EXERCISE FOURTEEN

Structural Geology

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PURPOSE

This exercise develops your ability to define, describe, and interpret geological structures in three dimensions. To do this, we will use three-dimensional block diagrams, geologic maps, and geologic cross sections.

MATERIALS

Ruler, set of colored pencils, paper, pencil, eraser.

INTRODUCTION

Structural geology is the study of how rocks or sediments are arranged when first formed, and how they are deformed afterward. Rock/sediment deformation is caused by *stress* (directed pressure). Deformation (such as a change in shape) caused by this stress is called *strain*. Therefore, much of structural geology involves deciphering stress and strain relations.

Generally, geologists can see how rocks or sediments are positioned only at Earth's *surface*. Geologists record this two-dimensional information on geologic maps like those you will use in this exercise. From the information on such maps, they then *infer* the three-dimensional arrangement of the rocks/sediments. From this 3-D picture, the structural geology of an area can be interpreted.

DEFINITIONS

Three representations of Earth are commonly used by structural geologists. These are the geologic map, cross section, and block diagram:

geologic map shows the distribution of rocks at Earth's surface. The rocks commonly are divided into mappable units that can be recognized and traced across the map area. This division is made on the basis of color, texture, or composition. Such mappable units are called **formations.** They may be subdivided into **members.** The boundaries between geologic units are **contacts.** A geologic map also may show the topography of the land surface with contour lines.

geologic cross section a drawing of a vertical slice through Earth, with the material in front of it removed—a cutaway view. It shows the arrangement of rock units and their contacts. A good cross section also shows the topography of the land surface, like a topographic profile.

block diagram a combination of the geologic map and cross section. It looks like a solid block, with a geologic map on top and a geologic cross section on each of its visible sides. You will work with six block diagrams in this exercise.

Because we are dealing with the three-dimensional arrangement of rocks, both at and beneath Earth's surface, we need a system to describe rock orientation, or attitude. Strike and dip serve this purpose (see Figures 14.1 and 14.2):

strike the *compass direction* of a line formed by the intersection of a horizontal plane (like the surface of a lake) and an inclined stratum, fault, fracture, or other surface (Figure 14.1). Because it is a compass direction, strike usually is expressed relative to north or south. Hence, strike is expressed as "north X degrees east," or "south X degrees west." (Refer back to Exercise Seven if necessary.)

dip the *angle* between a horizontal plane and the inclined stratum, fault, or fracture. As you can see in Figure 14.1, a thin stream of water poured onto an inclined surface always runs down the surface parallel to dip. The inclination of the water line down from the horizontal plane is the **dip angle.** Dip always is measured perpendicular to strike.

This "water-on-the-rock method" for finding the direction and angle of dip is very useful. Because strike is perpendicular to dip, strike easily

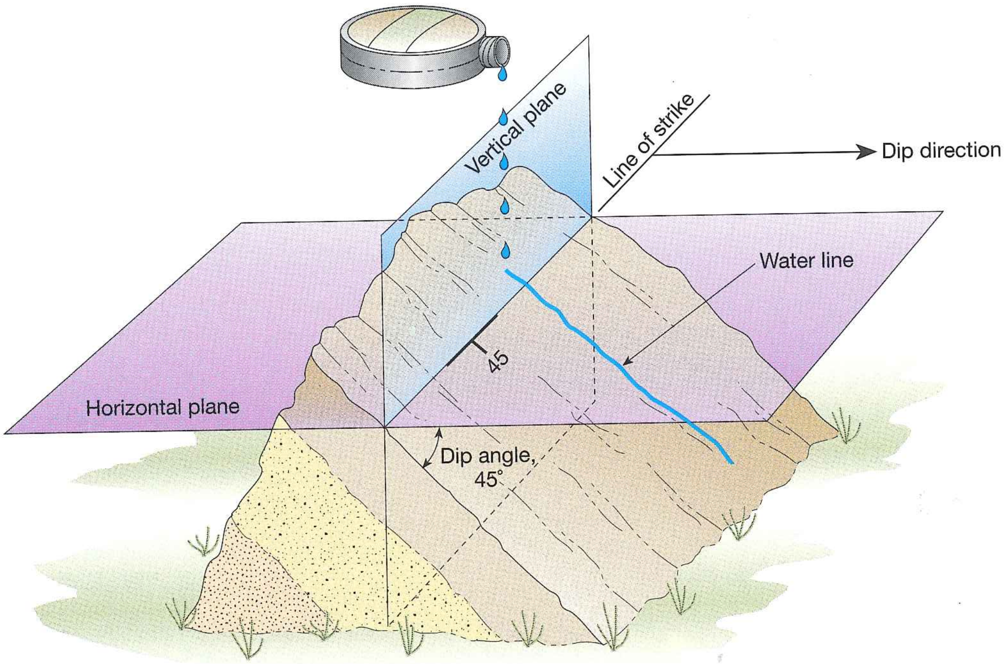
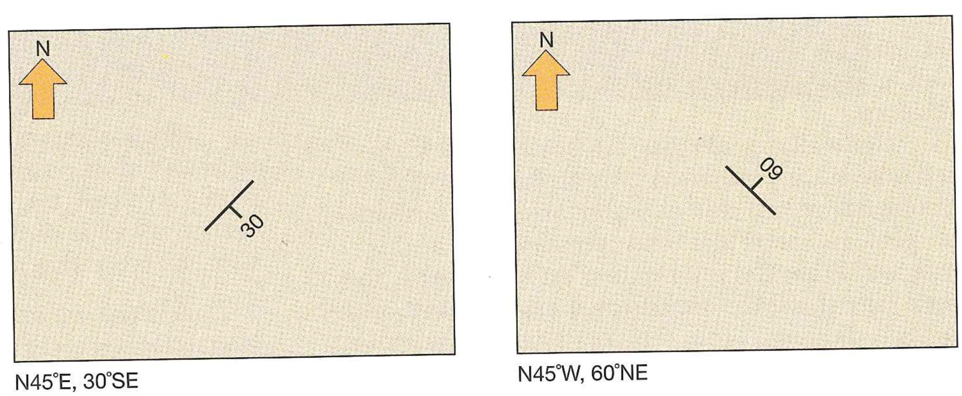


FIGURE 14.1 Strike and dip of a rock outcrop. *Strike* is the direction of a line formed by the intersection of rock strata and a horizontal plane. *Dip* is the maximum angle of inclination of the strata, always measured perpendicular to the line of strike (looking straight down on it, in map view). Water poured onto a dipping stratum drains along the angle of dip. The **T** and **45** together form the standard strike-and-dip symbol: the top of the **T** is the line of strike; the short upright of the **T** shows the dip direction; and the **45** is the dip angle in degrees.

FIGURE 14.2 How to read strike-and-dip symbols. In the left example, strike runs 45° east of north (N45°E), and the rocks dip 30° toward the southeast (30°SE). Strike and dip always are given in this order: N45°E, 30°SE. Compare to the example on the right.



can be determined relative to the water line. The direction that the water runs down an inclined geologic surface is the **dip direction**, and must be expressed together with the **dip angle** (e.g., 24° west).

Strike and dip are shown on maps by use of T-shaped symbols (Figure 14.2). The long line shows strike direction, and the short line shows dip direction. Again, dip always is drawn perpendicular to the line of strike. The short line "points" downdip. The accompanying numerals indicate the dip angle in degrees.

TYPES OF STRUCTURES

Structural geologists must locate, observe, and interpret many different structures. Fundamentally, these include unconformities, faults, and folds.

Unconformities are of three common types (Figure 14.3):

1. **Disconformity** an unconformity between *parallel* strata. The disconformity itself may be a very irregular surface, as shown.
2. **Angular unconformity** an unconformity between *nonparallel* strata.
3. **Nonconformity** an unconformity between sedimentary rock/sediment and *nonsedimentary* rock.

Faults are of two general classes, those having mostly vertical movement, and those having mostly lateral movement (Figure 14.4):

1. Vertical-motion faults are of two types, **normal faults** and **reverse faults.** Each is named by noting the *sense of motion* of the top block relative to the bottom block, regardless of which one actually has moved. Simply assume that the bottom block (foot wall) has not moved, and then determine which direction the top block (hanging wall) appears to have moved. If the top block appears to have moved downward, as gravity would normally pull it, then the fault is a **normal fault.** If the top block appears to have moved upward, the reverse of the way gravity would pull it, then the fault is a **reverse fault.**
2. Horizontal-motion faults are **lateral faults** (or **strike-slip faults**). Shown in the figure is a

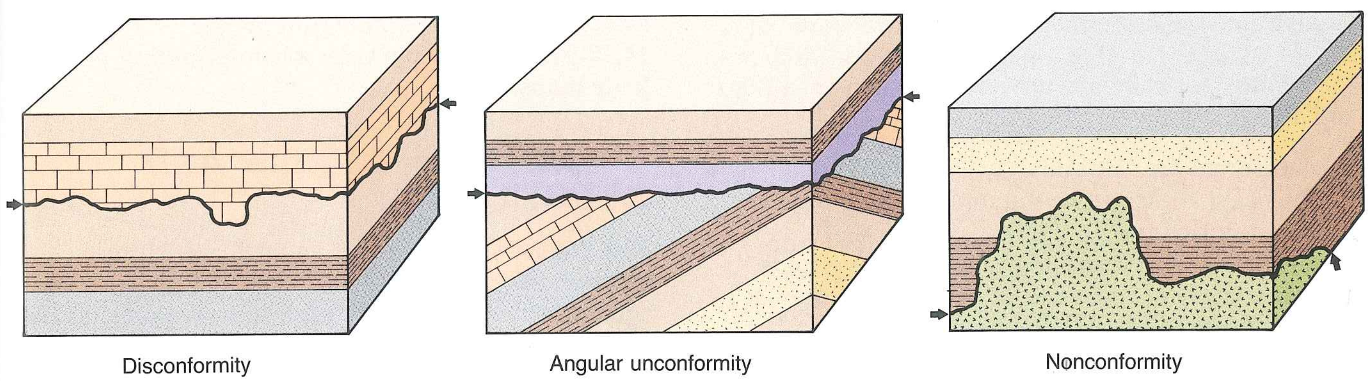


FIGURE 14.3 Unconformities—the three common types. Arrows mark the unconformity surfaces.

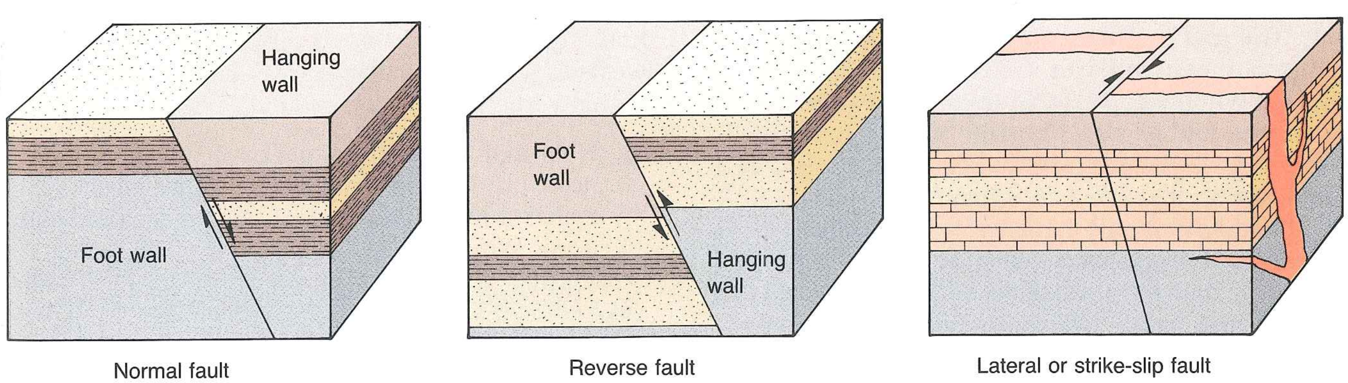


FIGURE 14.4 Faults—the three common types. Arrows show the direction of movement of each block. (Also refer back to Figure 1.12.)

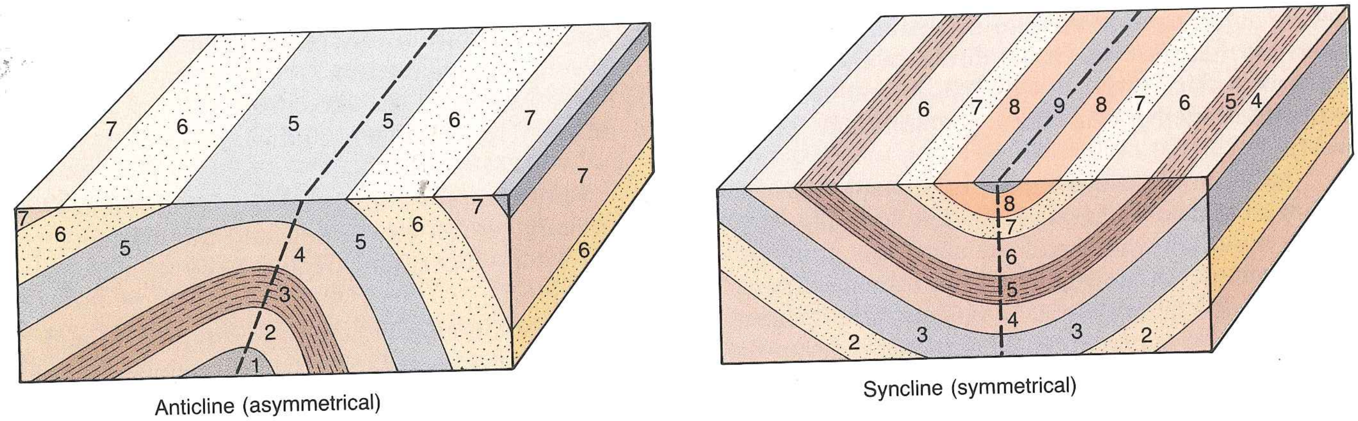


FIGURE 14.5 Folds—the two common types. Numbers indicate relative ages of the rock units. Lowest number (**1** or **2**) in each diagram = oldest unit, deposited first. Highest number in each diagram (**7** or **9**) = youngest unit, deposited last. Heavy dashed lines mark axial planes of the folds (see Figure 14.6).

right-lateral fault. If you stand on one side of the fault and look across it, the rocks on the opposite side of the fault appear to have moved to the right. *Left-lateral faults* have the opposite sense of motion. They also are called strike-slip faults because they slip along the direction of strike of the fault plane.

Folds basically are upward or downward (Figure 14.5):

1. **Antiforms** are "upfolds" or "convex folds." If the *oldest* rocks are in the middle, they are called **anticlines.**
2. **Synforms** are "downfolds" or "concave folds." If the *youngest* rocks are in the middle, they are called **synclines.**

In a fold, each stratum is bent around an imaginary axis, like the crease in folded paper. This is the **fold axis** (or **hinge line**). For all strata in a fold, the fold axes lie within the **axial plane** of the fold (Figure 14.6A).

The fold axis may not be horizontal, but rather plunge into Earth, called a **plunging fold** (Figures 14.6B and 14.7). **Plunge** is the angle between the fold axis and horizontal. The **trend** of the plunge is the compass direction, measured in the direction that the axis is inclined downward.

Folds commonly have two sides, or **limbs,** one on each side of the axial plane (Figure 14.6). However, **monoclines** have two axial planes that separate two nearly horizontal limbs from a more steeply inclined limb (Figure 14.8).

Domes and basins are large, circular structures formed when strata are warped upward (domes) or downward (basins). Strata are oldest at the center of a dome, and youngest at the center of a basin.

Geologic maps use many symbols to describe structures; some are shown in Figure 14.9. Figure 14.10 provides simple rules for interpreting geologic maps.

STRUCTURE MODELS AND QUESTIONS

It is easiest to learn about geologic structures through the use of three-dimensional models. We provide six models, printed on heavy paper, at the back of this manual. Carefully remove them from the book, so you can fold them into blocks. To fold them, follow the procedure in Figure 14.11.

Structure Model 1

This model shows a light brown (speckled) formation striking due north and dipping 25° to the west. A second formation (gray) strikes due north and is vertical (dip angle = 90°).

1. Note that both formations have the same thickness, but the one dipping 25° to the west makes a much wider band on the geologic map (top). Why?

We have printed the complete map for you, and the vertical cross sections on the south, east, and west sides. Now complete the vertical cross section on the north side. Also, draw on the map a strike and dip symbol on the bed that dips 25° to the west. Then draw a strike and dip symbol for the vertical bed (see Figure 14.9 for the strike and dip symbol for a vertical bed).

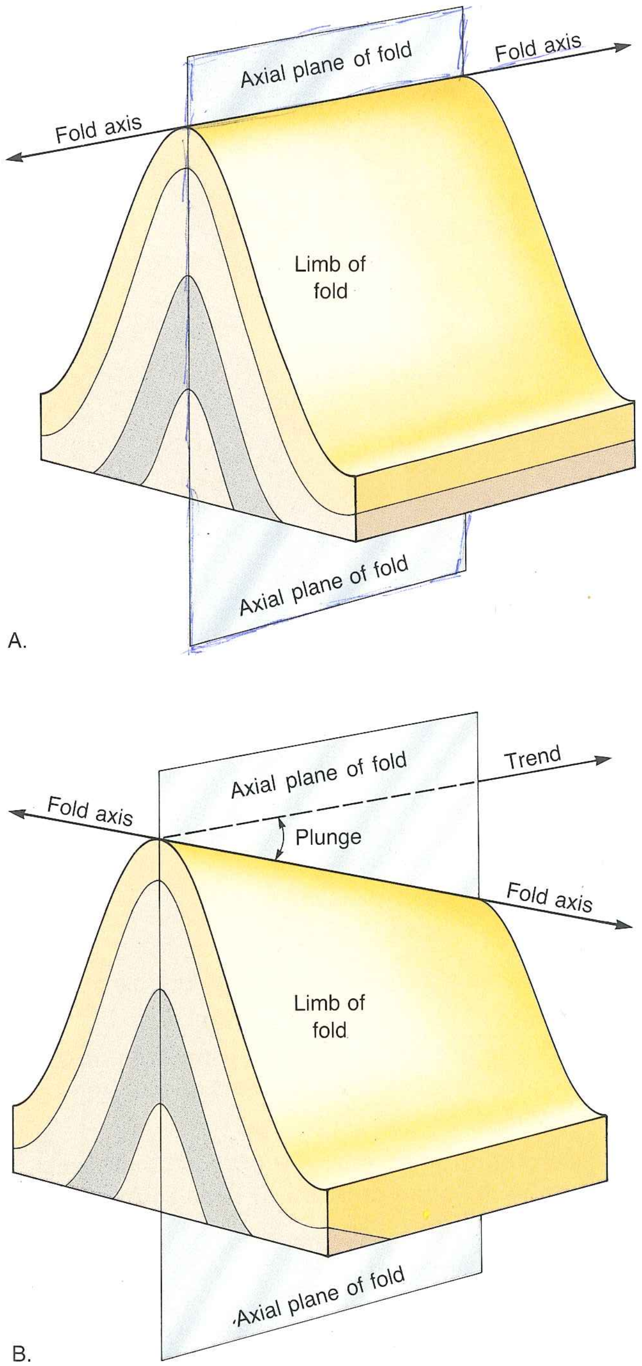


FIGURE 14.6 Fold terminology. A. Simple horizontal fold. B. More complex plunging fold. Note that the fold axis plunges into Earth, but the *trend* is the compass direction on the surface.

Structure Model 2

This model is slightly more complicated than the previous one. Complete the north and east sides of the block. Notice that the rock units define a fold. This fold is an antiform, because the strata are convex upward. We say it is nonplunging, because its axis is horizontal. (Consult Figure 14.6 for the differences between plunging and nonplunging folds if you are uncertain about this.) On the geologic map, draw strike and dip symbols showing the orientations of unit **E** at points **I, II, III,** and **IV.**

2. How do the strikes at all four locations compare with each other?
3. How does the dip direction at points **I** and **II** compare with the dip direction at points **III** and **IV?** In your answer, include the dip direction at all four points.
4. Draw the proper symbol along the axis of the structure (refer to Figure 14.9).

Structure Model 3

Complete all four cross sections, using as guides the geologic map on top of the block and the incomplete cross section at the south end. On the map, draw strike and dip symbols showing the orientation of unit **C** at points **I, II, III,** and **IV.**

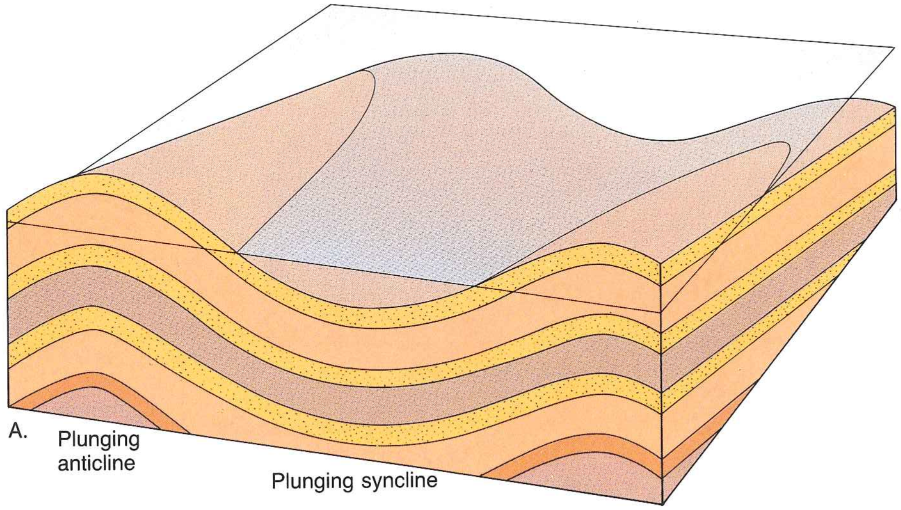
5. How do the strikes of all four locations compare with each other?
6. How does the dip direction at points **I** and **II** compare with the dip direction at points **III** and **IV?** Include the dip direction at all four points in your answer.
7. Is this fold plunging or nonplunging? Is it an antiform or a synform?
8. How much variation is there in the strike at all points in a nonplunging fold?
9. Draw the proper symbol along the axis of the structure (refer to Figure 14.9).

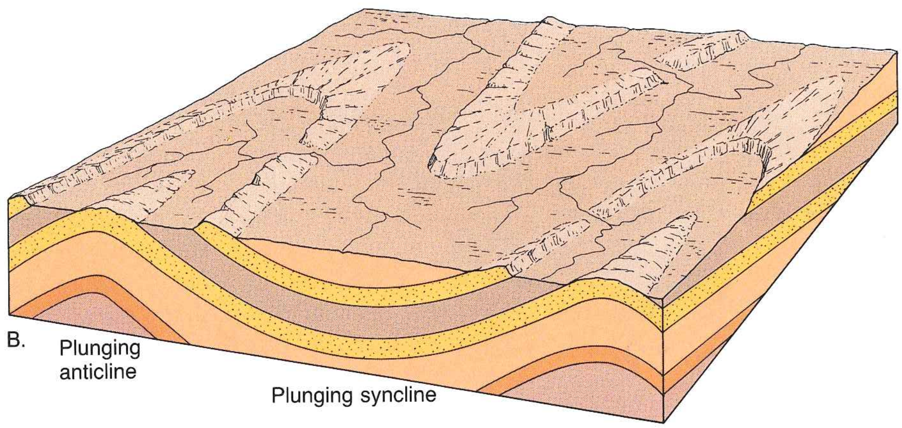
Structure Model 4

This model shows a plunging antiform and an unconformity. The antiform plunges to the north, following the general rule that *anticlines plunge in the direction in which the fold closes* (refer to rules, Figure 14.10). Complete the north and east sides of the block. Draw strike and dip symbols on the map at points **I, II, III, IV,** and **V.**

10. How do the directions of strike and dip differ from those in Model 2?

FIGURE 14.7 Plunging folds. A. Before erosion. Imaginary plane above strata is the *horizontal datum plane,* from which all data are measured. B. After erosion. Eroded plunging folds are exposed at the land surface.





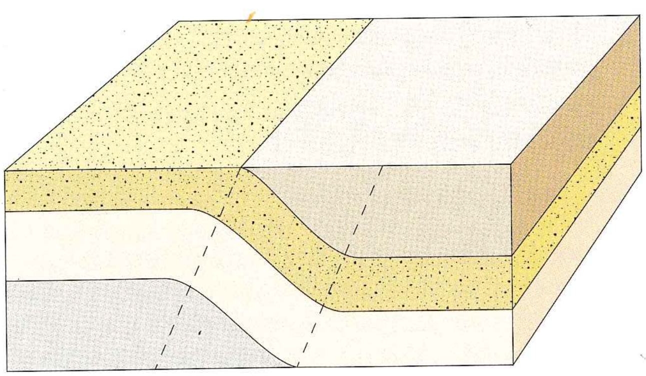


FIGURE 14.8 Monocline. Not all folds have two limbs. The monocline is a fold inclined in only one direction. A monocline has two axial planes (dashed) that separate two nearly horizontal limbs from a more steeply inclined limb.

11. What type of unconformity is at the base of unit **I?**
12. Draw the proper symbol along the axis of the structure. Indicate the direction of plunge. (Refer to Figure 14.9.)
13. Draw the proper symbol on the geologic map to indicate the orientation of beds in formation **I** (refer to Figure 14.9).

Structure Model 5

This model shows a plunging synform. Complete the north and east sides of the diagram. Draw strike and dip symbols on the map at points **I, II, III, IV,** and **V** to show the orientation of layer **G.** *Synforms plunge in the direction in which the fold opens* (refer to rules, Figure 14.10).

14. In which direction does this synform plunge?

15. Draw the proper symbol along the axis of the structure. Indicate the direction of plunge (refer to Figure 14.9).

Structure Model 6

This model shows a fault that strikes due west and dips 45° to the north. At point **I**, draw a strike and dip symbol showing the *orientation of the fault*. On the west edge of the block, draw arrows parallel to the fault, indicating relative motion. Label the hanging wall and the foot wall.

16. Is this fault a normal or a reverse fault? Why?

Complete the east side of the block. Draw arrows parallel to the fault to show the relative motion. Now look at the geologic map and at points **II** and **III**. Write **U** on the side that went up and **D** on the side that went down. At points **IV** and **V**, draw strike and dip symbols for unit **B**.

17. On the geologic map, what happens to the contact between units **A** and **B** where it crosses the fault?

The general rule is that, as erosion of the land proceeds, *contacts migrate downdip.*

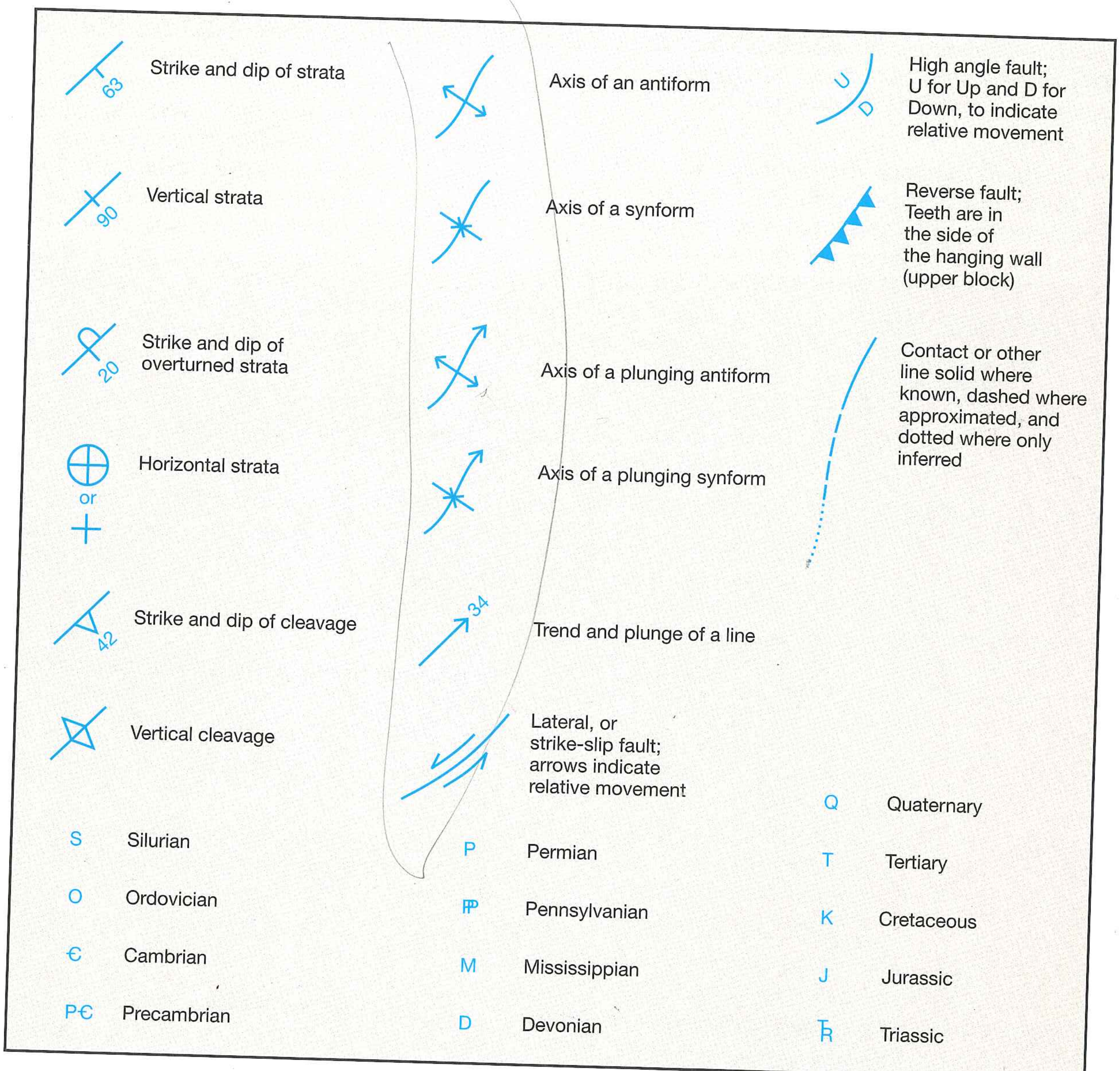


FIGURE 14.9 Structural symbols and abbreviations used on geologic maps. (For rock symbols, see Exercise Thirteen, Figure 13.1.)

FIGURE 14.10 Simple rules used by geologists to interpret geologic maps.

A SET OF SIMPLE RULES FOR INTERPRETING GEOLOGIC MAPS

1. Contacts between horizontal beds are parallel to topographic contours along those contacts.
2. Anticlines have their oldest beds in the center.
3. Synclines have their youngest beds in the center.
4. Anticlines plunge toward the nose (closed end) of the structure.
5. Synclines plunge toward the open end of the structure.
6. Contacts of horizontal beds, or of beds that have a dip lower than stream gradient, "V" upsteam.
7. Contacts of beds that have a dip greater than stream gradient "V" downstream.
8. Vertical beds do not "V" or migrate with erosion.
9. The upthrown blocks of faults tend to be eroded more than downthrown blocks.
10. Contacts migrate downdip upon erosion.
11. True dip angles can only be seen in cross section if the cross section is perpendicular to the fault or to the strike of the beds.

FORMING THE STRUCTURE MODELS

1. Lay the paper with the model on it face down in front of you. Orient the long dimension of the paper up-and-down, as if you were going to read a normal typewritten page.
2. Carefully curl back one side until you can see the solid black line that runs all the way from the top to the bottom of the page. Crease the paper exactly along that line.
3. Now repeat this process for the other side of the paper.
4. Unfold the two sides, and curl back the top until you see the solid black line that runs across the page. Crease the paper exactly along that line.
5. Now repeat this process for the bottom of the paper.
6. To make a block, you still need to do something about the extra material where the corners are. In each corner there is a dashed line. Start at one corner and push that line toward the inside of the block. Fold the sides down so that they match, and crease the flap you folded in. Your crease should be approximately along the dashed line. Do the same thing with the other three corners.
7. If the block is folded correctly, the top will be flat and the strata will match on the map (top) and on the cross sections (sides).
8. The block will not really stay together without tape, but do not tape it. You will find that it is easier to draw on the block if you can unfold it and lay it out flat.
9. Write your name on the blank inside of the block so that your instructor can identify your work when you hand it in.

FIGURE 14.11 Forming the structure models.

18. Is this true in this example?

19. Could the same offset have been produced by strike-slip motion?

GEOLOGIC MAPS AND QUESTIONS

Refer to Figure 14.12, a portion of the Bright Angel, Arizona quadrangle, including parts of the Grand Canyon. This is a topographic map like those you have used in previous exercises, but with geologic information superimposed. It shows where various rocks **crop out,** or where they are exposed at the surface. (Sometimes they are obscured by soil or vegetation, but it is where they *would be* exposed if not obscured.) In the southwestern United States, the semiarid climate prevents the formation of much soil, so rock formations and the contacts between them are largely visible in the field. In the explanation on the page facing the map, the formations are listed in the order of their age (youngest at top).

Examine the map and the explanation, and answer these questions:

20. What is the name of the oldest unit? In terms of geography and elevation, where is this unit exposed? (Note: Printing colors vary slightly between the map and the explanation. To find formations, use both the color and the formation designation, such as Pk, pCb.)

21. How old is the Kaibab Formation? (Give geologic period.)

22. In terms of geography and elevation, where is this unit exposed?

23. What is the youngest unit?

24. Note the pattern of the contour lines. Why do the contacts of most of the geologic formations mimic the contour lines? (Refer to rules, Figure 14.10.)

25. How do the contour lines indicate that the Redwall Limestone is a cliff-forming unit in the map area?

26. Would the Redwall Limestone be a cliff-former in a region of heavy rainfall? Why or why not?

27. Is the Hermit Shale a cliff-former?

28. Is the Supai Formation a cliff-former?

29. Approximately how thick is the Paleozoic sequence (Appendix 1) in this area? (You will find the contour lines helpful here.) What must you assume about how the rocks are oriented to make this estimation?

On this map, contacts between rock units are shown by thin black lines. Faults are shown as heavy black lines, dotted where covered by younger rock units. In the northwestern quadrant of the map, find the Cheops Pyramid, and the fault passing through it. Note how this fault offset the Dox and Shinumo Formations *before* the Tapeats Sandstone was deposited. Before continuing, make sure you clearly see how the map depicts these relationships among the Tapeats, Dox, and Shinumo.

30. In the southeastern quadrant, find the Cremation Fault. Identify the youngest formation affected by the Cremation Fault. Which formation was deposited first, after the faulting occurred?

31. In the southwestern quadrant, find the Pipe Fault and the Bright Angel Fault. Study the interesting relationship of these two faults. Now, Identify the youngest formation affected by the portion of the Pipe Fault that lies northwest of the Bright Angel Fault. Which formation was deposited first, after the fault had occurred?

32. Examine the portion of the Pipe Fault southeast of the Bright Angel Fault. When was this portion active?

33. According to the fine print in the explanation, what may have happened in the area during the Silurian Period?

Refer to Figure 14.13. This geologic map shows part of Somerset County, Pennsylvania, a bituminous coal mining area. Examine the map and you will see that the only difference from the Bright Angel geologic map is the addition of red contour lines. These are not topographic contours; we will discuss them shortly, but disregard them for now. This is an interesting area to study, both economically and structurally. In the stratigraphic column on the page facing the map, note the economic resources, especially the Upper Kittanning coal.

34. The contour interval on the Bright Angel quadrangle is 50 feet. But on this map, C.I. = 20 feet. Why are these different contour intervals used?

35. In the west-central part of the map, at the eastern crest of Glade Mountain (you will have to look closely for these localities), what is the

elevation of the contact between the two units exposed there?

36. The contact is between what two units?

37. Refer to the stratigraphic column. Coals are represented as black intervals on the typical rock sequence. The Upper Kittanning coal unit is near the top of the Kittanning Formation. Does the Upper Kittanning coal occur above or below the contact mentioned in Question 36?

38. In the southeastern part of the map, along the Berlin syncline, find the abandoned coal mine, 1½ miles north of the center of Salisbury. (It is just below the "n" in Coal Run). What is the elevation of this point? (Note it for a later question.)

39. Would the Upper Kittanning coal unit lie at or below ground level here?

40. What is the difference in elevation between this site (abandoned coal mine) and the one in Question 35?

The red lines on this map are **structure contours.** They are like topographic contours, but instead of giving the elevation above sea level of the land surface, they show the *elevation above sea level of a specified geologic surface*. In this case, the geologic surface is the top of the Upper Kittanning coal.

Figure 14.14 shows two views of a coal bed like the Upper Kittanning. The profile (side view) shows how the land surface and coal bed surface can intersect. The map view shows the same intersection by using topographic contours (for the surface) and structure contours (for the coal bed). The dashed line indicates where the two intersect, which is where the coal crops out at the surface.

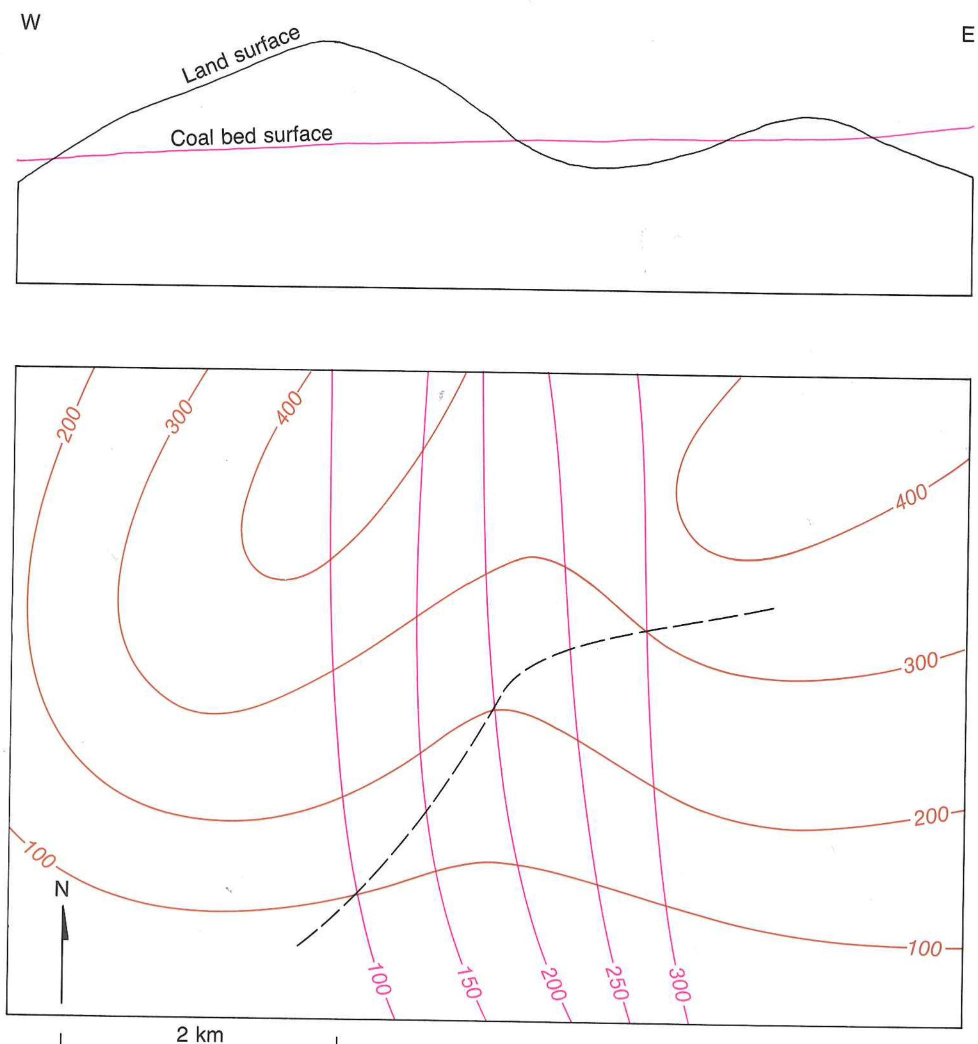


FIGURE 14.14 Profile (top) and map view (bottom) of a coal bed.

(Geologists who work for surface-mining companies use these maps to find outcrops where coal can be easily mined at the surface.)

Here are rules to remember about structure contours:

- If a structure contour is *lower* than the topographic contour, the geologic surface is buried underground.
- If a structure contour is *identical* to the topographic contour, the geologic surface is at ground level, and crops out (although it may be concealed by vegetation, soil, or alluvium).
- If a structure contour is *higher* than the topographic contour, the geologic surface is above the ground. In other words, it is up in the air, and there is nothing there. What happened? The geologic surface has been eroded away.

41. Returning to Figure 14.13, use both the structure contours and the topographic contours to determine the depth to the coal at the abandoned mine in Question 38. In other words, how many feet is the mine below the surface?

42. Based on what you learned from Figure 14.14, where would you look on this map to find outcrops of the coal unit?

43. How might a mining geologist use structure contours to estimate the costs of mining at a given place?

ADDITIONAL QUESTIONS

Refer to Figure 14.13, and note line *A–A′*. On the topographic profile of this line provided in Figure 14.15, do the following:

44. Plot the line of the Upper Kittanning coal (use red pencil) on the geologic cross section (Figure 14.15).

45. Mark points on the geologic cross section (Figure 14.15) that represent contacts between rock units.

46. Extend these contacts (from Question 45) throughout the subsurface portion of the geologic cross section.

47. Use colored pencils to tint the rock units of the geologic cross section (Figure 14.15). Use colors similar to those on the map.

48. Draw a line on the geologic cross section (Figure 14.15) representing the edge of the axial plane of the anticline, and label it.

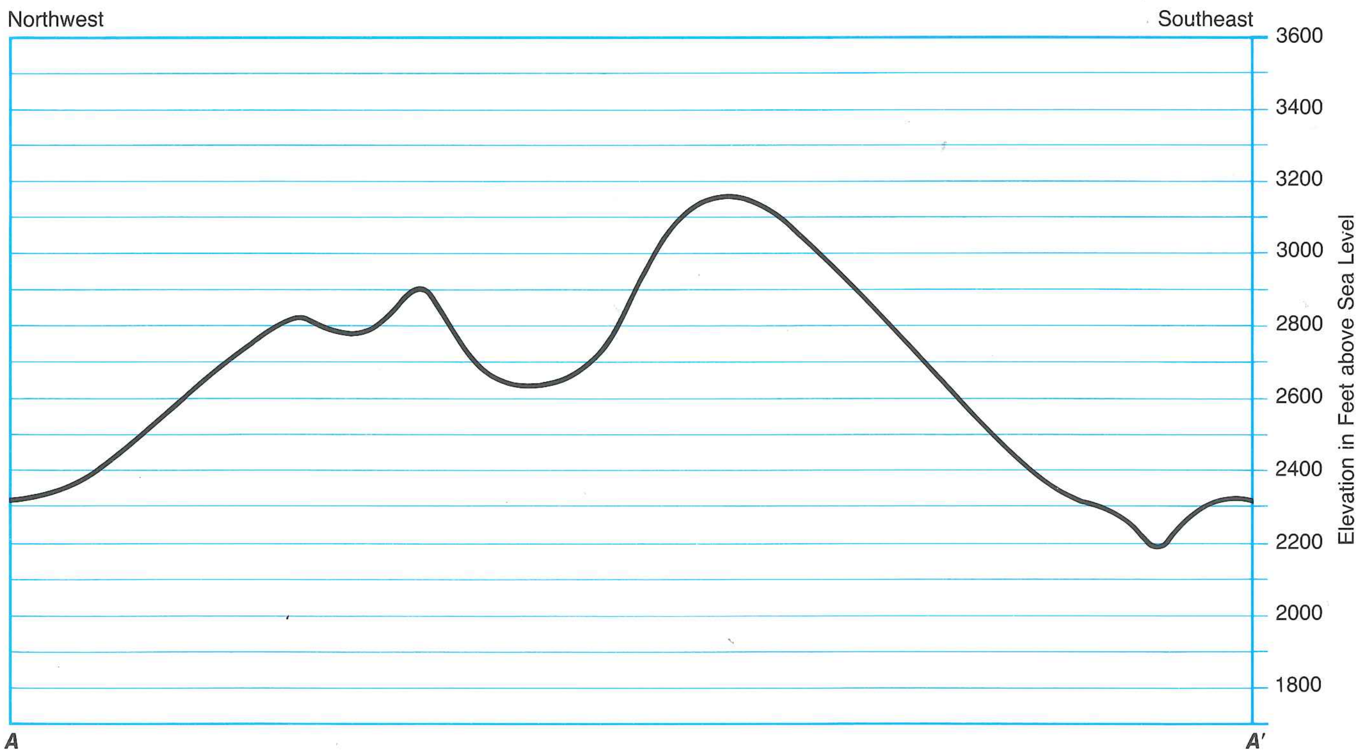


FIGURE 14.15 Topographic profile along line *A–A′* on geologic map in Figure 14.13.