CHAPTER 14

STRUCTURAL GEOLOGY

MATERIALS NEEDED

- Pencil and eraser
- Protractor
- Metric ruler
- Silly Putty® (provided by instructor)
- Scissors
- Removable tape (optional)

INTRODUCTION

Stresses within the Earth bend and break rocks, producing folds, faults, and other geologic structures. These structures are three-dimensional, and they are commonly too large or too poorly exposed to be easily recognized from a single vantage point on the ground. For these reasons, basic geologic data must be collected in the field and plotted on a map to understand the structure fully. This chapter will help you visualize geologic structures in three dimensions so that you can understand them when seen in two dimensions on a geologic map, aerial photograph, or on the Earth's surface. You will learn how the orientations of planar features, such as sedimentary bedding, are described and used to portray the geologic structure on a geologic map. Vertical cross sections of geologic maps illustrate what you expect to see below the surface, and block diagrams combine maps and cross sections to provide a three-dimensional view. A clear understanding of subsurface structures is vital for an understanding of groundwater resources, pollution migration, oil reserves, ore deposits, and the stability of road cuts, tunnels, bridge footings, and building foundations.

Structural geology is the study of the form, arrangement, and internal structure of rocks. It is concerned especially with the way in which rocks are deformed. Evidence for deformation is abundant. We see rocks broken during earthquakes, and evidence for deformation in the past—such as bent and broken layers of sedimentary rocks—is common.

Deformation is caused by **stress,** a force acting on an area of a body that tends to change its size or shape. Stress is a force per unit area, so the magnitude of stress depends not only on the magnitude of the force, but also on the area over which the force is applied. Stress will be greater if a given force is applied to a small, rather than large, area; a person wearing high-heeled shoes is more likely to punch a hole in a rotten floorboard than a person wearing tennis shoes. *Compressive stress,* or **compression,** causes shortening (Fig. 14.1A), and is an important type of stress at convergent tectonic plate boundaries. *Tensional stress,* or **tension,** the principal stress at divergent boundaries, causes stretching (Fig. 14.1B). **Shear stress** causes one side of a body to slide past the other (Fig. 14.1C), and is the principal type of stress along transform-fault plate boundaries.

Strain, the physical deformation that occurs in response to stress, is a change in size or shape. Strain may be temporary or permanent. **Elastic strain** is temporary; if the stress is removed, the object snaps back to its original shape. A stretched rubber band and a bouncing ball both undergo elastic strain. **Plastic strain** is permanent; if the stress is removed, the original size or shape is not restored. If you bend a piece of soft wire, the wire undergoes plastic strain; the bend is permanent. If it is bent back and forth at the same place, it eventually breaks or **ruptures.**

A rock undergoing elastic strain can suddenly break: this is **brittle deformation.** A dry stick of wood also behaves this way: it bends only so far before it suddenly breaks (ruptures), and each piece elastically recovers its original straight shape. A rock that undergoes much plastic strain without rupturing is **ductile.** The aforementioned bent wire is ductile.

Pressure, temperature, and rate of deformation determine brittle versus ductile

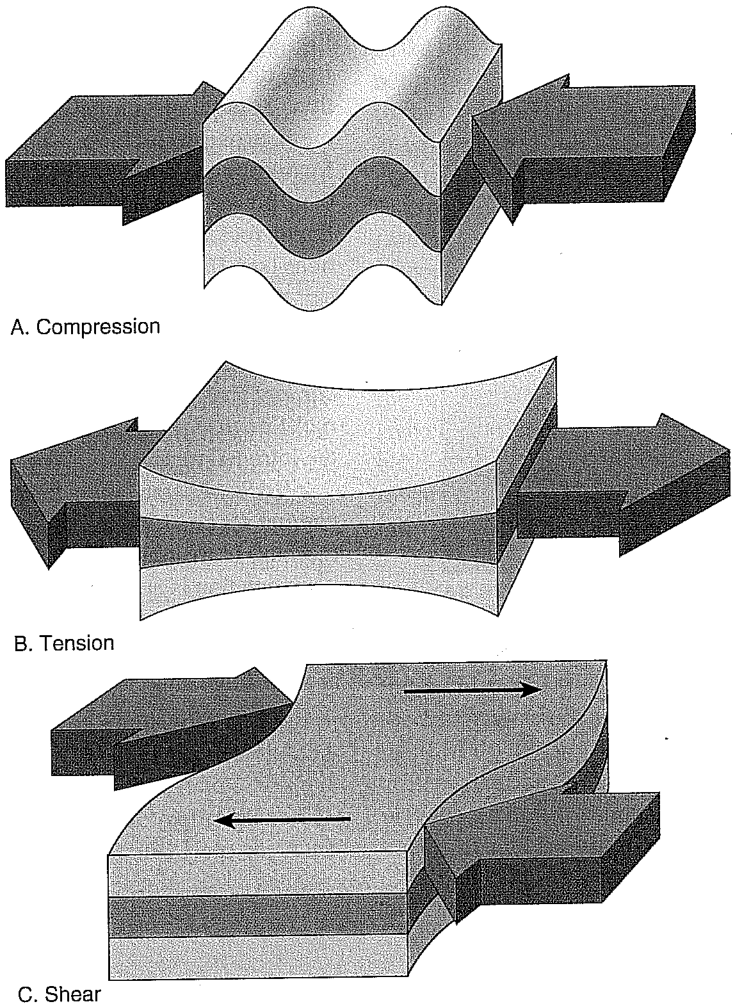

FIGURE 14.1
The three principal types of stress: A. compression; B. tension; C. shear.

TABLE 14.1
Conditions Required for Brittle Versus Ductile Deformation of Rocks

Surrounding Conditions	*Brittle*	*Ductile*
Pressure	low	high
Temperature	low	high
Stress rate	rapid	slow
Stress magnitude	high	low to high

behavior (Table 14.1). Cool rocks at the Earth's surface that experience a rapidly applied stress (like a hammer blow) tend to experience brittle fracture. Ductile deformation is more likely under the high temperature and pressures found deep underground, especially when stresses are applied slowly. The folded rocks visible in many mountain ranges were deformed well below the surface by forces acting over long periods of time (millions of years). The combination of depth and time enables deep rocks that would be brittle at the surface to behave plastically and gradually bend into folds. Eventually, erosion of overlying rock material and gradual uplift bring the deformed rocks to the surface where we can view them.

Recognizing and Describing Deformed Rocks

A geologist must be able to visualize rock structures in three dimensions. In some parts of the world, rocks are so well exposed at the surface that it is easy to see and understand their structure. In most areas, however, the rocks are buried beneath soil or young, unconsolidated sediment, and are exposed only in a few **outcrops** located far apart. In such places, it is difficult to understand the three-dimensional aspects without carefully examining the rocks, measuring their orientation, and plotting these data on a map.

What to Look For: Stratification, Contacts, and Fault and Joint Surfaces

How can you tell if sedimentary rocks have been deformed? It generally is easy—just look at the orientation of the strata. The original sediments were deposited as continuous horizontal or nearly horizontal **strata** (layers). If the strata are still horizontal and not broken, then they have not been deformed, although they may have undergone gentle uplift or subsidence. If strata are broken or not horizontal, then they have been deformed. Deformation takes many forms, from slight tilting of strata to complex folding, as described in a later section.

Contacts are surfaces separating adjacent bodies of rock of different types or ages. Understanding the nature of the contact is important, because the contact records a change, an event. There are several kinds of contacts.

Depositional contacts separate older bodies of rock from younger sedimentary rocks deposited upon them. In a sequence of sedimentary rocks deposited continuously, or **conformably,** in a basin of deposition, the contacts between adjacent

FIGURE 14.2
The steeply inclined surface in the center of the photograph is a fault contact. It cuts the sandstone and mudstone layers of the Haymond Formation (Pennsylvanian) near Marathon, Texas.

layers are planar **bedding planes** (see Fig. 4.3); they are parallel to—and, in fact, define—the bedding or stratification. Some depositional contacts are ancient erosion surfaces. These **unconformable** contacts can be uneven rather than planar, and can juxtapose very different rocks with very different orientations (see *Unconformities* in Chapter 13).

An ***intrusive contact*** separates intrusive igneous rock and the rock that it intruded; intrusive contacts are either *concordant* (parallel to layers in the intruded rock) or *discordant* (cut across layers in the intruded rock).

Rocks separated by a fault are in ***fault contact*** (Fig. 14.2). In the simplest case, the fault is exposed as a flat surface, and its orientation is apparent. However, faults commonly are expressed as zones along which rocks are brecciated (broken into angular fragments), or even pulverized, so

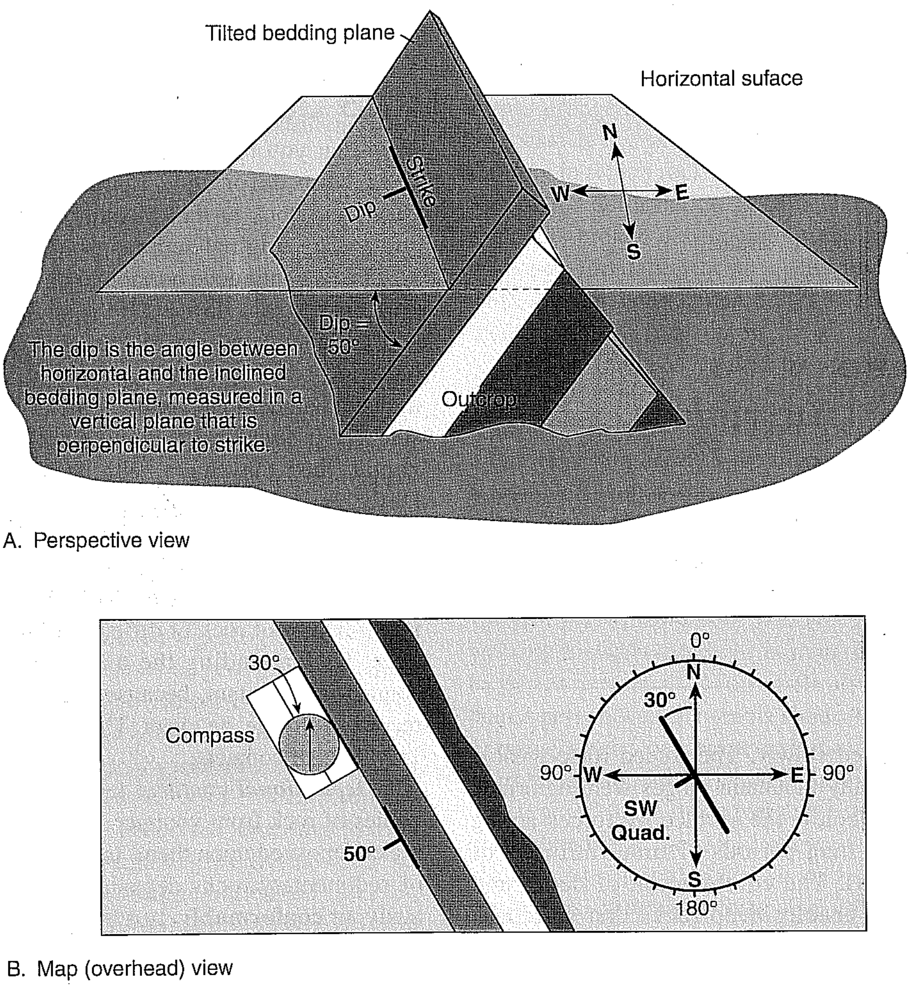

FIGURE 14.3
A. A tilted layer of sandstone with a smooth bedding plane is shown protruding through a horizontal plane. The intersection of the inclined plane with the horizontal plane creates a line that defines the strike of the bed. This line trends 30° west of the north arrow. The beds dip 50° below the horizontal plane. B. When viewed from above, as on a map, the strike and dip of the bed are shown with a T-like symbol. The top of the T parallels the strike, and the leg of the T points toward, and parallels, the dip direction. The dip angle is 50°. Comparison of the strike and dip symbol with the compass directions shows why the attitude of this bed is written as N30°W, 50°SW.

that fault orientation may be difficult to determine. Even more commonly, faults, like other types of contacts, are buried beneath soil or sediment. In such places, their orientation, and even their presence, must be inferred from data gathered from many outcrops and plotted on a map.

Describing Surface Orientation

You will see on geologic maps curious little T's called **strike and dip** symbols (Fig. 14.3). These are used to describe the orientation of bedding planes and other planar features so that the overall geometry of tilted and folded layers can be described and visualized on maps. The long top part of the T parallels the **strike,** which represents the intersection of a tilted bedding plane with a *horizontal* plane (Fig. 14.3A). It gives the trend of that plane. For example, if you hold a credit card at a 45° angle to a table and draw a line along where it touches the table, you get the strike of the plane defined by your credit card. Hold the card against the strike line and notice how the strike indicates which way a plane trends, but not which way it tilts. The **dip direction** of a plane is shown by a short line drawn perpendicular to the strike and pointing downhill (Fig. 14.3A). Draw a tick perpendicular to your strike, away from the credit card, and you have the dip direction. Write, for example, 45° (the **dip angle**) at the end of your dip line and you uniquely define the orientation of your credit card. You can easily visualize the orientation of a plane described by a strike and dip symbol by holding your hand parallel to the strike and tilted down toward the dip. Try it on the perspective drawings later in the chapter!

A geologist measures the orientation, or **attitude,** of a tilted bedding plane by holding a compass in a horizontal position, with a straight side against the bedding plane (Fig. 14.3B). While the compass arrow points north, the compass body points in the direction of strike, a certain number of degrees east or west of north. Figure 14.3B shows a strike line pointing 30° west of north, which is written as N30°W. Strike measurements are commonly given with the number of degrees less than 90. Thus, N95°E becomes N85°W, and N90°E is written E-W.

The dip angle, or **angle of inclination,** is measured from the horizontal plane down to the bedding plane (Fig. 14.3B). The measuring device must be held in a vertical plane that is perpendicular to the strike in order to be accurate. Because a dip can point either direction from a strike line, it is necessary when recording dips to specify the dip direction. Since the dip is always perpendicular to strike, it is necessary only to indicate the compass quadrant toward which the surface dips (that is, NW, NE, SE or SW). For example, with a strike of N30°W, the dip direction could either be NE or SW (Fig. 14.3B). In the example used in Figure 14.3A, the complete strike and dip of the bedding plane is written N30°W, 50°SW.

Geologists also measure the attitudes of fault planes, fracture surfaces, and other geologic features. Figure 14.4 shows special symbols for vertical, horizontal, and

Go to http://www.nd.edu/~cneal/PhysicalGeo/Lab7/Fig14.jpg for a better copy of this figure.

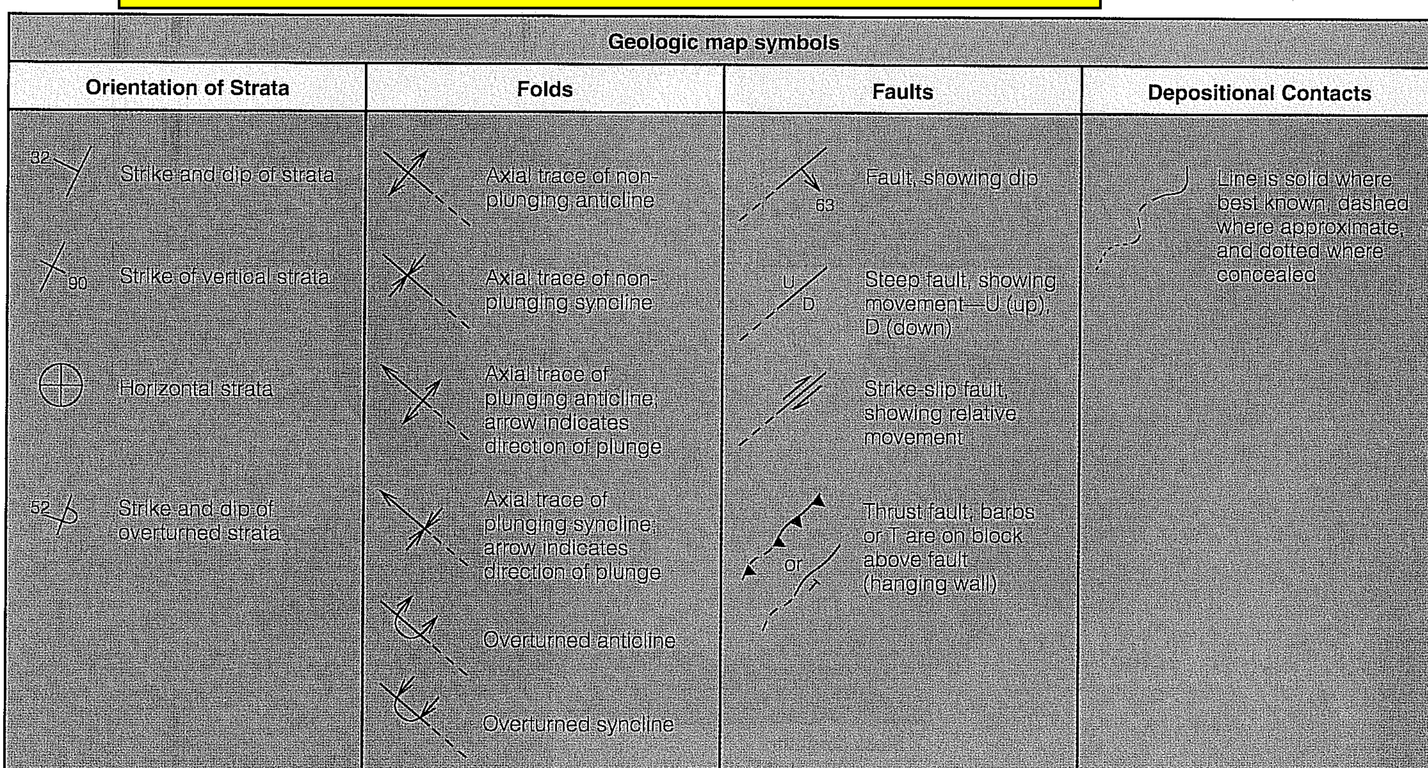

FIGURE 14.4
Geologic map symbols.
Source: Data from American Geological Institute and others.

overturned sedimentary layers, plus symbols for folds and faults. The arrows used in the fold and fault symbols point in the direction of dip.

Geologic Maps, Cross Sections, and Block Diagrams

Geologic information is compiled and displayed in three common ways, shown in Figure 14.5: geologic maps, geologic cross sections, and block diagrams.

Geologic maps show the distribution of rock units at or very near the surface of the Earth. They also portray the structure of the rock units by means of strike and dip symbols. An accompanying legend, or **explanation,** lists and briefly describes the rock units in order of age; major periods of erosion are also listed. Topography may be shown with an overlay of contour lines. The next chapter focuses on geologic maps.

Geologic cross sections are vertical slices that show how the rocks would appear if they could be viewed on a cliff face. They are topographic profiles with the area below the surface filled in with representations of rocks. Because such cut-away views do not usually present themselves in nature, they are interpretations based on information obtained on the surface or from wells or geophysical data.

Block diagrams combine maps and cross sections to show the three-dimensional aspects. The three-dimensional blocks are drawn as two-dimensional perspective drawings, with the map view shown on the top and cross sections on the ends and sides. Most block diagrams have a flat upper surface and do not attempt to show topography, but some, drawn by clever people, manage to illustrate topography as well as geology.

Folds

A fold is a bend in a layer of rock due to ductile (plastic) strain. Upward bends, or upfolds, with older rocks in the center, are called **anticlines;** downward bends, downfolds, with younger rocks in the center, are called **synclines** (Fig. 14.6). The sides or flanks of a fold are the **limbs.** The limbs

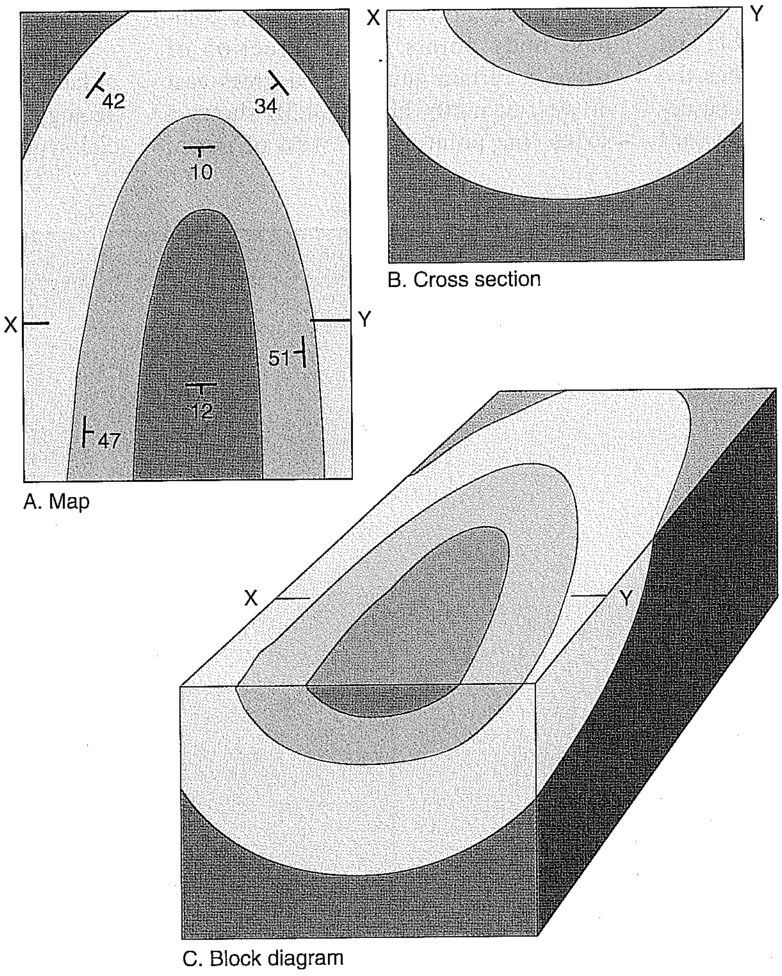

FIGURE 14.5
Three ways in which geologic information is illustrated: A. A geologic map shows rock units and geologic structure as they appear on the surface. You can use your hands to visualize the orientation of the bedding described by the strike and dip symbols. B. A geologic cross section of the map from X to Y is like a vertical slice into the Earth. C. Block diagrams combine map and cross-section views in a three-dimensional perspective drawing.

join at the **hinge line** of the fold, which is the line of maximum curvature (Fig. 14.6). The **axial surface** (or **axial plane** if it's not curved) of a stack of folded layers passes through the hinge lines and most nearly divides the fold into two equal parts (Fig. 14.6). An **upright fold** has a vertical or nearly vertical axial surface; beds on opposite limbs have similar dips, though in opposite directions (Fig. 14.7A). An **inclined fold** has an axial surface that is neither vertical nor horizontal (Fig. 14.7B). An inclined fold is **overturned** if beds on opposite limbs dip in the same direction; beds on the overturned limb are upside-down, as they have been overturned more than 90° (Fig. 14.7C). A **recumbent fold** has an approximately horizontal axial surface (Fig. 14.7D).

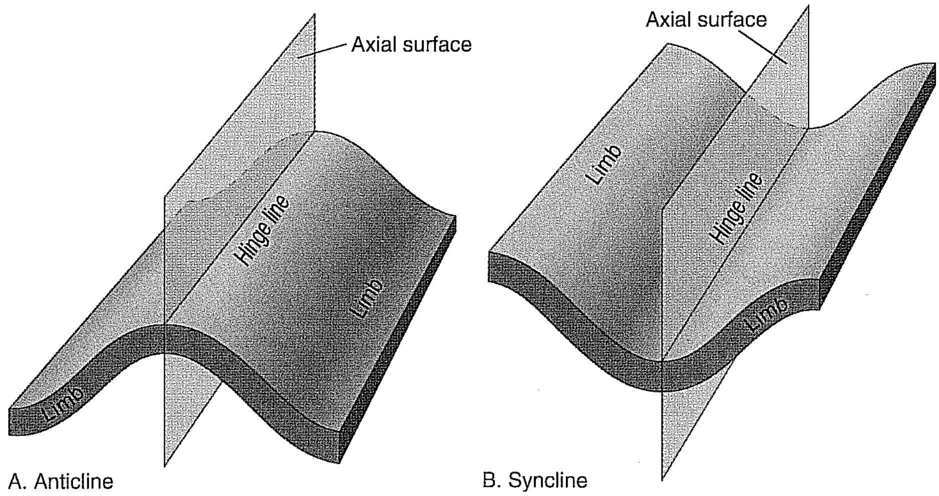

FIGURE 14.6
Folds are described in terms of limbs, hinge line, and axial surface, shown here for an anticline (A) and a syncline (B).

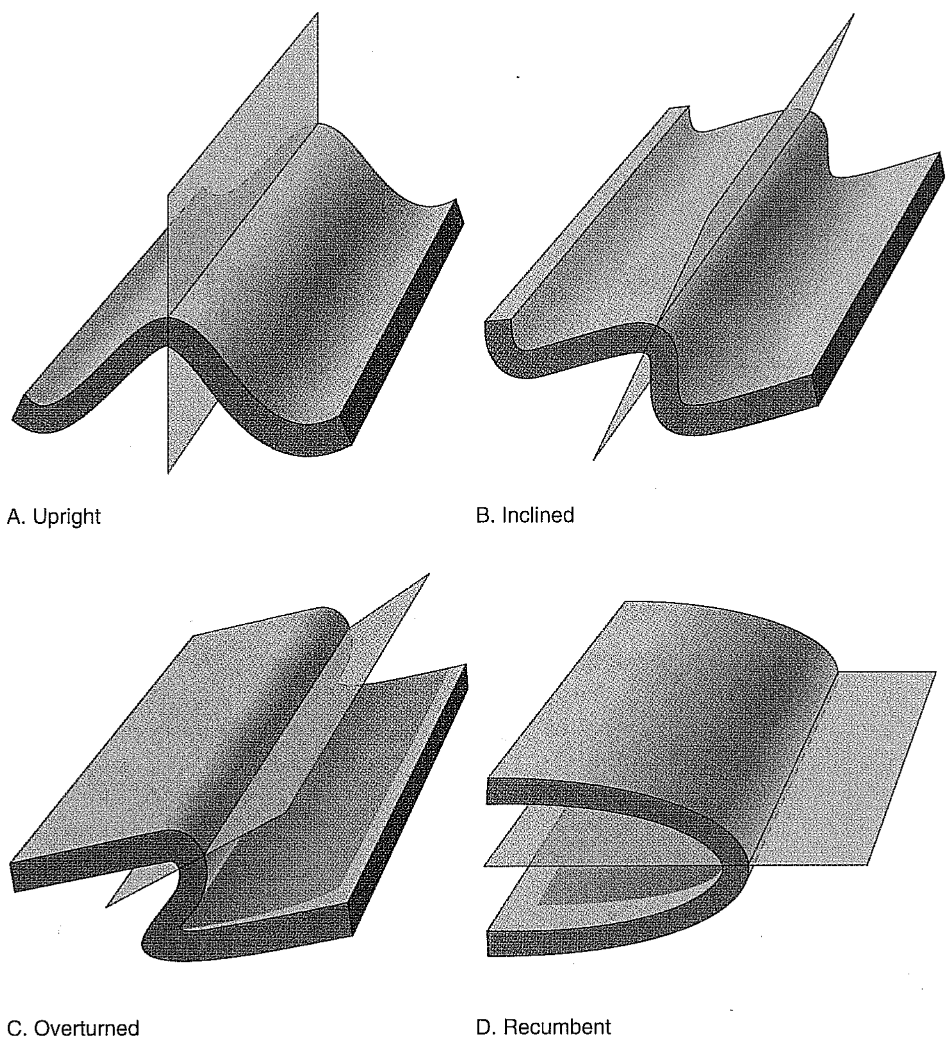

FIGURE 14.7
The axial surface of a fold can be: A. Vertical in **upright folds;** B. inclined in **inclined folds;** C. inclined so much that opposite limbs dip in the same direction in **overturned folds;** D. horizontal in **recumbent folds.**

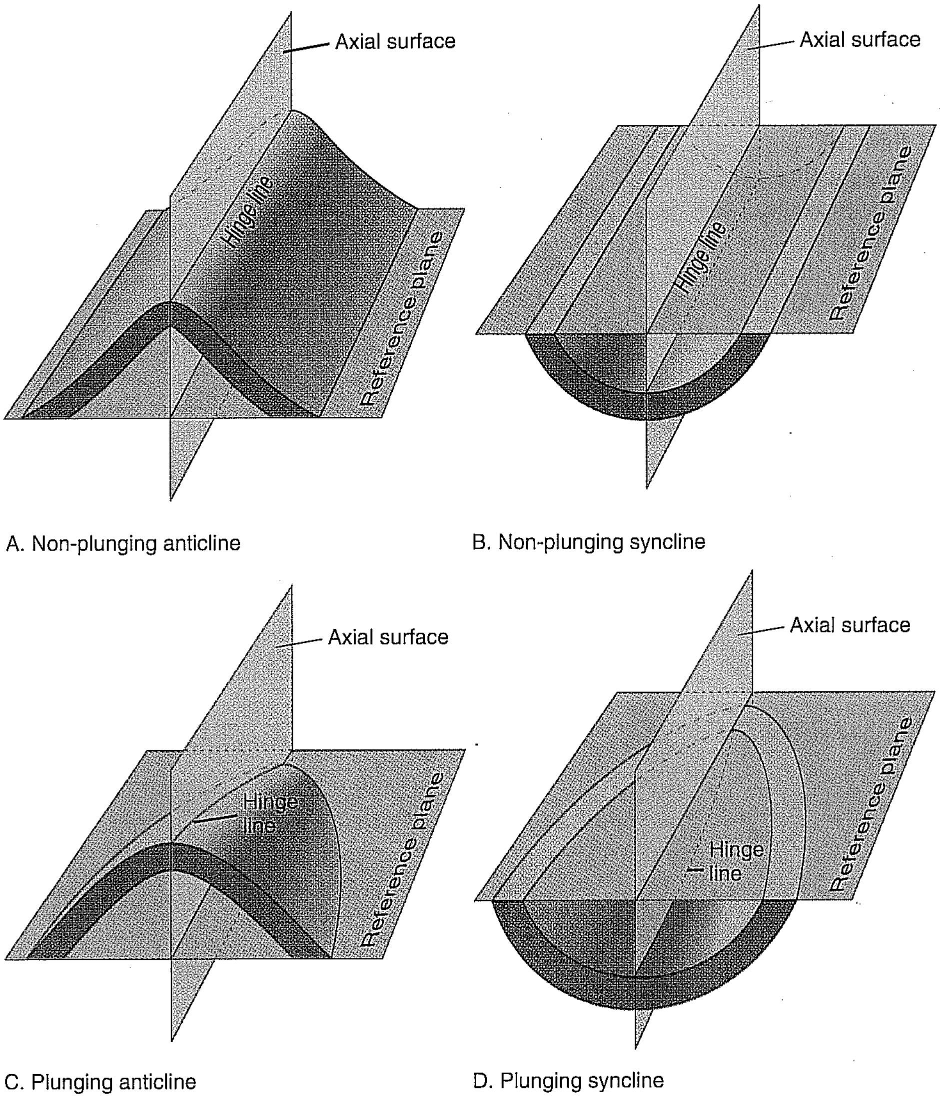

FIGURE 14.8
Non-plunging folds have horizontal hinge lines, as in a non-plunging anticline (A) and a non-plunging syncline (B). Plunging folds have inclined hinge lines, as in a plunging anticline (C) and a plunging syncline (D). Axial surfaces are vertical, and reference plane is horizontal.

A **non-plunging fold** has a horizontal or nearly horizontal hinge line (Figs. 14.8A, B). A **plunging fold** has an inclined hinge line (Figs. 14.8C, D).

Figure 14.9 illustrates folds using block diagrams in which the top surface is horizontal and flat. Note that when non-plunging folds intersect a horizontal surface, such as that approximated by the surface of the Earth, the contacts between adjacent beds are straight lines (Figs. 14.9A, B). When plunging folds intersect a horizontal surface, the contacts between adjacent beds are curved lines. In a plunging anticline, the contacts bend so that they "point" in the direction of plunge, whereas in a plunging syncline, they "point" in the direction opposite the plunge (Figs. 14.9C, D).

Using the Principle of Superposition (Chapter 13), you can see that in an eroded syncline, the *youngest* beds appearing on the surface are in the center of the syncline (Figs. 14.9B, D). In an eroded anticline, the *oldest* (originally deepest) beds are in the center (Figs. 14.9A, C).

Domes and **basins** have cross sections like anticlines and synclines, respectively, but are approximately circular or oval in map view (Fig. 14.10). Beds in domes dip outward in all directions, and like anticlines, the oldest rocks are found in the center. Similarly, the youngest rocks in basins are in the center, just as they are in synclines, and beds dip inward. Domes and basins may be quite large, with diameters of 100 km or more.

FAULTS

Faults are breaks or fractures in the Earth's crust along which movement has occurred. The rocks on one side of a fault have moved relative to those on the other side. Relative movement may be up and down, sideways, or a combination of the two. The amount of movement ranges from centimeters to kilometers.

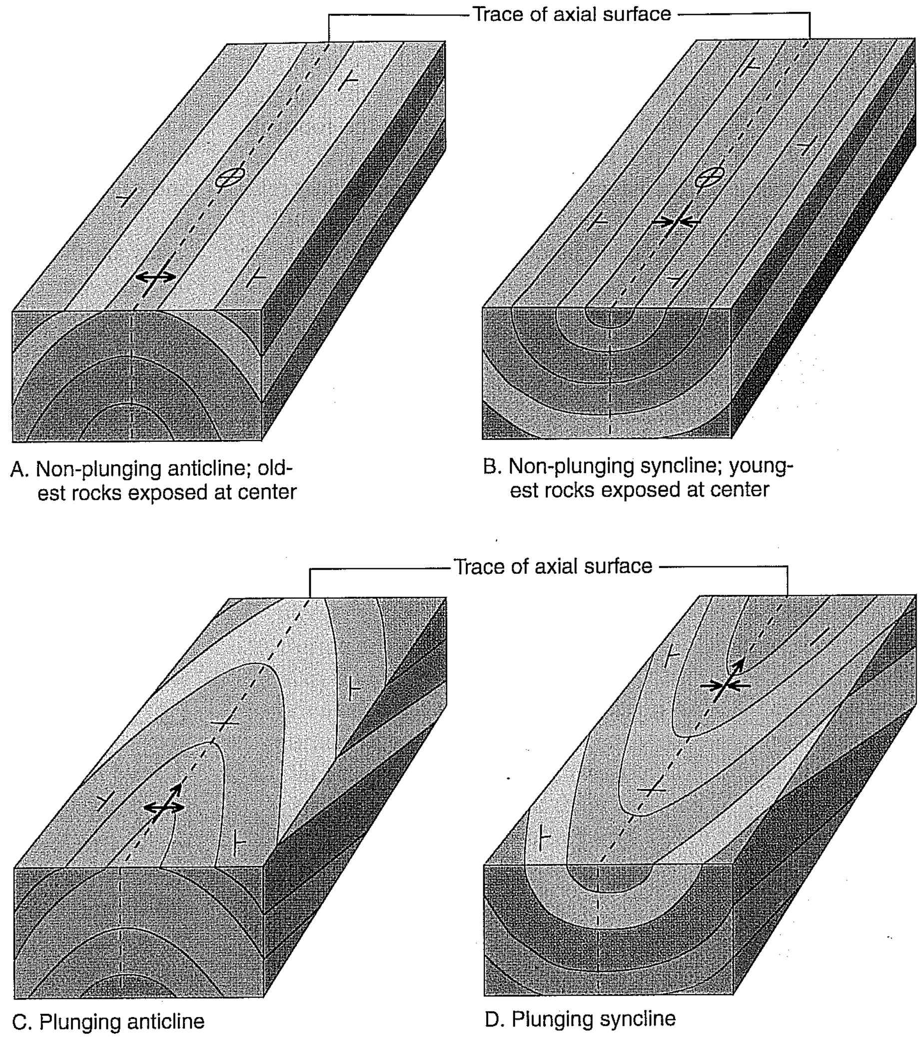

FIGURE 14.9
The top surface of these block diagrams, which is analogous to the Earth's surface, shows that older beds are exposed in the centers of eroded anticlines and younger beds are exposed in the centers of eroded synclines. Contact lines on the top surface are straight if folds do not plunge, but bend if they do. In plunging anticlines, the contact lines bend and point in the direction of plunge; in plunging synclines, they bend and point away from the direction of plunge. In C and D, both folds plunge into the page. The symbols on the top surface show the strike and direction of dip at various locations and the axial traces and type of folds. Note how these symbols help you visualize structure from map view alone.

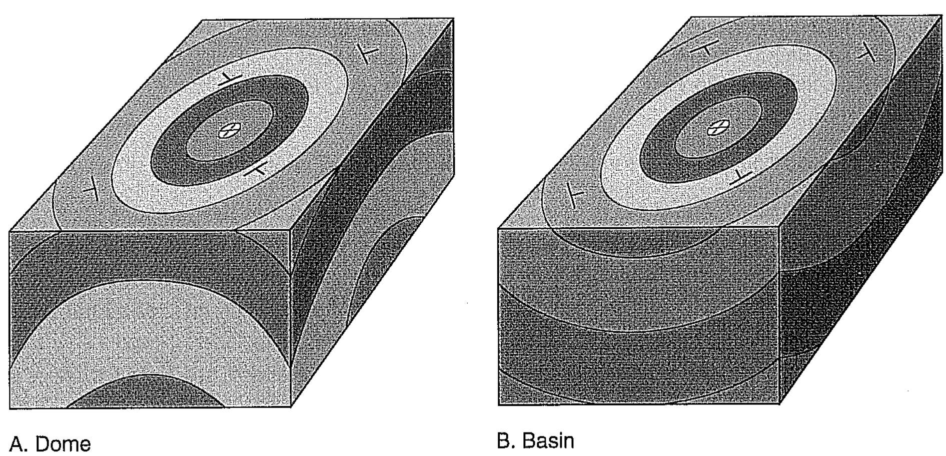

FIGURE 14.10
These block diagrams show that older beds appear in the center of an eroded dome, while younger beds appear in the center of an eroded basin. The symbols on the top surfaces show the strike and direction of dip at various locations.

Faults with inclined fault planes have **footwalls** and **hanging walls** (Fig. 14.11). The **footwall** is under the fault plane: if you dug a mine along the fault plane, you would stand on the footwall. The **hanging wall** is above the fault plane: in a mine, it would hang above your head.

Faults are classified according to their relative motion. When the hanging wall has dropped relative to the footwall, it is a **normal fault** (Fig. 14.11A). When the hanging wall has been pushed up relative to the footwall, it is a **reverse fault** if the fault plane is steeply dipping (more than 45°; Fig. 14.11B) or a **thrust fault** if the fault plane has shallow dip (less than 45°; Fig. 14.11C). **Lateral** or **strike-slip faults** have almost vertical fault planes and show offsets in a horizontal plane (Fig. 14.11D). *Right-lateral strike-slip faults* are those in which the block on the opposite side of the fault has moved relatively to the right. Thus, if you stood on one side of a right-lateral strike-slip fault, and looked across the fault, the rocks on the other side would be displaced to the right, as in Figure 14.11D. In *left-lateral strike-slip faults,* the block on the opposite side of the fault has moved relatively to the left. Whereas the other faults are most obvious in vertical outcrops, offsets along strike-slip faults are best seen from the air.

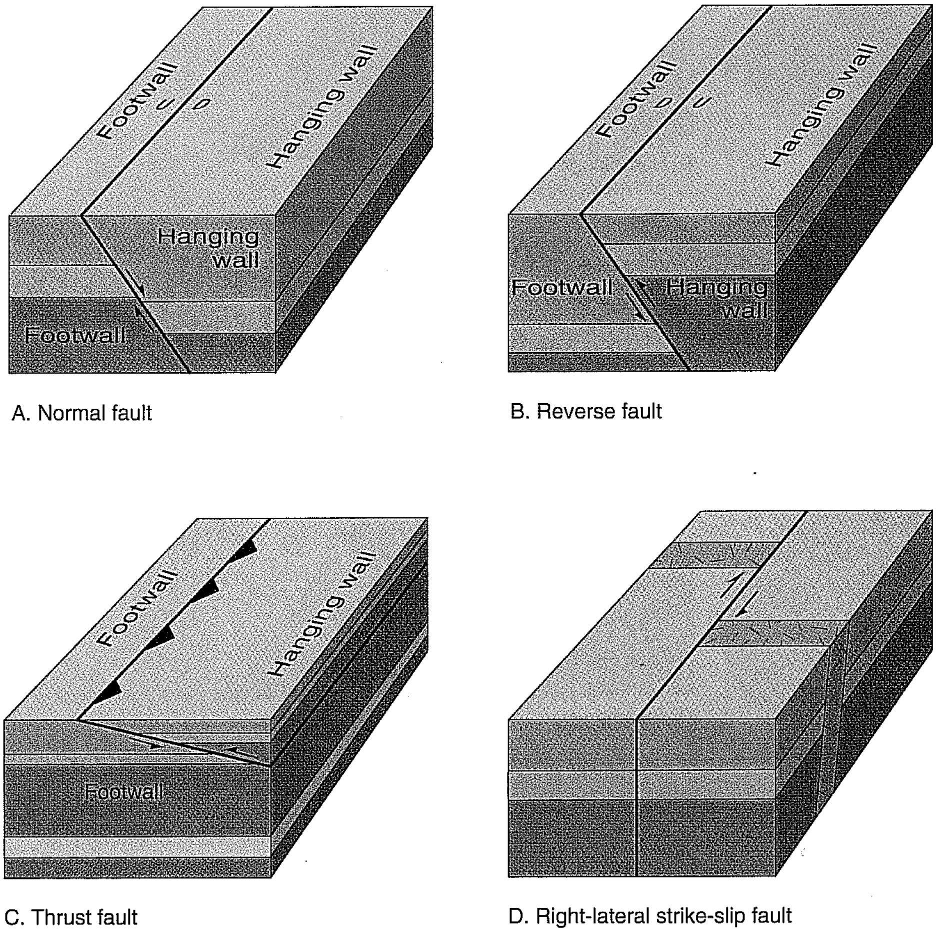

FIGURE 14.11
Four types of faults are illustrated in these block diagrams. If the fault plane is inclined, the side above the fault is the hanging wall, and the side below is the footwall. Displaced marker beds show the direction of movement. Note that in a map view, shown by the top surfaces of A, B, and C, the faults dip under the hanging wall.

Clues to the Past

Folds and faults record the history of geologic stresses in a given area. Such stresses may result, for example, from continental blocks pulling apart, sliding by one another, or colliding. Table 14.2 summarizes the types of stress and strain that are recorded by folds and the different types of faults. Assessing the type of stress and the directions from which it was applied helps us to unravel the long and complicated series of events that have shaped and reshaped large areas of especially eastern, southern, and western North America.

Table 14.2 Stress/Strain Conditions of Common Geologic Structures

Strain	*Stress*		
	Compression	*Tension*	*Shear*
Brittle strain or rupture	Reverse fault or thrust fault	Normal fault	Strike-slip fault
Ductile or plastic strain	Folds (anticlines and synclines)	Not discussed in text	Not discussed in text