CHAPTER

15

Geologic Structures

Rocks that were once horizontal have been contorted into folds during mountain building, Agio Pavlos in Southern Crete, Greece. *Photo © Marco Simoni/Robert Harding/Getty Images*

Tectonic Forces at Work
  Stress and Strain in the Earth's Lithosphere
  How Do Rocks Behave When Stressed?
How Do We Record and Measure Geologic Structures?
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Folds
  Geometry of Folds
  Interpreting Folds
Fractures in Rock
  Joints
  Faults
Summary

LEARNING OBJECTIVES

- Why are geologic structures important?
- Sketch and describe the three types of stress and the resulting strain.
- Explain how rocks behave when stressed.
- Define *strike, angle of dip,* and *direction of dip.*
- Sketch and describe the different types of folds, and explain how the shape and orientation of folds is used to interpret strain.
- Sketch and describe the relative displacement and type of stress for normal, reverse, and thrust faults as well as the two types of strike-slip faults.

In previous chapters, we have discussed how rock at the surface of Earth is affected by the atmosphere, hydrosphere, and biosphere. We now shift our focus to processes in the solid Earth system, or geosphere. In this chapter, we explain how rocks respond to tectonic forces caused by the movement of lithospheric plates and how geologists study the resulting geologic structures. Studying structural geology is very much like looking at the architecture of the crust and trying to relate how rocks that were once deposited under water in horizontal layers are now found bent (folded) and broken (faulted) many kilometers above sea level.

Subsequent chapters will require an understanding and knowledge of structural geology as presented in this chapter. To understand earthquakes, for instance, one must know about faults. Appreciating how major mountain belts and the continents have evolved (chapter 20) calls for a comprehension of faulting and folding. Understanding plate-tectonic theory as a whole (chapter 19) also requires a knowledge of structural geology. (Plate-tectonic theory developed primarily to explain certain structural features.) In areas of active tectonics, the location of geologic structures is important in the selection of safe sites for schools, hospitals, dams, bridges, and nuclear power facilities.

Also, understanding structural geology can help us more fully appreciate the problem of finding more of Earth's dwindling natural resources. Chapter 21 discusses the association of certain geologic structures with petroleum deposits and other valuable resources.

TECTONIC FORCES AT WORK

Stress and Strain in the Earth's Lithosphere

Tectonic forces deform parts of the lithosphere, particularly along plate margins. Deformation may cause a change in orientation, location, and shape of a rock body. In figure 15.1, originally horizontal rock layers have been deformed into wavelike folds that are broken by faults. The layers have been deformed, probably by tectonic forces that pushed or compressed the layers together until they were shortened by buckling and breaking.

When studying deformed rocks, structural geologists typically refer to **stress,** a force per unit area. Where stress can be measured, it is expressed as the force per unit area at a particular point; however, it is difficult to measure stress in rocks that are buried. We can observe the effects of past stress (caused by tectonic forces and confining pressure from burial) when rock bodies are exposed after uplift and erosion. From our observations, we may be able to infer the principal directions of stress that prevailed. We also can observe in exposed rocks the effect of forces on a rock that was stressed. **Strain** is the change in shape or size (volume), or both, in response to stress.

The relationship between stress and strain can be illustrated by deforming a piece of Silly Putty® (figure 15.2) or any other soft material such as pizza dough. If the Silly Putty is pushed together or squeezed from opposite directions, we say the stress is **compressive.** Compressive stress results in rocks being *shortened* or *flattened.* In figure 15.2*A,* an elongate piece of Silly Putty may shorten by bending, or folding, whereas a ball of Silly Putty will flatten by shortening in the direction parallel to the compressive stress and elongating or stretching in the direction perpendicular to it. Rocks that have been shortened or flattened are typically found along convergent plate boundaries where rocks have been pushed or shoved together.

A **tensional stress** is caused by forces pulling away from one another in opposite directions (figure 15.2*B*). Tensional stress results in a *stretching or extension* of material. If we apply a tensional stress on a ball of Silly Putty, it will elongate or stretch parallel to the applied stress. If the tensional stress is applied rapidly, the Silly Putty will first stretch and then break apart (figure 15.2*B*). At divergent plate boundaries, the lithosphere is undergoing extension as the plates move away from one another. Because rocks are very weak when pulled apart, fractures and faults are common structures.

When stresses act parallel to a plane, **shear stress** is produced. It is much like putting a deck of cards in your hands and shearing the deck by moving your hands in opposite directions (figure 15.3). A shear stress results in a *shear strain* parallel to the direction of the stresses. Shear stresses occur along actively moving faults.

How Do Rocks Behave When Stressed?

Rocks behave as elastic, ductile, or brittle materials, depending on the amount and rate of stress applied, the type of rock, and the temperature and pressure under which the rock is strained.

If a deformed material recovers its original shape after the stress is reduced or removed, the behavior is **elastic.** For

FIGURE 15.1

Deformed sedimentary beds exposed in a road cut near Palmdale, California. Squeezing due to movement along the San Andreas fault caused the sedimentary layers to be contorted into folds and broken by smaller faults. *Photo by C. C. Plummer*

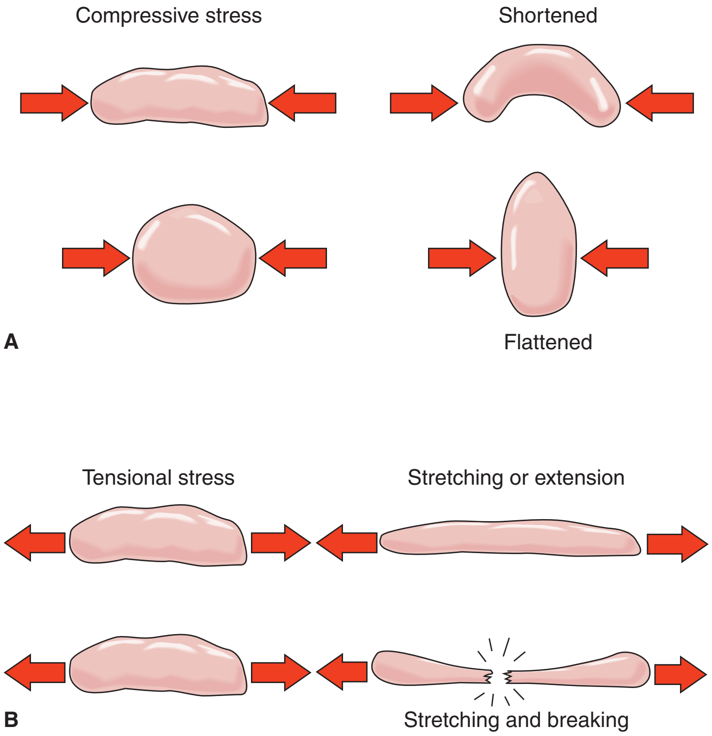


FIGURE 15.2

The effects of compressional and tensional stresses on Silly Putty®. (*A*) Compressing Silly Putty results in shortening either by folding or flattening. (*B*) Pulling (tensional stress) Silly Putty causes stretching or extension; if pulled (strained) too fast, or chilled, the Silly Putty will break after first stretching.

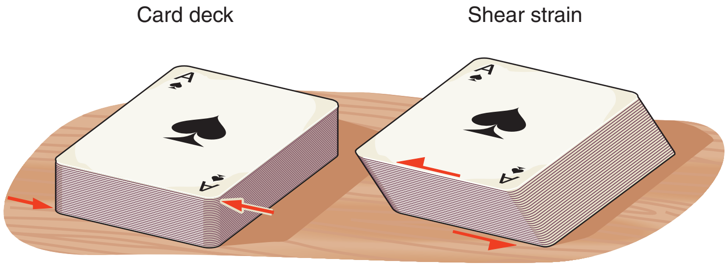


FIGURE 15.3

Shear strain can be modeled by shearing a deck of cards.

example, if a tensional stress is applied to a rubber band, it will stretch as long as the stress is applied, but once the stress is removed, the rubber band returns (or recovers) to its original shape and its behavior is elastic. Silly Putty will behave elastically if molded into a ball and bounced. Most rocks can behave in an elastic way at very low stresses (a few kilobars). However, once the stress applied exceeds the **elastic limit** (figure 15.4), the rock will deform in a permanent way, just as the rubber band will break if stretched too far.

A rock that behaves in a **ductile** or plastic manner will bend while under stress and does not return to its original shape after the stress is removed. Silly Putty behaves as a ductile material unless the rate of strain is rapid. As discussed in chapter 7, rocks exposed to elevated pressure and temperature during regional metamorphism also behave in a ductile manner

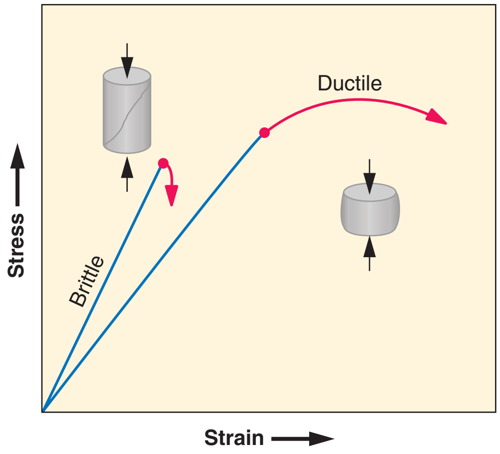


FIGURE 15.4

Graph shows the behavior of rocks with increasing stress and strain. Elastic behavior occurs along the straight-line portions (shown in blue) of the graph. At stresses greater than the elastic limit (red points), the rock will either deform as a ductile material or break, as shown in the deformed rock cylinders.

FIGURE 15.5

Geology students mapping tilted beds of rocks from a ridge-top vantage point, Mojave Desert, California. *Photo by Diane Carlson*

and develop a planar texture, or *foliation,* due to the alignment of minerals. As shown in figure 15.4, material behaving in a ductile manner does not require much of an increase in stress to continue to strain (relatively flat curve). Ductile behavior results in rocks that are permanently deformed mainly by folding or bending of rock layers (figure 15.1).

A rock exhibiting **brittle** behavior will fracture at stresses higher than its elastic limit, or once the stresses are greater than the strength of the rock. Rocks typically exhibit brittle behavior at or near Earth's surface, where temperatures and pressure are low. Under these conditions, rocks favor breaking rather than bending. Faults and joints are examples of structures that form by brittle behavior of the crust.

A sedimentary rock exposed at Earth's surface is brittle; it will fracture if you hit it with a hammer. How then do sedimentary rocks, such as those shown in figure 15.1, become bent (or deformed in a ductile way)? The answer is that either stress increased very slowly or the rock was deformed under considerable confining pressure (buried under more rock) and higher temperatures.

Note, however, that there are some fractures (faults) disrupting the bent layers in figure 15.1. This tells us that although the rock was ductile initially, the amount of stress increased or the rate of strain increased and the rock fractured.

HOW DO WE RECORD AND MEASURE GEOLOGIC STRUCTURES?

The study of geologic structures is of more than academic interest. The petroleum and mining industries, for example, employ geologists to look for and map geologic structures associated with oil and metallic ore deposits. Understanding and mapping geologic structures is also important for evaluating problems related to engineering decisions and seismic risk, such as determining the most appropriate sites for building dams, large bridges, or nuclear reactors, and even houses, schools, and hospitals.

Geologic Maps and Field Methods

In an ideal situation, a geologist studying structures would be able to fly over an area and see the local and regional patterns of bedrock from above. Sometimes this is possible, but very often soil and vegetation conceal the bedrock. Therefore, geologists ordinarily use observations from a number of individual *outcrops* (exposures of bedrock at the surface) in determining the patterns of geologic structures (figure 15.5). The characteristics of rock at each outcrop in an area are plotted on a map by means of appropriate symbols. With the data that can be collected, a geologist can make inferences about those parts of the area he or she cannot observe. A **geologic map,** which uses standardized symbols and patterns to represent rock types and geologic structures, is typically produced from the field map for a given area (for example, see the geologic map of North America inside the front cover). On such a map are plotted the type and distribution of rock units, the occurrence of structural features (folds, faults, joints, etc.), ore deposits, and so forth. Sometimes surficial features, such as deposits by former glaciers, are included, but these may be shown separately on a different type of geologic map.

Anyone trained in the use of geologic maps can gain considerable information about local geologic structures because standard symbols and terms are used on the maps and the accompanying reports. For example, the symbol ⊕

FIGURE 15.6

Tilted sedimentary beds along the coast of northern California near Point Arena. Here, the strike is the line formed by the intersection of the tilted sedimentary beds and the horizontal layer of sand in the foreground. The direction of dip is toward the left. *Photo by Diane Carlson*

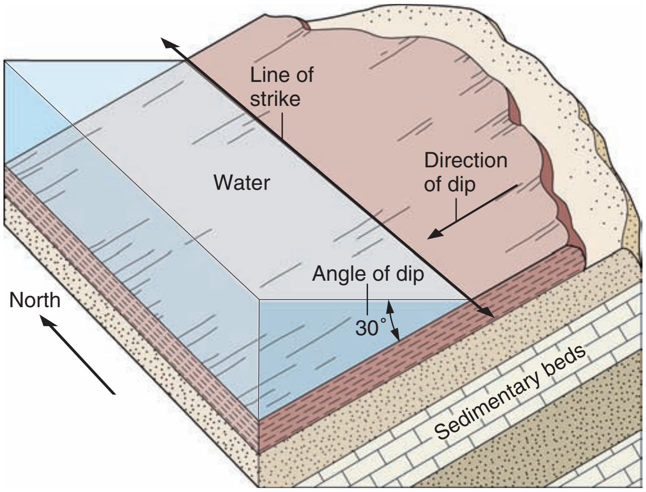


FIGURE 15.7

Strike, direction of dip, and angle of dip. The line of strike is found where an inclined bed intersects a horizontal plane (as shown here by the water). The dip direction is always perpendicular to the strike and in the direction the bed slopes (or a ball would roll down). The dip angle is the vertical angle of the inclined bed as measured from the horizontal.

on a geologic map denotes horizontal bedding in an outcrop. Different colors and patterns on a geologic map represent distinct rock units.

Strike and Dip

According to the principle of *original horizontality,* sedimentary rocks and some lava flows and ashfalls are deposited as horizontal beds or strata. Where these originally horizontal rocks are found tilted, it indicates that tilting must have occurred after deposition and lithification (figure 15.6). Someone studying a geologic map of the area would want to know the extent and direction of tilting. By convention, this is determined by plotting the relationship between a surface of an inclined bed and an imaginary horizontal plane. You can understand the relationship by looking carefully at figure 15.7, which represents sedimentary beds exposed alongside a lake (the lake surface provides a convenient horizontal plane for this discussion).

Strike is the compass direction of a line formed by the intersection of an inclined plane with a horizontal plane. In this example, the inclined plane is a bedding plane. You can see from figure 15.7 that the beds are striking from north to south. Customarily, only the northerly direction (of the strike line) is given, so we simply say that beds strike north a certain number of degrees east or west (such as N50°E).

Observe that the **angle of dip** is measured downward from the horizontal plane to the bedding plane (an inclined plane). Note that the angle of dip (30° in the figure) is measured within a vertical plane that is perpendicular to both the bedding and the horizontal planes.

The **direction of dip** is the compass direction in which the angle of dip is measured. If you could roll a ball down a bedding surface, the compass direction in which the ball rolled would be the direction of dip.

The dip angle is always measured at a right angle to the strike—that is, perpendicular to the strike line as shown in figure 15.7. Because the beds could dip away from the strike line in either of two possible directions, the general direction of dip is also specified—in this example, west.

A specially designed instrument called a Brunton pocket transit (after the inventor) is used by geologists for measuring the strike and dip (figure 15.8). The pocket transit contains a compass, a level, and a device for measuring angles of inclination. Besides recording strike and dip measurements in a field notebook, a geologist who is mapping an area draws strike and dip symbols on the field map, such as ⟋ or ⟋ for each outcrop with dipping or tilted beds. On the map, the intersection of the two lines at the center of each strike and dip symbol represents

FIGURE 15.8

Geology student measuring the strike and dip of an inclined limestone bed in the White Mountains of southern California. *Photo by Diane Carlson*

the location of the outcrop where the strike and dip of the bedrock were measured. The long line of the symbol is aligned with the compass direction of the strike. The small tick, which is always drawn perpendicular to the strike line, is put on one side or the other, depending on which of the two directions the beds actually dip. The angle of dip is given as a number next to the appropriate symbol on the map. Thus, ^{25}⟋ indicates that the bed is dipping 25° from the horizontal toward the northwest and the strike is northeast (assuming that the top of the page is north). The orientation of the bed would be written N45°E, 25°NW. Figure 15.9 is a geologic map with cross section that shows all the sedimentary layers striking north and dipping 30° to the west (N0°, 30°W).

Beds with vertical dip require a unique symbol because they dip neither to the left nor the right of the direction of strike. The symbol used is ✗, which indicates that the beds are striking northeast and that they are vertical (N30°E, 90°).

Geologic Cross Sections

A **geologic cross section** represents a vertical slice through a portion of Earth. It is much like a road cut (see figure 15.1) or the wall of a quarry in that it shows the orientation of rock units and structures in the vertical dimension. Geologic cross sections are constructed from geologic maps by projecting the dip of rock units into the subsurface (figure 15.9), and are quite useful in helping visualize geology in three dimensions. They are used extensively throughout this book as well as in professional publications.

FOLDS

Folds are bends or wavelike features in layered rock. Folded rock can be compared to several layers of rugs or blankets that have been pushed into a series of arches and troughs. Folds in rock often can be seen in road cuts or other exposures (figure 15.10). When the arches and troughs of folds are concealed (or when they exist on a grand scale), geologists can still determine the presence of folds by noticing repeated reversals in the direction of dip taken on outcrops in the field or shown on a geologic map.

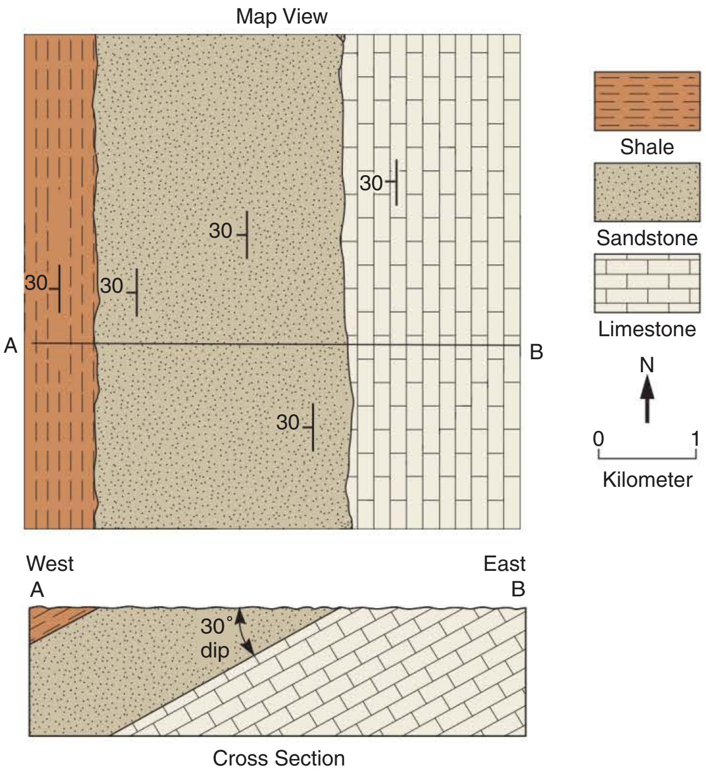


FIGURE 15.9

A geologic map and cross section of an area with three sedimentary formations. (Each formation may contain many individual sedimentary layers, as explained in chapter 6.) Beds strike north and dip 30° to the west. The geologic cross section (vertical cut) is constructed between points *A* and *B* on the map.

The fact that the rock is folded or bent shows that it behaved as a ductile material. Yet the rock exposed in outcrops is generally brittle and shatters when struck with a hammer. The rock is not metamorphosed (most metamorphic rock is intensely folded because it is ductile under the high pressure and temperature environment of deep burial and tectonic stresses). Perhaps folding took place when the rock was buried at a moderate depth where higher temperature and confining pressure favor ductile behavior. Alternatively, folding could have taken place close to the surface under a very low rate of strain.

Geometry of Folds

Determining the geometry or shape of folds may have important economic implications because many oil and gas deposits (see box 15.1) and some metallic mineral deposits are localized in folded rocks. The geometry of folds is also important in

FIGURE 15.10

Folded sedimentary rock layers exposed at Lulworth Cove, Dorset, England. *Photo © Martin Bond/Science Source*

unraveling how a rock was strained and how it might be related to the movement of tectonic plates. Folds are usually associated with shortening of rock layers along convergent plate boundaries, but they are also commonly formed where rock has been sheared along a fault.

Because folds are wavelike forms, two basic fold geometries are common—anticlines and synclines (figure 15.11).

An **anticline** is a fold shaped like an arch with the oldest rocks in the center of the fold. Usually the rock layers dip away from the **hinge line** (or *axis*) of the fold. The counterpart of an anticline is a **syncline,** a fold shaped like a trough with the youngest rocks in the center of the fold. The layered rock usually dips toward the syncline's hinge line. In the series of folds shown in figure 15.11, two anticlines are separated by a syncline. Each anticline and adjacent syncline share a **limb.** Note the hinge lines on the crests of the two anticlines and bottom of the syncline. Similar hinge lines could be located in the hinge areas at the contacts between any two adjacent folded layers. For each anticline and the syncline, the hinge lines are contained within the shaded vertical planes. Each of these planes is an **axial plane,** an imaginary plane containing all of the hinge lines of a fold. The axial plane divides the fold into its two limbs.

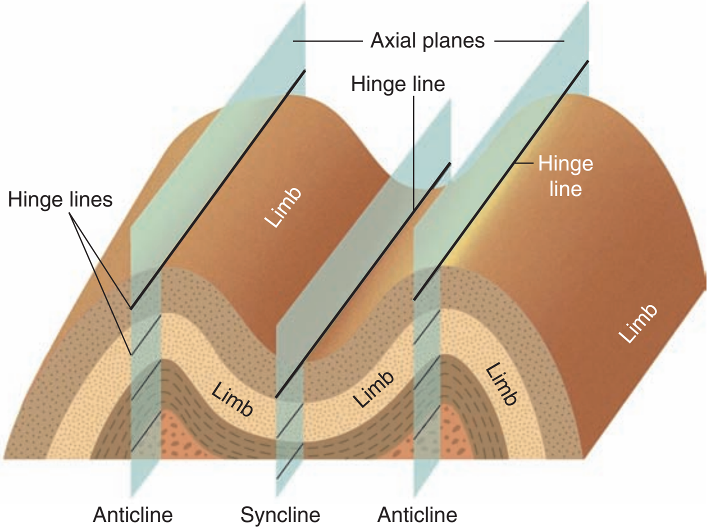


FIGURE 15.11

Diagrammatic sketch of two anticlines and a syncline illustrating the axial planes, hinge lines, and fold limbs.

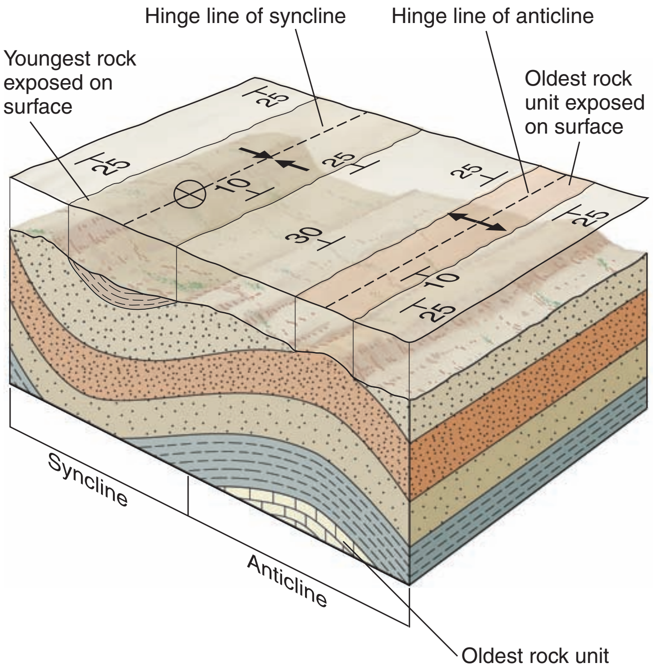


FIGURE 15.12

By measuring the strike and dip of exposed sedimentary beds in the field and plotting them on a geologic map (top surface), geologists can interpret the geometry of the geologic structure below the ground surface.

It is important to remember that anticlines are not necessarily related to ridges nor synclines to valleys, because valleys and ridges are nearly always erosional features. In an area that has been eroded to a plain, the presence of underlying anticlines and synclines is determined by the direction of dipping beds in exposed bedrock, as shown in figure 15.12. (In the field, of course, the cross sections are not exposed to view as they are in the diagram.)

IN GREATER DEPTH 15.1

Is There Oil Beneath My Property? First Check the Geologic Structure

An "oil pool" can exist only under certain conditions. Crude oil does not fill caves underground, as the term *pool* may suggest; rather, it simply occupies the pore spaces of certain sedimentary rocks, such as poorly cemented sandstone, in which void space exists between grains. Natural gas (less dense) often occupies the pore spaces above the crude oil, while water (more dense) is generally found saturating the rock below the oil pool (box figure 1). The oil and gas must be trapped by an overlying rock that is impermeable and will not let the petroleum seep to the surface.

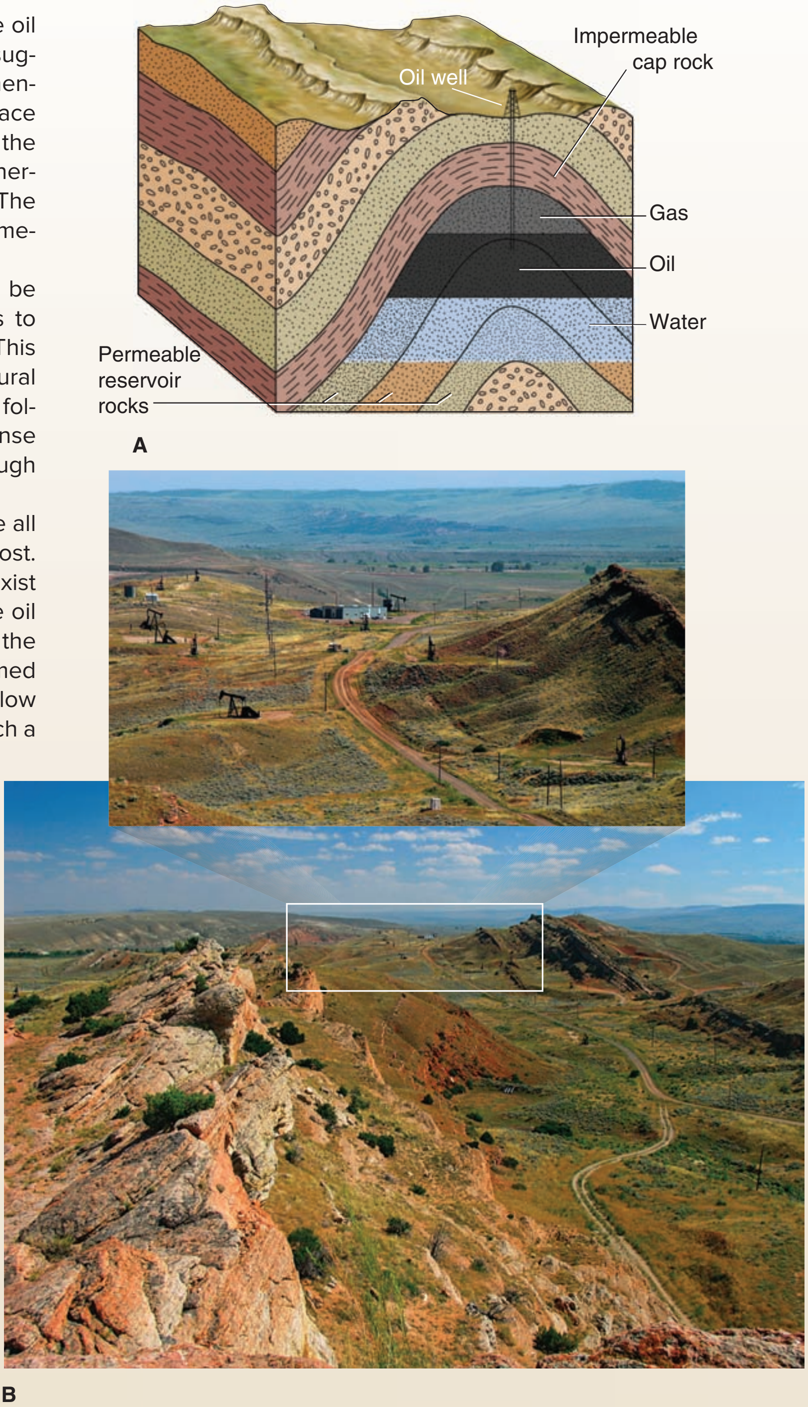
A **source rock**, which is always a sedimentary rock, must be present for oil to form. The sediment of the source rock has to include remains of organisms buried during sedimentation. This organic matter partially decomposes into petroleum and natural gas. Once formed, the droplets of petroleum tend to migrate, following fractures and interconnecting pore spaces. Being less dense than the rock, the petroleum usually migrates upward, although horizontal migration does occur.

If it is not blocked by impermeable rock, the oil may migrate all the way to the surface, where it is dissipated and permanently lost. Natural oil seeps, where leakage of petroleum is taking place, exist both on land and offshore. Where impermeable rock blocks the oil droplets' path of migration, an oil pool may accumulate below the rock, much like helium-filled balloons might collect under a domed ceiling. For any significant amount of oil to collect, the rock below the impermeable rock must be porous as well as permeable. Such a rock, when it contains oil, is called a **reservoir rock**.

Another necessary condition is that the geologic structure must be one that favors the accumulation and retention of petroleum. An "anticlinal trap" is one of the best structures for holding oil. As oil became a major energy source and the demand for it increased, most of the newly discovered wells penetrated anticlinal traps. Geologists discovered these by looking for indication of anticlines exposed at the surface. As time went by, other types of structures were also found to be oil traps. Many of these were difficult to find because of the lack of telltale surface patterns indicating favorable underground structures. Box figure 2 illustrates some structures other than anticlinal traps that might have a potential for oil production.

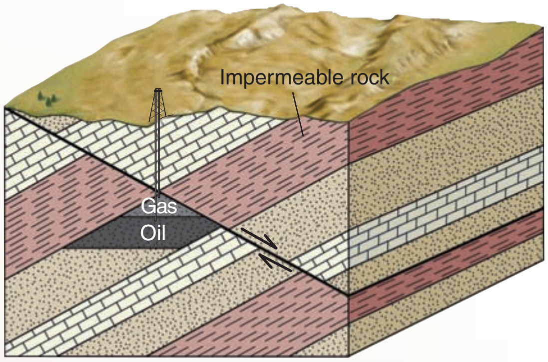
Oil companies employ large numbers of geoscientists to complete detailed and sophisticated geologic studies of an area they hope may have the potential for an "oil strike." The geoscientists working in the petroleum industry also depend heavily on geophysical techniques (see chapter 17) for determining, by indirect means, the subsurface structural geology.

Even when everything indicates that conditions are excellent for oil to be present underground, there is no guarantee that oil will be found. Eventually, an oil company must commit a million dollars or more to drill a deep test well, or "wildcat" well. Statistics indicate that the

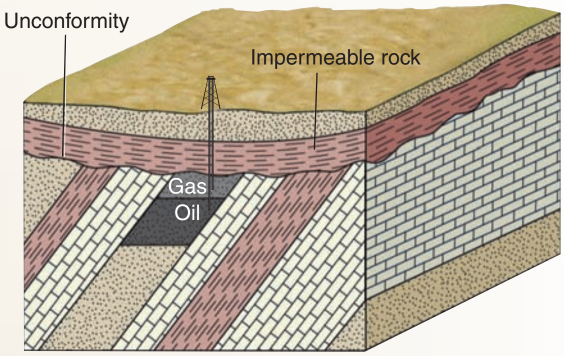


BOX 15.1 ■ FIGURE 1

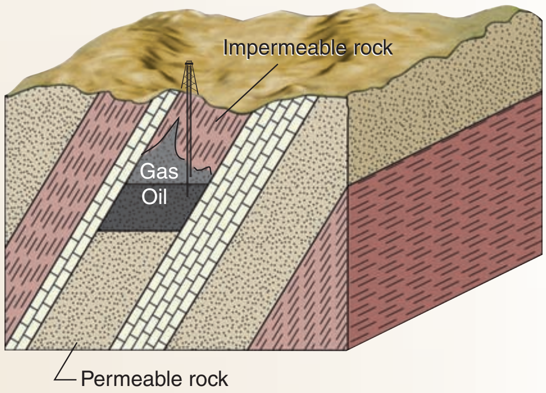
(*A*) Oil and gas are concentrated or trapped in hinge of anticline. Gas and oil float on water in porous and permeable reservoir rock (sandstone) and are trapped, or held, by the overlying impermeable shale layer. (*B*) Eroded anticline forms trap in Lander oil field, Wyoming. *Photos by Diane Carlson*



A Fault



B Unconformity



C Sedimentary facies change

BOX 15.1 ■ FIGURE 2

Structures other than anticlines that trap oil.

chance of a test well yielding commercial quantities of oil is much less than 1 in 10. As more and more of the world's supply of petroleum is used up, what is left becomes more difficult and costly to find.

Figure 15.12 also illustrates how determining the relative ages of the rock layers, or beds, can tell us whether a structure is an anticline or a syncline. Observe that the oldest exposed rocks are along the hinge line of the anticline. This is because lower layers in the originally flat-lying sedimentary or volcanic rock were moved upward and are now in the core of the anticline. The youngest rocks, on the other hand, which were originally in the upper layers, were folded downward and are now exposed along the synclinal hinge line.

Plunging Fold

The examples shown so far have been of folds with horizontal hinge lines. These are the easiest to visualize. In nature, however, anticlines and synclines are apt to be **plunging folds**—that is, folds in which the hinge lines are not horizontal. On a surface leveled by erosion, the patterns of exposed strata (beds) resemble Vs or horseshoes (figures 15.13 and 15.14) rather than the parallel, striped patterns of layers in nonplunging folds. However, plunging anticlines and synclines are distinguished from one another in the same way as are nonplunging folds—by directions of dip or by relative ages of beds.

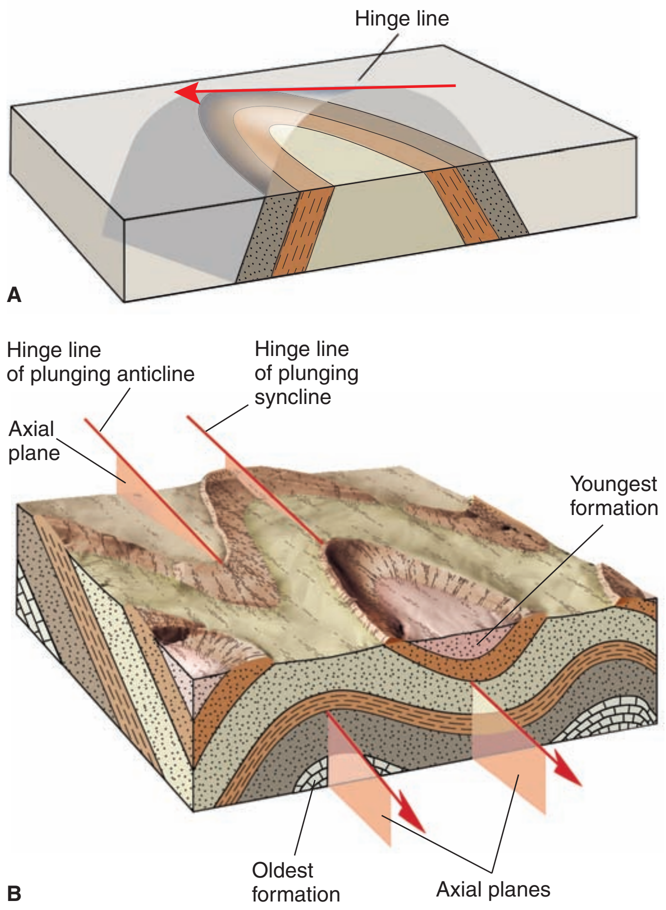


FIGURE 15.13

(*A*) Plunging fold that is cut by a horizontal plane has a V-shaped pattern. (*B*) Plunging anticline on left and right and plunging syncline in center. The hinge lines plunge toward front of block diagram and lie within the axial planes of the folds.

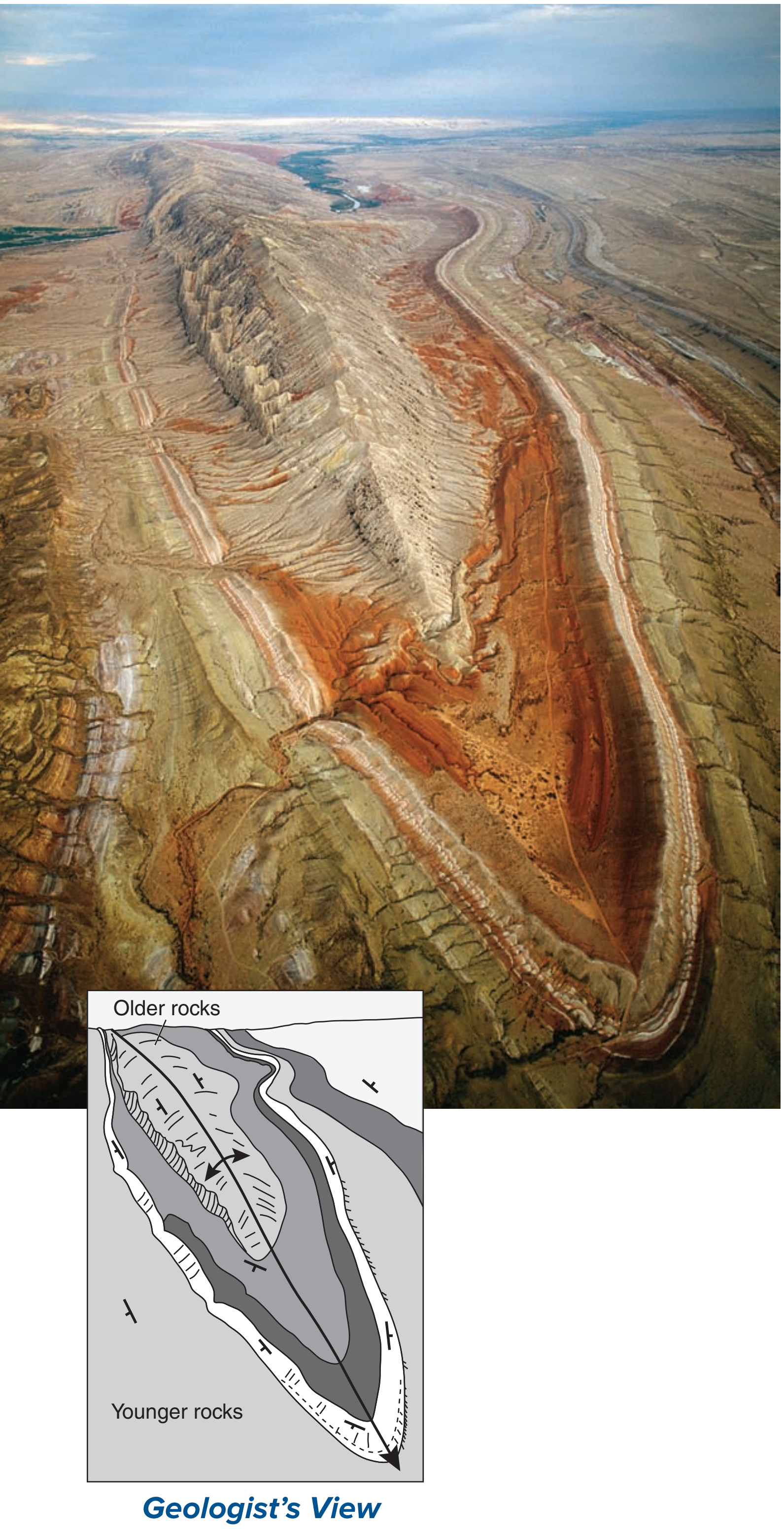


FIGURE 15.14

Rock layers dip away from center of a plunging anticline exposed at Sheep Mountain in Wyoming. Anticline plunges toward the bottom of the photo.
Photo © Michael Collier

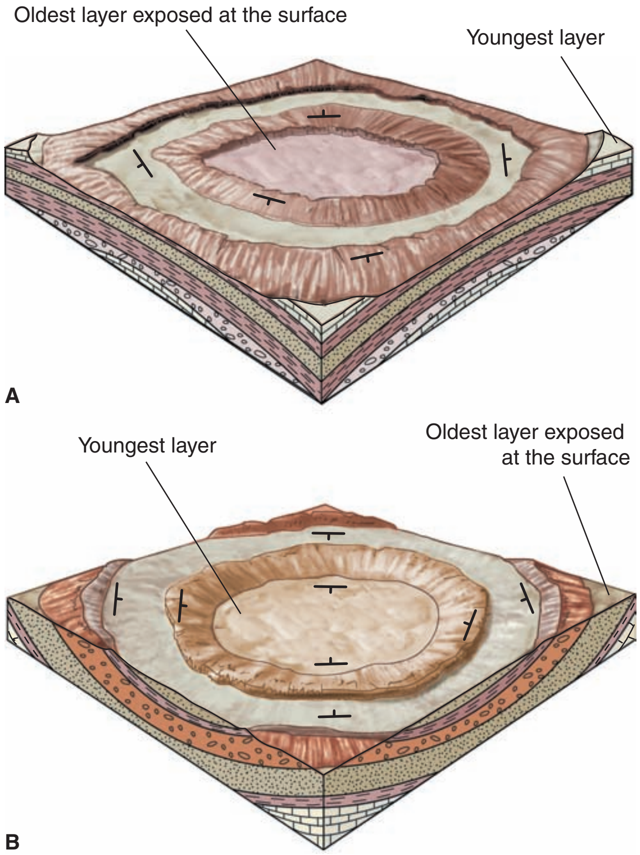


FIGURE 15.15

(*A*) Structural dome. (*B*) Structural basin.

A plunging syncline contains the youngest rocks in its center or core, and the V or horseshoe points in the direction opposite of the plunge. Conversely, a plunging anticline contains the oldest rocks in its core, and the V points in the same direction as the plunge of the fold.

Structural Domes and Structural Basins

A **structural dome** is a structure in which the beds dip away from a central point, and the oldest rocks are found in the center or core of the structure. In cross section, a dome resembles an anticline and is sometimes called a doubly plunging anticline. In a **structural basin,** the beds dip toward a central point, and the youngest rocks are exposed in the center of the structure (figure 15.15); in cross section, it is comparable to a syncline (doubly plunging syncline). A structural basin is like a set of nested bowls. If the set of bowls is turned upside down, it is analogous to a structural dome.

Domes and basins tend to be features on a grand scale (some are more than a hundred kilometers across), formed by uplift somewhat greater (for domes) or less (for basins) than that of the rest of a region. Michigan's lower peninsula and parts of adjoining states and Ontario are on a large structural basin (see map on the inside back cover). Domes of similar size are found in other parts of the Middle West. Smaller domes are found in the Rocky Mountains (figure 15.16).

FIGURE 15.16

Dome near Casper, Wyoming. The ridges are sedimentary layers that are resistant to erosion. Beds dip away from the center of the dome where the oldest rock layers are exposed. *Photo by D. A. Rahm, courtesy of Rahm Memorial Collection, Western Washington University*

Domes and anticlines (as well as some other structures) are important to the world's petroleum resources, as described in box 15.1 and in chapter 21.

Interpreting Folds

Folds occur in many varieties and sizes. Some are studied under the microscope, while others can have adjacent hinge lines tens of kilometers apart. Some folds are a kilometer or more in height. Figure 15.17 shows several of the more common types of folds. *Open folds* (figure 15.17*B*) have limbs that dip gently, and the angle between the limbs is large. All other factors being equal, the more open the fold, the less it has been strained by shortening. By contrast, if the angle between the limbs of the fold is small, then the fold is a *tight fold.* An *isoclinal fold,* one in which limbs are nearly parallel to one another, implies even larger shortening strain or shear strain (figure 15.17*C*).

A fold that has a vertical axial plane is referred to as an *upright fold.* However, where the axial plane of a fold is not vertical but is inclined or tipped over, the fold may be classified as *asymmetric.* If the axial plane is inclined to such a degree that the fold limbs dip in the same direction, the fold is classified as an *overturned fold* (figure 15.17*D*). Looking at an outcrop where only the overturned limb of a fold is exposed, you would probably conclude that the youngest bed is at the top. The principles of *superposition* (see chapter 8), however, cannot be applied to determine top and bottom for overturned beds. You must either see the rest of the fold or find primary sedimentary structures within the beds such as mud cracks that indicate the original top or upward direction.

Recumbent folds (figure 15.17*E*) are overturned to such an extent that the limbs are essentially horizontal. Recumbent folds are found in the cores of mountain ranges such as the Canadian Rockies, Alps, and Himalayas and record extreme shortening and shearing of the crust typically associated with plate convergence.

FRACTURES IN ROCK

If a rock is brittle, it will fracture. Commonly, there is some movement or displacement. If essentially no shear displacement occurs, a fracture or crack in bedrock is called a **joint.** If the rock on either side of a fracture moves parallel to the fracture plane, the fracture is a *fault.* Most rock at or near the surface is brittle, so nearly all exposed bedrock is jointed to some extent.

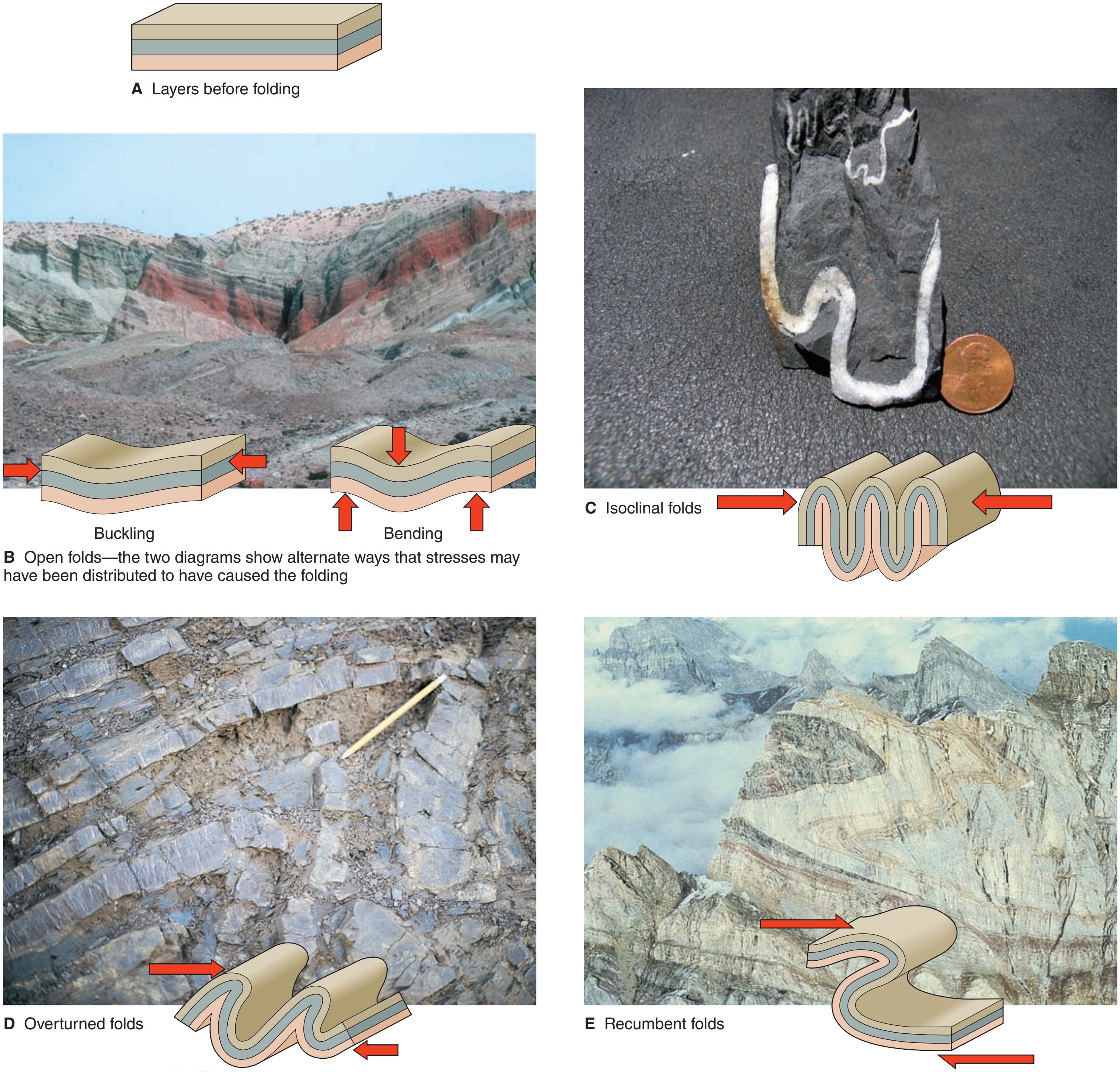
Joints

In discussing volcanoes, we described *columnar jointing,* in which hexagonal columns form as the result of contraction of a cooling, solidified lava flow (see figure 4.9). *Sheet jointing,* a type of jointing due to expansion (discussed along with weathering in chapter 5), is caused by the pressure release due to removal of overlying rock and has the effect of creating tensional stress perpendicular to the land surface.

Columnar and sheet joints are examples of fractures that form from nontectonic stresses and are therefore referred to as primary joints. In this chapter, we are concerned with joints that form not from cooling or unloading but from tectonic stresses.

Joints are among the most commonly observed structures in rocks (figure 15.18). A joint is a fracture or crack in a rock body along which essentially no displacement has occurred. Joints form at shallow depths in the crust where rock breaks in a brittle way and is pulled apart slightly by tensional stresses caused by bending or regional uplift. Where joints are oriented approximately parallel to one another, a **joint set** can be defined (figure 15.19).

Geologists sometimes find valuable ore deposits by studying the orientation of joints. For example, hydrothermal solutions may migrate upward through a set of joints and deposit quartz and economically important minerals such as gold, silver, copper, and zinc in the cracks. Accurate information about joints also is important in the planning and construction of large engineering projects, particularly dams and reservoirs. If the bedrock at a proposed location is intensely jointed, the possibility of dam failure or reservoir leakage may make that site too hazardous. The movement of contaminated groundwater from unlined landfills and abandoned mines may also be controlled by joints, which results in difficult and costly cleanups.



A Layers before folding

B Open folds—the two diagrams show alternate ways that stresses may have been distributed to have caused the folding

C Isoclinal folds

D Overturned folds

E Recumbent folds

FIGURE 15.17

Various types of folds. (*A*) Layers before folding. The length of the arrows in *B* through *E* is proportional to the amount and direction of shortening and shearing that caused folding. (*B*) Open fold from north of Barstow, California. (*C*) Isoclinal folds from the northern Sierra Nevada, California. (*D*) Overturned anticline from northern California. (*E*) Recumbent folds in the Alps. *Photo B by Diane Carlson; photo C by T. Nathan Manley and Diane Carlson; photo D by Diane Carlson; photo E courtesy of Professor John Ramsay, from J. G. Ramsay & M. J. Huber,* The Techniques of Modern Structural Geology, *v. 2., © 1987 Academic Press*

FIGURE 15.18

Vertical joints in sedimentary rock at Moab, Utah, formed in response to tectonic uplift of the region. *Photo © Michael Collier*

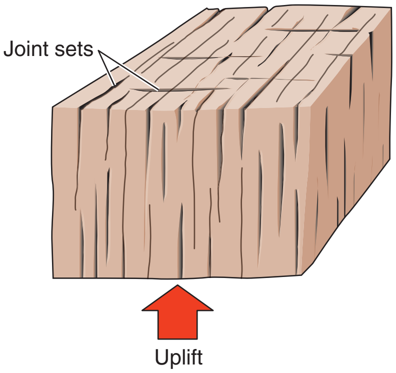


FIGURE 15.19

Two joint sets associated with uplift and a vertical compressional stress.

Faults

Faults are fractures in bedrock along which sliding has taken place. The displacement may be only several centimeters or may involve hundreds of kilometers. For many geologists, an active fault is regarded as one along which movement has taken place during the last 11,000 years. Most faults, however, are no longer active.

The nature of past movement ordinarily can be determined where a fault is exposed in an outcrop. The geologist looks for dislocated beds or other features of the rock that might show how much displacement has occurred and the relative direction of movement. In some faults, the contact between the two displaced sides is very narrow. In others, the rock has been broken or ground to a fractured or pulverized mass sandwiched between the displaced sides (figure 15.20).

Geologists describe fault movement in terms of direction of slippage: dip-slip, strike-slip, or oblique-slip (figure 15.21). In a **dip-slip fault,** movement is parallel to the dip of the fault surface. A **strike-slip fault** indicates *horizontal* motion parallel to the strike of the fault surface. An **oblique-slip fault** has both strike-slip and dip-slip components.

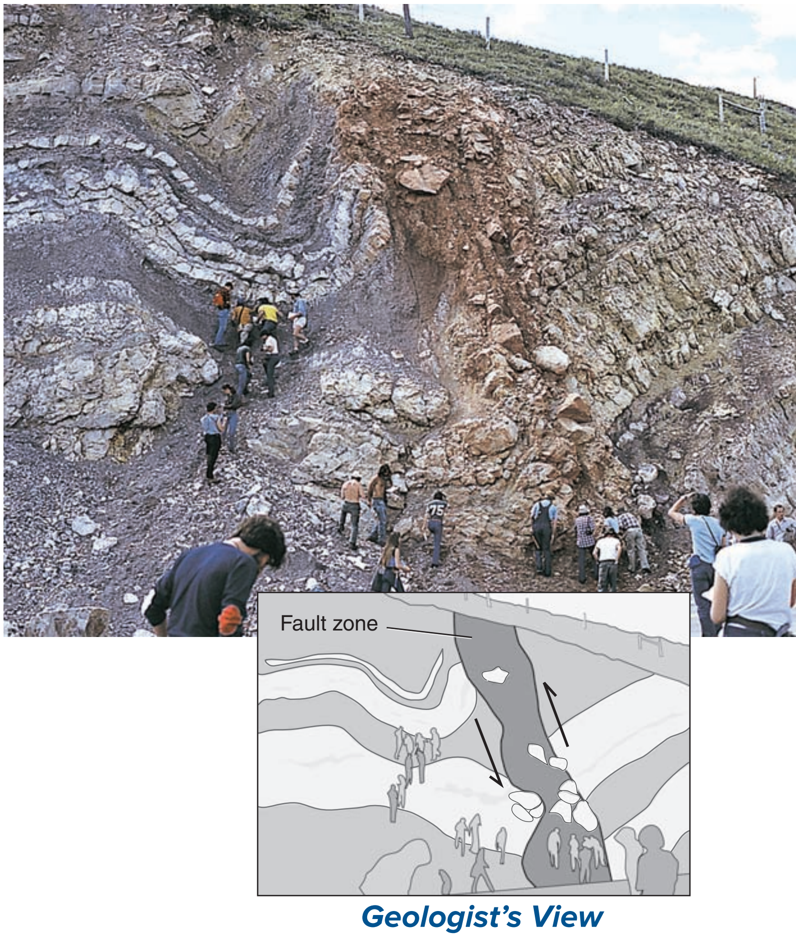
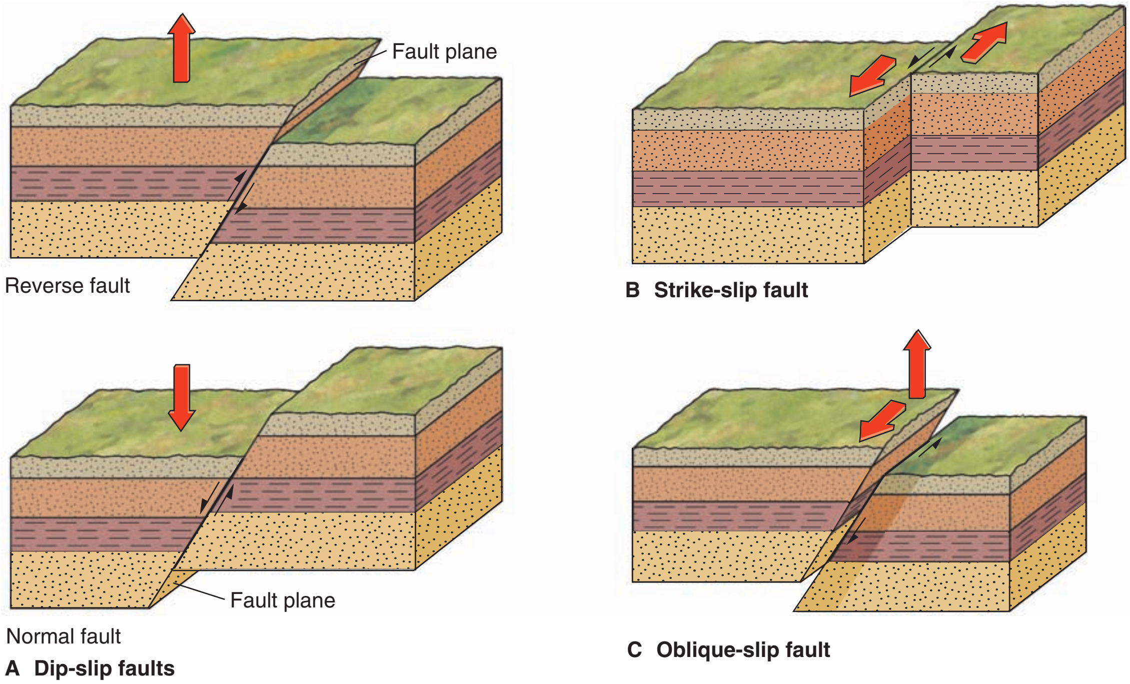


FIGURE 15.20

Fault in Big Horn Mountains, Wyoming, is marked by a 2-meter wide zone of broken, red-stained rocks that offset rock layers. *Photo by Diane Carlson*



A Dip-slip faults

B Strike-slip fault

C Oblique-slip fault

FIGURE 15.21

Three types of faults illustrated by displaced blocks. Although both blocks probably move when the fault slips, the heavier arrows show only the direction of movement on the left. (*A*) Dip-slip movement. (*B*) Strike-slip movement. (*C*) Oblique-slip movement. Black arrows show dip-slip and strike-slip components of movement.

Dip-Slip Faults

In a dip-slip fault, the movement is up or down parallel to the dip of the inclined fault surface. The side of the fault above the inclined fault surface is called the **hanging wall,** whereas the side below the fault is called the **footwall** (figure 15.22). These terms came from miners who tunneled along the fault looking for veins of mineralized rock (ore). As they tunneled, their feet were on the lower *footwall block* and they could hang their lanterns on the upper surface, or *hanging-wall block.*

Normal and reverse faults, the most common types of dip-slip faults, are distinguished from each other on the basis of the relative movement of the footwall block and the hanging-wall block. In a **normal fault** (figures 15.23 and 15.24), the hanging-wall block has moved down relative to the footwall block. The relative movement is represented on a geologic cross section by a pair of arrows, because geodetic measurement of normal faults indicates that both blocks move during slip. As shown in figure 15.23, a normal fault results in extension or lengthening of the crust. When there is extension of the crust, the hanging-wall block moves downward along the fault to compensate for the pulling apart of the rocks. Sometimes a block bounded by normal faults will drop down, creating a *graben,* as shown in figure 15.23*C.* (*Graben* is the German word for "ditch.") *Rifts* are grabens associated with divergent plate boundaries, either along mid-oceanic ridges or on continents (see chapters 18 and 19). The Rhine Valley in Germany and the Red Sea are examples of grabens.

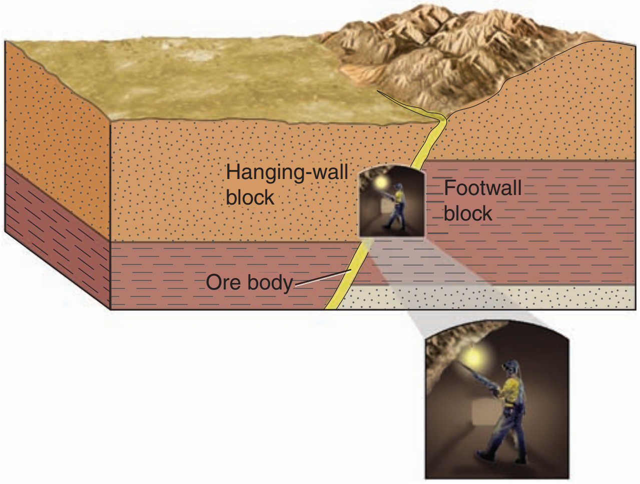


FIGURE 15.22

Relationship between the hanging-wall block and footwall block of a fault. The upper surface where a miner can hang a lantern is the hanging wall. The miner's feet are on the lower surface below the fault, which is the footwall.

If a block bounded by normal faults is uplifted sufficiently, it becomes a fault-block mountain range. (This is also called a *horst,* the opposite of a graben.) The Teton mountains and Sierra Nevada mountains are spectacular examples of fault-block mountain ranges. The Basin and Range province of Nevada and portions of adjoining states are also characterized by numerous mountain ranges (horsts) separated from adjoining valleys by

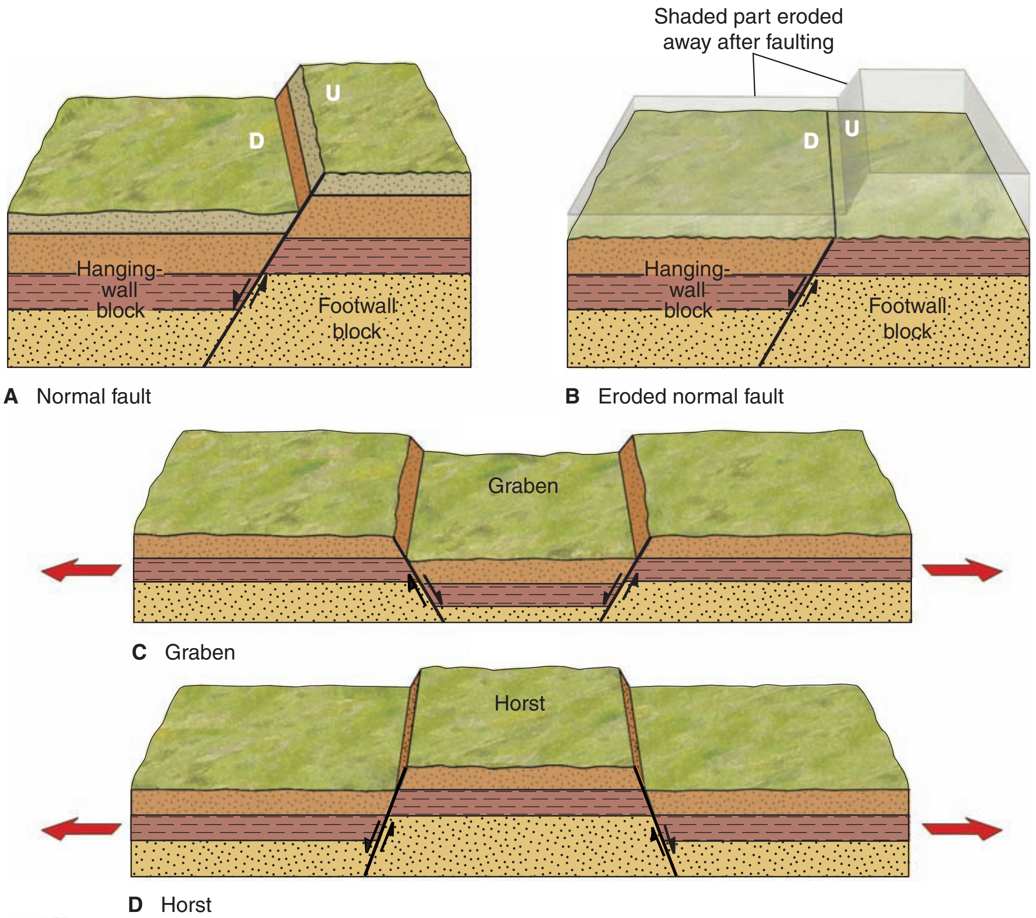


FIGURE 15.23

Normal faults. (*A*) Diagram shows the fault before erosion and the geometric relationships of the fault. (*B*) The same area after erosion. (*C*) A graben. (*D*) A horst. Arrows in *C* and *D* indicate horizontal extension of the crust.

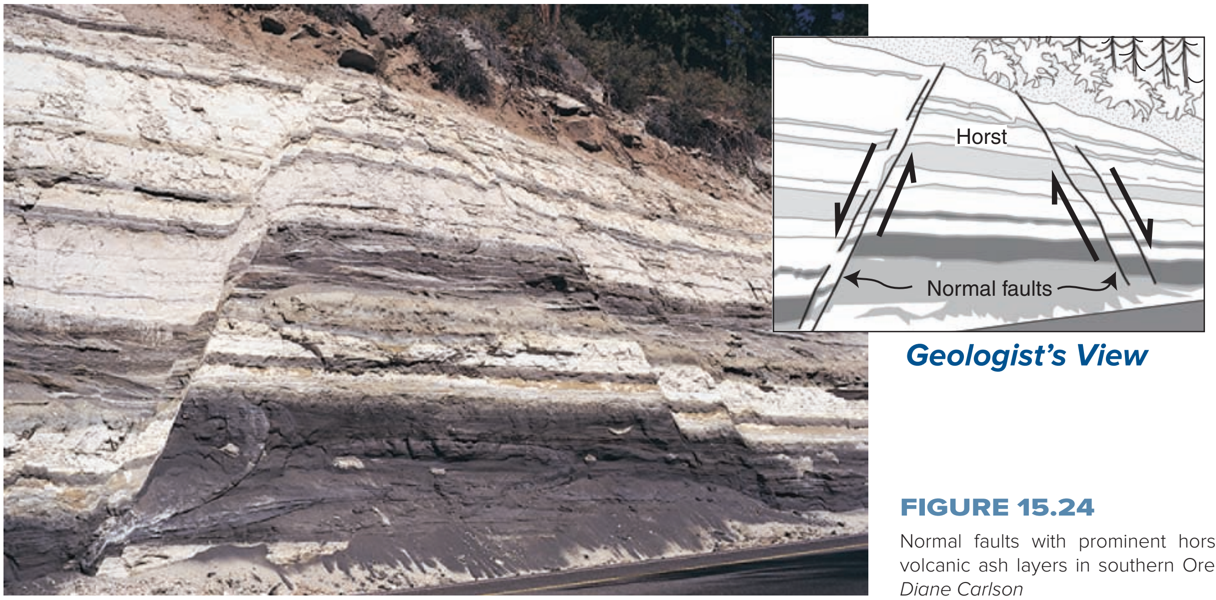


FIGURE 15.24

Normal faults with prominent horst block offset volcanic ash layers in southern Oregon. *Photo by Diane Carlson*

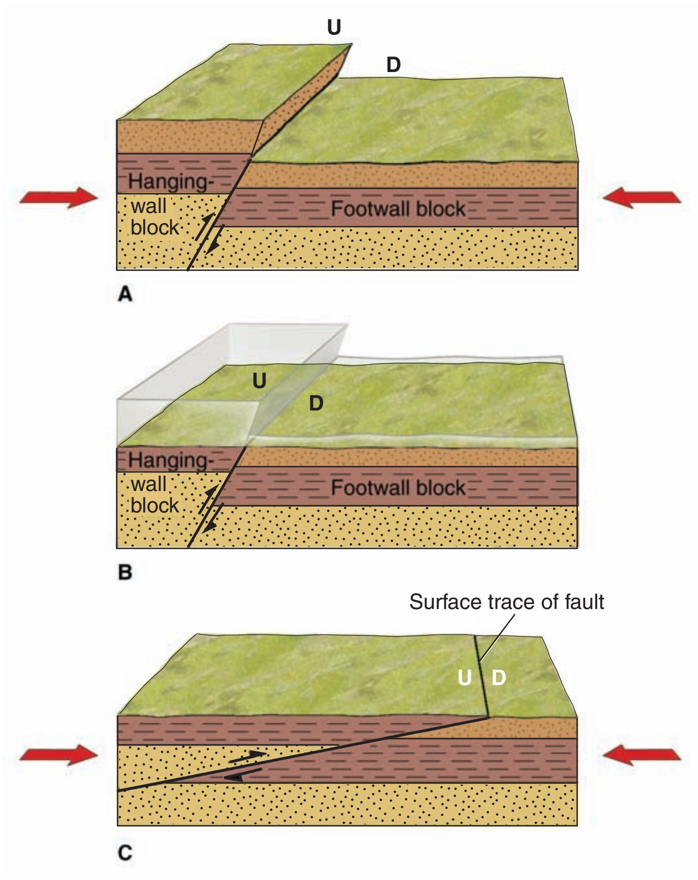


FIGURE 15.25

(*A*) A reverse fault. The fault is unaffected by erosion. Arrows indicate shortening direction. (*B*) Diagram shows area after erosion. (*C*) Thrust fault has a lower angle of dip and accommodates more shortening by stacking rock layers on top of one another.

normal faults (see chapter 20). Normal fault planes typically dip at steep angles (60°) at shallow depths but may become curved or even horizontal at depth (see figure 20.9).

In a **reverse fault,** the hanging-wall block has moved up relative to the footwall block (figures 15.25 and 15.26). As shown in figure 15.25, horizontal compressive stresses cause reverse faults. Reverse faults tend to shorten the crust.

A **thrust fault** is a reverse fault in which the dip of the fault plane is at a low angle (<30°) or even horizontal (figures 15.25*C* and 15.27). In some mountain regions, it is not uncommon for the upper plate (or hanging-wall block) of a thrust fault to have overridden the lower plate (footwall block) for several tens of kilometers. Thrust faults typically move or thrust older rocks on top of younger rocks (figure 15.27) and result in an extreme shortening of the crust. Thrust faults commonly form at convergent plate boundaries to accommodate the pushing together and shortening during convergence.

Strike-Slip Faults

A fault where the movement (or *slip*) is predominantly horizontal and therefore parallel to the strike of the fault is called a **strike-slip fault.** The displacement along a strike-slip fault is either left-lateral or right-lateral and can be determined by looking across the fault. For instance, if a recent fault displaced a stream (figure 15.28*A*), a person walking along the stream would stop where it is truncated by the fault. If the person looks across the fault and sees the stream displaced to the right, it is a **right-lateral fault.** In a **left-lateral fault,** a stream or other displaced feature would appear to the left across the fault. Again, we cannot tell which side actually moved, so pairs of arrows are used to indicate relative movement.

Large strike-slip faults, such as the San Andreas fault in California, typically define a zone of faulting that may be several kilometers wide and hundreds of kilometers long (see box 15.2). The surface trace of an active strike-slip fault is usually defined by a prominent linear valley that has been more easily eroded where the rock has been ground up along the fault during movement. The linear valley may contain lakes or sag ponds where the impermeable fault rock causes groundwater to pond at the surface. The trace of the fault may also be marked by offset surface features such as streams, fences, and roads or by distinctive rock units.

Strike-slip faults that have experienced a large amount of offset typically do not remain straight for long distances. They may either bend or step over to another fault that is parallel. Depending on the direction of the bend or stepover, the lithosphere is either pulled apart (*releasing bend*) or pushed together (*restraining bend*) (figure 15.28*B*). Normal faults and grabens form in

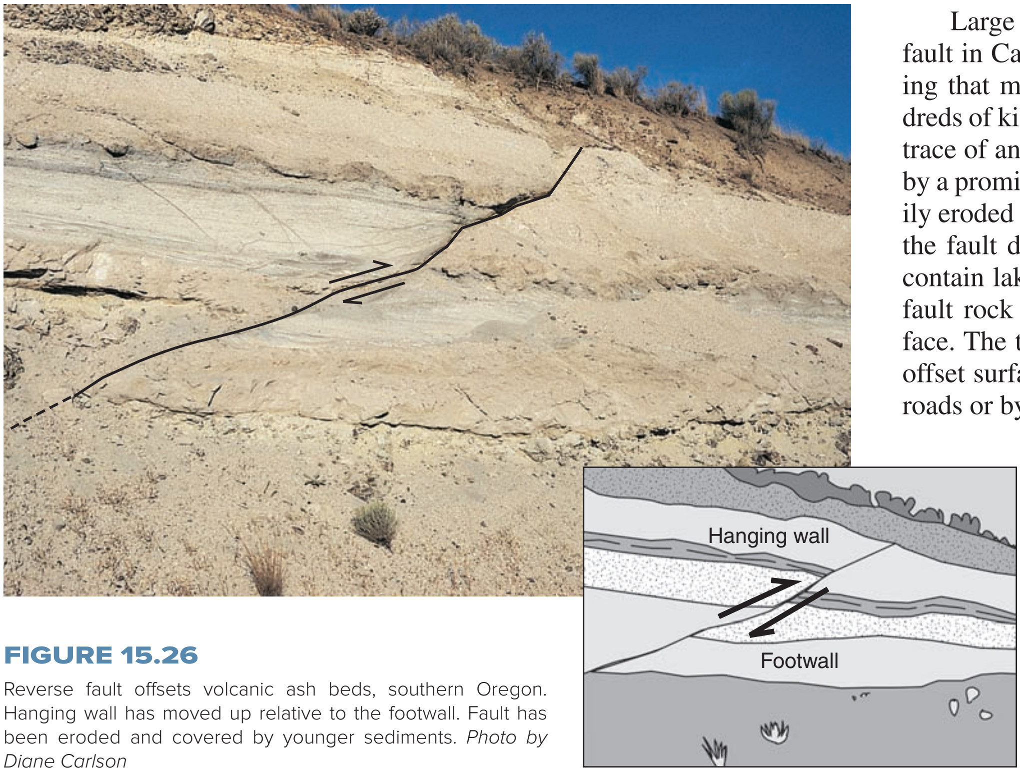


FIGURE 15.26

Reverse fault offsets volcanic ash beds, southern Oregon. Hanging wall has moved up relative to the footwall. Fault has been eroded and covered by younger sediments. *Photo by Diane Carlson*

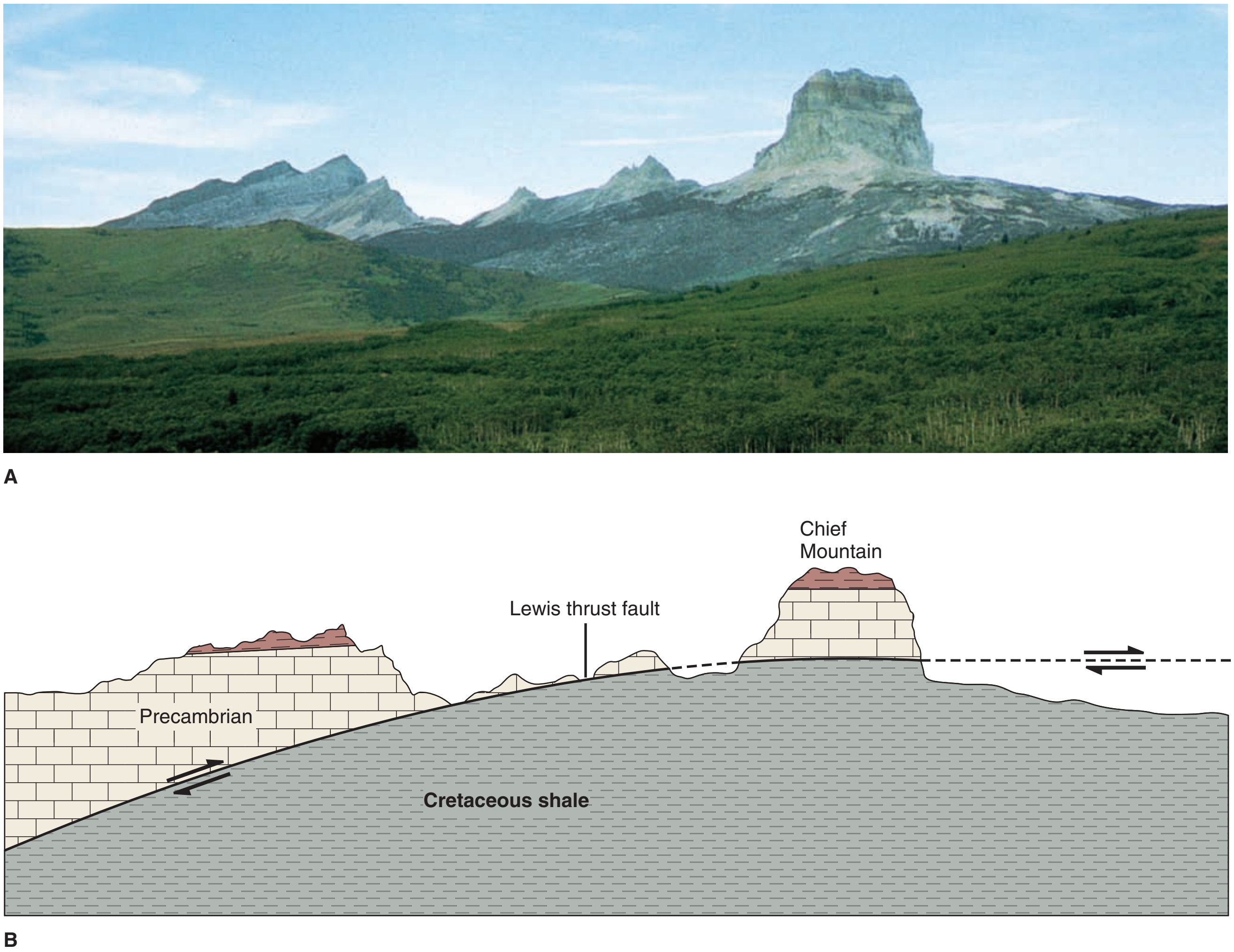


FIGURE 15.27

(*A*) Chief Mountain in Glacier National Park, Montana, is an erosional remnant of a major thrust fault. (*B*) Cross section of the area. Older (Precambrian) rocks have been thrust over younger (Cretaceous) rocks. Dashed lines show where the Lewis thrust fault has been eroded away. *Photo by Frank M. Hanna*

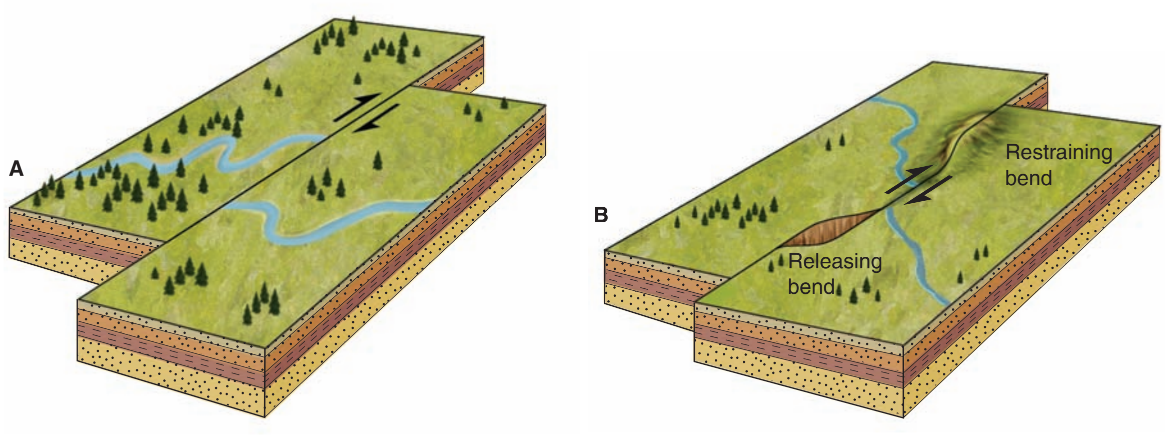


FIGURE 15.28

(*A*) Right-lateral strike-slip fault offsets a stream channel. Looking across the fault, you would need to walk to the right to find the continuation of the stream. (*B*) Strike-slip movement along curved faults produces gaps or basins at releasing bends where the lithosphere is pulled apart or shortening and hills where it is pushed together at restraining bends.

IN GREATER DEPTH 15.2

California's Greatest Fault—The San Andreas

The San Andreas fault in California is the best-known geologic structure in the United States. Actually, the San Andreas is the longest of several, subparallel faults that transect western California (box figure 1). Collectively, these right-lateral faults are known as the San Andreas fault system. The system is in a belt approximately 100 kilometers wide and 1,300 kilometers long that extends into Mexico, ending at the Gulf of California. The San Andreas fault forms the transform plate boundary between the North American and Pacific plates (see figures 1.8 and 19.23).

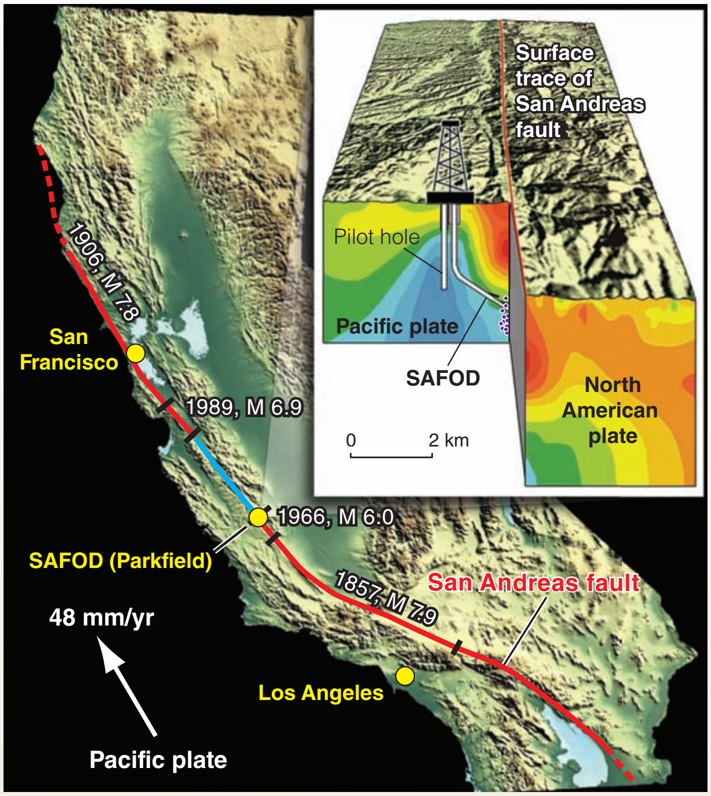
Los Angeles, located on the Pacific plate, is slowly moving toward the San Francisco Bay area because of San Andreas fault motion. At an average rate of movement of 48 millimeters per year, Los Angeles could be a western suburb of San Francisco (or San Francisco an eastern suburb of Los Angeles) in some 25 million years. Earthquakes are produced by sudden movement within the fault system, as explained in chapter 16. Bedrock along the San Andreas fault shifted as much as 4.5 meters in association with the 1906 quake that destroyed much of San Francisco. Most geologists think strike-slip movement began about 30 million years ago, and that the total offset on the fault has been at least 560 kilometers.

The San Andreas fault is not a simple crack but a belt of broken and ground-up rock, usually a hundred meters or more wide. Its presence is easy to determine throughout most of its length. Along the fault trace are long, straight valleys (box figures 1 and 2) that show quite different rocks on either side. Stream channels follow much of the fault zone because the weak, ground-up material along the fault is easily eroded. Locally, elongate lakes (called sag ponds) are found where the ground-up material has settled more than the surface of adjacent parts of the fault zone. The fault was named after one of these ponds, San Andreas Lake, just south of San Francisco.

One can visually follow the trace of the San Andreas fault through the Carizzo Plain in central California (box figure 2). Long linear valleys and fault scarps are common surface expressions of the fault. Some of the most obvious features produced by the fault motion are displaced ridges, valleys, and streams. Box figure 3 shows how the channel of Wallace Creek has been offset and diverted by the right-lateral slip along the San Andreas fault.

The San Andreas fault continues to be the most extensively instrumented and carefully studied fault in the world. The northern and southern portions of the fault are locked (shown in red in box figure 1), and the central portion (shown in blue) creeps or slips at regular intervals. Just north of the locked portion at Parkfield, California, the San Andreas fault generates moderate-size earthquakes about every 22 years. Because of the occurrence of earthquakes at fairly regular intervals here, geologists have been closely monitoring the fault for the past two decades to learn about its behavior before, during, and after an earthquake—as part of the Parkfield Earthquake Experiment. More recently, the San Andreas Fault Observatory at Depth (SAFOD) was funded to drill a 4-kilometer-long borehole from the Pacific plate, through the fault zone, to the North American plate at Parkfield (box figure 1). This is the first time scientists have drilled into an active fault to reveal the processes that control the generation of earthquakes.

Rock cores retrieved from within the fault contain pieces of serpentine and talc, and the fault surfaces are coated with a thin layer of clay. The presence of these soft, hydrated minerals suggests that soft, "slippery" rocks facilitate the gradual slip, or *creep,* along the central segment of the San Andreas fault.



BOX 15.2 ■ FIGURE 1

Map showing the trace of the San Andreas fault (red lines show locked segments and blue line represents creeping portion) and the San Andreas Fault Observatory at Depth (SAFOD) located at Parkfield, California. The San Andreas fault separates the Pacific plate on the west from the North American plate on the east. The SAFOD inset diagram shows the locations of the pilot hole drilled in 2002 and the main borehole that directly samples and monitors the active San Andreas fault. The small purple dots represent recurring small earthquakes that signal slip of the fault. The colors below the ground surface represent electrical resistivity of the rocks. Red represents low resistivity and is interpreted to represent fluid along the fault. *Diagram courtesy of Earthscope/USGS*

BOX 15.2 ■ FIGURE 2

Trace of San Andreas fault in the Carrizo Plain, central California. *Photo by Robert E. Wallace/U.S. Geological Survey*

BOX 15.2 ■ FIGURE 3

Stream channel (Wallace Creek) offset by the San Andreas fault in the Carrizo Plain. The arrows on either side of the fault trace indicate the right-lateral motion. *Photo by C. C. Plummer*

Sensitive seismic instruments have also been installed in the SAFOD borehole and will enable geologists to test hypotheses about how earthquakes are generated, and to evaluate the roles of fluid pressure, rock friction, and state of stress in controlling fault strength. These instruments are designed to remain in operation for the next 10 to 20 years, providing valuable insights into the workings of California's greatest fault.

Additional Resources

U.S. Geological Survey web page *The San Andreas Fault* by Sandra S. Schulz and Robert E. Wallace gives details about the fault.

- http://pubs.usgs.gov/gip/earthq3

An interactive map of the San Andreas fault.

- http://thulescientific.com/san-andreas-fault-map.html

Video describing the southern San Andreas fault system produced by the *Earthquake Country Alliance*.

- www.earthquakecountry.info/video/sanandreas.html

Web pages of the International Continental Scientific Drilling Program, Earthscope, and the U.S. Geological Survey that give details about the *San Andreas Fault Observatory at Depth* project.

- http://www-icdp.icdp-online.org/front_content.php?idcat=889
- http://www.earthscope.org/science/observatories//safod
- http://earthquake.usgs.gov/research/parkfield/safod_pbo.php

response to the pulling apart at the releasing bends and folds, and thrust faults form at the restraining bends to accommodate the pushing or pinching together of the lithosphere. Death Valley (see figure 13.10) is a good example of a deep graben formed along a releasing bend or stepover in the newly forming plate boundary along the eastern side of the Sierra Nevada Mountains in California. Where the San Andreas fault bends to the left, north of Los Angeles, the Transverse Mountains have been pushed up by folding and thrust faults.

Strike-slip faults accommodate shearing strain in the brittle, uppermost lithosphere, and may also represent transform plate boundaries where plates slide past one another. One of the most famous examples of a transform fault is the San Andreas fault. The San Andreas fault is a right-lateral strike-slip fault that forms part of the boundary between the North American and Pacific plates.

Summary

Tectonic forces result in deformation of the Earth's crust. *Stress* (force per unit area) is a measure of the tectonic force and confining pressure acting on bedrock. Stress can be *compressive, tensional,* or *shearing. Strained* (changed in shape or size) rock records past stresses, usually as joints, faults, or folds.

A geologic map shows the structural characteristics of a region. *Strike* and *dip* symbols on geologic maps indicate the orientations of inclined surfaces such as bedding planes. The strike and dip of a bedding surface indicate the relationship between the inclined plane and a horizontal plane.

If rock layers bend (ductile behavior) rather than break, they become folded. Rock layers are folded into *anticlines* and *synclines* and recumbent folds. If the hinge line of a fold is not horizontal, the fold is *plunging.* Older beds exposed in the core of a fold indicate an anticline, whereas younger beds in the center of the structure indicate a syncline. In places where folded rock has been eroded to a plain, an anticline can usually be distinguished from a syncline by whether the beds dip toward the center (syncline) or away from the center (anticline). Also, the oldest rocks are found in the center of an eroded anticline, whereas the youngest rocks are found in the center or core of a syncline.

Fractures in rock are either *joints* or *faults.* A joint indicates that movement has not occurred on either side of the fracture; displaced rock along a fracture indicates a fault. *Dip-slip* faults are either *normal* or *reverse,* depending on the motion of the hanging-wall block relative to the footwall block. The relative motion of the hanging wall is upward in a reverse fault and downward in a normal fault. A reverse fault with a low angle of dip for the fault plane is a *thrust fault.* Reverse faults accommodate horizontal shortening of the crust, whereas normal faults accommodate horizontal stretching or extension.

In a *strike-slip* fault, which can be either left-lateral or right-lateral, horizontal movement parallel to the strike has occurred.

Terms to Remember

angle of dip	365
anticline	367
axial plane	367
brittle	364
compressive stress	362
dip-slip fault	373
direction of dip	365
ductile	363
elastic	362
elastic limit	363
fault	373
fold	366
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left-lateral fault	376
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strike-slip fault	373 and 376
structural basin	370
structural dome	370
syncline	367
tensional stress	362
thrust fault	376

Testing Your Knowledge

Use the following questions to prepare for exams based on this chapter.

1. Sketch and describe the three types of stress and the resulting strain.
2. What factors control whether a rock behaves as a brittle material or a ductile material?
3. What is the difference between strike, direction of dip, and angle of dip?
4. Draw a sketch of an anticline and label the limbs, axial plane, and hinge line.
5. Sketch and describe the different types of folds, and explain how the shape and orientation of folds is used to interpret strain.
6. On a geologic map, if no cross sections were available, how could you distinguish an anticline from a syncline?
7. Draw a simple geologic map using strike and dip symbols for a syncline plunging to the west.
8. How does a structural dome differ from a plunging anticline?
9. What is the difference between a joint and a fault?
10. Which of the statements is true?
    a. When forces are applied to an object, the object is under stress.
    b. Strain is the change in shape or size (volume), or both, while an object is undergoing stress.
    c. Stresses can be compressive, tensional, or shear.
    d. All of the preceding.
11. Folds in a rock show that the rock behaved in a _____ way.
    a. ductile
    b. elastic
    c. brittle
    d. all of the preceding