Section 3.4

1 FOCUS

Section Objectives

3.11 **Predict** where most metamorphism takes place.

3.12 **Distinguish** contact metamorphism from regional metamorphism.

3.13 **Identify** the three agents of metamorphism and **explain** what changes they cause.

3.14 **Recognize** foliated metamorphic rocks and **describe** how they form.

3.15 **Classify** metamorphic rocks.

Reading Focus

Build Vocabulary L2

Paraphrase Explain vocabulary terms using words students know. For example, *contact metamorphism* occurs when two rocks come into contact with one another. *Regional metamorphism* takes place over a large region. *Foliated metamorphic rocks* have distinct layers. *Nonfoliated metamorphic rocks* do not. Once students are able to distinguish among the vocabulary terms, focus on the processes that cause the different types of metamorphism and the different types of metamorphic rock.

Reading Strategy L2

A.1. rock that forms when minerals recrystallize at right angles to the direction of pressure
A.2. Common example of foliated metamorphic rock is slate.
B.1. rock that does not have a banded texture
B.2. Common example of nonfoliated metamorphic rock is marble.

2 INSTRUCT

Formation of Metamorphic Rocks

Use Visuals L1

Figure 14 Ask students to describe the rocks. *(Sample answer: The rocks are folded and multicolored.)* **What force could cause the rocks to fold?** *(intense pressure)*
Visual

3.4 Metamorphic Rocks

Reading Focus

Key Concepts

- Where does most metamorphism take place?
- How is contact metamorphism different from regional metamorphism?
- What are three agents of metamorphism, and what kinds of changes does each cause?
- What are foliated metamorphic rocks, and how do they form?
- How are metamorphic rocks classified?

Vocabulary

- metamorphism
- contact metamorphism
- regional metamorphism
- hydrothermal solution
- foliated metamorphic rock
- nonfoliated metamorphic rock

Reading Strategy

Outlining Copy this outline beneath the outline you made for Section 3.3. Complete it as you read. Include points about how each of these rocks form, some of the characteristics of each rock type, and some examples of each.

III. Metamorphic Rocks
A. Foliated Rocks
1. ___?___
2. ___?___
B. Nonfoliated Rocks
1. ___?___
2. ___?___

Figure 14 Deformed Rock Intense pressures metamorphosed these rocks by causing them to fold as well as change composition.

Recall that metamorphic rocks form when existing rocks are changed by heat and pressure. **Metamorphism** is a very appropriate name for this process because it means *to change form.* Rocks produced during metamorphism often look much different from the original rocks, or parent rocks. The folds in the rocks shown in Figure 14 formed when the parent rocks were subjected to intense forces. These highly folded metamorphic rocks may also develop a different composition than the parent rocks had.

Formation of Metamorphic Rocks

Most metamorphic changes occur at elevated temperatures and pressures. These conditions are found a few kilometers below Earth's surface and extend into the upper mantle. Most metamorphism occurs in one of two settings—contact metamorphism or regional metamorphism.

Contact Metamorphism When magma intrudes—forces its way into—rock, contact metamorphism may take place. **During contact metamorphism, hot magma moves into rock.** Contact metamorphism often produces what is described as low-grade metamorphism. Such changes in rocks are minor. Marble, like that used to make the statue in Figure 15, is a common contact metamorphic rock. Marble often forms when magma intrudes a limestone body.

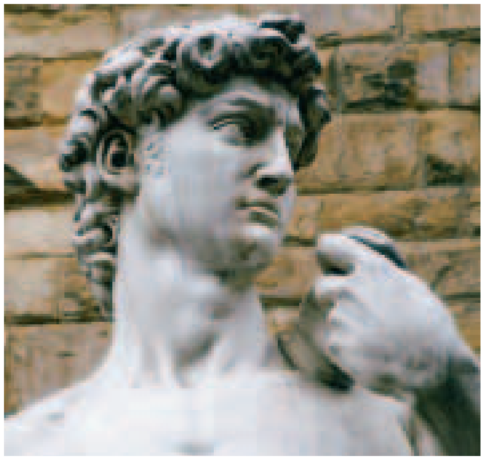


Figure 15 Statue Carved from Marble Marble is a common metamorphic rock that forms as the result of contact metamorphism of limestone.

Regional Metamorphism During mountain building, large areas of rocks are subjected to extreme pressures and temperatures. The intense changes produced during this process are described as high-grade metamorphism. **Regional metamorphism results in large-scale deformation and high-grade metamorphism.** The rocks shown in Figure 14 on page 80 were changed as the result of regional metamorphism.

Agents of Metamorphism

The agents of metamorphism are heat, pressure, and hydrothermal solutions. During metamorphism, rocks are usually subjected to all three of these agents at the same time. However, the effect of each agent varies greatly from one situation to another.

Heat The most important agent of metamorphism is heat. Heat provides the energy needed to drive chemical reactions. Some of these reactions cause existing minerals to recrystallize. Other reactions cause new minerals to form. The heat for metamorphism comes mainly from two sources—magma and the change in temperature with depth. Magma essentially "bakes" any rocks that are in contact with it. Heat also comes from the gradual increase in temperature with depth. In the upper crust, this increase averages between 20°C and 30°C per kilometer.

When buried to a depth of about 8 kilometers, clay minerals are exposed to temperatures of 150°C to 200°C. These minerals become unstable and recrystallize to form new minerals that are stable at these temperatures, such as chlorite and muscovite. In contrast, silicate minerals are stable at these temperatures. Therefore, it takes higher temperatures to change silicate minerals.

Reading Checkpoint *Compare and contrast contact and regional metamorphism.*

Q&A

Q *How hot is it deep in the crust?*

A The deeper a person goes beneath Earth's surface, the hotter it gets. The deepest mine in the world is the Western Deep Levels mine in South Africa, which is about 4 kilometers deep. Here, the temperature of the surrounding rock is so hot that it can scorch human skin. In fact, miners in this mine often work in groups of two. One miner mines the rock, and the other operates a large fan that keeps the worker cool.

Build Science Skills L2

Posing Questions Have students read the text about contact metamorphism and regional metamorphism. Then have them pose questions about the concepts that can be answered through experimentation, observation, or research. A sample question might be: During contact metamorphism, what causes the magma to move into the rock? *(Magma is less dense than surrounding rock so pressure forces it toward the surface. As it moves, it can come into contact with and alter surrounding rock.)*
Logical

Agents of Metamorphism

Integrate Physics L2

Buried rocks are subject to a force known as *confining pressure*, wherein pressure is applied equally in all directions. In contrast, *differential stress* is unequal force applied in different directions. Differential stress, which occurs during mountain-building, acts mainly along one plane. Rocks subjected to differential stress are shortened in the direction in which pressure is applied and lengthened in the direction perpendicular to the pressure. Have students observe while you squeeze a ball of clay between your palms. Ask: **Is this an example of confining pressure or differential stress?** *(differential stress)*
Kinesthetic, Visual

Customize for Inclusion Students

Behaviorally Disordered Minimize distractions for students with behavioral disorders. For example, have students sit near the front of the class so that they are focused on you, rather than their classmates. Before conducting any activities, make sure students clear off their desks. If necessary, provide storage space in the classroom for students' books and other materials.

Answer to . . .

Reading Checkpoint *Both processes change existing rocks into metamorphic rocks. Contact metamorphism is caused by magma and often produces slight changes in rocks. Regional metamorphism is large-scale deformation that can result in drastic changes to the rocks involved.*

Quick Lab

Observing Some of the Effects of Pressure on Mineral Grains L2

Objective
After completing this activity, students will be able to observe the effect of pressure on the rearrangement of mineral grains in a model rock.

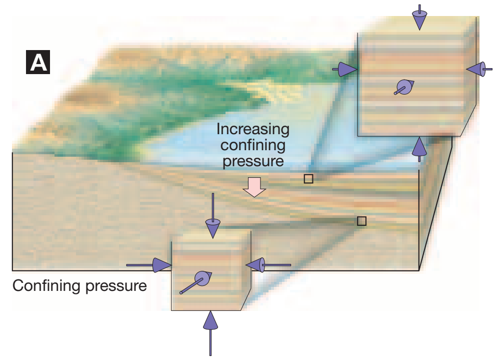
Skills Focus **Modeling, Observing, Inferring**

Prep Time 10 minutes to organize materials

Class Time 15 minutes

Expected Outcome Students will observe that the pressure from opposite directions—from above (their pushing down on the "rock") and below (the table's pushing up on the "rock")—will cause "minerals" to align at right angles to the direction of stress.

Analyze and Conclude
1. The model minerals were randomly distributed throughout the rock before pressure was applied. The minerals aligned themselves at right angles to the direction of stress.
2. Pressure causes the minerals to reorient themselves in the rock.
3. No, heat from the hand and contact with the table also affected the model rock.
Kinesthetic, Visual



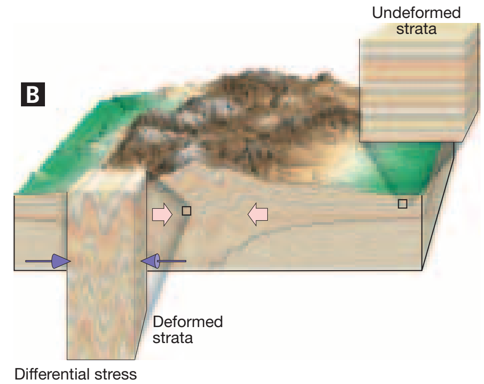


Figure 16 Pressure (Stress) As a Metamorphic Agent
A Forces in all directions are applied equally to buried rocks. **B** During mountain building, rocks subjected to differential stress are shortened in the direction that pressure is applied.

Figure 17 Imagine the tremendous amounts of pressure that caused these rocks to fold.

Pressure (Stress) Pressure, like temperature, also increases with depth. Like the water pressure you might have experienced at the bottom of a swimming pool, pressure on rocks within Earth is applied in all directions. See Figure 16. Pressure on rocks causes the spaces between mineral grains to close. The result is a more compact rock with a greater density. This pressure also may cause minerals to recrystallize into new minerals.

Increases in temperature and pressure cause rocks to flow rather than fracture. Under these conditions, mineral grains tend to flatten and elongate.

Quick Lab

Observing Some of the Effects of Pressure on Mineral Grains

Materials

soft modeling clay; 2 pieces of waxed paper (each 20 cm × 20 cm); 20–30 small, round, elongated plastic beads; small plastic knife

Procedure

1. Use the clay to form a ball about the size of a golf ball. Randomly place all of the beads into this model rock.
2. Make a sketch of the rock. Label the sketch *Before*.
3. Sandwich the model rock between the two pieces of waxed paper. Use your weight to apply pressure to the model rock.
4. Remove the waxed paper and observe your "metamorphosed" rock.
5. Draw a top view of your rock and label it *After*. Include arrows to show the directions from which you applied pressure.
6. Make a cut through your model rock. Sketch this view of the rock.

Analyze and Conclude

1. **Comparing and Contrasting** How did the *Before* sketch of your model rock compare with the *After* sketch?
2. **Drawing Conclusions** How does pressure affect the mineral grains in a rock?
3. **Inferring** Was pressure the only agent of change that affected your rock? Explain.

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During mountain building, horizontal forces caused by the collision of tectonic plates metamorphose large parts of the crust. This often produces intricately folded rocks like those in Figure 17.

Reactions in Solution Water solutions containing other substances that readily change to gases at the surface play an important role in some types of metamorphism. Solutions that surround mineral grains aid in recrystallization by making it easier for ions to move. When solutions increase in temperature reactions among substances can occur at a faster rate. When these hot, water-based solutions escape from a mass of magma, they are called **hydrothermal solutions.** These hot fluids also promote recrystallization by dissolving original minerals and then depositing new ones. As a result of contact with hydrothermal solutions, a change in a rock's overall composition may occur.

Classification of Metamorphic Rocks

Like igneous rocks, metamorphic rocks can be classified by texture and composition. **The texture of metamorphic rocks can be foliated or nonfoliated.**

Foliated Metamorphic Rocks When rocks undergo contact metamorphism, they become more compact and thus more dense. A common example is the metamorphic rock slate. Slate forms when shale is subjected to temperatures and pressures only slightly greater than those at which the shale formed. The pressure on the shale causes the microscopic clay minerals to become more compact. The increase in pressure also causes the clay minerals to align in a similar direction.

Under more extreme conditions, certain minerals will recrystallize. Some minerals recrystallize with a preferred orientation, which is at right angles to the direction of the force. The resulting alignment usually gives the rock a layered or banded appearance. This rock is called a **foliated metamorphic rock.** Gneiss, the metamorphic rock shown in Figure 18, is a foliated rock. Another foliated metamorphic rock is schist.

Nonfoliated Metamorphic Rocks A metamorphic rock that does not have a banded texture is called a **nonfoliated metamorphic rock.** Most nonfoliated rocks contain only one mineral. Marble, for example, is a nonfoliated rock made of calcite. When its parent rock, limestone, is metamorphosed, the calcite crystals combine to form the larger interlocking crystals seen in marble. A sample of marble is shown in Figure 19. Quartzite and anthracite are other nonfoliated metamorphic rocks.

Reading Checkpoint *Contrast foliated and nonfoliated metamorphic rocks.*

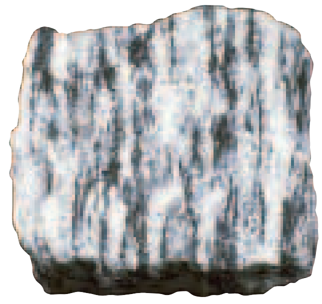


Figure 18 Gneiss is a foliated metamorphic rock.
Inferring ***In which directions was pressure exerted on this rock?***

Go Online SCI LINKS NSTA

For: Links on metamorphic rocks
Visit: www.SciLinks.org
Web Code: cjn-1033

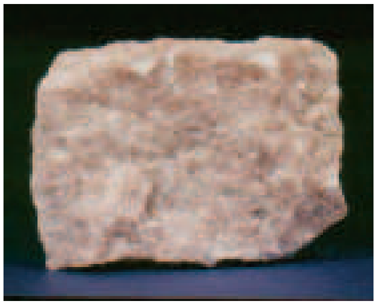


Figure 19 Marble is a nonfoliated metamorphic rock.

Classification of Metamorphic Rocks

Build Reading Literacy **L1**

Refer to **p.124D** in **Chapter 5**, which provides the guidelines for summarizing.

Summarize Have students read the text on page 83. In their own words, have them summarize how metamorphic rocks are classified. *(Sample answer: Metamorphic rocks are classified by texture. There are two kinds of textures—foliated and nonfoliated. Foliated metamorphic rocks have a layered look; nonfoliated metamorphic rocks do not have a layered appearance.)*

Verbal

Go Online NSTA SCI LINKS

Download a worksheet on metamorphic rocks for students to complete, and find additional teacher support from NSTA SciLinks.

Facts and Figures

Slate is a very fine-grained foliated rock composed of minute mica flakes. The most noteworthy characteristic of slate is its excellent rock cleavage, meaning that it splits easily into flat slabs. This property has made slate a most useful rock for roof and floor tiles, chalkboards, and billiard tables. Slate is most often generated by the low-grade metamorphism of shale, though less frequently it forms from the metamorphism of volcanic ash. Slate can be almost any color, depending on its mineral constituents. Black slate contains organic material; red slate gets it color from iron oxide; and green slate is usually composed of chlorite, a micalike mineral.

Answer to . . .

Figure 18 *Pressure was exerted from the sides.*

Reading Checkpoint *Foliated metamorphic rocks have a layered or banded appearance. Nonfoliated metamorphic rocks do not have a banded texture.*

Section 3.4 (continued)

Use Visuals **L1**

Table 3 Ask: **What is the parent rock of schist?** *(phyllite)* **Which has undergone more intense metamorphism, slate or gneiss? Explain your answer.** *(Gneiss has undergone more intense metamorphism, as indicated by the arrow in the table.)* **Which nonfoliated rock has the finest grains?** *(anthracite)*
Visual

3 ASSESS

Evaluate Understanding **L2**

Have students examine Table 3. Ask: **Generally, what can you say about the relationship between texture and increasing metamorphism that results in foliated rocks?** *(The more intense the metamorphism, the courser the texture, or larger the grain size.)*

Reteach **L1**

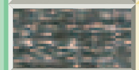
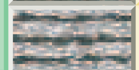
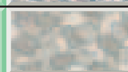
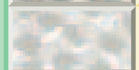
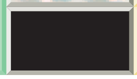
Have students make tables that compare and contrast contact metamorphism and regional metamorphism.

Writing in Science

Sample answer: All are solids that form and change because of Earth processes. All can be classified according to texture and/or composition. The major difference among the three rock types is that each forms at different temperatures and pressures.

To summarize, metamorphic rocks form when existing rocks are changed by heat, pressure, or hydrothermal solution. Contact metamorphism is often caused when hot magma intrudes a body of rock. Changes during this type of metamorphism are minor. Regional metamorphism is associated with mountain building. Such metamorphic changes can be extreme. Metamorphic rocks can be classified by texture as foliated or nonfoliated, as shown in Table 3.

Table 3 Classification of Major Metamorphic Rocks

Rock Name		Texture		Grain Size	Comments	Parent Rock
Slate	Increasing Metamorphism ↓	Foliated		Very fine	Smooth dull surfaces	Shale, mudstone, or siltstone
Phyllite		Foliated		Fine	Breaks along wavy surfaces, glossy sheen	Slate
Schist		Foliated		Medium to Coarse	Micaceous minerals dominate	Phyllite
Gneiss		Foliated		Medium to Coarse	Banding of minerals	Schist, granite, or volcanic rocks
Marble		Nonfoliated		Medium to coarse	Interlocking calcite or dolomite grains	Limestone, dolostone
Quartzite		Nonfoliated		Medium to coarse	Fused quartz grains, massive, very hard	Quartz sandstone
Anthracite		Nonfoliated		Fine	Shiny black organic rock that fractures	Bituminous coal

Section 3.4 Assessment

Reviewing Concepts

1. Where does most metamorphism take place?
2. Compare and contrast contact metamorphism and regional metamorphism.
3. Name the agents of metamorphism and explain how each changes a rock.
4. What are foliated rocks, and how do they form?
5. How are metamorphic rocks classified?

Critical Thinking

6. **Applying Concepts** What is the major difference between igneous and metamorphic rocks?
7. **Predicting** What type of metamorphism—contact or regional—would result in a schist? Explain your choice.
8. **Formulating Conclusions** Why can the composition of gneiss vary but overall texture cannot?

Writing in Science

Explanatory Paragraph Write a short paragraph that explains the major differences and similarities among the three major rock groups.

Section 3.4 Assessment

1. Most metamorphism takes place in a zone that begins several kilometers below the surface and extends into the upper mantle.
2. Contact metamorphism is a process whereby slight changes occur in rocks as the result of an increase in temperature resulting from a magma body. Regional metamorphism, which is associated with mountain-building, can result in high-grade changes in both composition and structure.
3. Heat can cause existing minerals to recrystallize or it can cause new minerals to form. Pressure produces a more compact rock with a greater density. Pressure also causes minerals to recrystallize. Fluids aid in recrystallization by making it easier for ions to move and by dissolving original minerals and depositing new ones.
4. Foliated rocks are banded metamorphic rocks that form when minerals realign as the result of pressure from opposing sides.
5. Metamorphic rocks can be classified according to composition and texture.
6. While both types of rocks form as the result of changes in temperature and pressure, metamorphism does not involve melting.
7. Schists, as indicated in Table 3, are the result of high-grade metamorphism that is generally associated with mountain-building.
8. Gneiss is a banded rock that forms as the result of pressure from opposing sides. This directional pressure results in foliation. However, because the parent rocks of gneisses can vary, so can the compositions of these metamorphic rocks.

earth as a SYSTEM

The Carbon Cycle

Carbon moves among Earth's major spheres by way of the carbon cycle. The carbon cycle is one of Earth's biogeochemical cycles. A biogeochemical cycle is a cycle in which matter and energy move through the Earth system in a series of steps. These steps in the carbon cycle have different flow characteristics: Some steps involve chemical changes, as when wood is burned, releasing carbon dioxide gas (CO_2). Other steps involve the movement of materials containing carbon. For example, during a volcanic eruption, carbon dioxide gas is released into the atmosphere. Some steps involve the life processes of living things.

At each step in the cycle, carbon is stored for varying lengths of time in different reservoirs, or parts of the Earth system. These reservoirs include the atmosphere, oceans, biomass, fossil fuels, and carbonate rocks. For example, carbon may be part of an organism's biomass for the short span of the organism's lifetime. But the carbon that makes up coal may remain in Earth for millions of years.

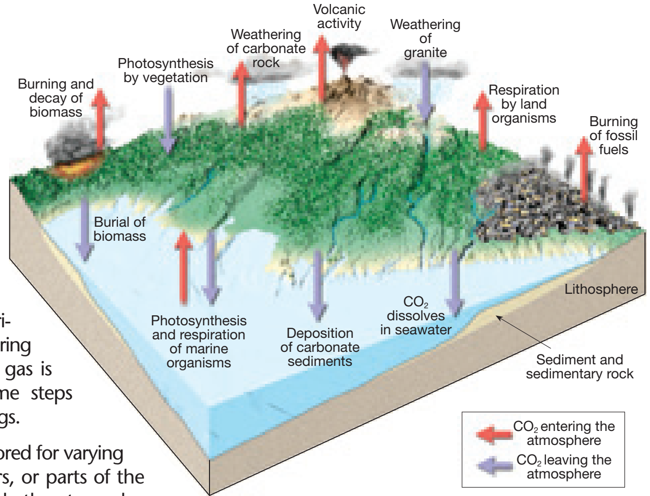


Figure 20 The Carbon Cycle

Carbon Dioxide on the Move

In the atmosphere, carbon is found mainly as carbon dioxide. The source of most CO_2 in the atmosphere is thought to be from volcanic activity early in Earth's history. Carbon dioxide moves into and out of the atmosphere by way of photosynthesis, respiration, organic decay, and combustion of organic material.

In photosynthesis, carbon dioxide gas is taken up by plants. Carbon thus becomes part of the compounds, called hydrocarbons, that make up living things. As a result, the biomass of all living organisms on Earth forms a major reservoir of carbon. Respiration, organic decay, and combustion release carbon from this reservoir back into the atmosphere as carbon dioxide.

Carbon and Fossil Fuels

The remains of once living things form another major reservoir of carbon. Some carbon from decayed organic matter is deposited as sediment. Over long periods of time, this carbon becomes buried. Under the right conditions, some of these carbon-rich deposits are changed to fossil fuels, such as coal. When fossil fuels are burned, carbon dioxide is released.

The Role of Marine Animals

Chemical weathering of certain rocks produce bicarbonate ions that dissolve in water. Rivers and streams carry these ions to the ocean. Here, some organisms extract this substance to produce shells and skeletons made of calcite ($CaCO_3$). When the organisms die, these hard parts settle to the ocean floor and become the sedimentary rock called limestone. If this rock is then exposed at the surface and subjected to chemical weathering, CO_2 is also produced. Use Figure 20 to follow the carbon cycle.

earth as a SYSTEM

The Carbon Cycle L2

Background

- During photosynthesis, plants absorb carbon dioxide from the atmosphere and use it to produce the essential organic compounds—complex sugars—that they need for growth. When animals consume plants or other animals that eat plants, the animals use these organic compounds as a source of energy. Then, through the process of respiration, the animals return carbon dioxide to the atmosphere. Plants also return some carbon dioxide to the atmosphere by way of respiration.
- When plants die and decay or are burned, this biomass is oxidized and carbon dioxide is returned to the atmosphere.
- The lithosphere is by far Earth's largest depository of carbon. A variety of rocks contain carbon. The most abundant is limestone. When limestone undergoes chemical weathering, the stored carbon is released into the atmosphere.

Teaching Tips

- Have students contrast different solids that contain carbon, such as coal, diamond, graphite, calcite, and limestone. Have students explain how the carbon is released from each of these components of the lithosphere into Earth's other spheres.
- Write the chemical equations for photosynthesis and respiration on the board or on an overhead transparency to reinforce the fact that the products of one reaction are the reactants of the other reaction.
- Use a clean, empty 2-L bottle, plants, soil, and a thermometer to make a mini-greenhouse to demonstrate how gases in the air, including carbon dioxide, can absorb solar energy. Refer to the following Web site for tips on such a demonstration: http://www.bigelow.org/virtual/handson/greenhouse_make.html