Metamorphic Rocks

Causes of Metamorphism

Sediments and sedimentary rocks are products of Earth's surface environments, whereas igneous rocks are products of the magmas that originate in the lower crust and mantle. Metamorphic rocks are the products of processes acting on rocks at depths ranging from the upper to the lower crust.

When a rock is subjected to significant changes in temperature or pressure, it will, given enough time—short by geologic standards, but usually a million years or more—undergo changes in its chemical composition, mineralogy, and texture, or all three, until it is in equilibrium with the new temperature and pressure. A limestone filled with fossils, for example, may be transformed into a white marble in which no trace of fossils remains. The mineral and chemical composition of the rock may be unaltered, but its texture may have changed drastically, from small calcite crystals to large, interlocked calcite crystals that erase such former features as fossils. Shale, a well-bedded sedimentary rock so fine-grained that no individual crystal can be seen with the naked eye, may become schist, in which the original bedding is obscured and the texture is dominated by large crystals of mica. In this case, both mineralogy and texture have changed, but the overall chemical composition of the rock has remained the same.

Most metamorphic rocks are formed at depths of 10 to 30 km, in the middle to lower half of the crust. Only later are those rocks *exhumed,* or transported back to Earth's surface, where they may be exposed as outcrops. But metamorphism can also occur at Earth's surface. We can see metamorphic changes, for example, in the baked surfaces of soils and sediments just beneath volcanic lava flows.

The heat and pressure in Earth's interior and its fluid composition are the three principal factors that drive metamorphism. In much of Earth's crust, the temperature increases at a rate of 30°C per kilometer of depth, although that rate varies considerably among different regions, as we will see shortly. Thus, at a depth of 15 km, the temperature will be about 450°C—much higher than the average temperature at Earth's surface, which ranges from 10°C to

20°C in most regions. The contribution of pressure is the result of vertically oriented forces exerted by the weight of overlying rocks as well as horizontally oriented forces developed as the rocks are deformed by plate tectonic processes. The average pressure at a depth of 15 km amounts to about 4000 times the pressure at the surface.

The Role of Temperature

Heat can transform a rock's chemical composition, mineralogy, and texture by breaking chemical bonds and altering the existing crystal structures of the rock. When rock is moved from Earth's surface to its interior, where temperatures are higher, the rock adjusts to the new temperature. Its atoms and ions recrystallize, linking up in new arrangements and creating new mineral assemblages. Many new crystals grow larger than the crystals in the original rock.

The increase in temperature with increasing depth in Earth's interior is called the *geothermal gradient.* The geothermal gradient varies among plate tectonic settings, but on average it is about 30°C per kilometer of depth. In areas where the continental lithosphere has been stretched and thinned, such as Nevada's Great Basin, the geothermal gradient is *steep* (for example, 50°C per kilometer of depth). In areas where the continental lithosphere is old and thick, such as central North America, the geothermal gradient is *shallow* (for example, 20°C per kilometer of depth) (**Figure 6.2**).

Because different minerals crystallize and remain stable at different temperatures, we can use a rock's mineral composition as a kind of *geothermometer* to gauge the temperature at which it formed. For example, as sedimentary rocks containing clay minerals are buried deeper and deeper, the clay minerals begin to recrystallize and form new minerals, such as micas. With additional burial at greater depths and temperatures, the micas become unstable and begin to recrystallize into new minerals, such as garnet.

Plate tectonic processes such as subduction and continent-continent collision, which transport rocks and sediments into the hot depths of the crust, are the mechanisms that form most metamorphic rocks. In addition, limited metamorphism may occur where rocks are subjected to elevated temperatures near igneous intrusions. The heat is locally intense, but does not penetrate deeply; thus, the intrusions can metamorphose the surrounding country rock, but the effect is local in extent.

The Role of Pressure

Pressure, like temperature, changes a rock's chemical composition, mineralogy, and texture. Solid rock is subjected to two basic kinds of pressure, also called **stress:**

1. *Confining pressure* is a general force applied equally in all directions, like the pressure a swimmer feels under water. Just as a swimmer feels greater confining pressure when diving to greater depths, a rock descending to greater depths in Earth's interior is subjected to progressively increasing confining pressure in proportion to the weight of the overlying mass.
2. *Directed pressure*, or *differential stress*, is force exerted in a particular direction, as when you squeeze a ball of clay between your thumb and forefinger. Directed pressure is usually concentrated within particular zones or along discrete planes.

The compressive force exerted where lithospheric plates converge is a form of directed pressure, and it results in deformation of the rocks near the plate boundary. Heat reduces the strength of a rock, so directed pressure is likely to cause severe folding and other forms of ductile deformation, as well as metamorphism, where temperatures are high. Rocks subjected to differential stress may be severely distorted, becoming flattened in the direction the force is applied and elongated in the direction perpendicular to the force (**Figure 6.3**).

The minerals in a rock under pressure may be compressed, elongated, or rotated to line up in a particular direction, depending on the kind of stress applied to the rock. Thus, directed pressure guides the shape and orientation of the new crystals formed as minerals recrystallize under the influence of both heat and pressure. During the recrystallization of micas, for example, the crystals grow with the planes of their sheet silicate structures aligned perpendicular to the directed stress. The rock may develop a banded pattern as minerals of different compositions are segregated into separate planes.

Marble owes its remarkable strength to this recrystallization process. When limestone, a sedimentary rock, is heated to the very high temperatures that cause it to recrystallize, the original minerals and crystals become reoriented and tightly interlocked to form a very strong structure with no planes of weakness.

The pressure to which rock is subjected deep in Earth's crust is related to both the thickness and the density of the overlying rocks. Pressure, which is usually recorded in *kilobars* (1000 bars, abbreviated kbar), increases at a rate of 0.3 to 0.4 kbar per kilometer of depth (see Figure 6.1). One bar is approximately equivalent to the pressure of air at Earth's surface. A diver touring the deeper part of a coral reef at a depth of 10 m would experience an additional bar of pressure.

Minerals that are stable at the lower pressures near Earth's surface become unstable and recrystallize into new minerals under the increased pressures deep in Earth's crust. As we will see in Chapter 7, geologists have subjected rocks to extremely high pressures in the laboratory and recorded the pressures required to cause these changes. With these laboratory data in hand, we can examine the mineralogy and texture of metamorphic rock samples and infer what the pressures were in the area where they formed. Thus, metamorphic mineral assemblages can be used as pressure gauges, or *geobarometers.* Given a specific assemblage of minerals in a metamorphic rock, we can determine the range of pressures, and therefore the depth, at which the rock must have formed.

The Role of Fluids

Metamorphic processes can alter a rock's mineralogy by introducing or removing chemical components that are soluble in heated water. Hydrothermal fluids accelerate metamorphic chemical reactions because they carry dissolved carbon dioxide as well as other chemical substances—such as sodium, potassium, silica, copper, and zinc—that are soluble in hot water under pressure. As hydrothermal solutions percolate up to the shallower parts of the crust, they react with the rocks they penetrate, changing their chemical and mineral compositions and sometimes completely replacing one mineral with another without changing the rock's texture. This kind of change in a rock's composition by fluid transport of chemical substances into or out of it is called **metasomatism.** Many valuable deposits of copper, zinc, lead, and other metallic ores are

Regional Metamorphism

Regional metamorphism, the most widespread type of metamorphism, takes place where both high temperatures and high pressures are imposed over large parts of the crust. We use this term to distinguish this type of metamorphism from more localized transformations near igneous intrusions or faults. Regional metamorphism is a characteristic feature of convergent plate boundaries. It occurs in volcanic mountain belts, such as the Andes of South America, and in the cores of mountain chains produced by continent-continent collisions, such as the Himalaya of central Asia. These mountain chains are often linear features, so zones of regional metamorphism are often linear in their distribution. In fact, geologists usually interpret regionally extensive belts of metamorphic rocks as representing sites of former mountain chains that were eroded over millions of years, exposing the rocks at their core.

Some regional metamorphic belts are created by the high temperatures and moderate to high pressures near volcanic mountain belts formed where subducted plates sink deep into the mantle. Others are formed under the very high pressures and temperatures found deeper in the crust along boundaries where colliding continents deform rock and raise high mountain chains. In both cases, the metamorphosed rocks are typically transported to great depths in Earth's crust, then eventually uplifted, exposed, and eroded at Earth's surface. A full understanding of the patterns of regional metamorphism, including how rocks respond to systematic changes in temperature and pressure over time, depends on an understanding of the specific plate tectonic settings in which metamorphic rocks form. We will discuss that topic later in this chapter.

Contact Metamorphism

In **contact metamorphism,** the heat from an igneous intrusion metamorphoses the rock immediately surrounding it. This type of localized transformation normally affects only a thin zone of country rock along the zone of contact. In many contact metamorphic rocks, especially at the margins of shallow intrusions, the mineral and chemical transformations are largely related to the high temperature of the intruding magma. Pressure effects are important only where the magma is intruded at great depths. Here, the pressure results not from the intrusion forcing its way into the country rock, but from the presence of regional confining pressure. Contact metamorphism by volcanic deposits is limited to very thin zones because lavas cool quickly at Earth's surface and their heat has little time to penetrate the surrounding rocks deeply and cause metamorphic changes. Contact metamorphism may also affect xenoliths that are not completely melted. Blocks of rock up to several meters wide may be torn off the sides of magma chambers and completely surrounded by hot magma. Heat projects

Plate Tectonics and Metamorphism

Soon after the theory of plate tectonics was proposed, geologists started to see how patterns of metamorphism fit into the larger framework of plate movements. Different types of metamorphism are likely to occur in different plate tectonic settings (see Figure 6.4):

- *Continental interiors.* Contact metamorphism, burial metamorphism, and perhaps regional metamorphism occur at different levels in the crust. Shock metamorphism is likely to be best preserved in continental interiors because their large areal extent provides a large target area to record rare meteorite impact events.
- *Divergent plate boundaries.* Seafloor metamorphism and contact metamorphism around plutons intruding into the oceanic crust occur at divergent plate boundaries.
- *Convergent plate boundaries.* Regional metamorphism, high-pressure and ultra-high-pressure metamorphism, and contact metamorphism.
- *Transform faults.* In oceanic settings, seafloor metamorphism may occur. In both oceanic and continental settings, we find extensive metamorphism caused by shearing forces along transform faults.