Section 6.3

Objectives

- **Compare and contrast** the different types and causes of metamorphism.
- **Distinguish** among metamorphic textures.
- **Explain** how mineral and compositional changes occur during metamorphism.
- **Apply** the rock cycle to explain how rocks are classified.

Review Vocabulary

intrusive: rocks that form from magma that cooled and crystallized slowly beneath Earth's surface

New Vocabulary

foliated
nonfoliated
regional metamorphism
contact metamorphism
hydrothermal metamorphism
rock cycle

Metamorphic Rocks

MAIN Idea Metamorphic rocks form when preexisting rocks are exposed to increases in temperature and pressure and to hydrothermal solutions.

Real-World Reading Link When you make a cake, all of the individual ingredients that you put into the pan change into something new. When rocks are exposed to high temperatures, their individual characteristics also change into something new and form a completely different rock.

Recognizing Metamorphic Rock

The rock layers shown in **Figure 6.14** have been metamorphosed (meh tuh MOR fohzd)—this means that they have been changed. How do geologists know that this has happened? Pressure and temperature increase with depth. When temperature or pressure becomes high enough, rocks melt and form magma. But what happens if the rocks do not reach the melting point? When high temperature and pressure combine and change the texture, mineral composition, or chemical composition of a rock without melting it, a metamorphic rock forms. The word *metamorphism* is derived from the Greek words *meta,* meaning *change*, and *morphé,* meaning *form.* During metamorphism, a rock changes form while remaining solid.

The high temperatures required for metamorphism are ultimately derived from Earth's internal heat, either through deep burial or from nearby igneous intrusions. The high pressures required for metamorphism come from deep burial or from compression during mountain building.

Figure 6.14 Strong forces were required to bend these rock layers into the shape they are today.
Hypothesize *the changes that occurred to the sediments after they were deposited.*

■ **Figure 6.15** Metamorphic minerals, such as mica, staurolite, garnet, and talc (shown above, clockwise from top left), occur in many colors, shapes, and crystal sizes. Colors can be dark or bright and crystal form can be unique.

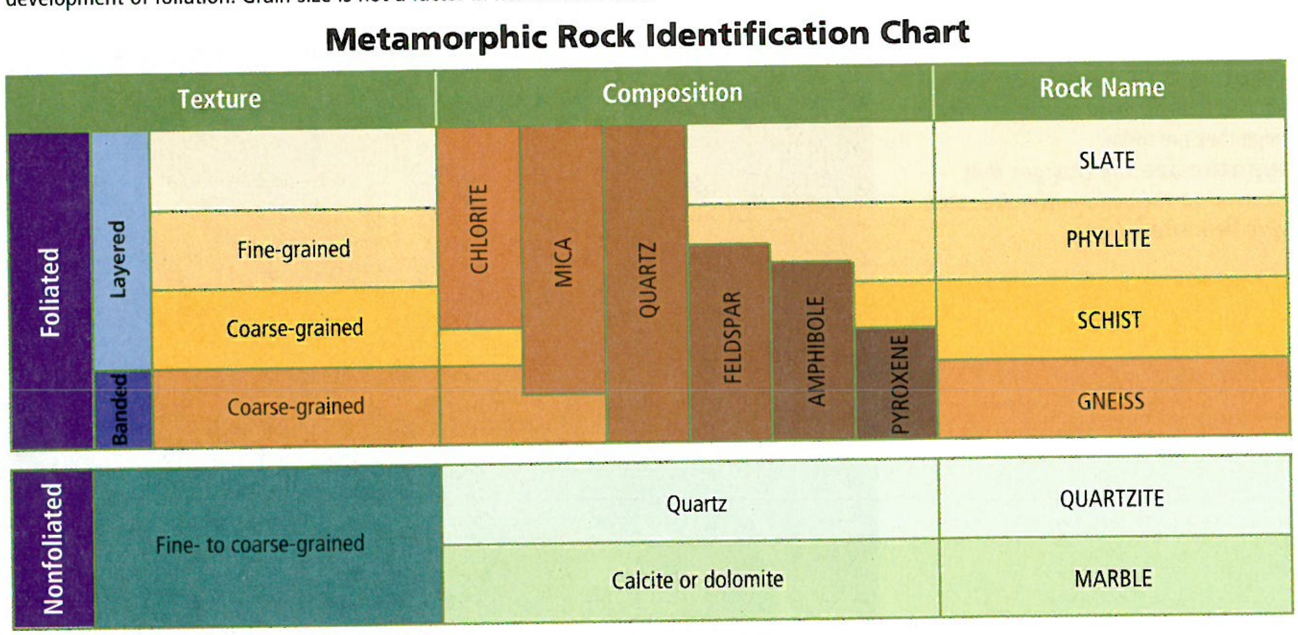
Metamorphic minerals How do minerals change without melting? Think back to the concept of fractional crystallization, discussed in Chapter 5. Bowen's reaction series shows that all minerals are stable at certain temperatures and they crystallize from magma along a range of different temperatures. Scientists have discovered that these stability ranges also apply to minerals in solid rock. During metamorphism, the minerals in a rock change into new minerals that are stable under the new temperature and pressure conditions. Minerals that change in this way are said to undergo solid-state alterations. Scientists have conducted experiments to identify the metamorphic conditions that create specific minerals. When the same minerals are identified in rocks, scientists are able to interpret the conditions inside the crust during the rocks' metamorphism. **Figure 6.15** shows some common metamorphic minerals.

✔ **Reading Check** **Explain** what metamorphic minerals are.

Metamorphic textures Metamorphic rocks are classified into two textural groups: foliated and nonfoliated. Geologists use metamorphic textures and mineral composition to identify metamorphic rocks. **Figure 6.16** shows how these two characteristics are used in the classification of metamorphic rocks.

Foliated rocks Layers and bands of minerals characterize **foliated** metamorphic rocks. High pressure during metamorphism causes minerals with flat or needlelike crystals to form with their long axes perpendicular to the pressure, as shown in **Figure 6.17.** This parallel alignment of minerals creates the layers observed in foliated metamorphic rocks.

■ **Figure 6.16** Increasing grain size parallels changes in composition and development of foliation. Grain size is not a factor in nonfoliated rocks.



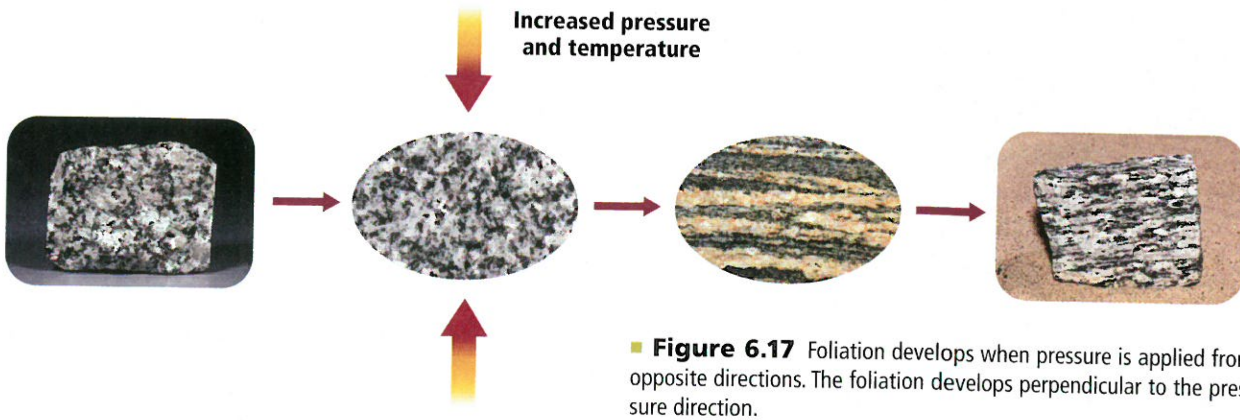
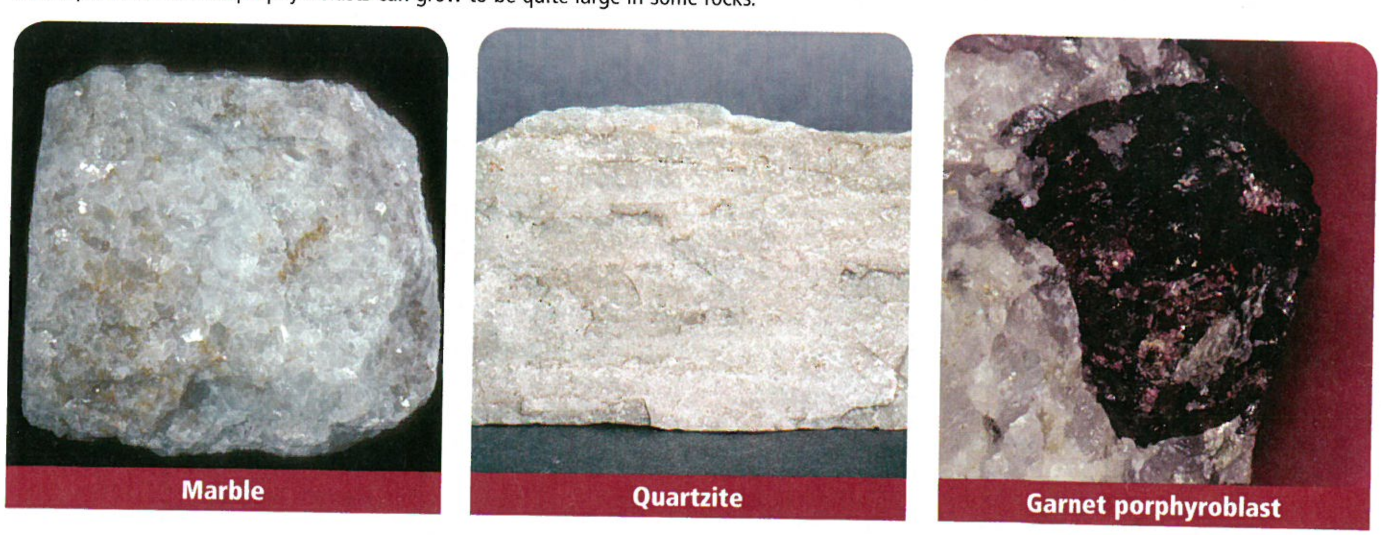


Figure 6.17 Foliation develops when pressure is applied from opposite directions. The foliation develops perpendicular to the pressure direction.

Nonfoliated rocks Unlike foliated rocks, **nonfoliated** metamorphic rocks are composed mainly of minerals that form with blocky crystal shapes. Two common examples of nonfoliated rocks, shown in **Figure 6.18,** are quartzite and marble. Quartzite is a hard, often light-colored rock formed by the metamorphism of quartz-rich sandstone. Marble is formed by the metamorphism of limestone. Some marbles have smooth textures that are formed by interlocking grains of calcite. These marbles are often used in sculptures. Fossils are rarely preserved in metamorphic rocks.

Under certain conditions, new metamorphic minerals can grow large while the surrounding minerals remain small. The large crystals, which can range in size from a few millimeters to a few centimeters, are called porphyroblasts. Although these crystals resemble the very large crystals that form in pegmatite granite, they are not the same. Instead of forming from magma, they form in solid rock through the reorganization of atoms during metamorphism. Garnet, shown in **Figure 6.18,** is, a mineral that commonly forms porphyroblasts.

Figure 6.18 As a result of the extreme heat and pressure during metamorphism, marble rarely contains fossils. Metamorphism does not, however, always destroy cross-bedding and ripple marks, which can be seen in some quartzites. Garnet porphyroblasts can grow to be quite large in some rocks.



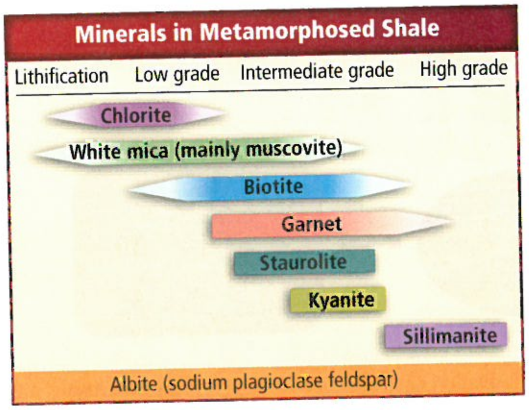


Figure 6.19 Metamorphism of shale results in the formation of minerals that provide the wide variety of color observed in slate.

Grades of Metamorphism

Different combinations of temperature and pressure result in different grades of metamorphism. Low-grade metamorphism is associated with low temperatures and pressures and a particular suite of minerals and textures. High-grade metamorphism is associated with high temperatures and pressures and a different suite of minerals and textures. Intermediate-grade metamorphism is in between low- and high-grade metamorphism.

Figure 6.19 shows the minerals present in metamorphosed shale. Note the change in composition as conditions change from low-grade to high-grade metamorphism. Geologists can create metamorphic maps by plotting the location of metamorphic minerals. Knowing the temperatures that certain areas experienced when rocks were forming helps geologists locate valuable metamorphic minerals such as garnet and talc. Studying the distribution of metamorphic minerals helps geologists to interpret the metamorphic history of an area.

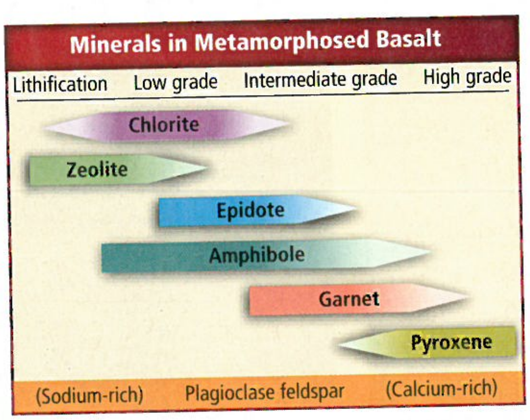
Types of Metamorphism

The effects of metamorphism can be the result of contact metamorphism, regional metamorphism, or hydrothermal metamorphism. The minerals that form and the degree of change in the rocks provide information as to the type and grade of metamorphism that occurred.

PROBLEM-SOLVING LAB

Interpret Scientific Illustrations

Which metamorphic minerals will form? The minerals that form in metamorphic rocks depend on the metamorphic grade and composition of the original rock. The figure below and **Figure 6.19** show the mineral groups that form under different metamorphic conditions.



Analysis

1. What mineral is formed when shale and basalt are exposed to low-grade metamorphism?
2. Under high-grade metamorphism, what mineral is formed in shale but not in basalt?

Think Critically

3. **Compare** the mineral groups that you would expect to form from intermediate-grade metamorphism of shale and basalt.
4. **Describe** the major compositional differences between shale and basalt. How are these differences reflected in the minerals formed during metamorphism?
5. **Explain** When limestone is metamorphosed, there is little change in mineral composition. Calcite is still the dominant mineral. Explain why this happens.

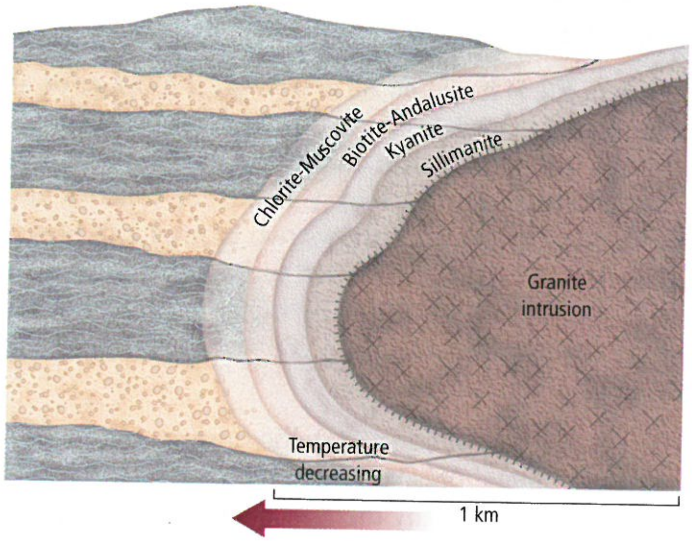


Figure 6.20 Contact metamorphism from the intrusion of this granite batholith has caused zones of metamorphic minerals to form.

Apply ***what you know about contact metamorphism to determine the type of rock that is now present along the edge of the intrusion.***

Regional metamorphism When high temperature and pressure affect large regions of Earth's crust, they produce large belts of **regional metamorphism.** The metamorphism can range in grade from low to high grade. Results of regional metamorphism include changes in minerals and rock types, plus folding and deforming of the rock layers that make up the area. The folded rock layers shown in **Figure 6.14** experienced regional metamorphism.

Contact metamorphism When molten material, such as that in an igneous intrusion, comes in contact with solid rock, a local effect called **contact metamorphism** occurs. High temperature and moderate-to-low pressure form mineral assemblages that are characteristic of contact metamorphism. **Figure 6.20** shows zones of different minerals surrounding an intrusion. Because temperature decreases with distance from an intrusion, metamorphic effects also decrease with distance. Recall from Chapter 5 that minerals crystallize at specific temperatures. Metamorphic minerals that form at high temperatures occur closest to the intrusion, where it is hottest. Because lava cools too quickly for the heat to penetrate far into surface rocks, contact metamorphism from extrusive igneous rocks is limited to thin zones.

Hydrothermal metamorphism When very hot water reacts with rock and alters its chemical and mineral composition, **hydrothermal metamorphism** occurs. The word *hydrothermal* is derived from the Greek words *hydro,* meaning *water,* and *thermal,* meaning *heat.* As hot fluids migrate in and out of the rock during metamorphism, the original mineral composition and texture of the rock can change. Chemical changes are common during contact metamorphism near igneous intrusions and active volcanoes. Valuable ore deposits of gold, copper, zinc, tungsten, and lead are formed in this manner. The gold deposited in the quartz shown in **Figure 6.21** is the result of hydrothermal metamorphism.

VOCABULARY

SCIENCE USAGE V. COMMON USAGE

Intrusion

Science usage: the placement of a body of magma into preexisting rock

Common usage: joining or coming into without being invited

Figure 6.21 When the hydrothermal solution in the quartz cooled, gold veins formed.

Economic Importance of Metamorphic Rocks and Minerals

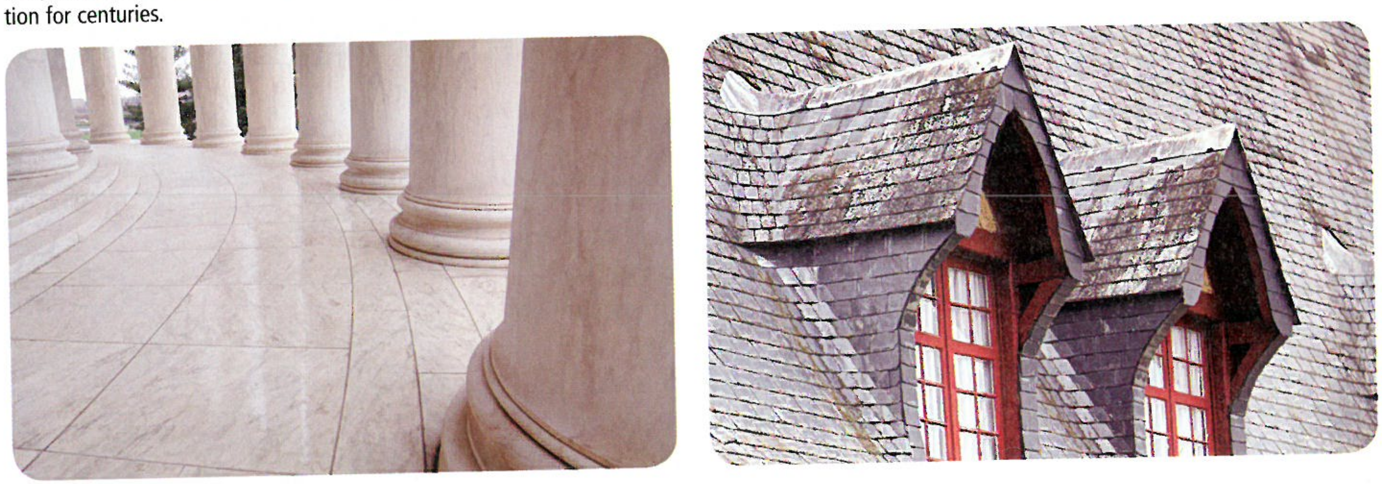
The modern way of life is made possible by a great number of naturally occurring Earth materials. We need salt for cooking, gold for trade, other metals for construction and industrial purposes, fossil fuels for energy, and rocks and various minerals for construction, cosmetics, and more. **Figure 6.22** shows two examples of how metamorphic rocks are used in construction. Many of these economic mineral resources are produced by metamorphic processes. Among these are the metals gold, silver, copper, and lead, as well as many significant nonmetallic resources.

Metallic mineral resources Metallic resources occur mostly in the form of metal ores, although deposits of pure metals are occasionally discovered, many metallic deposits are precipitated from hydrothermal solutions and are either concentrated in veins or spread throughout the rock mass. Native gold, silver, and copper deposits tend to occur in hydrothermal quartz veins near igneous intrusions or in contact metamorphic zones. However, most hydrothermal metal deposits are in the form of metal sulfides such as galena (PbS) or pyrite (FeS_2). The iron ores magnetite and hematite are oxide minerals often formed by precipitation from iron-bearing hydrothermal solutions.

Reading Check **State** what resources hydrothermal metamorphism produces.

Nonmetallic mineral resources Metamorphism of ultrabasic igneous rocks produces the minerals talc and asbestos. Talc, with a hardness of 1, is used as a dusting powder, as a lubricant, and to provide texture in paints. Because it is not combustible and has low thermal and electric conductivity, asbestos has been used in fireproof and insulating materials. Prior to the recognition of its cancer-causing properties, it was also widely utilized in the construction industry. Many older buildings still have asbestos-containing materials. Graphite, the main ingredient of the lead in pencils, may be formed by the metamorphism of coal.

Figure 6.22 Marble and slate are metamorphic rocks that have been used in construction for centuries.



The Rock Cycle

Metamorphic rocks form when other rocks change. The three types of rock—igneous, sedimentary, and metamorphic—are grouped according to how they form. Igneous rocks crystallize from magma; sedimentary rocks form from cemented or precipitated sediments; and metamorphic rocks form from changes in temperature and pressure.

Once a rock forms, does it remain the same type of rock always? Possibly, but it most likely will not. Heat and pressure can change an igneous rock into a metamorphic rock. A metamorphic rock can be changed into another metamorphic rock or melted to form an igneous rock. Alternately, the metamorphic rock can be weathered and eroded into sediments that might become cemented into a sedimentary rock. In fact, any rock can be changed into any other type of rock. The continuous changing and remaking of rocks is called the **rock cycle.** The rock cycle is summarized in **Figure 6.23.** The arrows represent the different processes that change rocks into different types.

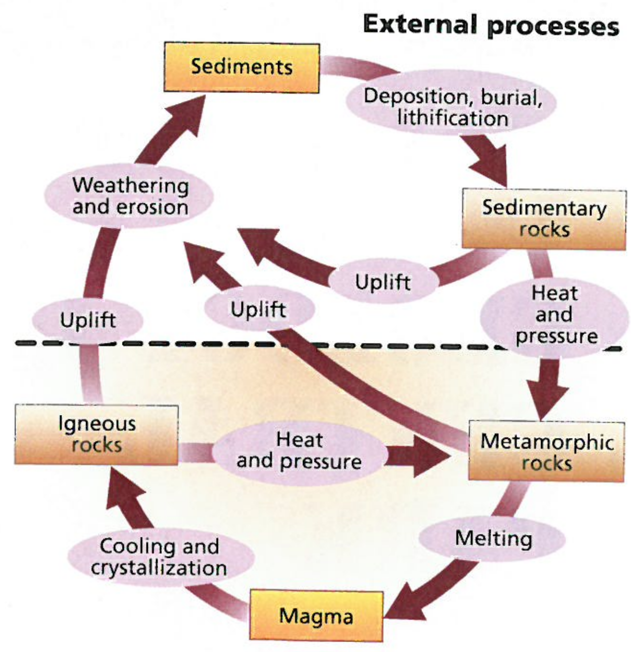


Figure 6.23 Rocks are continually being changed above and beneath Earth's surface. The rock cycle shows some of the series of changes rocks undergo.

Section 6.3 Assessment

Section Summary

- The three main types of metamorphism are regional, contact, and hydrothermal.
- The texture of metamorphic rocks can be foliated or nonfoliated.
- During metamorphism, new minerals form that are stable under the increased temperature and pressure conditions.
- The rock cycle is the set of processes through which rocks continuously change into other types of rocks.

Understand Main Ideas

1. MAIN Idea **Summarize** how temperature increases can cause metamorphism.
2. **Summarize** what causes foliated metamorphic textures to form.
3. **Apply** the concept of the rock cycle to explain how the three main types of rocks are classified.
4. **Compare and contrast** the factors that cause the three main types of metamorphism.

Think Critically

5. **Infer** which steps in the rock cycle are skipped when granite metamorphoses to gneiss.
6. **Predict** the location of an igneous intrusion based on the following mineral data. Muscovite and chlorite were collected in the northern portion of the area of study; garnet and staurolite were collected in the southern portion of the area.

MATH in Earth Science

7. Gemstones often form as porphyroblasts. Gemstones are described in terms of carat weight. A carat is equal to 0.2 g or 200 mg. A large garnet discovered in New York in 1885 weighs 4.4 kg and is 15 cm in diameter. What is the carat weight of this gemstone?