Formation of Metamorphic Rocks

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.

A. Foliated Rocks

1. rocks that form when minerals recrystallize at right angles to the direction of pressure
2. common example of foliated metamorphic rock is slate

B. Nonfoliated Rocks

1. rocks that do not have a banded texture
2. common example of nonfoliated metamorphic rock is marble

Reading Strategy

1. recall that metamorphic rocks form when existing rocks are changed by heat and pressure.
2. contact metamorphism occurs when two rocks come into contact with one another and the processes that cause the different types of metamorphism and the different types of metamorphic rock.
3. common example of foliated metamorphic rock is slate.
4. common example of nonfoliated metamorphic rock is marble.

Visual

Why does the rock have a striped appearance?

Recall that metamorphic rocks form when existing rocks are changed by heat and pressure.

Vocabulary

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

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.
**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.

**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.

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**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.

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**Build Science Skills**

**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**

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**

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**Answer to . . .**

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.
Chapter 3

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.

Observing Some of the Effects of Pressure on Mineral Grains

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

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 compare with the After sketch of your model rock?
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.

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.
During mountain building, horizontal forces metamorphose large segments of Earth's crust. This often produces intricately folded rocks like those shown 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 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.

Contrast foliated and nonfoliated metamorphic rocks.

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 its color from iron oxide; and green slate is usually composed of chlorite, a mica-like mineral.

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

Foliated metamorphic rocks have a layered look; nonfoliated metamorphic rocks do not have a layered appearance.

Inferring In which directions was pressure exerted on this rock?

Contrast foliated and nonfoliated metamorphic rocks.
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

<table>
<thead>
<tr>
<th>Rock Name</th>
<th>Texture</th>
<th>Grain Size</th>
<th>Comments</th>
<th>Parent Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slate</td>
<td>Fine</td>
<td>Medium</td>
<td>Smooth dull surfaces</td>
<td>Shale, mudstone, or siltstone</td>
</tr>
<tr>
<td>Phyllite</td>
<td>Medium</td>
<td>Coarse</td>
<td>Breaks along wavy surfaces, glossy sheen</td>
<td>Slate</td>
</tr>
<tr>
<td>Schist</td>
<td>Medium</td>
<td>Coarse</td>
<td>Micaceous minerals dominate</td>
<td>Phyllite</td>
</tr>
<tr>
<td>Gneiss</td>
<td>Medium</td>
<td>Coarse</td>
<td>Banding of minerals</td>
<td>Schist, granite, or volcanic rocks</td>
</tr>
<tr>
<td>Marble</td>
<td>None</td>
<td>Medium</td>
<td>Interlocking calcite or dolomite grains</td>
<td>Limestone, dolostone</td>
</tr>
<tr>
<td>Quartzite</td>
<td>None</td>
<td>Medium</td>
<td>Fused quartz grains, massive, very hard</td>
<td>Quartz sandstone</td>
</tr>
<tr>
<td>Anthracite</td>
<td>Fine</td>
<td>Medium</td>
<td>Shiny black organic rock that fractures</td>
<td>Bituminous coal</td>
</tr>
</tbody>
</table>

**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.
To illustrate the movement of material and energy in the Earth system, we can take a brief look at the carbon cycle, shown in Figure 20. Pure carbon is rare in nature. It is found mainly as two minerals—diamond and graphite. Most carbon is bonded to other elements to form compounds. Carbon dioxide (CO$_2$), for example, is an important gas in Earth’s atmosphere. Calcite (CaCO$_3$) is a mineral found in many sedimentary and metamorphic rocks. Hydrocarbons, such as coal, oil, and natural gas, are compounds made of carbon and hydrogen. Carbon also combines with hydrogen and oxygen to form the basic compounds that make up living things. This important element moves continually among Earth’s major spheres by way of the carbon cycle.

**Carbon Dioxide on the Move**

In the atmosphere, carbon is found mainly as carbon dioxide. This gas absorbs much of the energy given off by Earth. Therefore, carbon dioxide influences the heating of the atmosphere. Carbon dioxide constantly moves into and out of the atmosphere by way of four major processes: photosynthesis, respiration, organic decay, and combustion of organic material.

**Carbon and Fossil Fuels**

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, huge quantities of carbon dioxide enter into the air.

**The Role of Marine Animals**

Chemical weathering of certain rocks produce bicarbonate ions that dissolve water. Groundwater, rivers, and streams carry these ions to the ocean. Here, some organisms extract this substance to produce body parts—shells, skeletons, and spines—made of calcite. When the organisms die, these hard parts settle to the ocean floor and become the sedimentary rock called limestone.

**The Complete Cycle**

The source of most CO$_2$ in the atmosphere is thought to be from volcanic activity early in Earth’s history. When CO$_2$ combines with water, it forms carbonic acid. This substance reacts with rock through chemical weathering to form bicarbonate ions that are carried by groundwater and streams to the ocean. Here, marine organisms take over and sedimentary rock is eventually produced. If this rock is then exposed at the surface and subjected to chemical weathering, CO$_2$ is also produced. Use Figure 20 to trace the path of carbon from the atmosphere to the hydrosphere, the geosphere, the biosphere, and back to the atmosphere.

**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/hands on/greenhouse_make.html