?
- What is a metamorphic facies?

DISCUSSION QUESTIONS

- Discuss processes that might cause the composition of a rock to change during metamorphism. What would be the effects of a change in composition?
- Referring to Figure 8–8, what metamorphic grades would be expected to occur in rocks exposed to the following conditions? a. 400°C and 3 kilobars; b. 400°C and a depth of 12 kilometers; c. 600°C at the Earth's surface; d. 200°C and a depth of 15 kilometers. Referring to Figure 8–17, what metamorphic facies would be expected to form under the same sets of conditions?
- What types of metamorphic rocks would you expect to find in the following environments? a. adjacent to a hot spring in Yellowstone Park; b. in the Appalachian Mountains, which is an old region of mountain building caused by collision of two tectonic plates; c. at a depth of 6000 meters beneath southern Louisiana.
- Referring to Figure 8–17, what metamorphic facies would you expect to find at 600°C and at a depth of 20 kilometers?