Deformation of Sedimentary Strata

During the course of geologic history, sedimentary strata have been subjected to vertical and horizontal forces that may alter the original horizontal position of the rock layers. Some strata may be uplifted in a vertical direction only, so their original horizontality remains more or less intact. In other cases, the forces of deformation produce architectural patterns ranging from simple to extremely complex structures.

In order to decipher these structures, geologists measure certain features of a given formation where it crops out at the surface of the earth. These measurements define the position of the formation with respect to a horizontal plane of reference. The precise orientation of a contact, bedding plane, or any planar feature, including a fault surface, associated with a rock mass is called the attitude. When attitudes from many outcrops are plotted on a base map, such as a topographic map or aerial photograph, and combined with the contacts between formations, the overall geometric pattern or structural configuration of the strata can be determined.

Components of Attitude

The attitude of a structural surface such as a bedding plane or a fault plane consists of two parts, strike and dip, that collectively define the position of the surface at a given location with respect to a horizontal plane and compass direction (fig. 5.1).

1. **Strike** is defined as the line of intersection between a horizontal plane and a structural surface expressed as a compass direction.

2. **Dip** is measured at right angles to the strike and is defined as the maximum angle of slope of a surface measured in a vertical plane downward from the horizontal and is measured in degrees. **Dip direction** is the compass direction of the dip measured at right angles to the strike.

![Figure 5.1](image)

Three-dimensional view of an outcropping of sandstone in which the **attitude** of a bedding plane is measured with respect to horizontal and vertical planes. The shaded slanting plane represents the bedding plane of the layered sandstone. The intersection of the bedding plane and a horizontal plane results in a line called the **strike** of the formation. This line is expressed as a compass direction. The angle formed by the horizontal plane and the bedding plane is the **dip** of the formation. The dip, measured in degrees, is always measured in a vertical plane that is perpendicular (at right angles) to the direction of strike. **Dip direction** is the compass direction of that vertical plane and is measured at right angles to the strike.

The number that appears next to a strike and dip symbol on a geologic map refers to the angle of dip of the rock layers as measured by a field geologist at a specific rock outcrop or exposure. When these numbers occur near a line on the map along which a geologic cross section is to be constructed, they should be considered approximations of the dip angles rather than absolute values. Dip angles within a few tens of feet of each other can vary as much as 5 to 10 degrees.

As an example of a verbal description of the attitude of a formation at a particular site, the following notation would be used: On the south side of the Arbuckle Anticline, the Kindblade Formation strikes N50°W or 310° azimuthal and
dips to the south at an angle of 50 degrees (fig. 5.2). On a
gologic map, however, the attitude of a formation would be
shown by a **strike and dip symbol**. Various forms of this
symbol are given in figure 5.3. In illustrations used in parts of
this manual, the strike and dip symbols may appear without
the notation of the angle of dip.

## Methods of Geologic Illustration

Geologic information, gathered by the study of outcrops at
the surface and through the use of subsurface information
obtained from wells, is displayed in a number of ways in
order to depict the overall structural features and relative
age relations of the strata involved. The three main types of
geologic illustrations or diagrams and their relationships are
shown in figure 5.4 and are described below.

1. **Geologic map**: A map that shows the distribution of
   geologic formations (fig. 5.4A). Contacts between for-
   mations appear as lines, and the formations themselves
   are differentiated by various colors and symbols (refresh
   your memory by looking again at fig. 2.3). The map may
   also show topography by standard contour lines.
2. **Geologic cross section**: A diagram in which the geo-
   logic formations and other pertinent geologic informa-
   tion are shown in a vertical section (fig. 5.4B). It may
   also show a topographic profile, or it may be schematic
   and show a flat ground surface.
3. **Block diagram**: A perspective drawing in which the
   information on a geologic map and geologic cross
   section are combined (fig. 5.4C). This mode of geologic
   illustration is used to show the three-dimensional aspects
   of a geologic structure.

## Sedimentary Rock Structures

Sedimentary strata that have been subjected to forces of
deformation may form one of three fold structures as shown
in the block diagrams of figure 5.5.

1. **Monocline**: A one-limb flexure (fold) in which the
   strata have a uniform direction of strike but a variable
   angle of dip.
2. **Anticline**: A fold, generally convex upward, whose core
   contains the stratigraphically older rocks.
3. **Syncline**: A fold, generally concave upward, whose core
   contains the stratigraphically younger rocks.

Notice that in figure 5.5B the arch of the anticline is
not reflected in a corresponding topographic arch and that the
synclinal trough in figure 5.5C is a geologic trough, not a
topographic one. The surface topography of the parallel
ridges in figures 5.5B and 5.5C is controlled by a formation
that is more resistant to erosion than the other formations in
the structure.

## Geometry of Folds

The geometry of a fold is more precisely defined by the atti-
itude of the **axial plane** of the fold, an imaginary plane that sepa-
rates the **limbs** of the folds into two parts (as symmetrically
as possible) as shown in figure 5.6. The **axial trace** of the fold appears as a line on a geologic map. The **hinge line** marks the axis along which the curvature of the fold is greatest.

If the axial surface is essentially vertical, the fold is said to be **symmetric** (fig. 5.7A); if the axial surface is inclined so that the limbs dip in opposite directions but one limb is steeper than the other, the fold is **asymmetric** (fig. 5.7B); and if the axial surface is inclined to the extent that one limb of the fold has tilted beyond the perpendicular, the fold is **overturned** (fig. 5.7C). A **recumbent fold** is an overturned fold in which the axial surface is nearly horizontal. The symbols used on geologic maps to show the traces of axial surfaces are shown in figure 5.3.

The folds shown in figures 5.4, 5.5, 5.6, and 5.7 are **nonplunging folds** because the strikes of the limbs are parallel. Another way of describing a nonplunging fold is to say that the strikes of the folded formations are all parallel, as shown in figure 5.4.
Figure 5.4

(A) A geologic map shows the areal extent of geologic formations at the earth’s surface and exhibits certain symbols that further define the geometry of the rock masses as they extend beneath the surface. (B) A geologic cross section is a view of the geologic formations in a vertical plane. (C) A block diagram is a three-dimensional drawing in which the geometric configuration is depicted. (Note that there is no surface expression of the limestone unit. This subsurface information came from local wells.)
Figure 5.5
Block diagrams of three common folds. The dissected ridges formed by resistant layers in diagrams B and C are called hogback ridges.

Figure 5.6
(A) Nomenclature of a fold. (B) Age relationships of strata in an anticline.

Figure 5.7
Block diagram in which three variations of a fold are shown: (A) symmetric anticline; (B) asymmetric anticline; (C) overturned anticline. Note the different attitudes of the three axial planes.
Figure 5.8
Block diagram and geologic map of plunging folds. The map shows the characteristic outcrop pattern of plunging folds. Here, two anticlines and one syncline plunge to the west. If this area were in a humid region, the arkose formation would be more resistant to erosion than the shale, limestone, or siltstone formations and would therefore form a hogback ridge.

Figure 5.9
Small plunging anticline in the Kindblade Formation, Oklahoma, exposed along the east side of Interstate Highway 35. The angle of plunge is 24 degrees towards the viewer.

Photo by Robert Rutford.

If, however, the strikes of the same formations on either side of an axial surface converge, as in figure 5.8, the fold is said to be a plunging fold. A geologic map on which a series of plunging folds is displayed shows a zig-zag outcrop pattern. A small plunging anticline is shown in figure 5.9. The plunge direction is toward the viewer, and the angle of plunge is about 24 degrees. The direction of plunge is shown by an arrow placed on the trace of the axial plane, as in figure 5.8. The direction of plunge of a plunging anticline is toward the apex of the converging formations as seen on a geologic map, and the direction of plunge of a plunging syncline is toward the open end of the V-shaped pattern of diverging formations. Figure 5.8 shows both cases.

An anticline that plunges in opposite directions is a doubly plunging anticline, and a syncline that plunges in opposite directions is a doubly plunging syncline. Variations of doubly plunging folds are the structural dome and structural basin, as shown in figure 5.10. The outcrop patterns of these two structures are more or less concentric circles.
Geologic Maps and Cross Sections

Geologic Maps
A geologic map shows the distribution of exposed rock types in an area. The map is constructed by plotting strikes and dips of formations and the contacts between formations on a base map or aerial photograph. This information is based on field observations on outcrops in the map area. Because a single isolated outcrop rarely yields sufficient information from which the overall structural pattern for a given area can be understood, the geologist must visit enough outcrops in the map area to permit the filling of the gaps from one outcrop to another.

We are not concerned here with the making of actual geologic maps but rather with their interpretation and the construction of geologic cross sections from them. The interpretation of a geologic map requires an understanding of the information shown on it and the ability to translate that information onto a geologic cross section. To accomplish this, one must learn to visualize three-dimensional relationships from a two-dimensional pattern of geologic formations as they appear on a geologic map. This is perhaps the most difficult aspect of structural geology for a beginning student to master, but if you follow step-by-step instructions, these relationships eventually will become clear.

In general, keep in mind that a geologic map shows the distribution of formations as they appear at the surface of the earth. How this surface information can be used to visualize the unseen components of the rocks below the surface constitutes the subject matter to follow.

You may find it useful to review the relationship between a geologic map and a geologic cross section as shown in figure 5.4. If you thoroughly understand how the geologic cross section of figure 5.4 relates to the geologic map and how both relate to the block diagram, you will be in a good position to proceed with the next steps in map interpretation.

Geologic Cross Sections
The purpose of a geologic cross section is to display geologic features in a vertical section, perpendicular to the ground surface. A crude but nonetheless accurate analogy is
Figure 5.11
Block diagram and maps showing the relationship of topography to outcrop patterns. In all cases, the stream flows from north to south. (A) Horizontal strata dissected by a drainage system. Numbers refer to relative ages of the formations. The formation labeled 1 is the oldest. The apex of the V formed will point upstream and will be parallel to the contours. (B) Tilted rock strata dipping downstream at an angle steeper than the stream channel. The oldest beds (i.e., 1, 2, and 3) dip toward the youngest beds (5 and 6). The apex of the V formed points downstream and in the direction of dip. (C) Tilted strata dipping upstream. The apex of the V formed points upstream and in the direction of dip, but the contact crosses contours. (D) Vertical sedimentary beds, one of which is more resistant to erosion than the other two. In this case, the law of V’s cannot be used, because no V’s are formed. Thus, the age relationship cannot be determined from the information either on the block diagram or on the map.
to be found in the ordinary layer cake. When a layer cake is viewed from above, all that can be seen is the frosting; the “structure” of the cake is obscured. However, if the cake is cut vertically and the two halves are separated, the component layers of the cake constitute a cross section of the cake so that its structure will be revealed.

Geologic formations do occur in “layer-cake” structures, but they commonly occur in much more complex structures, and it is through the construction of a geologic cross section that these complexities are unraveled. Following are some general rules and guidelines for use in constructing a geologic cross section from a geologic map.

1. A geologic cross section is constructed on a vertical plane. The cross section is shown on the corresponding geologic map by a line that is equivalent to the line along which the cake was cut in the layer-cake analogy. Information on or near the line of the cross section on the map is transferred to the cross section as the first step in its construction. Such notations as directions and angles of dip, formational contacts, traces of axial surfaces, supplemented by subsurface information from cuttings, and well logs provide the basic elements used to make a geologic cross section from a geologic map.

2. Sedimentary formations to be drawn on cross sections in the exercises in this manual are assumed to have a constant thickness. That is to say, they do not thicken or thin with depth or along the strike.

3. Dip angles from strike and dip symbols on the map can be used as a basis for estimating the inclination of strata on a cross section. If dip angles are not shown, keep the dip angles as small as possible but consistent with the thickness of the strata and structural relationships. (Note no vertical exaggeration for dip measurements.)

4. The relative ages of sedimentary strata in some of the maps and cross sections used herein are designated by Arabic numerals. For example, if four formations are shown on a map or block diagram, the oldest formation is assigned the number “1,” and the youngest, a number “4” (fig. 5.11A).

5. If you are required to draw a geologic cross section from a geologic map on which no strike and dip symbols are present, the direction of dip can be determined in the following manner.

(a) Where a formation contact crosses a stream on the map, it forms a V, the apex of which points in the direction of dip as shown in the geologic map of figures 5.11B and 5.11C. (This rule is not to be confused with the “law of V’s” as applied to contour lines when they cross a stream.)
(b) The shape of a V formed by a contact that crosses a stream may be used to estimate the angle of dip of the contact. A broad V is indicative of a steep dip angle, and a narrow V is indicative of a shallow dip angle. Where no V is formed, the formation contact is vertical, as shown in figure 5.11D. The foregoing method for determining the direction of dip takes precedence over the method described next.

(c) In a sequence of formations, none of which has been overturned, the oldest beds dip toward the youngest, as shown in the geologic map of figures 5.11B and 5.11C.

**Width of Outcrop**

Strata exposed to erosion at the earth’s surface appear as bands on the geologic map. The width of a single band is called the **width of outcrop**, although the full thickness of the formation may not be exposed in a single outcrop. The width of outcrop is controlled by three factors: the thickness of the formation, the angle of dip of the formation, and the slope of the land surface where the outcrop is exposed.

To illustrate these controlling factors in the simplest case, consider the three horizontal formations of equal thickness in figure 5.12. The geologic cross section in figure 5.12A shows how the thickness of each formation varies with the slope of the land surface. A gentle slope results in a width of outcrop that is greater than the thickness of the formation, as in the case of the shale formation; and a steeper slope produces a width of outcrop that is less than the thickness of the formation, as in the case of the sandstone and limestone formations.

Two other cases of the relationship of thickness to the width of outcrop are shown in figures 5.12B and 5.12C. In figure 5.12B, where the beds are dipping 30 degrees, the thickness of each formation is shown on the cross section, and the corresponding width of outcrop is shown on the geologic map. In figure 5.12C, the formations are vertical; that is, they dip 90 degrees. In this case, the true thickness of a formation is the same as the width of outcrop. The general rule, however, is that the **width of outcrop on a geologic map is not necessarily the same as the true thickness of the formation as seen in a geologic cross section**.

This rule must be kept in mind when drawing cross sections from a geologic map or a block diagram in the exercise that follows.
Figure 5.12
Cross section and geologic maps of three sedimentary formations showing the relationship of the true thickness of each formation (Tss, Tsh, and Tvd) to their widths of outcrop on a geologic map. The thickness of each formation is the same on all three cross sections. The width of outcrop (Wss, Wsh, and Wvd) on the geologic map depends on the thickness and attitude of the formations and the slope of the surface. In the three cases shown—(A) horizontal strata, (B) inclined strata, and (C) vertical strata—only in C does the thickness of each formation in the cross section equal the width of outcrop of the same formation on the geologic map.
1. Complete the four block diagrams in figure 5.13. Below each block diagram, print the name of one or more of the geologic structures shown. Remember that the numbers on the map indicate the relative ages of the formations, with number 1 being the oldest. Assume that the topography in all four diagrams is essentially flat except in diagrams C and D, where a stream cuts across the formational contacts. In these four block diagrams, dip directions in A and B are to be determined by the rule that older beds dip toward younger beds, and in C and D, dip directions are to be determined by the rule of V's.

2. On figure 5.8, place a strike and dip symbol at points a, b, c, d, and e on the geologic map and the block diagram. Use a black pencil.

3. Figure 5.10 shows two geologic maps. All formations shown there are sedimentary in origin.

(a) Label each formation with a number indicating its relative age in the sequence of strata. The oldest should be labeled number 1.

(b) Draw strike and dip symbols on each map.

4. On the geologic maps of figures 5.12A and 5.12B, draw the appropriate geologic symbol that shows the attitude of each of the three formations, and show by numbers the relative age of each.

5. Why is it impossible to tell the relative ages of the formations shown in figure 5.12C without reference to figures 5.12A or 5.12B?