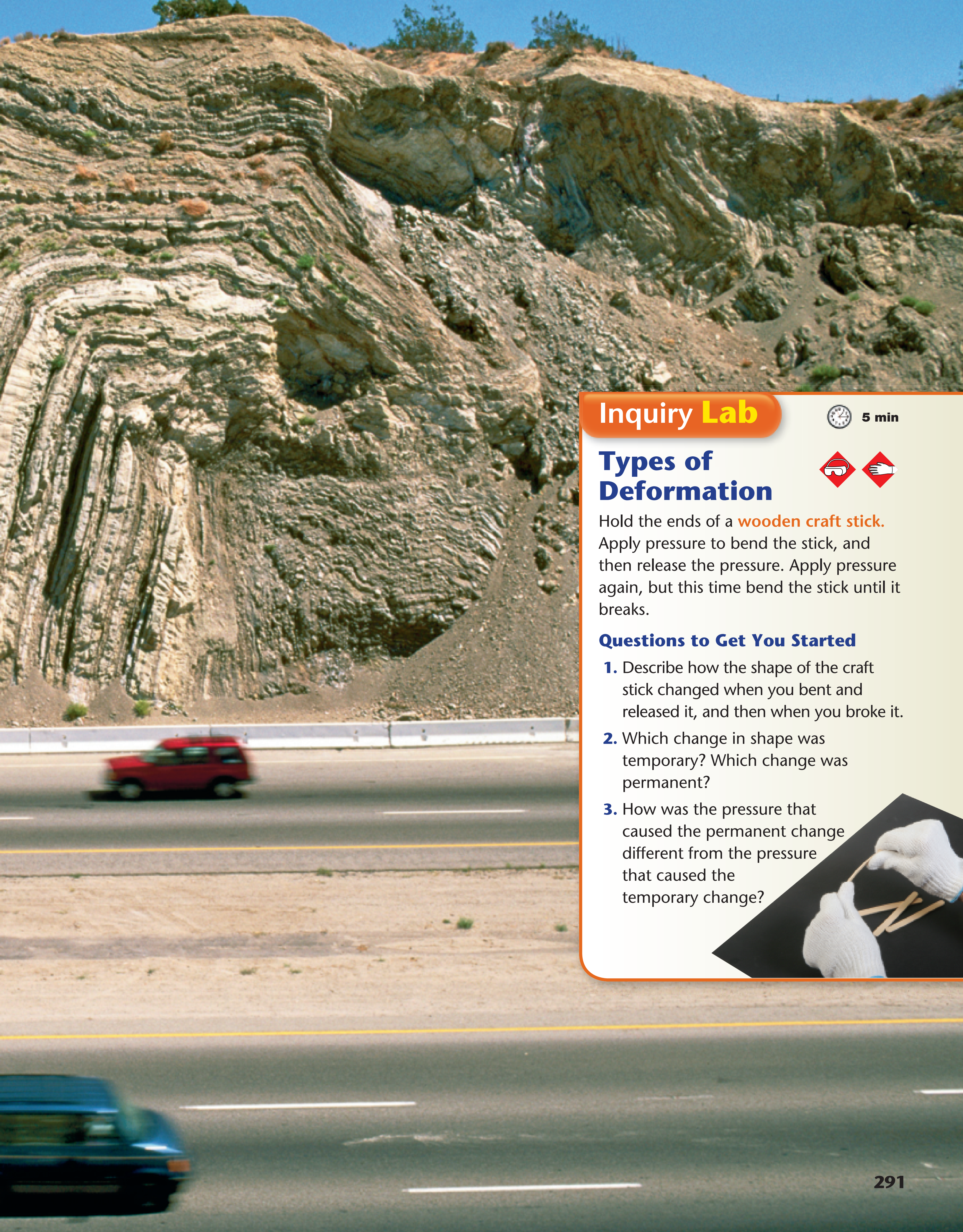
Chapter 11

Deformation of the Crust

Chapter Outline

Why It Matters

Understanding how rock deforms by bending or breaking helps us understand the processes that shape Earth's surface. When building Highway 14 in California, construction crews cut through this hill. The exposed rock layers were folded by stress that was caused by movement along the nearby San Andreas fault.



Inquiry Lab

5 min

Types of Deformation

Hold the ends of a **wooden craft stick.** Apply pressure to bend the stick, and then release the pressure. Apply pressure again, but this time bend the stick until it breaks.

Questions to Get You Started

1. Describe how the shape of the craft stick changed when you bent and released it, and then when you broke it.
2. Which change in shape was temporary? Which change was permanent?
3. How was the pressure that caused the permanent change different from the pressure that caused the temporary change?

READING TOOLBOX

These reading tools will help you learn the material in this chapter.

Science Terms

Everyday Words Used in Science Many words that are used in science are also used in everyday speech. When these words are used in science, however, their meanings are often different from their everyday meanings, or more precise. Pay special attention to the definitions of such words so that you use the words correctly in scientific contexts.

Your Turn As you read Section 1, complete a table like the one below.

Word	Everyday meaning	Scientific meaning
stress	an emphasis; a state of anxiety	the amount of force per unit area that acts on a rock
strain	make an intense effort	
fault		

Comparisons

Analyzing Comparisons When you compare two things, you describe how they are similar or different. Words that may signal comparisons include *like*, *unlike*, *more*, and *less*, as well as words formed by using the suffixes -*er* and -*est*.

Your Turn Make a table like the one below. As you read the chapter, list the two things being compared in the first two columns. In the third column, describe how they are similar or different. In the last column, note any words or phrases that signal the comparison. The sample entry below is for the sentence "Like folds, faults vary greatly in size."

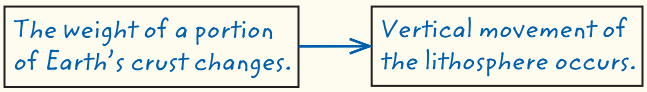
First thing	Second thing	Similarity or difference	Signaling word or phrase
folds	faults	Both can be very small or very large.	like

Graphic Organizers

Cause-and-Effect Maps You can use cause-and-effect maps to show how processes are related to each other. To make a cause-and-effect map, follow these steps.

1. Draw a box, and write a cause inside it. Add as many cause boxes as you want.
2. Draw another box to represent an effect. Add as many effect boxes as you want.
3. Connect each cause box to one or more effect boxes with arrows.
4. An effect can be the cause of one or more other effects. You may want to connect an effect box to one or more other effect boxes.

Your Turn As you read Section 1, use a separate sheet of paper to complete the cause-and-effect map started below. Add at least two more effects.



For more information on how to use these and other tools, see **Appendix A.**

SECTION 1 How Rock Deforms

Key Ideas	Key Terms	Why It Matters
❯ Summarize the principle of isostasy. ❯ Identify the three main types of stress. ❯ Compare folds and faults.	**deformation** **isostasy** **stress** **strain** **fold** **fault**	Both folding and faulting can create tall mountains and deep valleys. Understanding how deformed rock behaves can help engineers determine how stable a hillside or a cliff is.

Mountain ranges are visible reminders that the shape of Earth's surface is constantly changing. These changes result from **deformation,** or the bending, tilting, and breaking of Earth's crust.

Isostasy

Deformation sometimes occurs because the weight of some part of Earth's crust changes. When the lithosphere (of which the crust is a part) thickens and becomes heavier, it sinks deeper into the asthenosphere. If the lithosphere thins and becomes lighter, it rises higher in the asthenosphere.

Vertical movement of the lithosphere depends on two opposing forces. One force is the force due to gravity, or weight, of the lithosphere pressing down on the asthenosphere. The other force is the buoyant force of the asthenosphere pressing up on the lithosphere. When these two forces are balanced, the lithosphere and asthenosphere are in a state called **isostasy.** However, when the weight of the lithosphere changes, the lithosphere sinks or rises until a balance of the forces is reached again. One type of this isostatic adjustment is shown in **Figure 1.** As these adjustments occur, areas of the crust are bent up and down. This bending causes rock in these areas to deform.

deformation the bending, tilting, and breaking of Earth's crust; the change in the shape of rock in response to stress

isostasy a condition of gravitational and buoyant equilibrium between Earth's lithosphere and asthenosphere

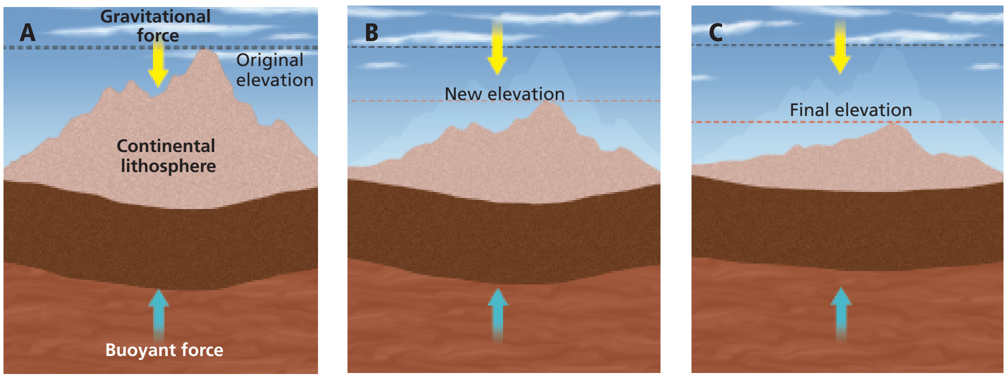


Figure 1 (A) When gravitational and buoyant forces are equal, a state of isostasy exists. (B) As erosion wears away the crust, the lithosphere becomes lighter and rises. (C) As erosion continues, the isostatic adjustment also continues.

Figure 2 Mt. Katahdin in Baxter State Park, Maine, has been worn down by weathering and erosion. As the mountain shrinks, the crust underneath it is uplifted.

Mountains and Isostasy

In mountainous regions, isostatic adjustments constantly occur. Over millions of years, the rock that forms mountains is worn away by the erosive actions of wind, water, and ice. This erosion can significantly reduce the height and weight of a mountain range, such as the one shown in **Figure 2.** As a mountain becomes smaller and lighter, the area may rise by isostatic adjustment in a process called *uplift*.

Deposition and Isostasy

Another type of isostatic adjustment occurs in areas where rivers carrying large amounts of mud, sand, and gravel flow into larger bodies of water. When a river flows into the ocean, most of the material that the river carries is deposited on the nearby ocean floor. The added weight of the deposited material causes the ocean floor to sink by isostatic adjustment in a process called *subsidence*. This process is occurring in the Gulf of Mexico at the mouth of the Mississippi River, where a thick accumulation of deposited materials has formed.

Glaciers and Isostasy

Isostatic adjustments also occur as a result of the growth and retreat of glaciers and ice sheets. When a large amount of water is held in glaciers and ice sheets on land, the weight of the ice causes the lithosphere beneath the ice to sink. Simultaneously, the ocean floor rises because the weight of the overlying ocean water is less. When glaciers and ice sheets melt, the land that was covered with ice slowly rises as the weight of the crust decreases. As the water returns to the ocean, the ocean floor sinks.

Quick Lab 5 min

Modeling Isostasy

Procedure

1. Fill a **1 L beaker** with **500 mL of water.**
2. Place a **wooden block** in the water. Use a **grease pencil** to mark on the side of the beaker the levels of the top and the bottom of the block.
3. Place a **small mass,** of about 1 g, on the wooden block. Use a **second grease pencil** to mark the levels of the top and the bottom of the block.

Analysis

1. What happens to the block of wood when the weight is added?
2. What type of isostatic adjustment does this activity model?

Stress

As Earth's lithosphere moves, the rock in the crust is squeezed, stretched, and twisted. These actions exert force on the rock. The amount of force that is exerted on each unit of area is called **stress.** For example, during isostatic adjustments, the lithosphere sinks and rises atop the asthenosphere. As the lithosphere sinks, the rock in the crust is squeezed and the direction of stress changes. As the lithosphere rises, the rock in the crust is stretched and the direction of stress changes again. Similarly, stress occurs in Earth's crust when tectonic plates collide, separate, or scrape past each other. **Figure 3** shows the three main types of stress.

stress the amount of force per unit area that acts on a rock

Compression

The type of stress that squeezes and shortens a body, such as rock, is called *compression*. Compression can reduce the amount of space that rock occupies. More commonly, however, compression changes the shape of the rock while pushing it higher up or deeper down into the crust. Much of the stress that occurs at or near convergent boundaries, where tectonic plates collide, is compression.

Tension

Another type of stress is tension. *Tension* is stress that stretches and pulls a body apart. When rock is pulled apart by tension, it tends to become thinner. Much of the stress that occurs at or near divergent boundaries, where tectonic plates pull apart, is tension.

Shear Stress

The third type of stress is shear stress. *Shear stress* distorts a body by pushing parts of the body in opposite directions. Sheared rock bends, twists, or breaks apart as it slides past neighboring rock. Shear stress is common at transform boundaries, where tectonic plates slide horizontally past each other. However, each type of stress occurs at or near all types of plate boundaries and in various other regions of the crust, too.

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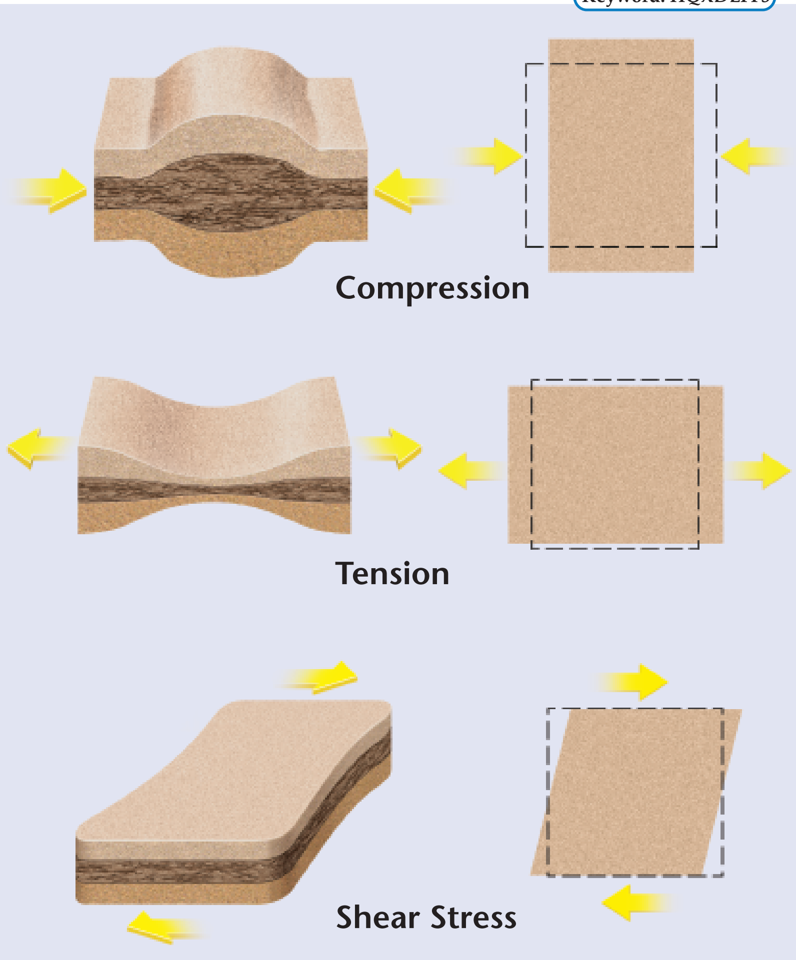
Figure 3 Types of Stress



Academic Vocabulary

distort (di STOHRT) to change the natural appearance of something

Reading Check **Which two kinds of stress pull rock apart?**
(See Appendix G for answers to Reading Checks.)

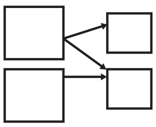
Figure 4 This rock deformation in Kingman, Arizona, is an example of brittle strain.

strain any change in a rock's shape or volume caused by stress

READING TOOLBOX

Cause-and-Effect Map

Make a cause-and-effect map to show why rock deforms in a brittle or ductile way.



Strain

When stress is applied to rock, rock may deform. Any change in the shape or volume of rock that results from stress is called **strain**. When stress is applied slowly, the deformed rock may regain its original shape when the stress is removed. However, the amount of stress that rock can withstand without permanently changing shape is limited. This limit varies with the type of rock and the conditions under which the stress is applied. If a stress exceeds the rock's limit, the rock's shape permanently changes.

Types of Permanent Strain

Materials that respond to stress by breaking or fracturing are *brittle*. Brittle strain appears as cracks or fractures, as **Figure 4** shows. *Ductile* materials respond to stress by bending or deforming without breaking. Ductile strain is a change in the volume or shape of rock in which the rock does not crack or fracture. Brittle strain and ductile strain are types of permanent strain.

Factors That Affect Strain

The composition of rock determines whether rock is ductile or brittle. Temperature and pressure also affect how rock deforms. Near Earth's surface, where temperature and pressure are low, rock is likely to deform in a brittle way. At higher temperature and pressure, rock is more likely to deform in a ductile way.

The type of strain that stress causes is determined by the amount and type of stress and by the rate at which stress is applied to rock. The greater the stress on rock is, the more likely rock is to undergo brittle strain. The more quickly stress is applied to rock, the more likely rock is to respond in a brittle way.

Quick Lab — Modeling Stress and Strain

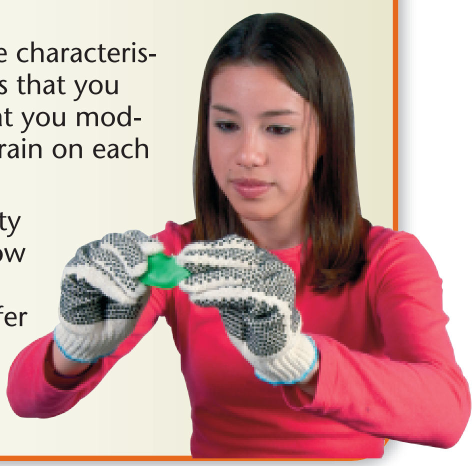
15 min

Procedure

1. Put on a pair of **gloves,** and pick up a 5 cm × 5 cm square of **frozen plastic play putty.** Hold one edge of the frozen putty in each hand.
2. Try to pull the putty apart by pulling the edges away from each other.
3. Push the edges of the frozen putty toward each other. (You may have to reshape the putty between steps.)
4. Push one edge of the frozen putty away from you, and pull the other edge toward you.
5. Repeat steps 2–4, but use a 5 cm × 5 cm square of **warm plastic play putty.**

Analysis

1. What types of stress did you model in steps 2, 3, and 4?
2. Make a table that lists the characteristics of the two substances that you modeled, the stresses that you modeled, and the resulting strain on each model.
3. How does the frozen putty respond to the stress? How does the warm putty's response to the stress differ from the frozen putty's response?



Folds

When rock responds to stress by deforming in a ductile way, folds commonly form. A **fold** is a bend in rock layers that results from stress. A fold is most easily observed where flat layers of rock were compressed or squeezed inward. As stress was applied, the rock layers bent and folded. Cracks sometimes appear in or near a fold, but most commonly the rock layers remain intact. Although a fold commonly results from compression, it can also form as a result of shear stress.

fold a form of ductile strain in which rock layers bend, usually as a result of compression

Anatomy of a Fold

Folds have features by which they can be identified. Scientists use these features to describe folds. The main features of a fold are shown by the illustration in **Figure 5.** The sloping sides of a fold are called *limbs*. The limbs meet at the bend in the rock layers, which is called the *hinge*. Some folds also contain an additional feature. If a fold's structure is such that a plane could slice the fold into two symmetrical halves, the fold is symmetrical. The plane is called the fold's *axial plane*. However, the two halves of a fold are rarely symmetrical.

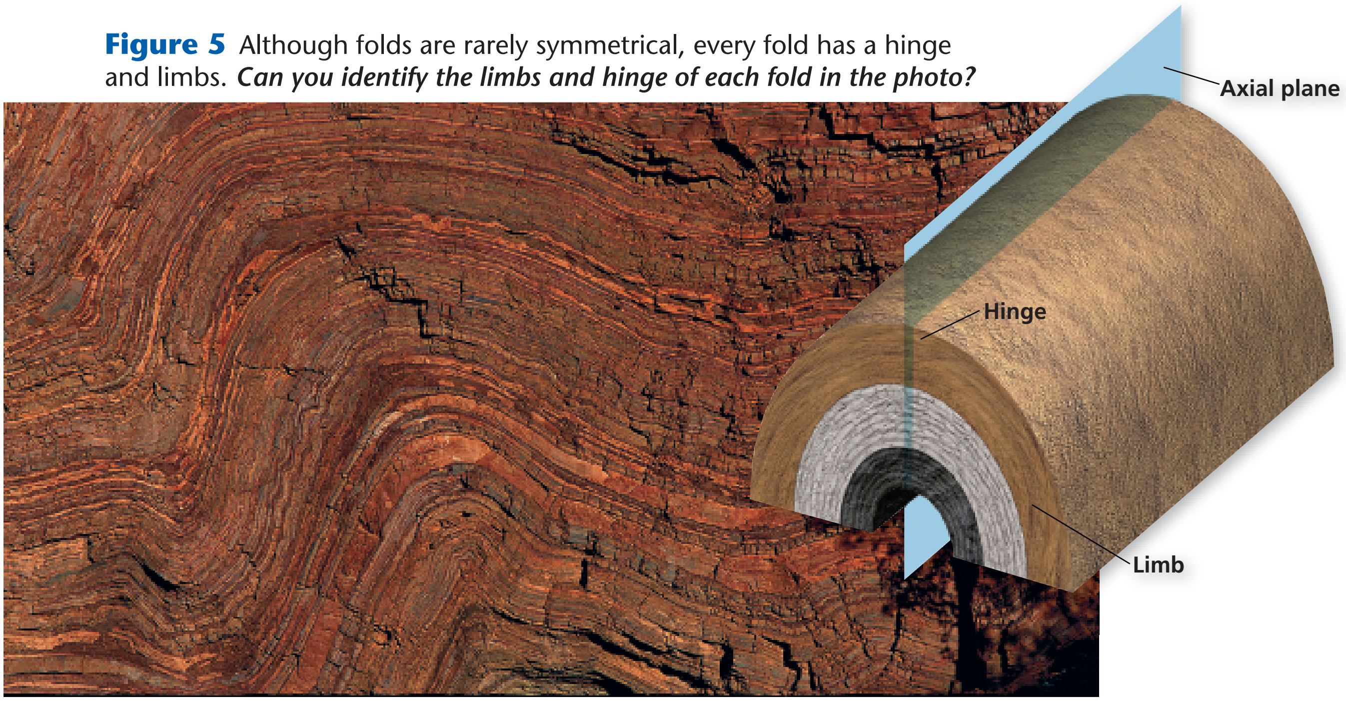
Many folds bend vertically, but folds can have many other shapes, as shown by the photograph in **Figure 5.** Folds are usually asymmetrical. Sometimes, one limb of a fold dips more steeply than the other limb does. If a fold is *overturned*, the fold appears to be lying on its side. Folds can have open shapes or be as tight as a hairpin. A fold's hinge can be a smooth bend or may come to a sharp point. Each fold is unique because the combination of stresses and conditions that caused the fold was unique.

Math Skills

Units of Stress Two units are commonly used to describe stress or pressure. One unit is the pascal (Pa). A pascal is a measure of force (in newtons) divided by area (in square meters). The other unit of stress is the pound per square inch (psi). If the pressure in a region of Earth's crust is measured as 25 MPa (megapascals) and as 3,626 psi, how many pounds per square inch does 1 MPa equal? (Note: 1 MPa = 1,000,000 Pa)

Reading Check **Name two features of a fold.**

Figure 5 Although folds are rarely symmetrical, every fold has a hinge and limbs. ***Can you identify the limbs and hinge of each fold in the photo?***



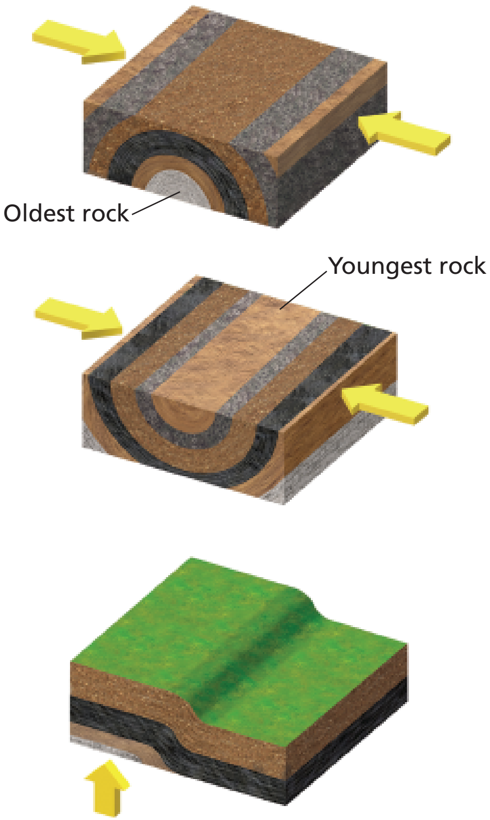


Figure 6 The three major types of folds are anticlines (top), synclines (middle), and monoclines (bottom).

Types of Folds

To categorize a fold, scientists study the relative ages of the rocks in the fold. The rock layers of the fold are identified by age from youngest to oldest. An *anticline* is a fold in which the oldest layer is in the center of the fold. Anticlines are commonly arch shaped. A *syncline* is a fold in which the youngest layer is in the center of the fold. Synclines are commonly bowl shaped. A *monocline* is a fold in which both limbs are horizontal or almost horizontal. Monoclines form when one part of Earth's crust moves up or down relative to another part. The three major types of folds are shown in **Figure 6.**

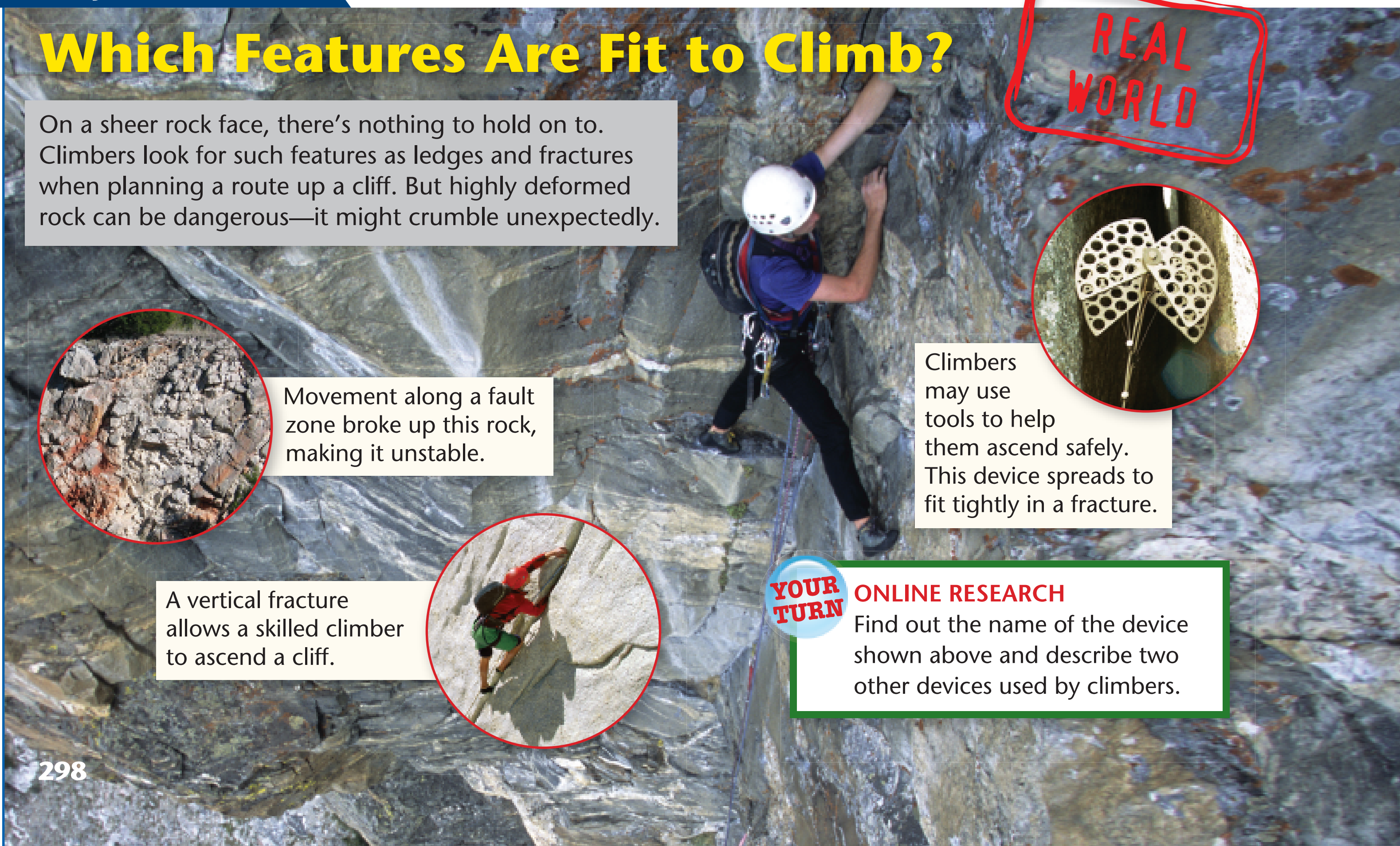
Sizes of Folds

Folds, which appear as wavelike structures in rock layers, vary greatly in size. Some folds are small enough to be contained in a hand-held rock specimen. Other folds cover thousands of square kilometers and can be seen only from the air.

Sometimes, a large anticline forms a ridge. A *ridge* is a large, narrow strip of elevated land that can occur near mountains. Nearby, a large syncline may form a valley. Over time, however, the varying resistance to erosion of rock in anticlines and synclines can change this simple landscape pattern.

Why It Matters

Which Features Are Fit to Climb?



On a sheer rock face, there's nothing to hold on to. Climbers look for such features as ledges and fractures when planning a route up a cliff. But highly deformed rock can be dangerous—it might crumble unexpectedly.

Movement along a fault zone broke up this rock, making it unstable.

A vertical fracture allows a skilled climber to ascend a cliff.

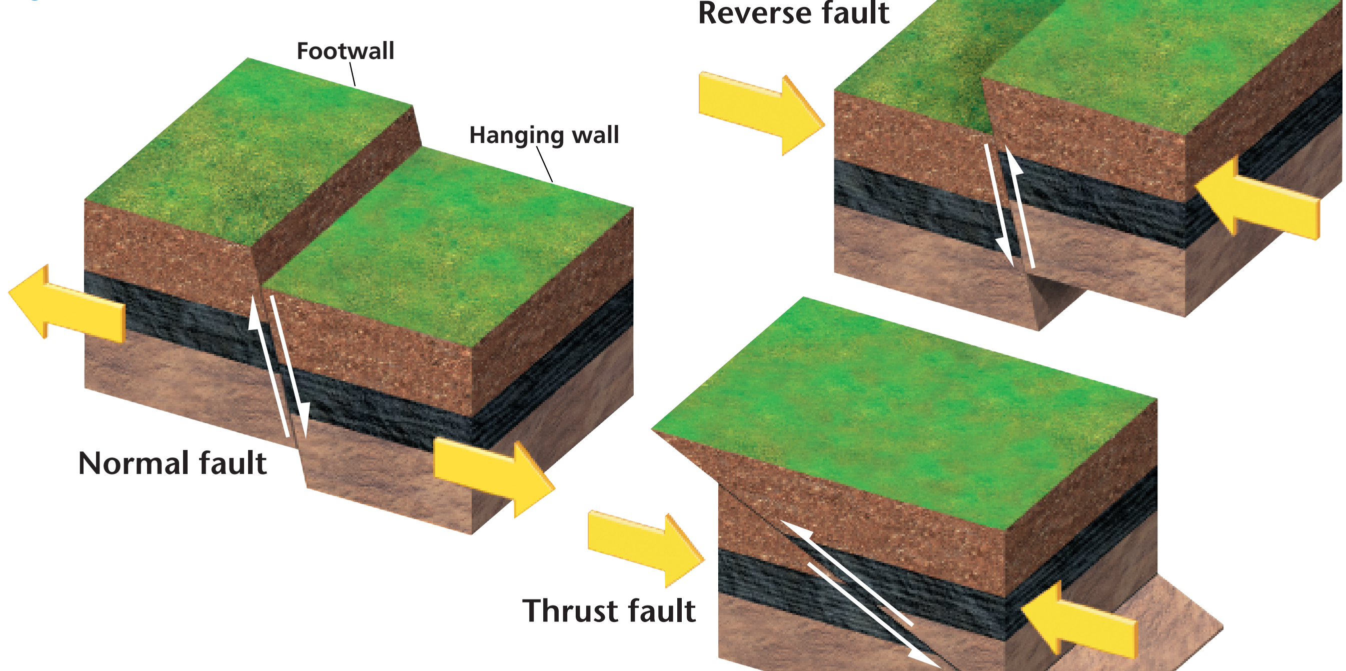
Climbers may use tools to help them ascend safely. This device spreads to fit tightly in a fracture.

YOUR TURN

ONLINE RESEARCH

Find out the name of the device shown above and describe two other devices used by climbers.

Figure 7 Normal and Reverse Faults



Faults

Stress does not always cause rock to fold. Near Earth's surface, where temperatures and pressure are low, stresses may simply cause rock to break. Breaks in rock are divided into two categories. A break along which there is no movement of the surrounding rock is called a *fracture*. A break along which the surrounding rock moves is called a **fault.** The surface or plane along which the motion occurs is called the *fault plane*. In a nonvertical fault, the *hanging wall* is the rock above the fault plane. The *footwall* is the rock below the fault plane.

fault a break in a body of rock along which one block slides relative to another; a form of brittle strain

Normal Faults

As shown in **Figure 7,** a *normal fault* is a fault in which the hanging wall moves downward relative to the footwall. Normal faults commonly form at divergent boundaries, where the crust is being pulled apart by tension. Normal faults may occur as a series of parallel fault lines, forming steep, steplike landforms. The Great Rift Valley of East Africa formed by large-scale normal faulting.

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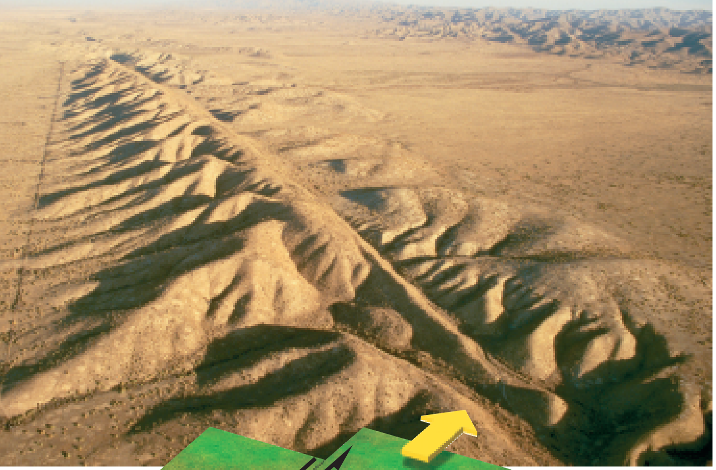
Reverse Faults

When compression causes the hanging wall to move upward relative to the footwall, also shown in **Figure 7,** a *reverse fault* forms. A *thrust fault* is a special type of reverse fault in which the fault plane is at a low angle or is nearly horizontal. Because of the low angle of the fault plane, the rock of the hanging wall is pushed up and over the rock of the footwall. Reverse faults and thrust faults are common in mountain ranges, such as the Rockies and the Alps, that formed mainly due to compression.

Reading Check **How does a thrust fault differ from a reverse fault?**



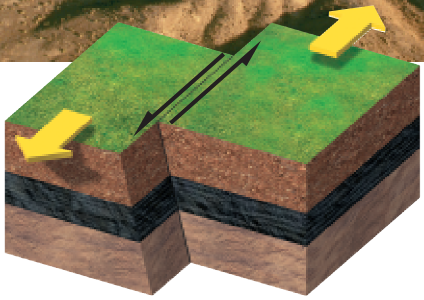


Figure 8 The San Andreas fault system stretches more than 1,200 km across California and is the result of two tectonic plates moving in different directions.

Strike-Slip Faults

In a *strike-slip fault*, the rock on either side of the fault plane slides horizontally in response to shear stress. Strike-slip faults got their name because they slide, or *slip*, parallel to the direction of the length, or *strike*, of the fault. Some strike-slip fault planes are vertical, but many are sloped.

Strike-slip faults commonly occur at transform boundaries, where tectonic plates grind past each other as they move in opposite directions. These motions cause shear stress on the rocks at the edges of the plates. Strike-slip faults also occur at fracture zones between offset segments of mid-ocean ridges. Commonly, strike-slip faults occur as groups of smaller faults in areas where large-scale deformation is happening.

Sizes of Faults

Like folds, faults vary greatly in size. Small faults may affect only a few layers of rock in a small region. Other faults are thousands of kilometers long and may extend many kilometers below Earth's surface. Generally, large faults that cover thousands of kilometers are composed of systems of many smaller, related faults, rather than a single fault. The San Andreas fault in California, shown in **Figure 8,** is an example of a large fault system.

Section 1 Review

Key Ideas

1. **Summarize** how isostatic adjustments affect isostasy.
2. **Identify and describe** three types of stress.
3. **Compare** stress and strain.
4. **Describe** one type of strain that results when rock responds to stress by permanently deforming without breaking.
5. **Identify** features that all types of folds share and features that only some types of folds have.
6. **Describe** four types of faults.
7. **Compare** folding and faulting as responses to stress.

Critical Thinking

8. **Applying Ideas** Why is faulting most likely to occur near Earth's surface and not deep within Earth?
9. **Making Comparisons** How would the isostatic adjustment that results from the melting of glaciers differ from the isostatic adjustment that may occur when a large river empties into the ocean?
10. **Analyzing Relationships** You are examining a rock outcrop that shows a fold in which both limbs are horizontal but occur at different elevations. What type of fold does this outcrop show, and what can you say about the type of stress that the rock underwent?
11. **Predicting Consequences** You are watching a lab experiment in which a rock sample is being gently heated and slowly bent. Would you expect the rock to fold or to fracture? Explain your reasoning.

Concept Mapping

12. Use the following terms to create a concept map: *stress, compression, strain, tension, shear stress, folds,* and *faults.*

SECTION 2

How Mountains Form

Key Ideas	Key Terms	Why It Matters
❯ Identify the types of plate collisions that form mountains. ❯ Identify four types of mountains. ❯ Compare how folded and fault-block mountains form.	**mountain range** **folded mountain** **fault-block mountain** **dome mountain**	Many mountain ranges and volcanoes are growing taller. Scientists can measure the rate at which Earth's surface is moving and deforming.

Many mountains form due to extreme deformation. Mount Everest, whose elevation is more than 8 km above sea level, is Earth's highest mountain. Forces inside Earth cause Mount Everest to grow taller every year. Some mountains form by volcanic activity. Mount St. Helens is a volcano that captured the world's attention in 1980 when its explosive eruption devastated the surrounding area.

Mountain Ranges and Systems

A group of adjacent mountains that are related to each other in shape and structure is called a **mountain range.** Mount Everest is part of the Great Himalaya Range, and Mount St. Helens is part of the Cascade Range. A group of adjacent mountain ranges is called a *mountain system*. In the eastern United States, for example, the Great Smoky, Blue Ridge, Cumberland, Green, and White mountain ranges make up the Appalachian mountain system.

mountain range a series of mountains that are closely related in orientation, age, and mode of formation

The largest mountain systems are part of two larger systems called *mountain belts*. Earth's two youngest major mountain belts, the circum-Pacific belt and the Eurasian-Melanesian belt, are shown in **Figure 1.**

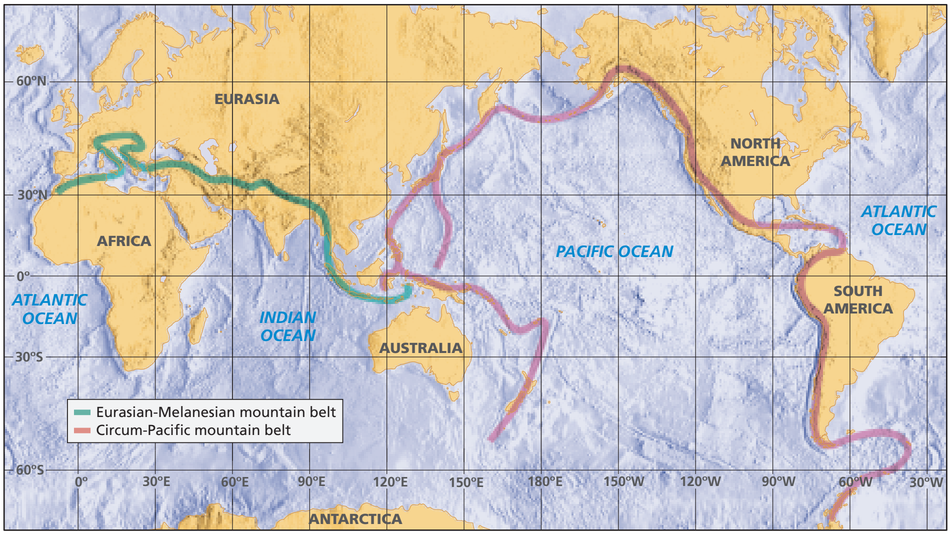


Figure 1 Most tall, young mountain ranges lie along either the Eurasian-Melanesian mountain belt or the circum-Pacific mountain belt.

Plate Tectonics and Mountains

Academic Vocabulary

collision (kuh LIZH uhn) the event in which two bodies merge or combine; the act of colliding

Both the circum-Pacific and the Eurasian-Melanesian mountain belts are located along convergent plate boundaries. The location of these two mountain belts provides evidence that most mountains form as a result of collisions between tectonic plates. Some mountains, such as the Appalachians, do not lie along active convergent plate boundaries. However, evidence indicates that the places at which these ranges formed were previously active plate boundaries.

Collisions Between Continental and Oceanic Crust

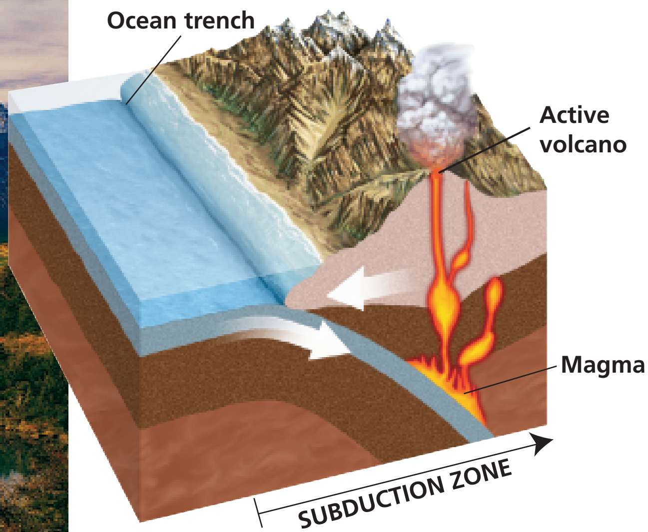
READING TOOLBOX

Analyzing Comparisons
As you read about different mountain ranges and belts, look for comparisons among them. Make a table of their similarities and differences.

Some mountains form when oceanic lithosphere and continental lithosphere collide at convergent plate boundaries. When the moving plates collide, the oceanic lithosphere subducts beneath the continental lithosphere, as shown in **Figure 2.** This type of collision produces such large-scale deformation of rock that high mountains are uplifted. In addition, the subduction of the oceanic lithosphere causes partial melting of the overlying mantle and crust. This melting produces magma that may eventually erupt to form volcanic mountains on Earth's surface. The mountains of the Cascade Range in the northwest region of the United States formed in this way. The Andes mountains on the western coast of South America are another example of mountains that formed by this type of collision.

Some mountains at the boundary between continental lithosphere and oceanic lithosphere may form by a different process. As the oceanic lithosphere subducts, pieces of crust called *terranes* are scraped off. These terranes then become part of the continent and may form mountains.

Figure 2 The Andes, shown below, are being uplifted as the Pacific plate subducts beneath the South American plate.



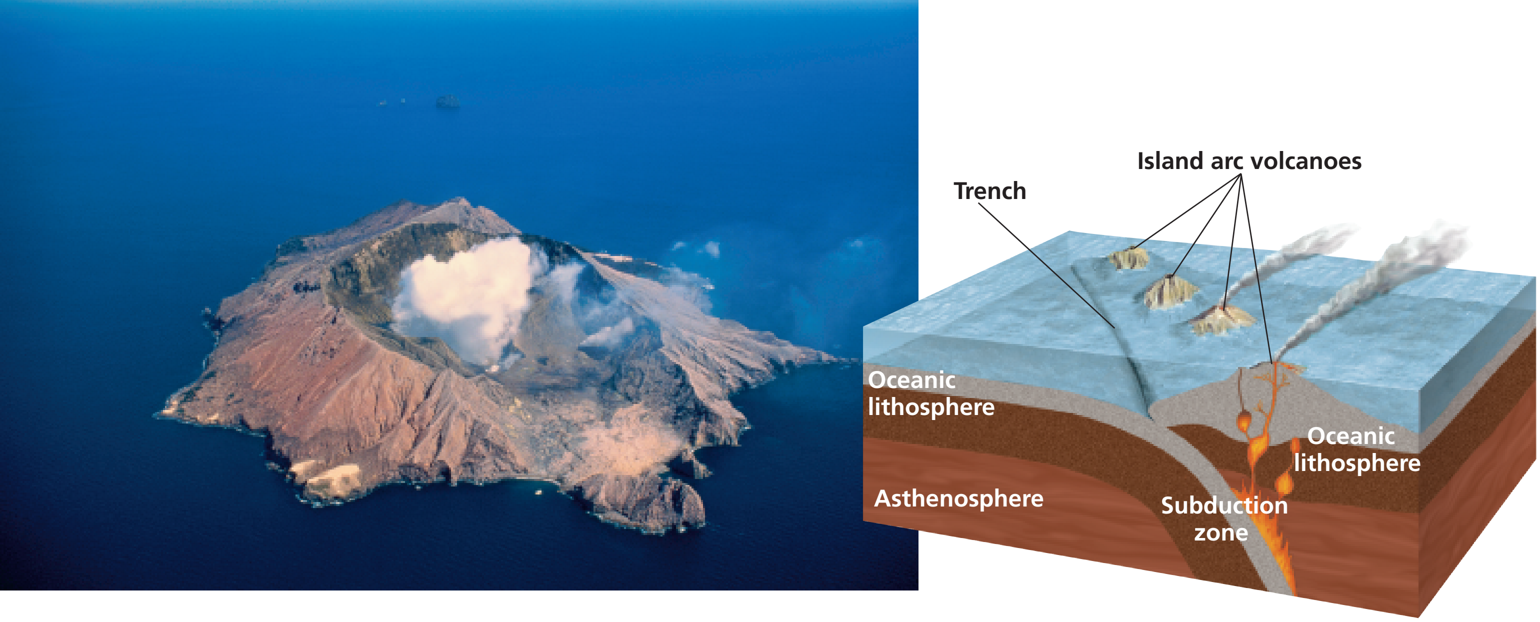


Figure 3 The Mariana Islands in the North Pacific Ocean are volcanic mountains that formed by the collision of two oceanic plates.

Collisions Between Oceanic Crust and Oceanic Crust

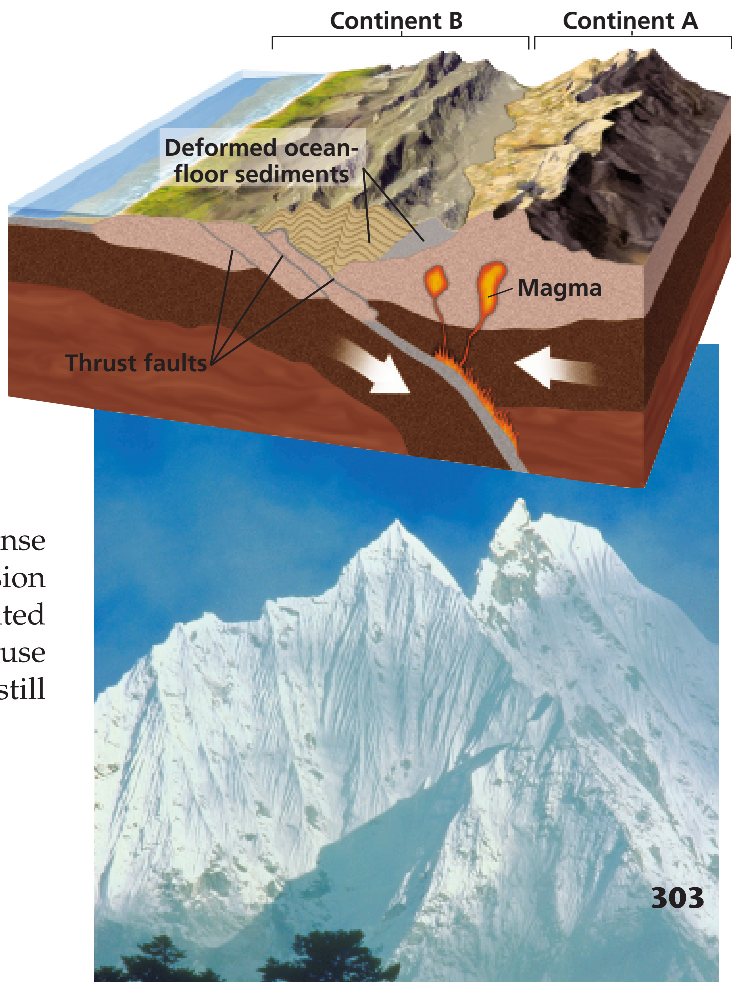
Volcanic mountains commonly form where two plates whose edges consist of oceanic lithosphere collide. In this collision, the denser oceanic plate subducts beneath the other oceanic plate, as shown in **Figure 3.** As the denser oceanic plate subducts, fluids from the subducting lithosphere cause partial melting of the overlying mantle and crust. The resulting magma rises and breaks through the oceanic lithosphere. These eruptions of magma form an arc of volcanic mountains on the ocean floor. The Mariana Islands are the peaks of volcanic mountains that rose above sea level.

Collisions Between Continents

Mountains can also form when two continents collide, as **Figure 4** shows. The Himalaya Mountains formed from such a collision. About 165 million years ago, India broke apart from Africa and Antarctica and became a separate continent. The Indian plate then began moving north toward Eurasia. The oceanic lithosphere of the Indian plate subducted beneath the Eurasian plate. This subduction continued until the continental lithosphere of India collided with the continental lithosphere of Eurasia. Because the two continents have equally dense lithosphere, subduction stopped but the collision continued. The intense deformation that resulted from the collision uplifted the Himalayas. Because the plates are still colliding, the Himalayas are still growing taller.

Reading Check **Why are the Himalayas growing taller today?**

Figure 4 The Himalayas formed when India collided with Eurasia.



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Types of Mountains

Mountains are more than just elevated parts of Earth's crust. Mountains are complicated structures whose rock formations provide evidence of the stresses that created the mountains. Scientists classify mountains according to the way in which the crust was deformed and shaped by mountain-building stresses. Examples of several types of mountains are shown in **Figure 5.**

Folded Mountains and Plateaus

folded mountain a mountain that forms when rock layers are squeezed together and uplifted

Many of the highest mountain ranges in the world consist of folded mountains that form when continents collide. **Folded mountains** form when tectonic movements squeeze rock layers together into accordion-like folds. Parts of the Alps, the Himalayas, the Appalachians, and Russia's Ural Mountains consist of very large and complex folds.

The same stresses that form folded mountains also uplift plateaus. *Plateaus* are large, flat areas of rock high above sea level. Most plateaus form when thick, horizontal layers of rock are slowly uplifted so that the layers remain flat instead of faulting and folding. Most plateaus are located near mountain ranges. For example, the Tibetan Plateau is next to the Himalaya Mountains, and the Colorado Plateau is next to the Rockies. Plateaus can also form when layers of molten rock harden and pile up on Earth's surface or when large areas of rock are eroded.

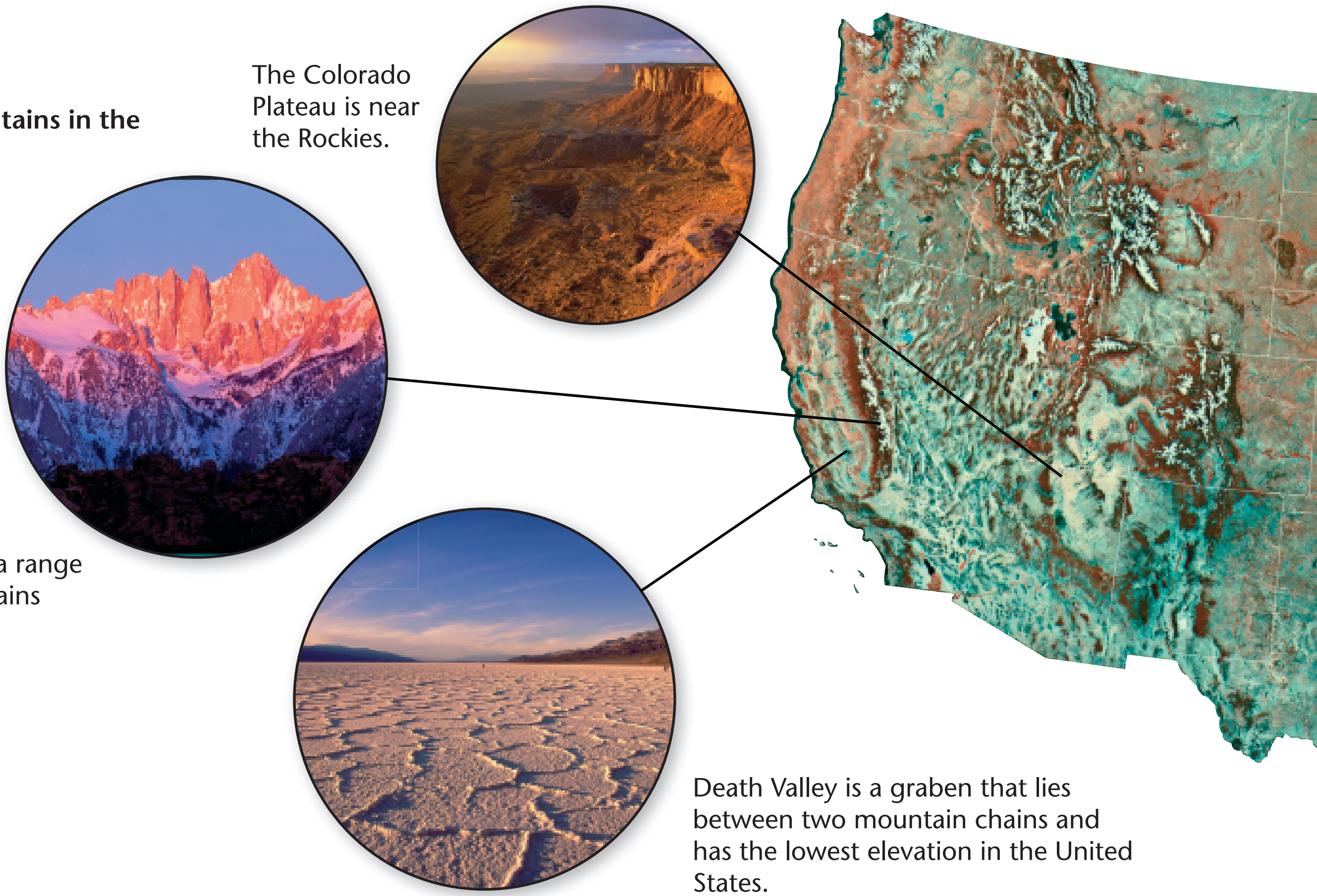


Figure 5 Mountains in the United States

The Colorado Plateau is near the Rockies.

The Sierra Nevada range in California contains many fault-block mountains.

Death Valley is a graben that lies between two mountain chains and has the lowest elevation in the United States.

Fault-Block Mountains and Grabens

Where parts of Earth's crust have been stretched and broken into large blocks, faulting may cause the blocks to tilt and drop relative to other blocks. The relatively higher blocks form **fault-block mountains.** The Sierra Nevada range of California consists of many fault-block mountains.

The same type of faulting that forms fault-block mountains also forms long, narrow valleys called *grabens*. Grabens develop when steep faults break the crust into blocks and one block slips downward relative to the surrounding blocks. Grabens and fault-block mountain ranges commonly occur together. For example, the Basin and Range Province of the western United States consists of grabens separated by fault-block mountain ranges.

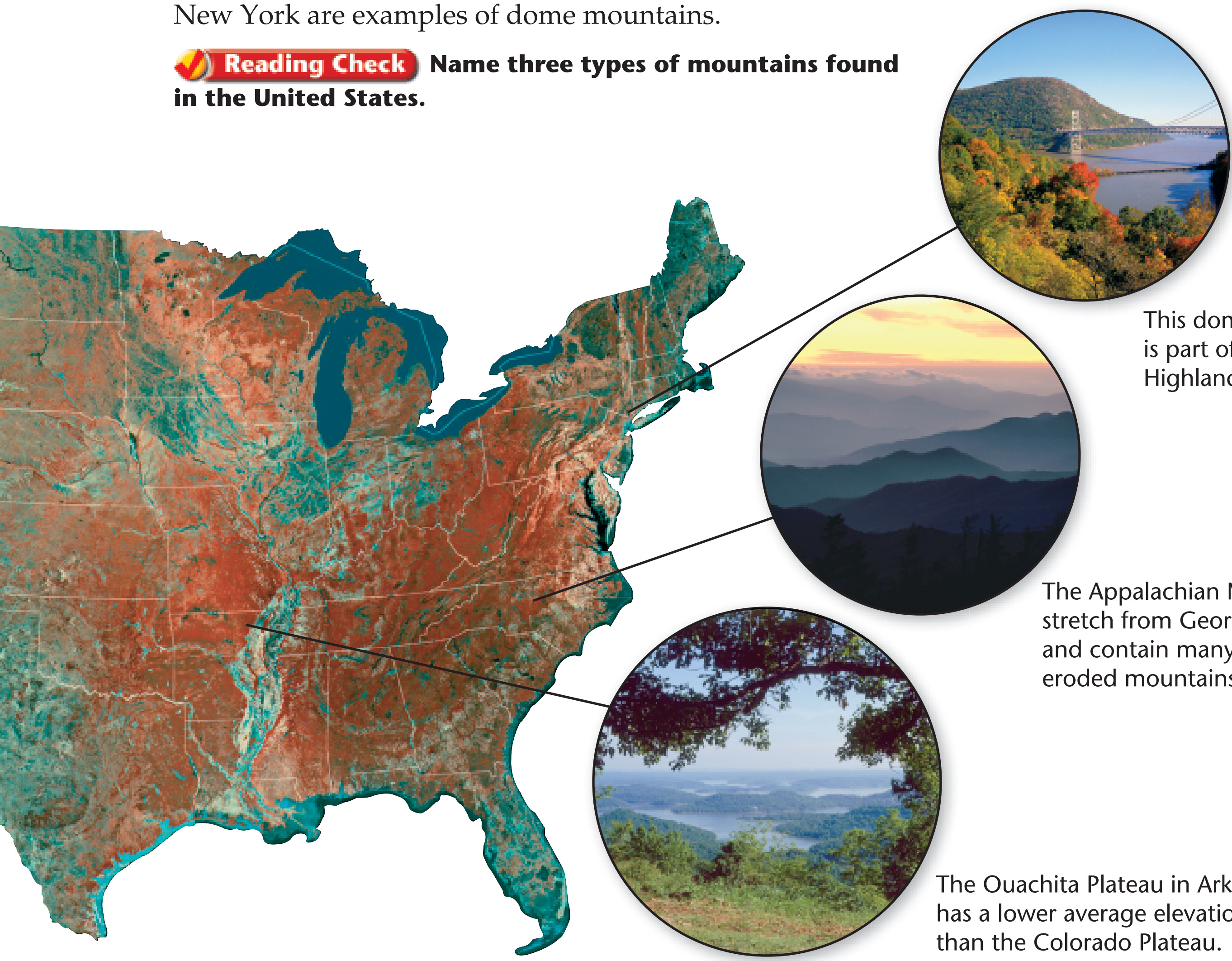
fault-block mountain a mountain that forms where faulting breaks Earth's crust into large blocks, which causes some blocks to drop down relative to other blocks

dome mountain a circular or elliptical, almost symmetrical elevation or structure in which the stratified rock slopes downward gently from the central point of folding

Dome Mountains

A less common type of mountain forms when magma rises through the crust and pushes up the rock layers above the magma. The result is a **dome mountain,** a circular structure made of rock layers that slope gently away from a central point. Dome mountains may also form when tectonic forces gently uplift rock layers. The Black Hills of South Dakota and the Adirondack Mountains of New York are examples of dome mountains.

Reading Check **Name three types of mountains found in the United States.**



This dome mountain is part of the Hudson Highlands in New York.

The Appalachian Mountains stretch from Georgia to Canada and contain many older, more eroded mountains.

The Ouachita Plateau in Arkansas has a lower average elevation than the Colorado Plateau.

Figure 6 Mount St. Helens (front) and Mount Rainier (back) in the Cascade Range of the western United States are volcanic mountains that formed along a convergent boundary.

Volcanic Mountains

Mountains that form when magma erupts onto Earth's surface are called *volcanic mountains*. Volcanic mountains commonly form along convergent plate boundaries. The Cascade Range of Washington, Oregon, and northern California is composed of this type of volcanic mountain, two of which are shown in **Figure 6.**

Some of the largest volcanic mountains are part of the mid-ocean ridges along divergent plate boundaries. Magma rising to Earth's surface at divergent boundaries makes mid-ocean ridges volcanically active areas. The peaks of these volcanic mountains sometimes rise above sea level to form volcanic islands, such as the Azores in the North Atlantic Ocean.

Other large volcanic mountains form at hot spots. *Hot spots* are volcanically active areas that can lie far from tectonic plate boundaries. These areas seem to correspond to places where hot material rises through Earth's interior and reaches the lithosphere. The Hawaiian Islands are an example of this type of volcanic mountain. The main island of Hawaii is a volcanic mountain that reaches over 10 km above the ocean floor and has a base that is more than 160 km wide.

Section 2 Review

Key Ideas

1. **Describe** three types of tectonic plate collisions that form mountains.
2. **Summarize** the process by which folded mountains form.
3. **Compare** how plateaus form with how folded mountains form.
4. **Describe** the formation of fault-block mountains.
5. **Explain** how dome mountains form.
6. **Explain** how volcanic mountains form.

Critical Thinking

7. **Making Connections** Explain two ways in which volcanic mountains might get smaller.
8. **Making Connections** Explain why fault-block mountains and grabens are commonly found near each other.
9. **Analyzing Ideas** You are standing on a large, flat area of land and are examining the nearby mountains. You notice that many of the mountains have large folds. Are you standing on a plateau or a graben? Explain your answer.
10. **Making Predictions** Igneous rocks form from cooled magma. Near what types of mountains would you expect to find new igneous rocks?

Concept Mapping

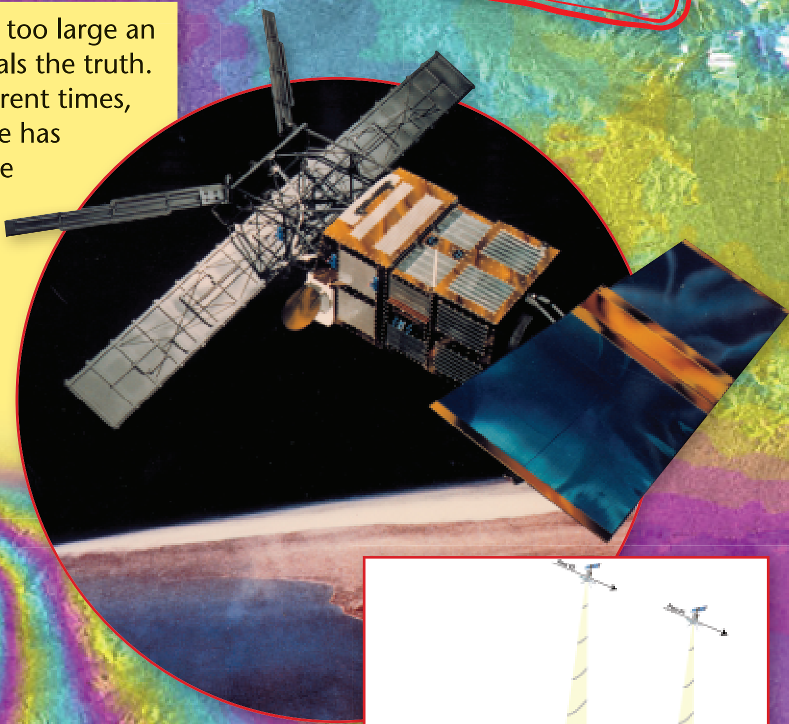
11. Use the following terms to create a concept map: *mountain range, fault-block mountains, mountain belt, folded mountains, mountain system, dome mountains,* and *volcanic mountains.*

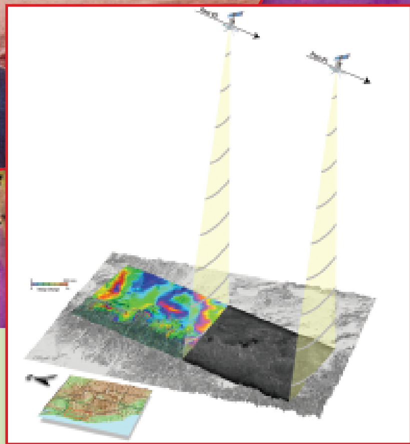
Why It Matters

SCIENCE & SOCIETY

Spying on Earth's Movements

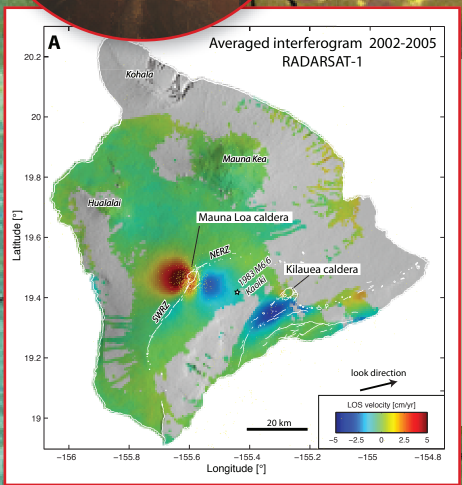
Earth's surface often changes too slowly or over too large an area for humans to detect, but technology reveals the truth. By comparing satellite images produced at different times, scientists can identify areas where Earth's surface has undergone deformation. This background image shows surface movement caused by an earthquake in California. Areas of deformation are shown in false colors. The color bands are closer together where the ground moved farther. In the future, these types of measurements may help scientists predict such events as volcanic eruptions or earthquakes.





A satellite uses radar energy to produce detailed images of Earth's surface at two different times. A computer digitally compares the images and displays any differences.

Mauna Loa Volcano makes up much of Hawaii's Big Island. It is carefully monitored for signs of an imminent eruption.



Satellite data show deformation of Mauna Loa and Kilauea Volcanoes. Movement of magma inside the crust causes changes to the ground at the surface. The areas of greatest deformation are shown in dark blue and dark red.

YOUR TURN

UNDERSTANDING CONCEPTS
How are satellite data used to measure deformation of Earth's crust?

CRITICAL THINKING
Why are false colors used to show movement of the ground?

Continental Collisions

What You'll Do

- **Model** collisions between continents.
- **Explain** how mountains form at convergent boundaries.

What You'll Need

blocks, wooden, 3 cm × 3 cm × 6 cm
bobby pins, long (5)
cardboard, thick, 15 cm × 30 cm
napkins, paper, light- and dark-colored
paper, adding-machine, 6 cm × 35 cm
ruler, metric
scissors
tape, masking

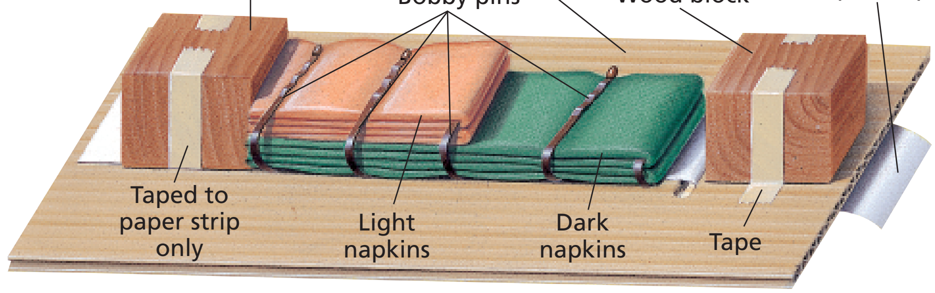
Safety

When the subcontinent of India broke away from Africa and Antarctica and began to move northward toward Eurasia, the oceanic crust on the northern side of India began to subduct beneath the Eurasian plate. The deformation of the crust resulted in the formation of the Himalaya Mountains. Earthquakes in the Himalayan region suggest that India is still pushing against Eurasia. In this lab, you will create a model to help explain how the Himalaya Mountains formed as a result of the collision of the Indian and Eurasian tectonic plates.

Procedure

1. To assemble the continental-collision model, cut a 7-cm slit in the cardboard. The slit should be about 6 cm from (and parallel to) one of the short edges of the cardboard. Cut the slit wide enough such that the adding-machine paper will feed through the slit without being loose.
2. Securely tape one wood block along the slit between the slit and the near edge of the cardboard. Tape the other block across the paper strip about 6 cm from one end of the paper. The blocks should be parallel to one another, as shown in the illustration on the next page.

Step 8



3. Cut two strips of the light-colored paper napkin that are about 6 cm wide and 16 cm long. Cut two strips of the dark-colored paper napkin that are about 6 cm wide and 32 cm long. Fold all four strips in half along their width.
4. Stack the napkin strips on top of each other such that all of the folds are along the same side. Place the two dark-colored napkins on the bottom.
5. Place the napkin strips lengthwise on the paper strip. The nonfolded ends of the napkin strips should be butted up against the wood block that is taped to the paper strip.
6. Using the bobby pins, attach the napkins to the paper strip, as shown in the illustration above.
7. Push the long end of the paper strip through the slit in the cardboard until the first fold of the napkin rests against the fixed wood block.
8. Hold the cardboard at about eye level, and pull down gently on the paper strip. You may need a partner's help. Observe what happens as the dark-colored napkins contact the fixed wood block and as you continue to pull down on the paper strip. Stop pulling when you feel resistance from the strip.

Analysis

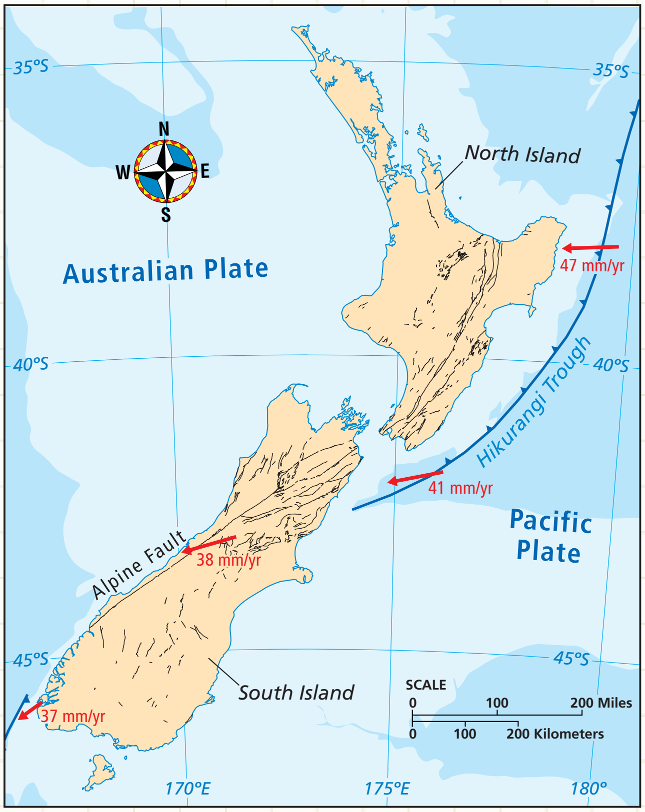
1. **Evaluating Methods** Explain what is represented by the dark napkins, the light napkins, and the wood blocks.
2. **Analyzing Processes** What plate-tectonics process is represented by the motion of the paper strip in the model? Explain your answer.
3. **Applying Ideas** What type of mountain would result from the kind of collision shown by the model?
4. **Evaluating Models** Explain how the process modeled here differs from the process that formed the Himalaya Mountains.

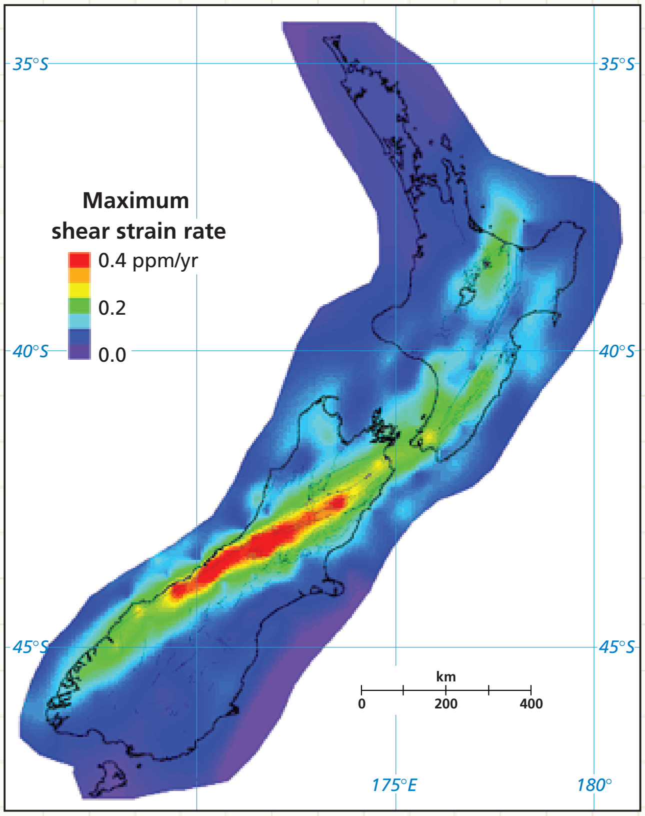
Extension

Analyzing Data Obtain a world map of earthquake epicenters. Study the map. Describe the pattern of epicenters in the Himalayan region. Does the pattern suggest that the Himalaya Mountains are still rising?

Writing from Research Read about the breakup of Gondwanaland and the movement of India toward the Northern Hemisphere. Write about stages in India's movement. List the time frame in which each important event occurred.

Shear Strain in New Zealand





Map Skills Activity

The map above shows the plate boundary zone of New Zealand. In this region, the Australian plate is moving north, while the Pacific plate is moving west. These complex plate movements create areas of tension, compression, and shear stress, which result in strain. Strain is measured in parts per million (ppm) per year (yr). The map on the right shows strain in New Zealand. Use the two maps to answer the questions below.

1. **Using a Key** What is the highest amount of shear strain shown in the map on the right?
2. **Identifying Locations** Using latitude and longitude, describe the location of the area that has the highest amount of shear strain.
3. **Using a Key** What is the approximate length of the area of maximum shear strain?
4. **Understanding Relationships** What type of plate boundary is located along the east coast of the North Island? Explain your answer.
5. **Comparing Areas** In what areas might you expect to find compression? Explain your answer.
6. **Making Inferences** What type of fault is the Alpine Fault? Explain your answer.
7. **Drawing Conclusions** A mountain range known as the Southern Alps runs through the center of the South Island. What type of mountains do you think the Southern Alps are? Explain your answer.

Chapter 11

Summary

THINK central
SUPER SUMMARY
Keyword: HQXDEFS

Key Ideas | **Key Terms**

Section 1

How Rock Deforms

- Isostasy occurs when there is a balance between the gravitational force of the lithosphere pressing downward and the buoyant force of the asthenosphere pressing upward.
- The three main types of stress are compression, which squeezes rock together; tension, which pulls rock apart; and shear stress, which bends and twists rock.
- Folds form when rock is bent without breaking. Faults form when a block of rock on one side of a fracture moves relative to the block on the other side.

Key Terms

deformation, p. 293
isostasy, p. 293
stress, p. 295
strain, p. 296
fold, p. 297
fault, p. 299

Section 2

How Mountains Form

- Collisions that form mountains can occur between an oceanic plate and a continental plate, between an oceanic plate and another oceanic plate, or between two continental plates.
- Four types of mountains are folded mountains, fault-block mountains, dome mountains, and volcanic mountains.
- Folded mountains form as tectonic movements squeeze Earth's crust into folds. Faulted mountains form as large blocks of crust tilt and move relative to other blocks of crust.

Key Terms

mountain range, p. 301
folded mountain, p. 304
fault-block mountain, p. 305
dome mountain, p. 305

Chapter 11 Review

1. **Everyday Words Used in Science** The word *range* is used to describe mountains that are related by size and structure. What does the word *range* mean in everyday speech? What does it mean in a scientific context?

READING TOOLBOX

USING KEY TERMS

Use each of the following terms in a separate sentence.

2. *isostasy*
3. *compression*
4. *shear stress*

For each pair of terms, explain how the meanings of the terms differ.

5. *stress* and *strain*
6. *fold* and *fault*
7. *syncline* and *monocline*
8. *dome mountains* and *volcanic mountains*
9. *folded mountains* and *fault-block mountains*

UNDERSTANDING KEY IDEAS

10. When the weight of an area of Earth's crust increases, the lithosphere
    a. sinks.
    b. melts.
    c. rises.
    d. collides.
11. The force per unit area that changes the shape and volume of rock is
    a. footwall.
    b. isostasy.
    c. rising.
    d. stress.
12. Shear stress
    a. bends, twists, or breaks rock.
    b. causes isostasy.
    c. causes rock to melt.
    d. causes rock to expand.
13. When stress is applied under conditions of high pressure and high temperature, rock is more likely to
    a. fracture. **c.** fault.
    b. sink. **d.** fold.
14. Folds in which both limbs remain horizontal are called
    a. monoclines. **c.** synclines.
    b. fractures. **d.** anticlines.
15. When a fault is not vertical, the rock above the fault plane makes up the
    a. tension. **c.** hanging wall.
    b. footwall. **d.** compression.
16. A fault in which the rock on either side of the fault plane moves horizontally in nearly opposite directions is called a
    a. normal fault. **c.** strike-slip fault.
    b. reverse fault. **d.** thrust fault.
17. The largest mountain systems are part of still larger systems called
    a. continental margins.
    b. ranges.
    c. belts.
    d. synclines.
18. Large areas of flat-topped rock high above the surrounding landscape are
    a. grabens. **c.** hanging walls.
    b. footwalls. **d.** plateaus.

SHORT ANSWER

19. Name two types of deformation in Earth's crust, and explain how each type occurs.
20. Explain how to identify an anticline.
21. Identify the two major mountain belts on Earth.
22. Describe how the various types of mountains are categorized.
23. Identify the two forces that are kept in balance by isostatic adjustments.
24. Compare the features of dome mountains with those of fault-block mountains.

CRITICAL THINKING

25. Evaluating Ideas If thick ice sheets covered large parts of Earth's continents again, how would you expect the lithosphere to respond to the added weight of the continental ice sheets? Explain your answer.

26. Analyzing Relationships When the Indian plate collided with the Eurasian plate and produced the Himalaya Mountains, which type of stress most likely occurred? Which type of stress is most likely occurring along the Mid-Atlantic Ridge? Which type of stress would you expect to find along the San Andreas fault? Explain your answers.

27. Making Predictions If the force that causes a rock to deform slightly begins to ease, what may happen to the rock? What might happen if the force causing the deformation becomes greater?

28. Analyzing Processes Why do you think that dome mountains do not always become volcanic mountains?

CONCEPT MAPPING

29. Use the following terms to create a concept map: *stress, strain, brittle, ductile, folds, faults, normal fault, reverse fault, thrust fault,* and *strike-slip fault.*

MATH SKILLS

Math Skills

30. Making Calculations Scientists calculate that parts of the Himalayas are rising at a rate of 6.1 mm per year. At this rate, in how many years will the Himalayas be 1 m taller than they are today?

31. Analyzing Data Rock stress is measured as 48 MPa at point A below Earth's surface. At point B nearby, stress is measured as 12 MPa. What percentage of the stress at point A is the stress at point B equal to?

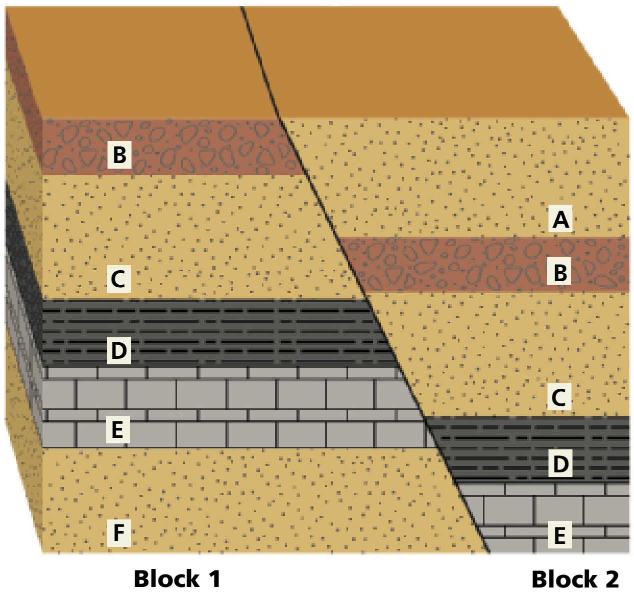
WRITING SKILLS

32. Creative Writing Write a short story from the perspective of a rock that is being deformed. Describe the stresses that are affecting the rock and the final result of the stress.

33. Writing from Research Look for photos or illustrations of folding and faulting in a particular area. Then, research the geologic history of the area, and write a report based on your findings. Use any photos or drawings that you find to illustrate your report.

INTERPRETING GRAPHICS

The diagram below shows a fault. Use this diagram to answer the questions that follow.



34. Is Block 2 a footwall or a hanging wall? Explain your answer.

35. What type of fault is illustrated? Explain your answer.

36. What type of stress generally causes this type of fault?

Chapter 11 Standardized Test Prep

Understanding Concepts

Directions (1–4): For each question, write on a separate sheet of paper the letter of the correct answer.

1. Where are most plateaus located?
- **A.** near mountain ranges
- **B.** bordering ocean basins
- **C.** beneath grabens
- **D.** alongside diverging boundaries

2. Which of the following features form where parts of the crust have been broken by faults?
- **F.** monoclines
- **G.** plateaus
- **H.** synclines
- **I.** grabens

3. Which of the following statements describes the formation of rock along strike-slip faults?
- **A.** Rock on either side of the fault plane slides vertically.
- **B.** Rock on either side of the fault plane slides horizontally.
- **C.** Rock in the hanging wall is pushed up and over the rock of the footwall.
- **D.** Rock in the hanging wall moves down relative to the footwall.

4. Which does not result in mountain formation?
- **F.** collisions between continental and oceanic crust
- **G.** subduction of one oceanic plate beneath another oceanic plate
- **H.** deposition and isostasy
- **I.** deformation caused by collisions between two or more continents

Directions (5–7): For each question, write a short response.

5. What is the term for a condition of gravitational equilibrium in Earth's crust?

6. What is the term for a type of stress that squeezes and shortens a body?

7. As a volcanic mountain range forms, what does isostatic adjustment cause the crust beneath the mountain range to do?

Reading Skills

Directions (8–10): Read the passage below. Then, answer the questions.

Stress and Strain

Stress is defined as the amount of force per unit area on a rock. When enough stress is placed on a rock, the rock becomes strained, usually by bending and breaking. For example, if you put a small amount of pressure on the ends of a drinking straw, the straw may not bend—even though you have put stress on it. However, when you put enough pressure on it, the straw bends, or becomes strained.

One example of stress is when tectonic plates collide. When plates collide, a large amount of stress is placed on the rocks that make up the plates, especially the rocks at the edges of the plates involved in the collision. Because of the stress, these rocks become extremely strained. In fact, even the shapes of the tectonic plates can change as a result of these powerful collisions.

8. Based on the passage, which of the following statements is not true?
- **A.** Strain can cause rock to deform by bending or breaking.
- **B.** Rocks, like drinking straws, will not bend when pressure is applied to them.
- **C.** Stress is defined as amount of force per unit area that is put on rock.
- **D.** A large amount of stress is placed on the rocks involved in tectonic plate collisions.

9. Which of the following statements can be inferred from the information in the passage?
- **F.** The stress of tectonic plate collisions often creates large, smooth plains of rock.
- **G.** The stress of tectonic plate collisions often creates large mountain chains.
- **H.** Bending a drinking straw requires the same amount of pressure that is needed to bend a rock.
- **I.** The only time that rock has stress is when the rock is involved in a tectonic collision.

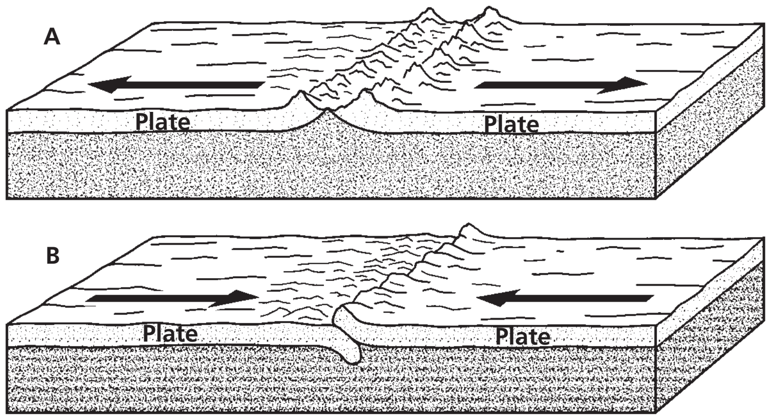
10. What happens to rocks when plates collide?

Interpreting Graphics

Directions (11–14): For each question below, record the correct answer on a separate sheet of paper.

The diagrams below show a divergent and a convergent plate boundary. Use these diagrams to answer questions 11 and 12.

Divergent and Convergent Plate Boundaries



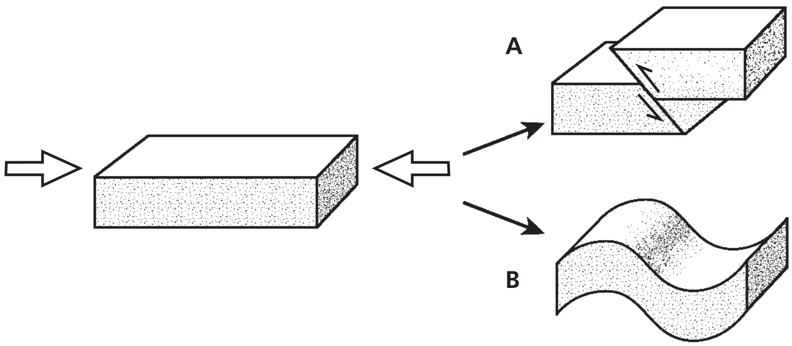
11. Which of the following is not likely to be found at or occur at the boundary shown in diagram A?

A. volcanoes
B. lava flows
C. earthquakes
D. subduction

12. How does the subduction of the oceanic crust shown in diagram B produce volcanic mountains?

The diagram below shows two possible outcomes when pressure, which is represented by the large arrows, is applied to the rock on the left. Use this diagram to answer questions 13 and 14.

Rock Deformation



13. What type of deformation is seen in rock A?

F. brittle
G. ductile
H. folding
I. monocline

14. Describe the type of rock deformation shown in rock B. Under what conditions is this type of deformation likely to occur?

Test Tip

Carefully study all of the details of a diagram before answering the question or questions that refer to it.