9

Faults

OBJECTIVES

Measure net slip

Measure rotational slip

Describe geometry, sense of slip, and age of faults

Reconstruct the history of faulting from outcrop patterns on a geologic map

A fault is a fracture along which movement has occurred. Sometimes there is a single discrete fault surface, or *fault plane*, but often movements take place on numerous subparallel surfaces resulting in a *fault zone* of fractured rock. The San Andreas fault in California, for example, in most places has a single recently active fault plane lying within a highly sheared fault zone that is tens or hundreds of meters wide.

Some faults are only a few centimeters long, while others are hundreds of kilometers long. On geologic maps it is usually impossible to show every fault. Only those faults that affect the outcrop pattern of two or more map units are usually shown. The scale of the map determines which faults can be shown.

Below are some terms used to describe faults and their movements.

Slip vector The displacement of originally adjacent points, called *piercing points*, on opposite sides of the fault.

Strike-slip fault A fault in which movement is parallel to the strike of the fault plane (Fig. 9.1). Strike-slip faults are sometimes called *wrench* faults, *tear* faults, or *transcurrent* faults. A right-lateral (dextral) strike-slip fault is one in which the rocks on one fault block

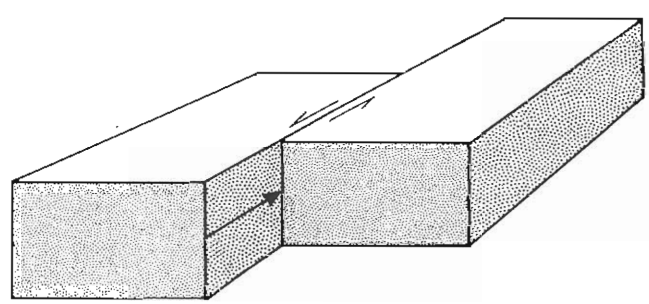


Fig. 9.1 Block diagram showing left-lateral strike-slip fault. Bold arrow shows slip vector.

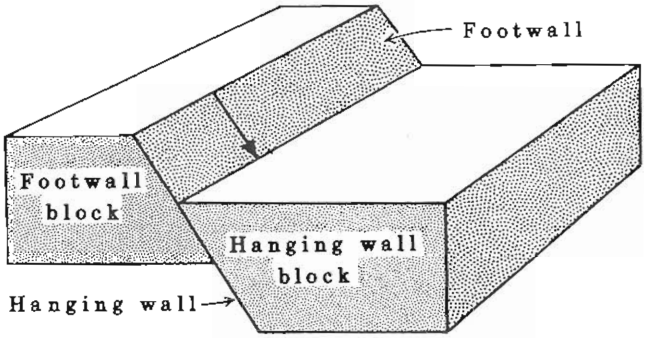


Fig. 9.2 Block diagram showing dip-slip fault. This is a normal fault because the hanging-wall block has moved down relative to the footwall block. Bold arrow shows slip vector.

appear to have moved to the right when viewed from the other fault block. A left-lateral (sinistral) strike-slip fault, shown in Fig. 9.1, displays the opposite sense of displacement.

Dip-slip fault A fault in which movement is parallel to the dip of the fault plane (Fig. 9.2).

Oblique-slip fault A fault in which movement is parallel to neither the dip nor the strike of the fault plane.

Hanging-wall block The fault block that overlies a high-angle, nonvertical fault (Fig. 9.2).

Footwall block The fault block that underlies a high-angle, nonvertical fault (Fig. 9.2).

Normal fault A dip-slip fault in which the hanging wall has moved down relative to the footwall (Fig. 9.2).

Reverse fault A dip-slip fault in which the hanging wall has moved up relative to the footwall.

Thrust fault A low-angle reverse fault.

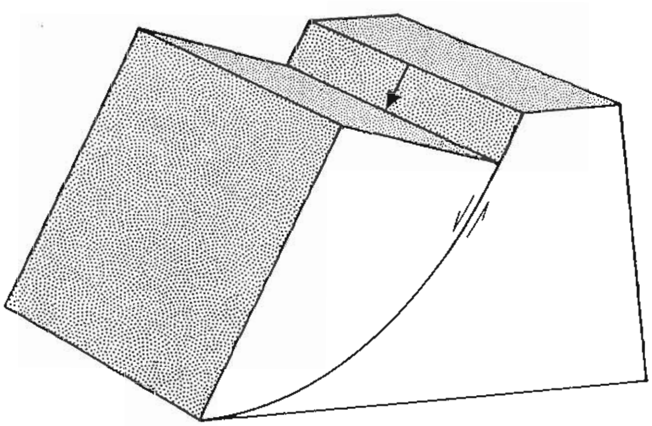


Fig. 9.3 Block diagram showing listric fault. Bold arrow shows slip vector.

Detachment fault A low-angle normal fault, also called a *denudation* fault.

Listric fault A fault shaped like a snow-shovel blade, steeply dipping in its upper portions, becoming progressively less steep with depth (Fig. 9.3).

Translational fault One in which no rotation occurs during movement, so that originally parallel planes on opposite sides of the fault remain parallel (Figs 9.1 and 9.2).

Rotational fault One in which one fault block rotates relative to the other (Fig. 9.4).

Scissor fault A rotational fault whose sense of displacement is reversed across a point of zero slip and whose amount of displacement increases away from this point (Fig. 9.4).

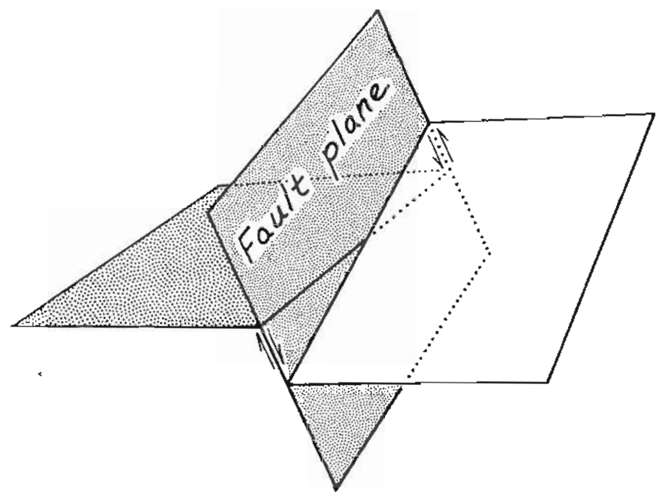


Fig. 9.4 Block diagram showing rotational fault. This is a scissor fault because there is a reversed sense of displacement across a point of zero slip.

Slickensides A thin film of polished mineralized material that develops on some fault planes. Slickensides contain striations parallel to the direction of latest movement. Often it is not possible to tell from slickenside lineations alone in which of two possible directions movement actually occurred.

Fault trace Exposure of the fault plane on the earth's surface.

Offset Horizontal separation of a stratigraphic horizon measured perpendicular to the strike of the horizon (Fig. 9.5a).

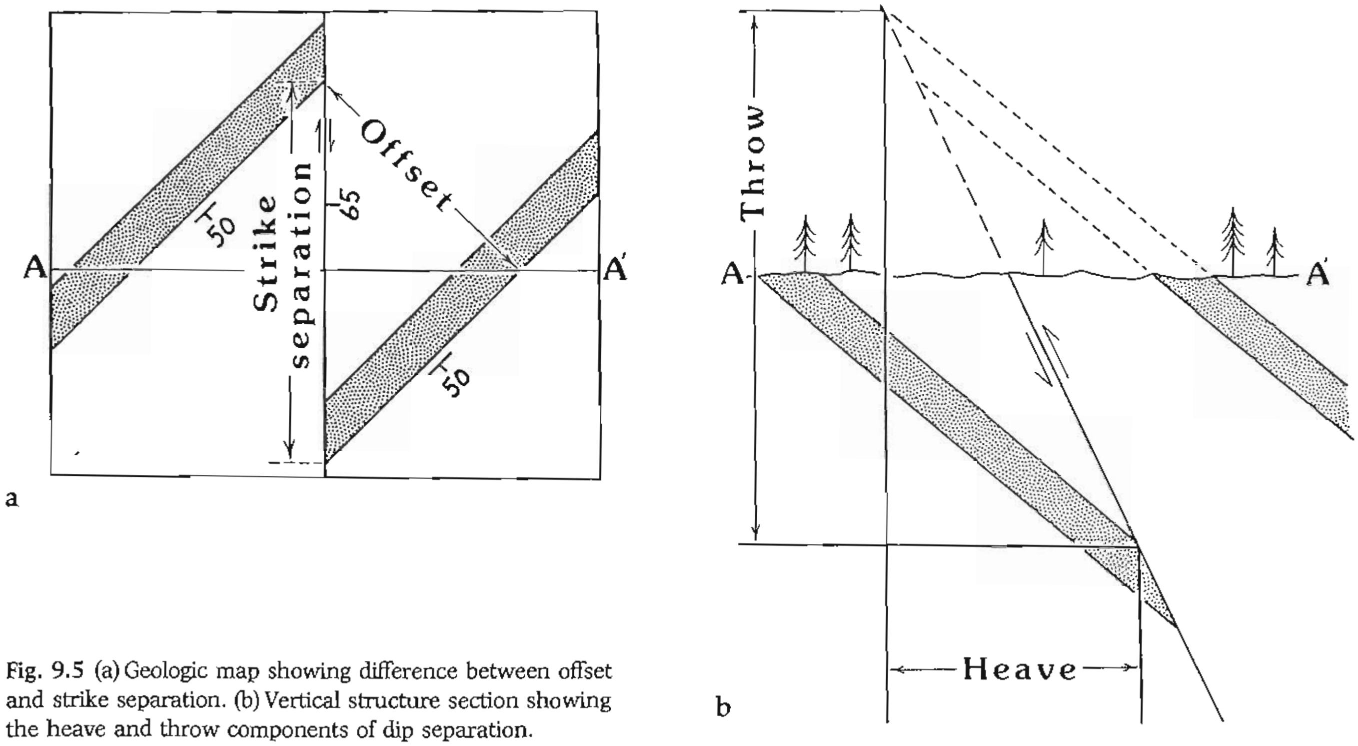


Fig. 9.5 (a) Geologic map showing difference between offset and strike separation. (b) Vertical structure section showing the heave and throw components of dip separation.

Strike separation Horizontal distance parallel to the strike of the fault between a stratigraphic horizon on one side of the fault and the same horizon on the other side. Strike separation may be described as having either a right-lateral (dextral) or left-lateral (sinistral) sense of displacement (Fig. 9.5a).

Dip separation Horizontal (heave) and vertical (throw) distance between a stratigraphic horizon on one side of the fault and the same horizon on the other side as seen in a vertical cross-section drawn perpendicular to the fault plane (Fig. 9.5b). Dip separation has either a normal or reverse sense of displacement.

Notice that the term separation is concerned with the *apparent* displacement of some reference horizon, and the terms right-lateral, left-lateral, normal, and reverse can be used to describe the separation whether or not the actual direction of movement is known. Similarly, arrows are often drawn along faults on geologic maps to indicate the sense of strike separation, even on faults with no history of strike-slip movement. More often than not, the actual slip path of a fault cannot be determined. When describing faults it is important to distinguish clearly between separation and net slip.

Measuring net slip

Of fundamental importance in the study of faults is the distance that two originally contiguous points have been separated. This displacement is called *net slip*. Net slip is a vector, having both magnitude and direction. In order for the net slip to be determinable, the slip direction must be known or two originally contiguous points must be recognized. In the ideal situation, two intersecting planes, such as a dike and a bed, are located on both fault blocks. The points of intersection on the hanging wall and footwall serve as the piercing points. Unfortunately, one almost never finds such a happy situation in the field. More commonly the structural geologist must use a single distinctive bed together with slickenside lineations to estimate net slip. The danger here is that the slickenside lineations indicate the orientation of only the latest movement. Some faults have complex slip paths that cannot be reconstructed from slickenside lineations.

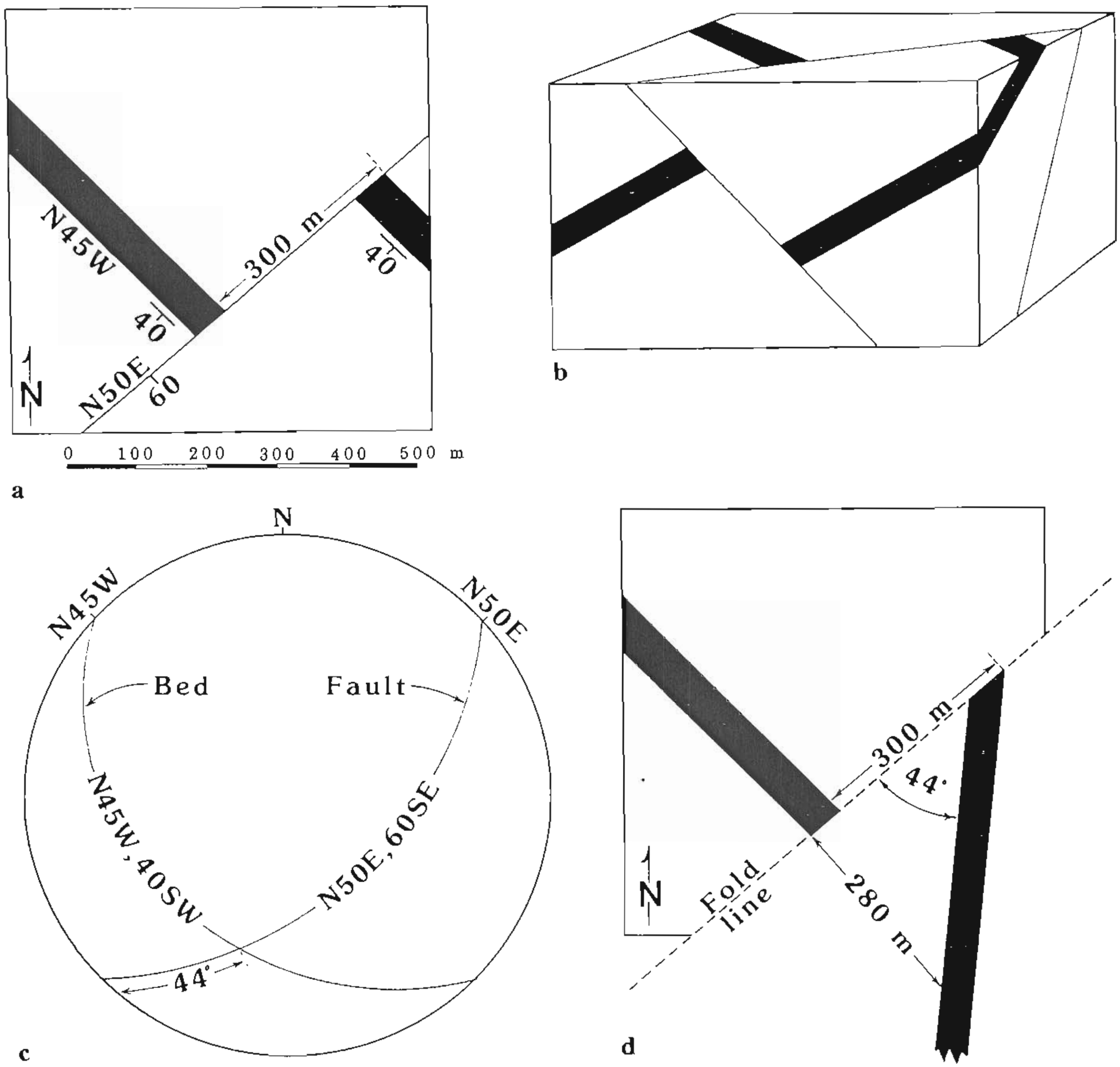


Fig. 9.6 Diagrams showing solution of net-slip problem. (a) Geologic map. (b) Block diagram. (c) Equal-area net plot of fault plane and bedding plane. (d) Orthographic projection of fault plane showing pitch of bedding. Net slip is 280 meters in same direction as dip (direction indicated by slickenside lineations).

Figure 9.6a is a geologic map showing the trace of a fault plane (N50E, 60SE) and a bed (N45W, 40SW) with 300 m of strike separation. Figure 9.6b is a block diagram of the situation. Without further information it is impossible to know if this fault is a left-lateral strike-slip fault, a normal fault, or an oblique-slip fault. It would also be impossible to determine the net slip. The relative sense of offset may be easily visualized by the down-dip viewing method described in Chapter 6. Orient Figure 9.6a so that your line of sight is directly down the plunge of the line of intersection of the fault and the layers on one of the fault blocks. The left or east block (hanging wall) can be seen to have moved down relative to the right or west block (footwall), but this does not reveal the actual slip path.

Let us assume that the fault in Figure 9.6a is a normal fault, as indicated by slickenside lineations on the fault plane. The net slip is determined as follows.

1 On an equal-area net, draw the great circles that represent the fault plane and the plane that is offset (Fig. 9.6c).

2 Find the pitch of the offset plane in the fault plane (Fig. 9.6c). In this example the pitch is 44°.

3 Place a piece of tracing paper over the map. Draw the fault trace on the map view, and draw the offset layer on the *upthrown* block. Mark the place where the offset layer on the downthrown block intersects the fault, but do not draw it in (Fig. 9.6d).

4 The fault trace on your tracing paper is now considered to be a fold line, and the fault plane is imagined to be folded up into the horizontal plane. We know that the pitch of the offset bed in the fault plane is 44°. With the fault plane now horizontal we can draw this 44° angle on the tracing paper, showing what the offset layer looks like in the fault plane (Fig. 9.6d).

5 If we know the pitch of the net-slip direction within the fault plane we can now measure the amount of net slip. Because we know that this is a normal fault, the net-slip direction is 90° from the fault trace in the fault plane, that is, directly down-dip. The amount of net slip in this example is 280 m (Fig. 9.6d). The direction of net slip is the same as the dip of the fault plane, 60, S40E.

Problem 9.1
Figure 9.7 shows the trace of a fault (N30W, 50SW) and a dike (N40E, 35SE) with 450 m of strike separation. Assume that this is a normal fault. What is the amount of net slip?

Problem 9.2
Measure the net slip in Problem 9.1 if slickenside lineations trend northwest and have a pitch of 60°.

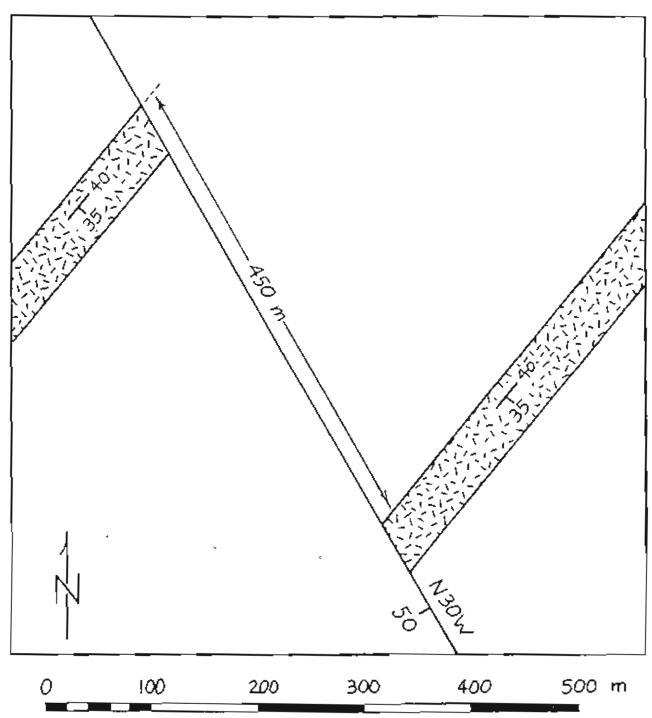


Fig. 9.7 Geologic map for use in Problem 9.1.

Rotational faulting

In Figure 9.7 the beds on opposite sides of the fault have identical attitudes, indicating that all of the movement was translational. Fault movement often has a rotational component as well, which can be measured.

Consider the example in Fig. 9.8a. Obviously some rotation has occurred on the fault because the beds have different attitudes on the two fault blocks. The hanging wall has rotated counterclockwise relative to the footwall. (The sense of movement on rotational faults, as on strike-slip faults, is determined by imagining yourself on one fault block looking across the fault at the other fault block.) Before we determine how much rotation has

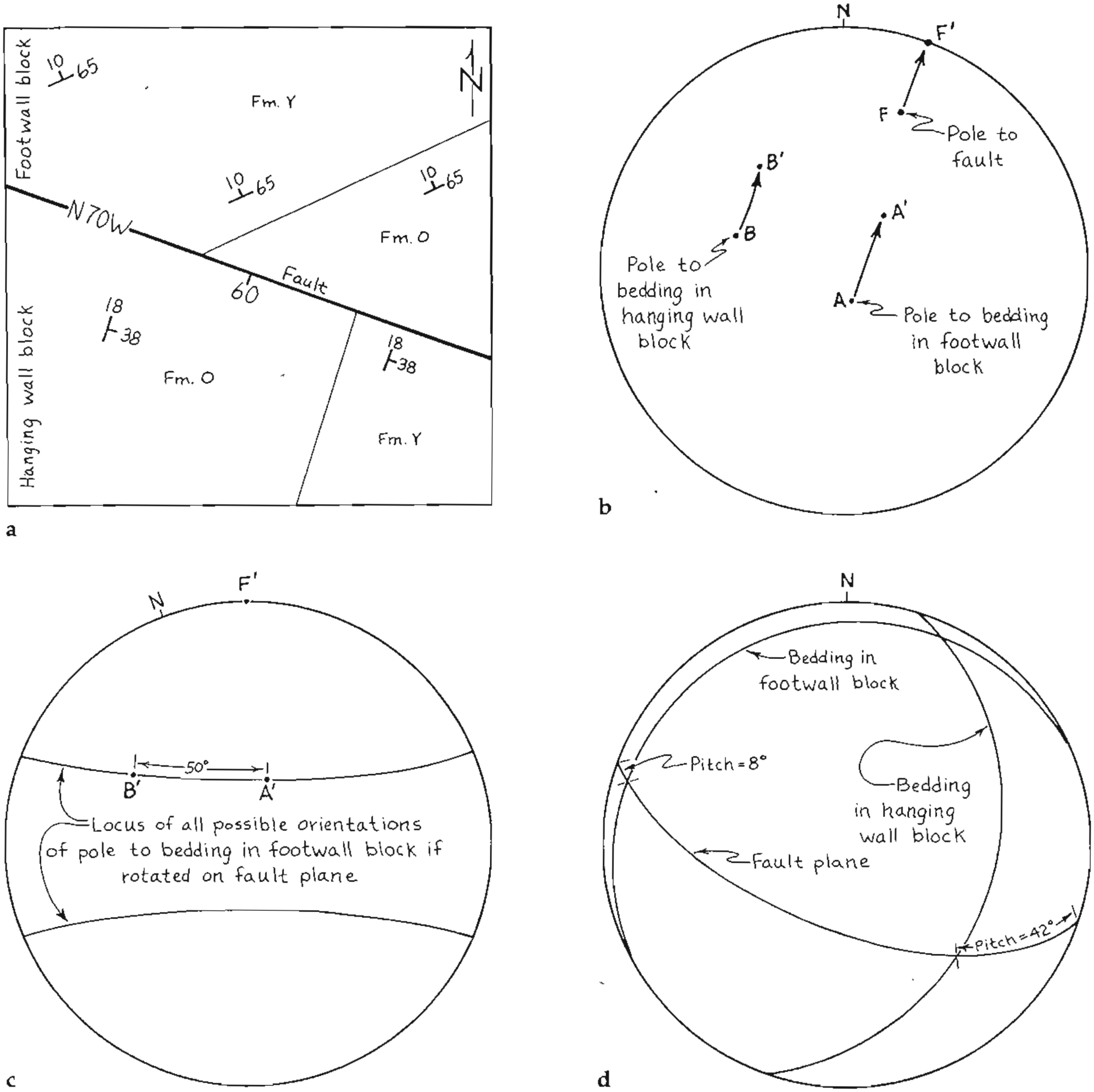


Fig. 9.8 Diagrams showing solution to rotational-slip problem. (a) Geologic map. (b) Equal-area net plot of pole of fault (point F′), and poles to bedding in each fault block. (c) Small circles that define the locus of possible poles to bedding in footwall block if rotated on fault plane. (d) Measuring rotation by pitch of bedding on each wall of fault.

occurred in this example it will be instructive to examine the range of possible attitudes that rotation on this fault could produce. This can be done as follows.

1 Plot the pole of the fault (point F) and the poles of the bedding in the footwall block (point A) and in the hanging-wall block (point B) on the equal-area net (Fig. 9.8b).

2 We now need to orient the fault so that it is vertical, so we move point F 30° to point F′ on the primitive circle. Points A and B move 30° to points A′ and B′ (Fig. 9.8b). (You may want to review the procedure for rotating lines on the equal-area net in Chapter 5.)

3 During rotational faulting the axis of rotation is perpendicular to the fault plane. Look at the geologic map (Fig. 9.8a) again and imagine rotating the fault from its 60S dip into a vertical position. Use your left hand to represent the fault and your right hand to represent the bedding in the footwall. Stick a pencil through the fingers of your right hand to represent the pole to bedding. Now, keeping your left hand vertical, rotate your hands 180° and observe the relationship between the vertical fault plane and the pole to bedding. This relationship can be plotted on the equal-area net by turning the tracing paper to put the pole of the fault (point F′) at the north (or south) pole of the net. The small circle on which A′ now lies, together with its mirror image across the equator, defines the locus of all possible pole-to-bedding orientations if the footwall block is rotated about an axis perpendicular to the fault (Fig. 9.8c).

Having plotted the range of possible attitudes that rotation on this fault could produce, we can confirm that B′ is included within this set. Rotation on this fault is equal to the angle between A′ and B′, which is 50° (Fig. 9.8c).

Another approach to measuring rotation on faults involves determining the pitch of each apparent dip in the fault plane. Because the pitch on the footwall and hanging wall were identical prior to rotation, the difference in pitch equals the amount of rotation. In this problem the apparent dips are in opposite directions so the pitches are added together. The pitch on the hanging wall in the fault plane is 42° and the pitch on the footwall is 8° (Fig. 9.8d), indicating 50° of rotation.

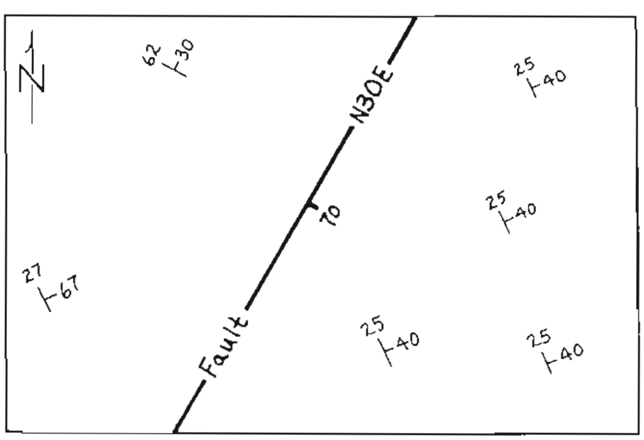


Fig.9.9 Geologic map for use in Problem 9.3.

Problem 9.3

Figure 9.9 is a geologic map showing a fault. On the east side of the fault the beds all have an attitude of N25W, 40E. West of the fault the rocks are poorly exposed, with only two outcrops, which have different attitudes.

1 Plot the hanging wall attitude on the equal-area net, and also plot the range of possible attitudes in the footwall that could result from rotation on this fault. Determine if either of the two exposures west of the fault could be the result of rotation on the fault.

2 Determine the direction and amount of rotation.

Tilting of fault blocks

Layers that were deposited horizontally and then tilted provide an opportunity for measuring rotation of fault blocks. Tilting occurred after the deposition of the youngest tilted beds and before the deposition of the oldest horizontal beds within the fault block. Review, for example, Problem 5.11, in which you determined the amount of post-Rohan Tuff/pre-Helm's Deep Sandstone tilting of the northeastern fault block of the Bree Creek Quadrangle.

Problem 9.4

By stereographic projection, using the attitudes determined in Problem 3.1, determine the amount (in degrees) and direction of Neogene tilting on the fault blocks of the Bree Creek Quadrangle that contain Tertiary rocks.

	Post-Rohan Tuff/pre-Helm's Deep Sandstone tilting	Post-Helm's Deep Sandstone tilting
Northeastern fault block	________	________
Central fault block	________	________
Western fault block		________

Map patterns of faults

The map patterns of faults and strata can provide useful clues regarding the types of fault present in an area as long as the deformational history is relatively simple. For example, the attitude of a fault surface can commonly be determined by its trace across the topography. Steeply dipping faults will appear on geologic maps as nearly straight lines across rugged topography, whereas gently dipping faults, such as thrusts or low-angle normal faults, will tend to follow the rule of "Vs" (Figs 2.1 through 2.7). Relative offset of strata across faults may allow one to distinguish between normal, reverse, and strike-slip faults. The discussions below assume that the original stratigraphic order has not been disrupted by a previous deformational event.

Normal faults

Normal faults may dip at any angle. High-angle normal faults generally dip between 50° and 70° and show relatively straight traces across topography; detachment faults may dip less than 30° and conform closely to topographic contours. Normal faults typically place young rocks in the hanging wall against old rocks in the footwall; that is, the fault dips *toward the younger* rocks (Fig. 9.10b). This results in omission of strata across individual faults but repetition of certain layers across domino-style normal fault blocks (Fig. 9.10c).

Reverse and thrust faults

Reverse faults are those in which the hanging wall has moved up relative to the footwall. Reverse faults that dip at angles less than 30° and show large displacements are called *thrusts*. The structural style of thrust faults is explored in greater detail in Chapter 15. In reverse faulting, older rocks are placed on top of younger rocks; that is, the fault dips *toward the older* rocks (Fig. 9.11a). This results in a repetition of strata across individual

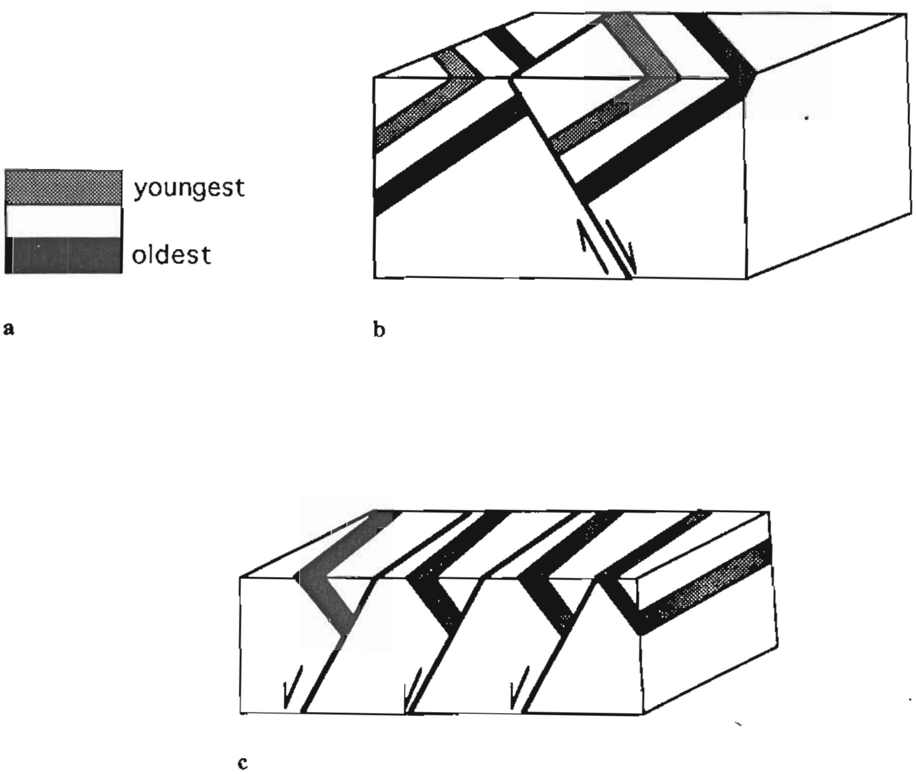


Fig. 9.10 Typical relations in normal-fault systems. (a) Normal stratigraphic order. (b) Block diagram showing younger strata in hanging wall dropped down against older strata in footwall. Fault dips toward younger rocks. (c) Domino-style normal block faulting results in repetition of strata on adjacent fault blocks.

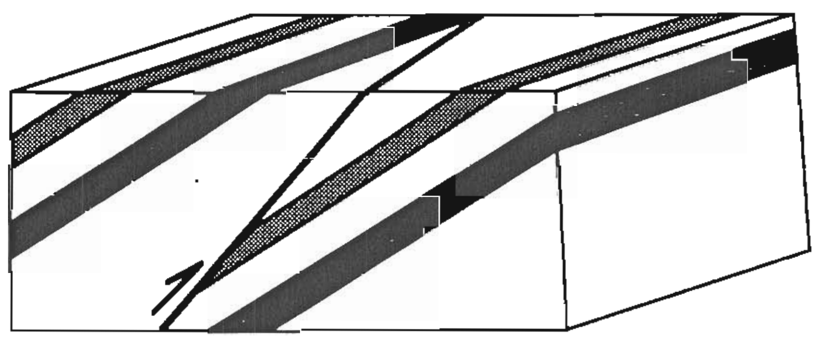
faults. Erosion of a low-angle thrust sheet can significantly modify its original map configuration. An erosional window (*fenster*) and outlier (*klippe*) are shown in Fig. 9.11b. Motion of the thrust sheet is to the east. In addition, differential movement along different parts of a thrust sheet can result in the development of *tear faults*. Tear faults are strike-slip faults that are confined to the upper plate (hanging wall) of the thrust and strike parallel to the movement direction (Fig. 9.11).

Strike-slip faults

Strike-slip faults are characterized by horizontal slip vectors. Strike-slip faults commonly, but not always, show dips greater than about 70°. Because there is no differential vertical motion across a pure strike-slip fault, no predictable age relationships exist between rocks on the opposite sides of these faults. Note that strike-slip faulting in an area of horizontal strata will produce no offset in map view. If old and young rocks occur in a nonsystematic manner on both sides of a high-angle fault, one should consider the possibility of either strike-slip faulting or a complex, multiphase deformational history.

Timing of faults

An important goal of structural analysis in complexly deformed terranes is to determine the timing of movement along faults. This is accomplished by means of the principle of cross-cutting relationships which states that any geologic feature (e.g., fault, fold, sedimentary layer, pluton) must be younger than another feature that it cuts or truncates. In general, the age of faults cannot be determined precisely. Typically the timing of movement along a fault is *bracketed* between the *youngest* unit or feature that the fault cuts and the *oldest* unit or feature that cuts the fault.



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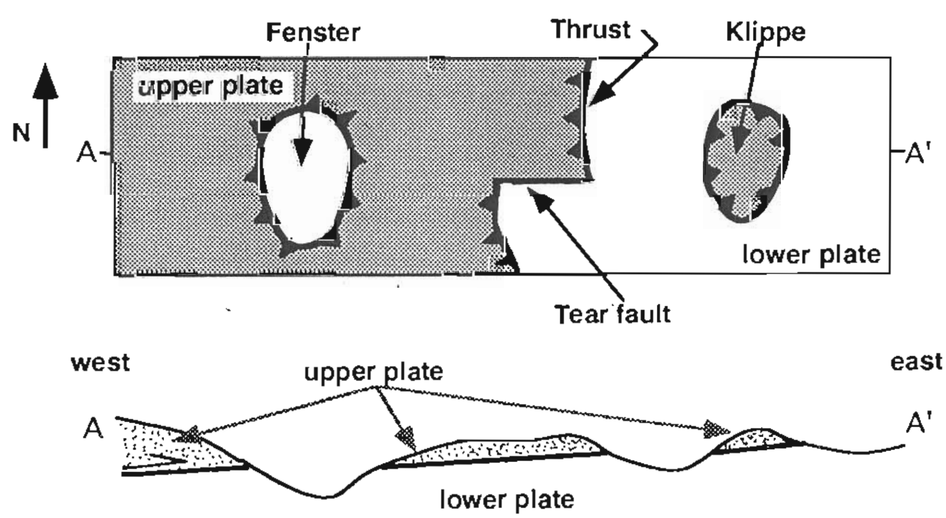


b

Fig. 9.11 Typical relations along reverse fault. Stratigraphic order same as in Fig. 9.10a. (a) Block diagram showing older rocks in hanging wall placed over younger rocks in footwall. Fault dips toward older strata. Note repetition of strata across fault. (b) Map (top) and cross-section (bottom) showing typical elements in thrust belt. Sawtooth pattern on upper-plate (hanging-wall) rocks. See text for discussion.

Problem 9.5

Answer the following questions regarding features on the geologic map shown in Fig. 9.12. This exercise will require you to integrate information from previous chapters as well as this one.

1 For each fault (A, B, C, D, and E) determine the type of faulting that has occurred and bracket the age of faulting as precisely as possible.

2 Identify the following features indicated by circled, lower-case letters on the map.

(a) Type of contacts at localities a, b, c, d.

(b) Specific geologic structure present at localities e, f, g, h.

3 Strike and dip directions shown are correct; however, three of the dips shown are actually overturned. Correct these directly on the map by substituting the correct symbol for overturned beds.

4 Is the unit on the east side of the map labeled Tm older or younger than the other Miocene rocks on the map? Give a reason for your answer.

5 Determine the *minimum* amount of displacement on Fault C.

6 Write a one-paragraph geologic history of the area shown in Fig. 9.12. Include all periods of deposition, erosion, plutonism, and indicate when specific deformational styles (folding and faulting) occurred.

Problem 9.6

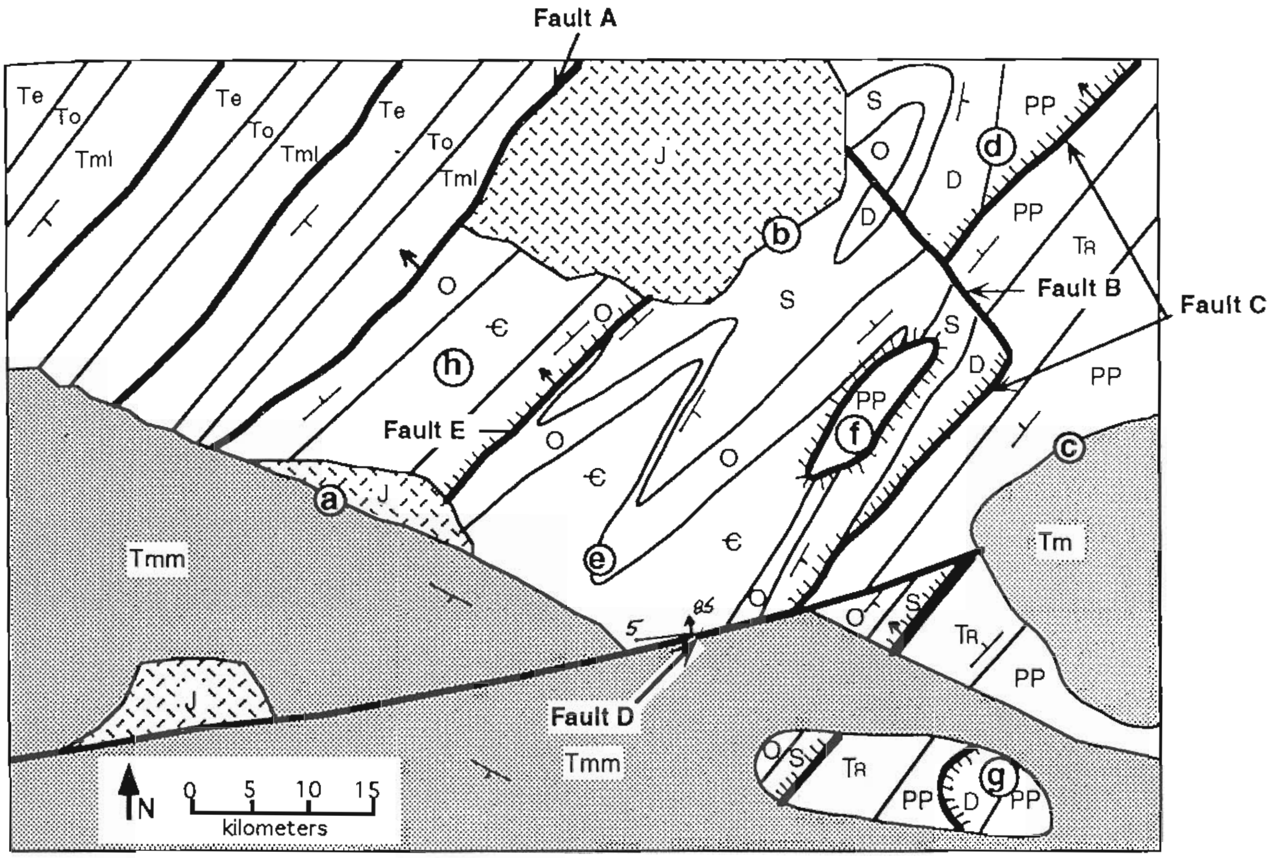
Using the geologic map, your structure sections, and your work in this chapter, write a succinct, complete description of each fault in the Bree Creek Quadrangle. Use complete sentences. Avoid long, rambling sentences. Include the following information for each fault:

1 Type of fault (normal, reverse, strike-slip). (If you cannot determine the sense of movement with certainty, describe the possible senses of movement and the evidence for each.)

2 Attitude of the fault plane (including geographic variation).

3 Strike separation and dip separation (heave and throw) as the data allow (sometimes only a minimum amount of separation may be determined).

4 Age of movement as specifically as the evidence permits.



Units	
Tm	- Miocene
Tmm	- Middle Miocene
Tml	- Lower Miocene
To	- Oligocene
Te	- Eocene
J	- Jurassic (plutonic rocks)
TR	- Triassic
PP	- Pennsylvanian-Permian
D	- Devonian
S	- Silurian
O	- Ordovician
C	- Cambrian

Symbols

- Strike and dip of beds
- Dip of fault (arrow) and plunge of fault striae (line)
- Contact
- Fault, high angle
- Fault, low angle (hachures on upper plate)

Fig. 9.12 Geologic map for use in Problem 9.5.