Chapter 11: Maps of Faults in Planar Beds

FAULTS ARE disruptions of the rock, accommodating relative displacement of the walls separated by them. On geological maps, faults usually show as abrupt terminations of otherwise smooth lithological boundaries. Accurate assessment of the displacement across faults may further be of economic importance. Fault surfaces commonly act as seals for hydrocarbon traps and, also, are preferential sites of mineralization, as faults often control hydrothermal circulation in the subsurface. Faults may involve displacements of up to several hundreds of kilometers, in which case the fault motion is frequently accompanied by earthquakes. Faults may have formed at any moment in geological history and can still be traced at present by the mapping of dislocated outcrop patterns in the field.

Contents: The tectonic setting of faults is discussed in section 11-1. The important distinction of fault slip and fault separation is explained in section 11-2. The effects on map patterns caused by dip-slip faulting are systematically discussed for horizontal beds in section 11-3 and for uniformly inclined beds in section 11-4. Map symbols, used to facilitate the reading of geological maps, are outlined in section 11-5. The map analysis of faulted strata in areas of rugged topography is outlined in section 11-6.

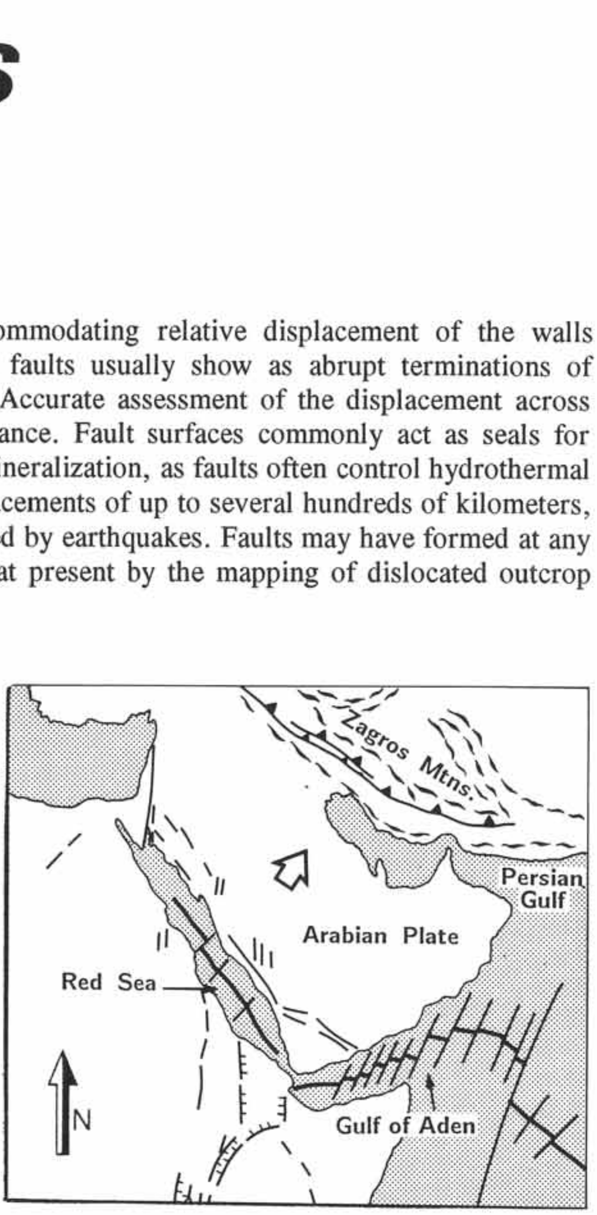


Figure 11-1a: *General tectonic map of the Arabian plate.*

11-1 Tectonic setting of faults

Penetrative disruption of crustal rocks by faulting is common along the boundaries of the major *lithospheric plates*. The boundaries of the plates themselves are faults, because they are

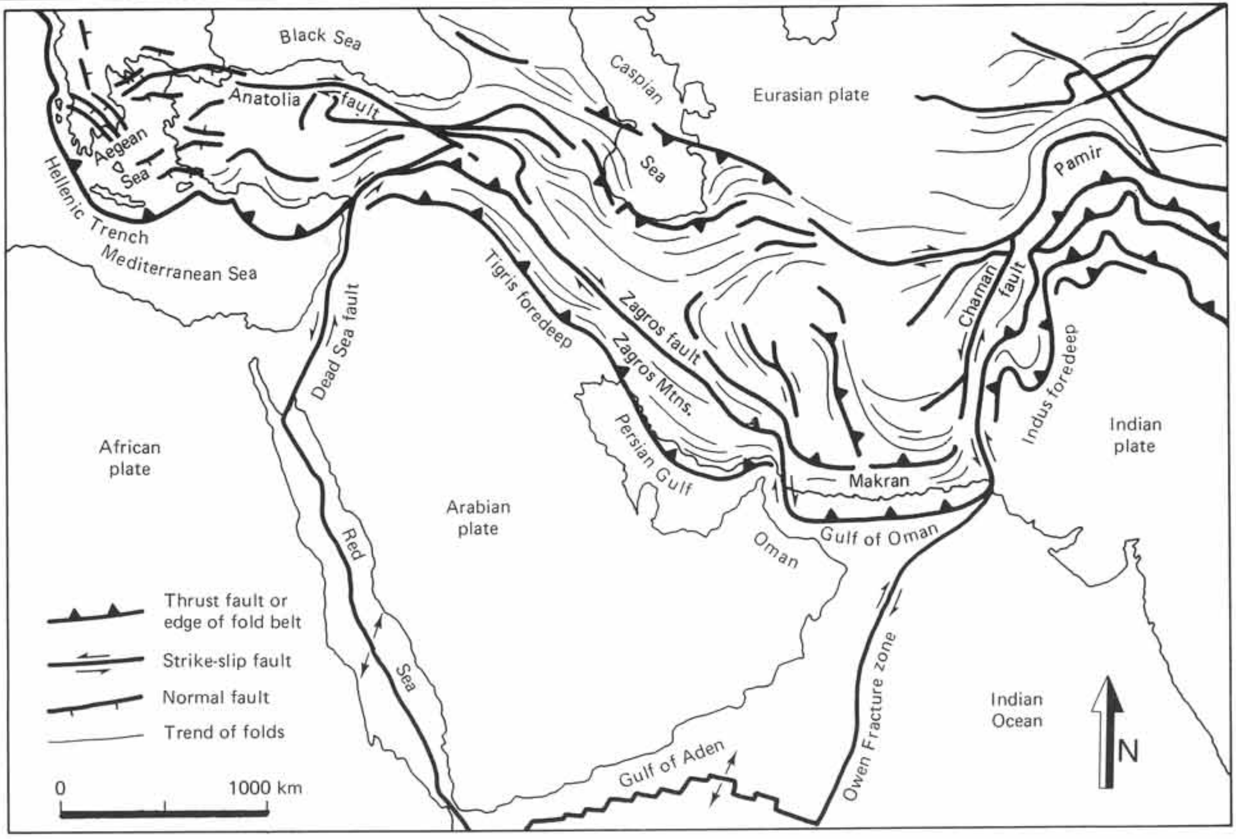


Figure 11-1b: Detailed tectonic map of the Arabian plate.

zones which accommodate the movement between juxtaposed plates. The Arabian plate provides a good example of a *tectonic plate*, surrounded by all of the three major types of plate boundaries (Fig. 11-1a & b). The plate is bordered in the south and west by the interconnected *spreading ridges* of the Gulf of Aden and the Red Sea. The northeast boundary of the Arabian plate is located in the diffuse *collision zone* with the adjacent Eurasian continent, that formed the Zagros Mountains. The differential horizontal movement of the Arabian plate is further accommodated by *transfer faults* along its northwest (Dead Sea fault) and southeast (Owen fracture zone) boundaries. Each of these boundaries includes one or more fundamental type(s) of fault(s), that will be outlined in turn below. The most commonly used classification distinguishes faults on the basis of their orientation and sense of displacement. Normal and reverse (dip-slip) faults and strike-slip faults are all introduced below.

Crustal extension and normal faults

The Red Sea has opened after thinning and rifting of the initially continuous continental crust, which led to the separation of the Arabian Peninsula from Africa about forty million years ago. The rifting itself was the result of northwestward propagation of the Indian spreading ridge, and subsequent opening of the Red Sea has occurred at an average annual rate of one to two centimeter(s). Figure 11-2a illustrates the incipient rift valley that was created by the extension and thinning of the crust above the propagating *spreading zone*. Progressive widening eventually allowed chemically fractionated mantle rocks to surface in the floor of the *rift valley*, which became flooded when the Indian Ocean transgressed into the growing Red Sea (Fig. 11-2b). The initial rifting and crustal *extension* were accommodated by *normal faults*, which, by definition, have a *hanging wall* that has moved

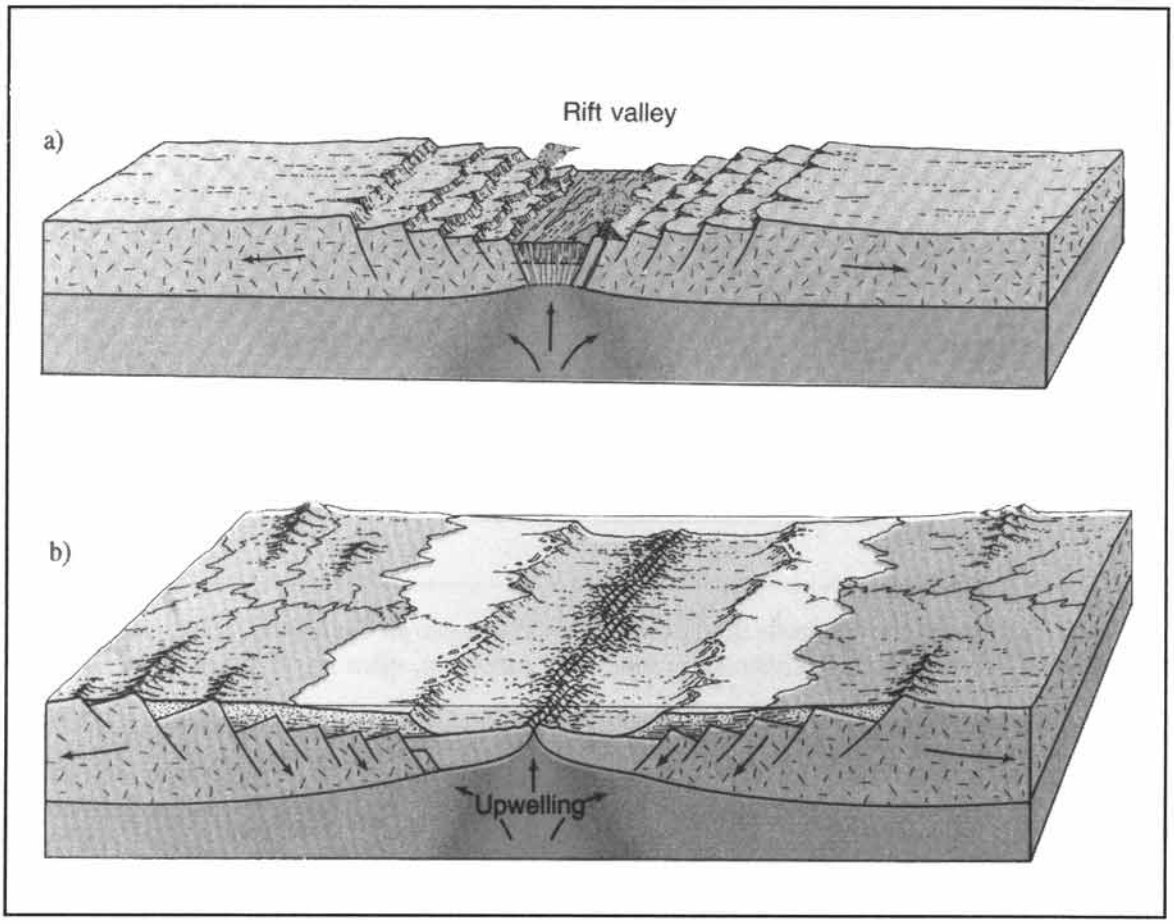


Figure 11-2: a) & b) Stages in the break-up of a continent. a) Crustal thinning and rift valley formation by normal faulting. b) Accretion of oceanic crust by magmatic spreading of mid-oceanic rift zone.

down relative to the *foot wall* (Fig. 11-3). The hanging wall always is understood as the crustal rock portion leaning against or onto the foot wall. The movement of normal faults can be described by *slip vectors* on the hanging wall, pointing down the dip of the fault plane. Normal faults form one particular class of so-called *dip-slip faults*. *Reverse faults*, like normal faults, also, move along slip vectors on the hanging wall, pointing in the direction of dip of the fault plane and constitute another class of *dip-slip faults* (see, also, section 11-2). Slip vectors are synonymous with the displacement vectors of formerly adjacent points on the fault plane, attached to either side of the faulted block.

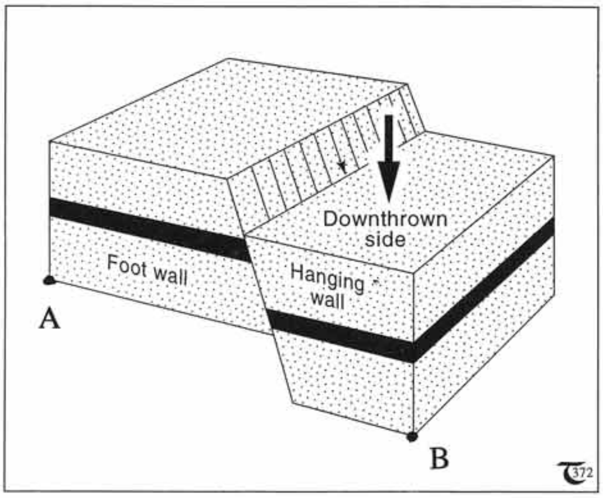


Figure 11-3: Normal fault - the hanging wall moved down relative to the foot wall.

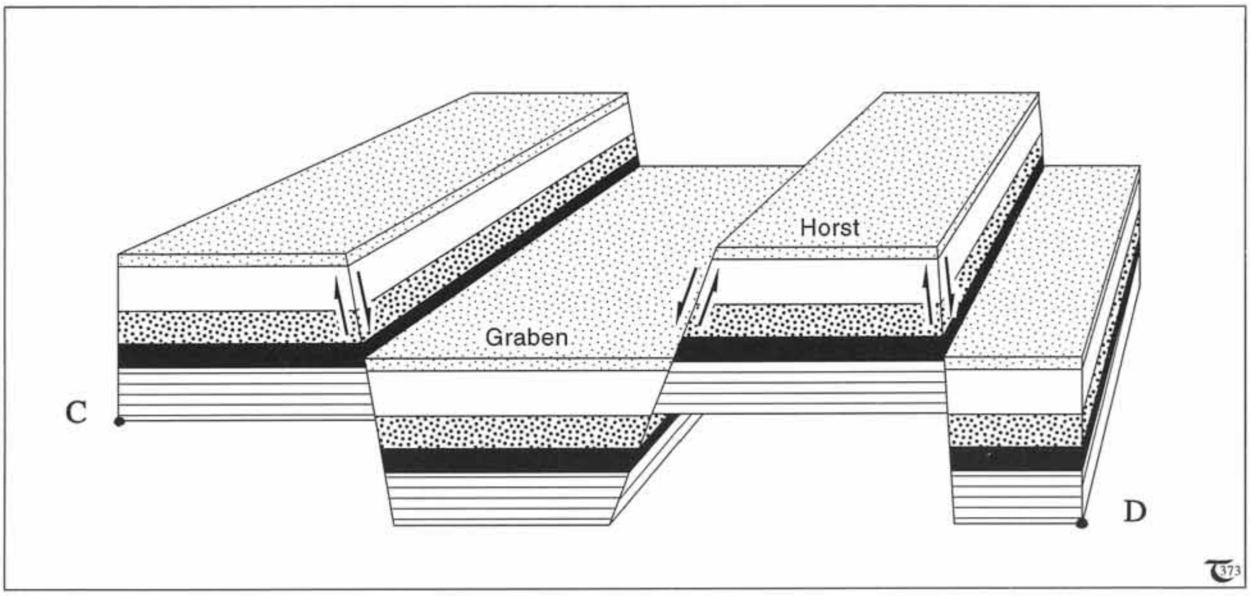


Figure 11-4: Conjugate normal faults of opposite inclination separate upthrown (horst) and downthrown (graben) blocks. Normal faults accommodate horizontal extension, often in rift zones. See exercise 11-1.

☐Exercise 11-1: a) Measure the crustal stretch associated with the single normal fault of Figure 11-3. The stretch can be calculated as the ratio of the final and the initial lengths between points A and B. b) Measure the crustal stretch between points C and D, caused by the system of normal faults separating downthrown (graben) and upthrown (horst) blocks in Figure 11-4. The terms graben and horst originate from the original German terminology.

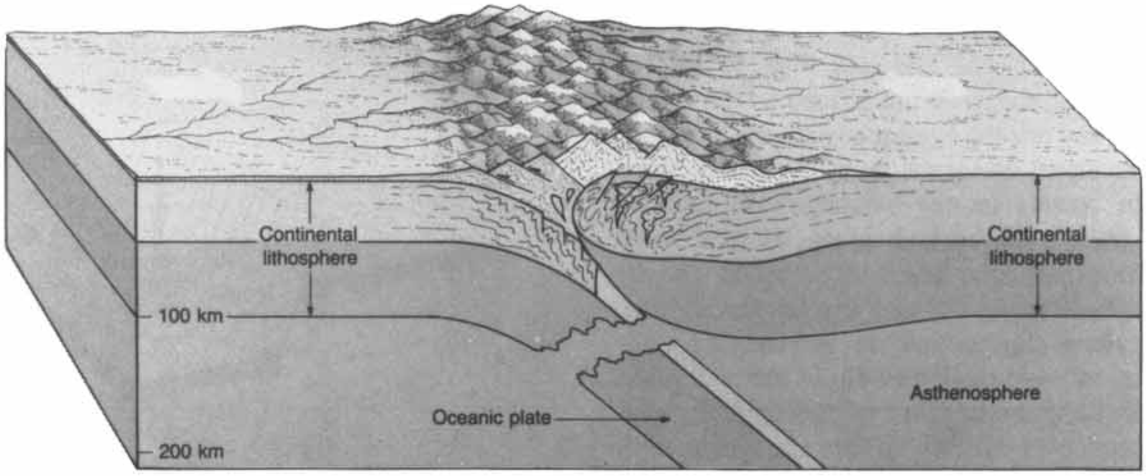


Figure 11-5: Reverse faults accommodate crustal shortening, and the majority of them are formed in orogenic zones of active continental margins.

Crustal shortening and reverse faults

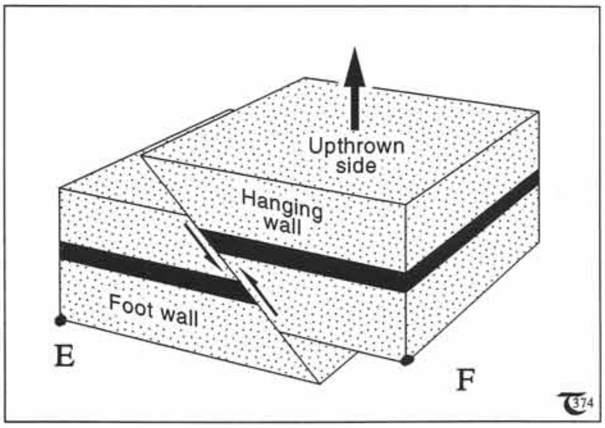


Figure 11-6: Reverse fault - the hanging wall moved up relative to the foot wall.

The Zagros Mountains were uplifted by the impingement of the Arabian and Eurasian plates, which started after closure of the Tethys Ocean, which had separated the two continental areas until about twenty million years ago. The Zagros Mountains contain well-exposed, doubly plunging folds, and some of the crustal *shortening* associated with the plate collision has been accommodated by *reverse faults* (Fig. 11-5). These faults have a hanging wall that has moved up relative to the foot wall (Fig. 11-6). A special class of reverse faults is constituted by *thrust faults*. These are very low angle faults with hanging walls that may have translated for tens of kilometers over the foot wall (Fig. 11-7). Such translated masses of rock are termed *thrust nappes*. Estimates of

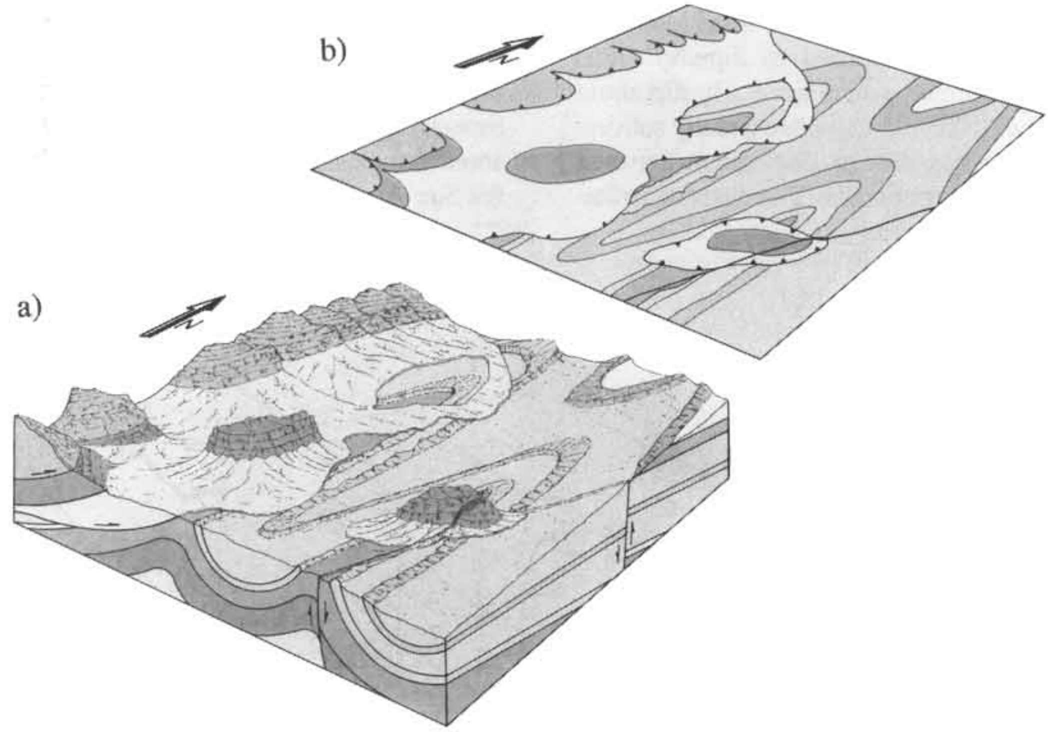


Figure 11-7: a) Perspective diagram of thrust faults, transferring subhorizontal strata over a folded substratum. b) Geological map of the same area, showing the outlines of the eroded thrust fault contacts.

☐Exercise 11-2: Measure the fractional change of crustal length EF (stretch, here leading to shortening) associated with the single reverse fault portrayed in Figure 11-6.

☐Exercise 11-3: Estimate the minimum horizontal displacement involved in the emplacement of the rock units above the major thrust plane in Figure 11-7b.

the minimum displacement over basal thrust faults can be inferred from the maximum distance between basement *inliers* (windows or fenster) and cover *outliers* (klippes).

Horizontal crustal transfer by strike-slip faults

The Owen fracture zone and the Dead Sea fault are examples of *strike-slip faults*. Such faults are typically vertical as opposed to dip-slip faults (normal and reverse), which generally dip about 60°. Because strike-slip faults are usually subvertical, it is not possible to distinguish between hanging walls and foot walls. The walls of strike-slip faults are displaced in opposite directions but mainly by horizontal slip, parallel to the trace or strike of the fault (Fig. 11-8). Unlike what is suggested in Figure 11-8, strike-slip faults are likely to terminate in the *asthenosphere*, where the motion of the juxtaposed plates is maintained by mantle rock convecting at differential rates. The sense of movement on strike-slip faults can be further described as clockwise, counterclockwise, right-lateral (dextral), or left-lateral (sinistral) (see examples below). The term strike-slip fault is entirely synonymous with *transfer fault*, *transcurrent fault*, *wrench fault*, *horizontal shear fault*, and, also, includes *transform faults* - the latter, by definition, occurring in oceanic crust only.

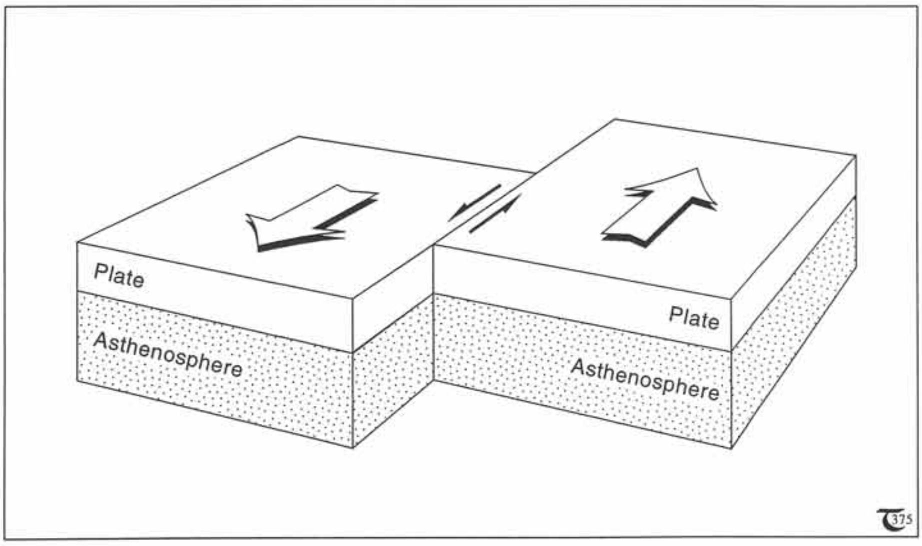


Figure 11-8: Strike-slip faults, usually subvertical, separate two lithospheric plates moving in opposite directions, parallel to the fault trace.

Figure 11-9 is a tectonic map of the Dead Sea fault, which accommodates the northward movement of the Arabian plate relative to the Sinai block by sinistral strike-slip movement. The complementary movement on the Owen fracture zone (Fig. 11-1b) can be described as clockwise or right-lateral (dextral). Some extension along the Dead Sea fault causes rifting and subsidence of its *central graben system*, which now hosts the Gulf of Aqaba and the Dead Sea. The estimated strike-slip displacement on the Dead Sea fault totals some 110 kilometers and started about 15 million years ago. The time-averaged rate of movement has varied between 0.5 and 1 millimeter per year.

Figure 11-10 is a tectonic map of the Alpine fault, New Zealand, with an estimated dextral strike-slip displacement of 480 kilometers. This fault is responsible for many earthquakes. The time-averaged rate of strike-slip is relatively fast - about 2.2 centimeters per year. For comparison, the San Andreas fault in California moves at a

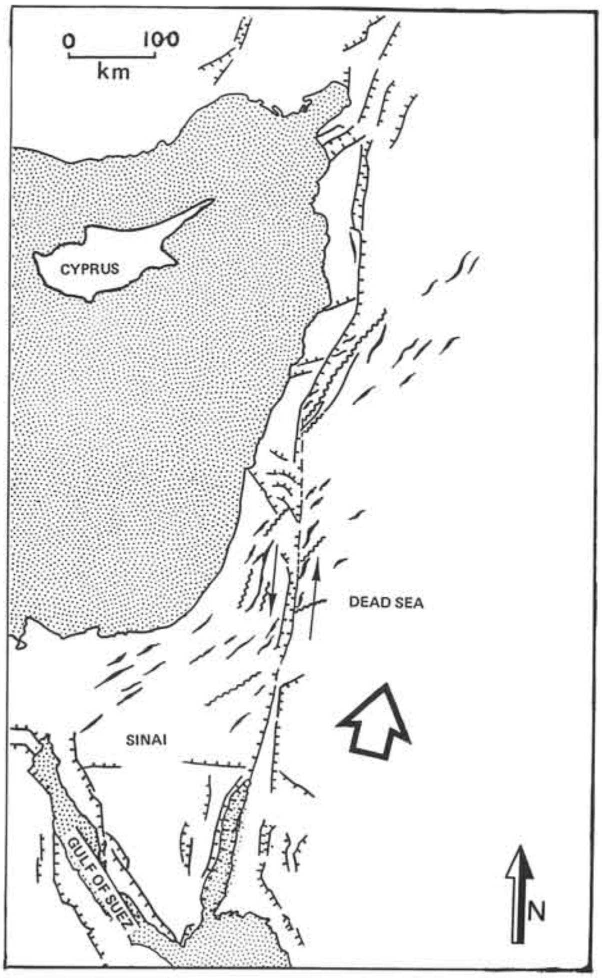


Figure 11-9: Left-lateral (sinistral) strike-slip movement on the Dead Sea fault accommodates differential movement of the Arabian plate. The relative subsidence of the central graben results from transtension.

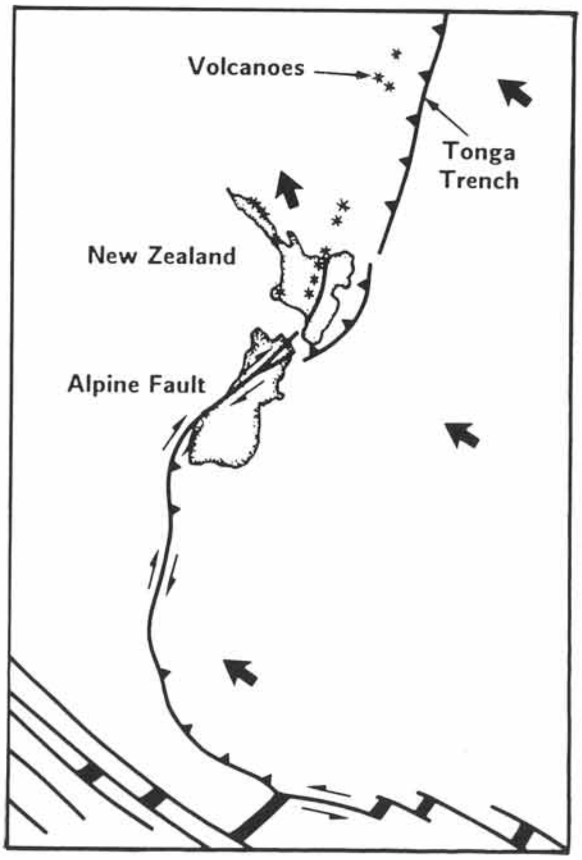


Figure 11-10: Right-lateral (dextral) strike-slip movement on the Alpine fault accommodates part of the westward movement of the Pacific plate relative to the Australian plate. The uplift of the Alpine Mountains of New Zealand is due to a significant component of transpression near the Alpine fault.

time-averaged rate of about 5 centimeters per year. It is worth noting that the strike-slip on the Alpine fault is accompanied by crustal thickening of its walls. Such thickening deformation, if accompanied by strike-slip movement, is termed *transpression*. Conversely, if a strike-slip motion is accompanied by extension, such as documented for the Dead Sea fault, *transtension* is said to occur.

☐Exercise 11-4: Consider the map of the Alpine fault, transecting New Zealand (Fig. 11-10). a) Is this a left- or right-lateral wrench? b) Give alternative terms for the same sense of shear. c) Describe, also, the sense of shear of the transform fault to the right of the spreading ridge in the south of the map area. d) Also, list all the alternative terms for this sense of shear.

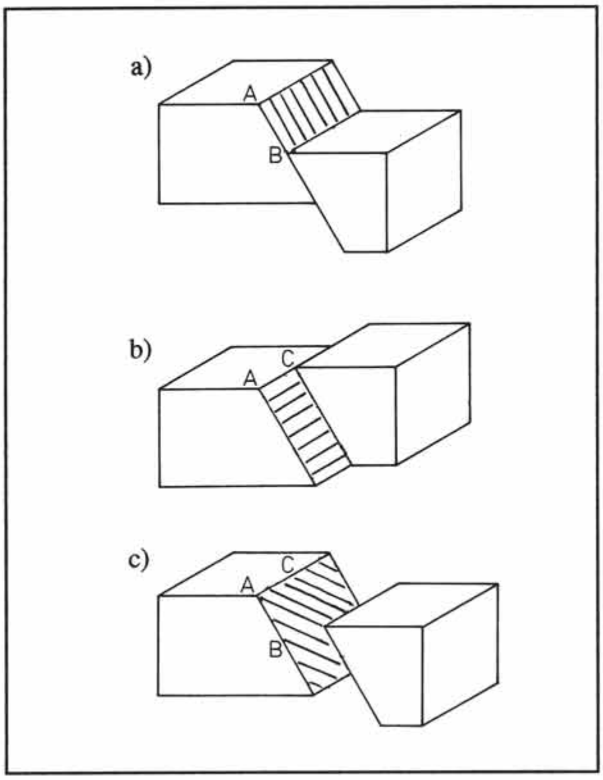


Figure 11-11: *a) to c) Examples of fault slip: (a) Dip-slip fault, (b) strike-slip fault, (c) oblique-slip fault.*

11-2 Fault slip and fault separation

Faults can be classified, on the basis of the actual movement on the fault surface, as dip-slip, strike-slip, or oblique-slip faults (Figs. 11-11a to c). The *fault slip* measures the relative movement of rock units, separated by the fault, by slip vectors that have displaced formerly adjacent points. Fault slip is different from *fault separation*, which does not refer to the actual fault movement. In determinations of the fault separation, distances between displaced marker planes are measured in a particular direction. Figure 11-12a illustrates an example of a fault displacing a hypothetical marker plane. The actual displacement may have been caused by an infinite number of possible slip movements (e.g., labeled 1 to 5 in Figure 11-12a). It is sometimes not possible to determine the unique direction of fault slip that led to this situation. However, the fault separation can be used to characterize displacements of a marker plane, as measured in a number of specified directions (Fig. 11-12b). The separation is measured in the plane of the fault. Indicated are: net separation (A), strike separation (B), and dip separation (C). Unlike fault slip, the term fault separation refers to the geometrical displacement only and does not imply any direction of actual movement.

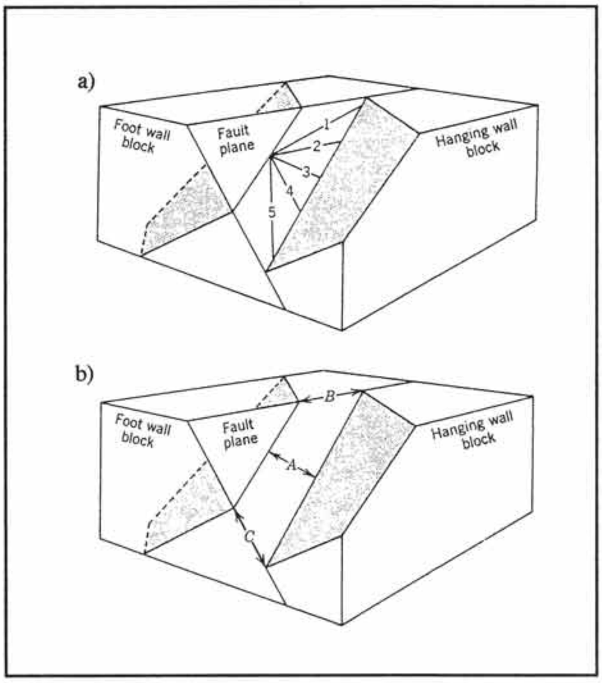


Figure 11-12: *a) Displaced marker plane, and five arbitrary slip directions. b) Various slip separations: net separation (A), strike separation (B), and dip separation (C).*

11-3 Dip-slip faulted, horizontal beds

Normal and reverse faults, the two types of dip-slip faults distinguished, generally affect the map pattern of rock units. One or both of the walls on either side of a faulted block may have made the movement. It is usually impossible to tell which wall has moved, and only a *relative displacement* direction can be established. The sense of relative displacement is indicated by half-arrows (Figs. 11-13a & b). Dip-slip faulting in a region underlaid by subhorizontal strata will

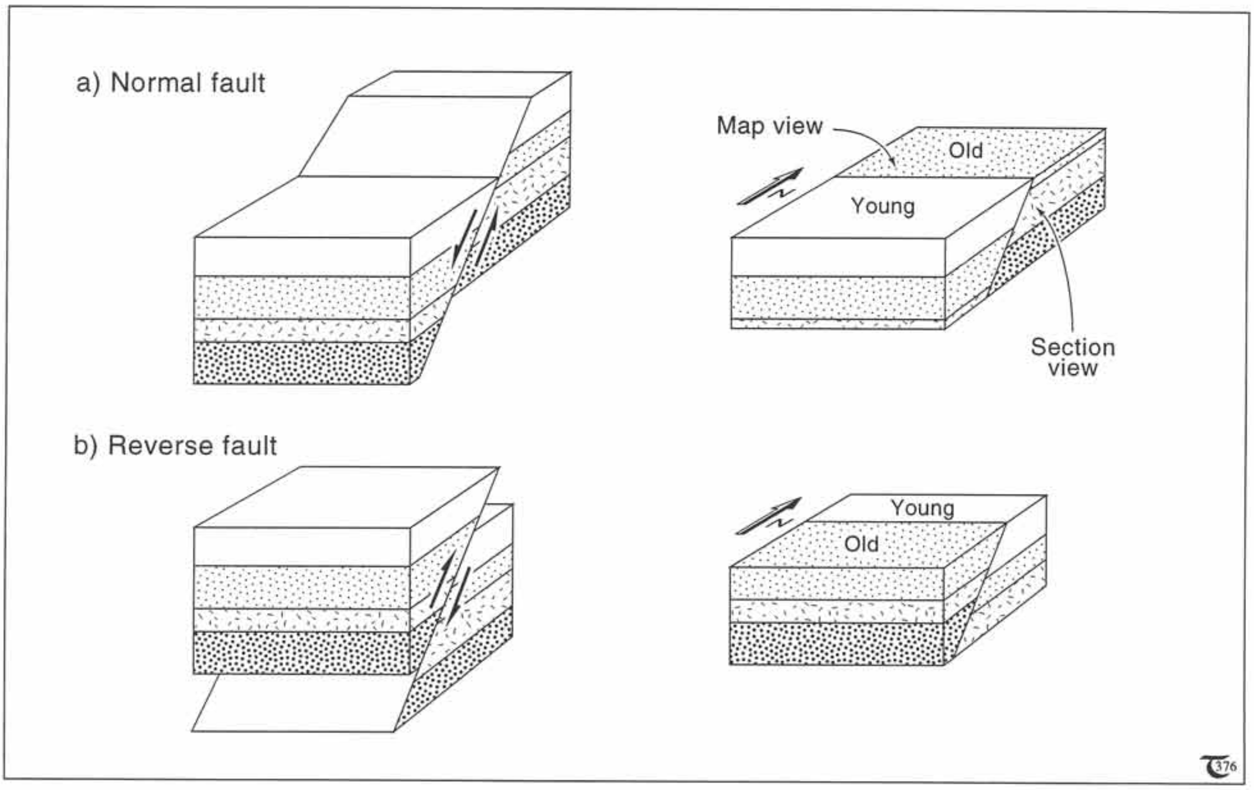


Figure 11-13: Block diagrams, before and after erosion: (a) normal faulting, and (b) reverse faulting. Hanging walls of normal faults show younger rocks; reverse faults expose older rocks in hanging walls.

result in map patterns juxtaposing younger rocks against older rocks. Obviously, the older rocks are exposed at the side of the *upthrown block*, after erosion has leveled the upthrown block to the same elevation as the *downthrown block*. Younger rocks are exposed above the downthrown, hanging wall when the fault is normal (Fig. 11-13a). Older rocks are exposed above the upthrown, hanging wall when the fault is reverse (Fig. 11-13b). However, *it is impossible to tell whether a fault is normal or reverse from the map pattern alone if the dip of the fault plane is unknown*; the map patterns of Figures 11-13a and 11-13b are similar after 180° rotation about the vertical axis.

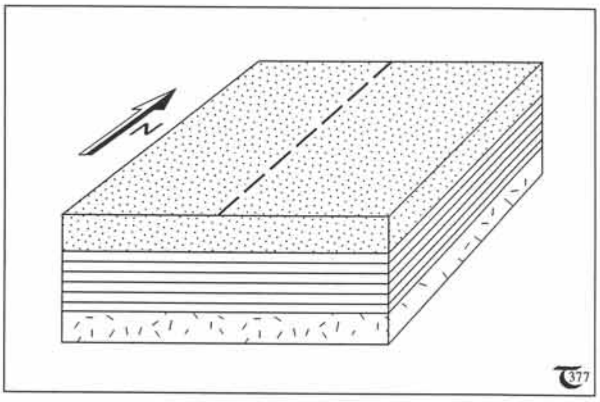


Figure 11-14: Perspective diagram of subhorizontal strata before faulting. See exercise 11-5.

☐Exercise 11-5: Consider the block diagram of Figure 11-14, and draw the resultant map patterns after erosional leveling of the ground surface, for (a) an east-dipping normal fault, and (b) a west-dipping reverse fault.

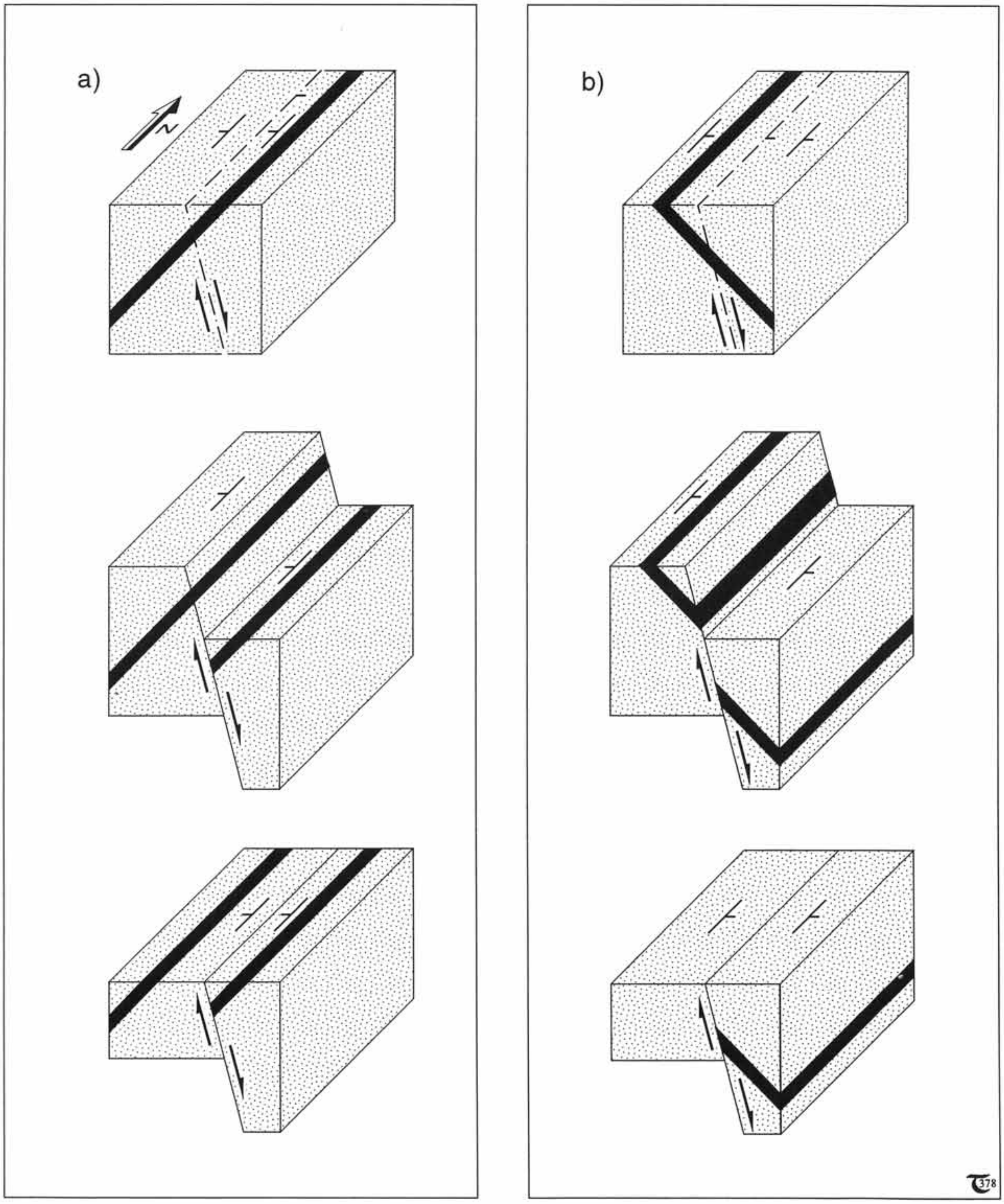


Figure 11-15: *a) & b) Three-stage perspective diagrams (pre-faulting, post-faulting, post-erosional) for normal faulting longitudinal or parallel to the strike of a sedimentary sequence. (a) Dipping opposite to, or (b) dipping in the same direction as the fault plane. Case (a) leads to stratigraphic repetition. Case (b) involves reduction of the stratigraphic section.*

11-4 Dip-slip faulted, homoclinal beds

Strata dipping uniformly may be dislocated by dip-slip faults in two fundamentally different orientations. The dip-slip fault may be either parallel (longitudinal) or oblique (transverse) to the strike of the strata - the latter including the orientation normal to the strike. Each of the two fault types may cause a distinctive disturbance of the map pattern, outlined in turn below.

Longitudinal dip-slip faults

The sequence of block diagrams of Figures 11-15a and 11-15b shows the effect of faulting on the map pattern of inclined strata after leveling of the ground surface by erosion. Figure 11-15a portrays a case where the normal fault is dipping in a direction opposite to that of the beds cut by the fault. The associated final map pattern includes a repetition of the stratigraphic sequence. Figure 11-15b portrays a case where the normal fault is dipping in the same direction as the strata it transects. The final map pattern includes lags (missing strata); the black markerbed is not seen in the map after faulting and erosion.

☐Exercise 11-6: Consider the block diagram of Figure 11-16, and draw the resultant map patterns after erosional leveling of the ground surface, for: (a) a steep, east-dipping reverse fault, and (b) a west-dipping reverse fault. Indicate whether repetition or omissions of parts of the stratigraphic sequence occur. Compare the result with that of the normal faults in Figures 11-15a and b.

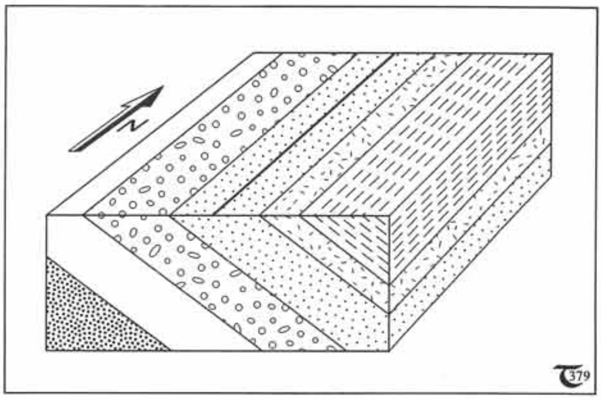


Figure 11-16: Inclined sedimentary sequence, prior to fault displacement. See exercise 11-6.

☐Exercise 11-7: Refer to the map of Figure 11-17. a) Complete the cross-section along A-B. b) Interpret the outcrop pattern in a short description of the tectonic history of the map region.

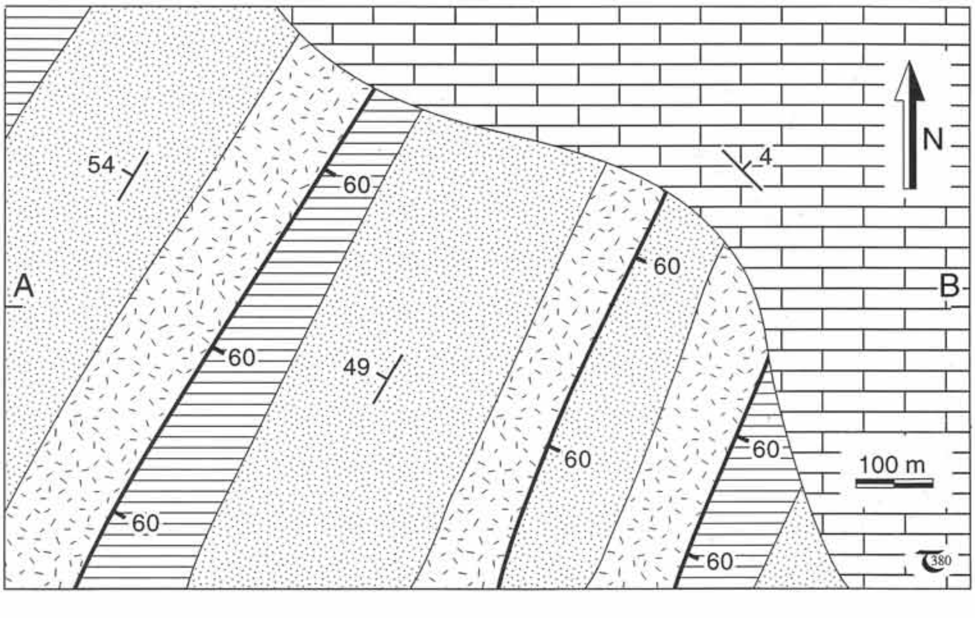


Figure 11-17: Geological map of a flat area. See exercise 11-7.

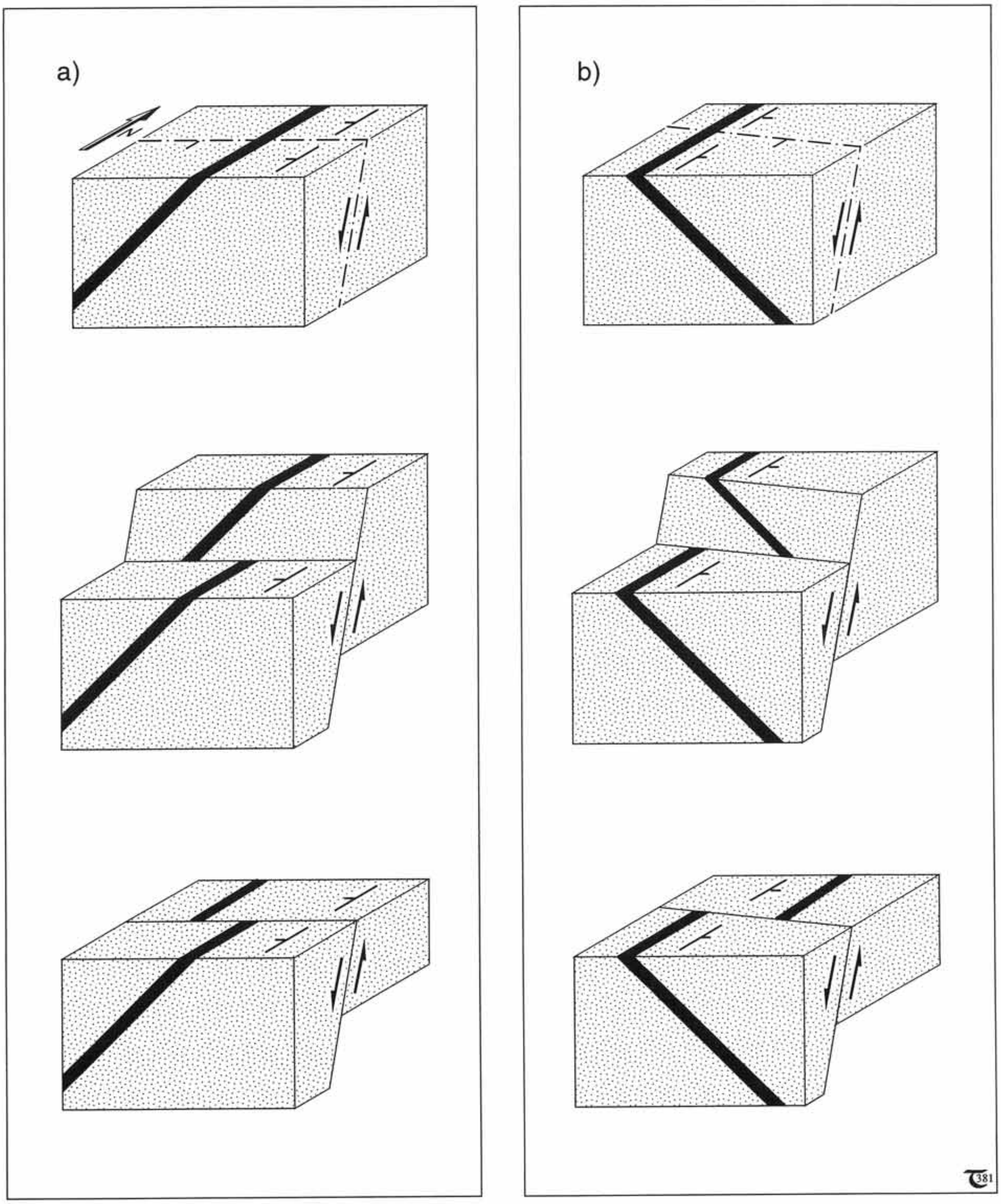


Figure 11-18: *a) & b) Three-stage perspective diagrams (pre-faulting, post-faulting, post-erosional) for normal faulting transverse or oblique to the strike of a sedimentary sequence. The post-erosional diagrams illustrate the apparent strike-slip displacement. The sense of off-set (strike separation) depends upon the initial inclination of the displaced layer(s). Case (a) illustrates apparent left-lateral displacement; case (b) shows apparent right-lateral off-set.*

Transverse dip-slip faults

The sequence of block diagrams of Figures 11-18a and 11-18b shows the effect of faulting on the map pattern of inclined strata after faulting oblique to their strike and subsequent leveling of the ground surface by erosion. The normal fault portrayed cannot lead to either any repetition or omission of the stratigraphic sequence, as exposed at the surface. The strike separation visible on maps alone could be misinterpreted as the result of a strike-slip movement. Yet no component of strike-slip movement is involved; all movement is by dip-slip only. The direction of the strike-slip inferred would be different for layers dipping in opposite directions, as follows from comparing the final outcrop patterns of the models in Figures 11-18a and 11-18b.

Figures 11-18a and b have illustrated that it may be difficult to distinguish *transverse dip-slip faults* from *transverse strike-slip faults*, because their respective map pattern may be similar in regions of uniformly dipping strata. The ambiguity can be avoided if the uniformly dipping beds are cut by another planar feature, e.g., an igneous dike or another, older fault plane (or by determining the dip of the beds and faults in the field). Figure 11-19a to c illustrates such a case and excludes any explanation involving strike-slip alone, because each of the marker units is displaced in opposite directions with different strike separations. Additionally, the horizontal distance between the units at the surface of the eroded, upthrown block is much shorter than in the downthrown block. Such a situation requires an explanation involving a component of dip-slip.

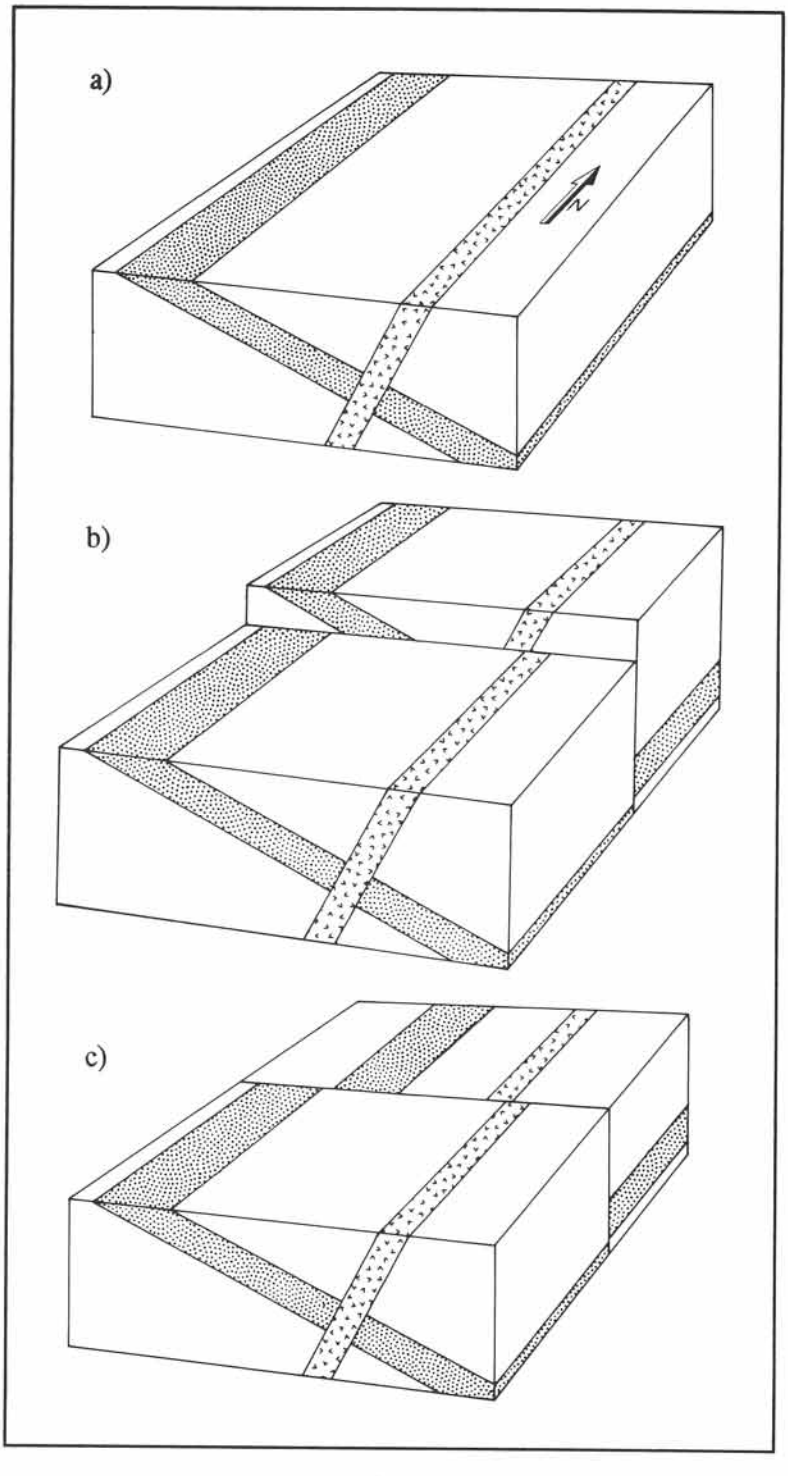
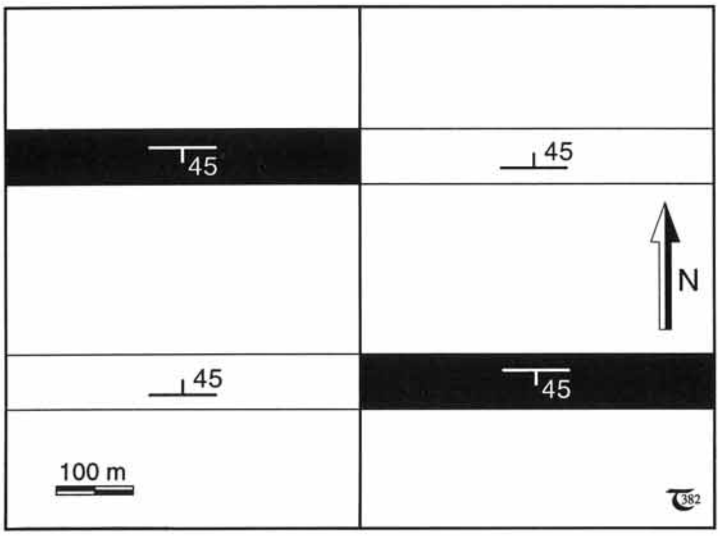


Figure 11-19: *a) to c) Three-stage perspective diagrams (pre-faulting, post-faulting, post-erosional), showing dip-slip movement on a transverse, vertical fault through a sandstone bed and an oppositely-dipping igneous dike.*



☐Exercise 11-8: Draw a series of three block diagrams, i.e., pre-faulting, pre-erosional, and post-erosional, illustrating how the faulted map pattern of Figure 11-20 can be explained.

Figure 11-20: Map for exercise 11-8.

☐Exercise 11-9: Refer to the map of Figure 11-21a. a) Interpret the outcrop pattern in a short description of the tectonic history of the map region. Assume that strike-slip faulting has not occurred at any time. b) Complement and illustrate your story further by completing the cross-section of Figure 11-21b.

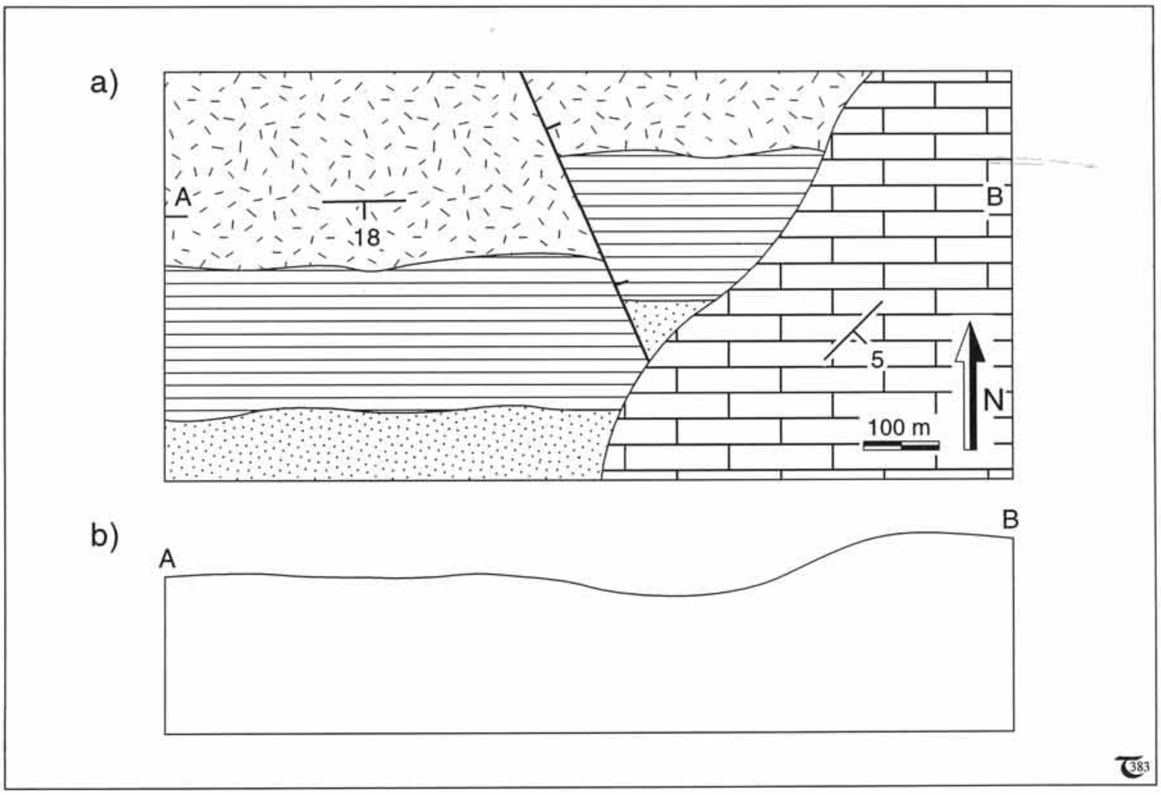


Figure 11-21: a) & b) Map and cross-section for exercise 11-9.

☐**Exercise 11-10: a) Excluding strike-slip movement, is the central region on the map of Figure 11-22 a graben or a horst? b) Construct an accurate E-W cross-section A-B across the map.**

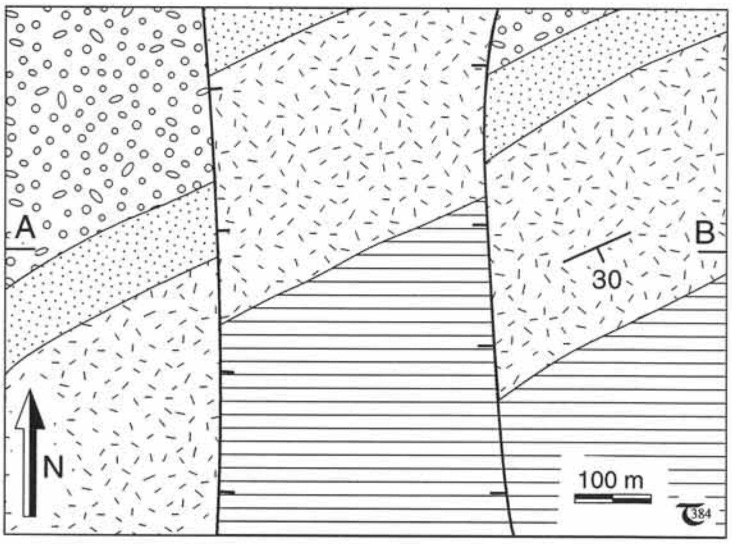


Figure 11-22: *Map for exercise 11-10. Assume the area has no topographic relief.*

☐**Exercise 11-11: Refer to the map of Figure 11-23. Assume only dip-slip faults are involved. a) Interpret the outcrop pattern in a short description of the tectonic history of the map region. b) Complement and illustrate your story further by completing the E-W cross-section A-B across the map of Figure 11-23.**

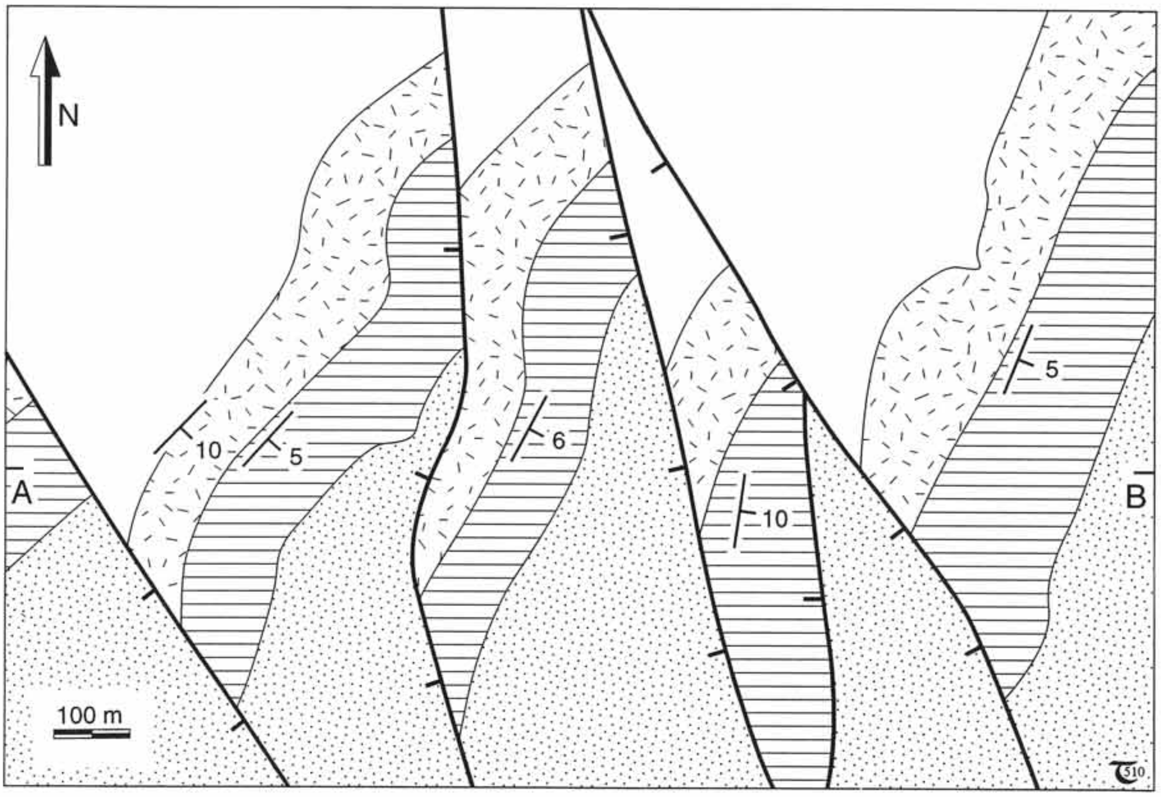


Figure 11-23: *Map for exercise 11-11. Assume the area illustrated is a nearly flat terrain.*

11-5 Map symbols for fault traces

A variety of geological symbols is used on geological maps to facilitate the interpretation of fault structures. The faults used in most of the figures of this chapter were not marked with any special notation to encourage assessment of the implication of the dislocated outcrop patterns. On professional geological maps, most of the faults have been interpreted for the user by the field geologist, who included special map symbols denoting the nature of the fault. Some of the map symbols, used to characterize faults along their trace, are given in Figure 11-24. It is possible to annotate on the map both the direction and the amount of dip of a fault plane. A bar and ball are used for downthrown blocks if the fault plane is subvertical. Hachures are used to indicate the downthrown block for normal faults. Reverse faults can be marked either by a combination of dip symbols and *U(p)* and *D(own)* markings or by writing an *R* on the upthrown side. Strike-slip faults are marked by a solid line with a conjugate pair of half-arrows, indicating sinistral or dextral sense of shear. Fault breccia, if extensive, may be included on the map as a local rock unit, concentrated along the trace of the fault plane. Finally, thrust faults - a special class of low angle reverse faults, which will be discussed later - are marked with sawteeth on the hanging wall or upper plate.

☐Exercise 11-12: Draw a conjugate pair of half-arrows on either side of a hypothetical strike-slip fault trace, indicating (a) sinistral, and (b) dextral sense of shear.

11-6 Faulted strata in topographic relief

The map patterns, outlined above, considered ground surfaces that were completely leveled by erosion. More complex map patterns of faulted layers arise in terrains of rugged topography. In such cases the true direction of strike and dip of layers and fault planes can be obtained using structure contours, according to the principles

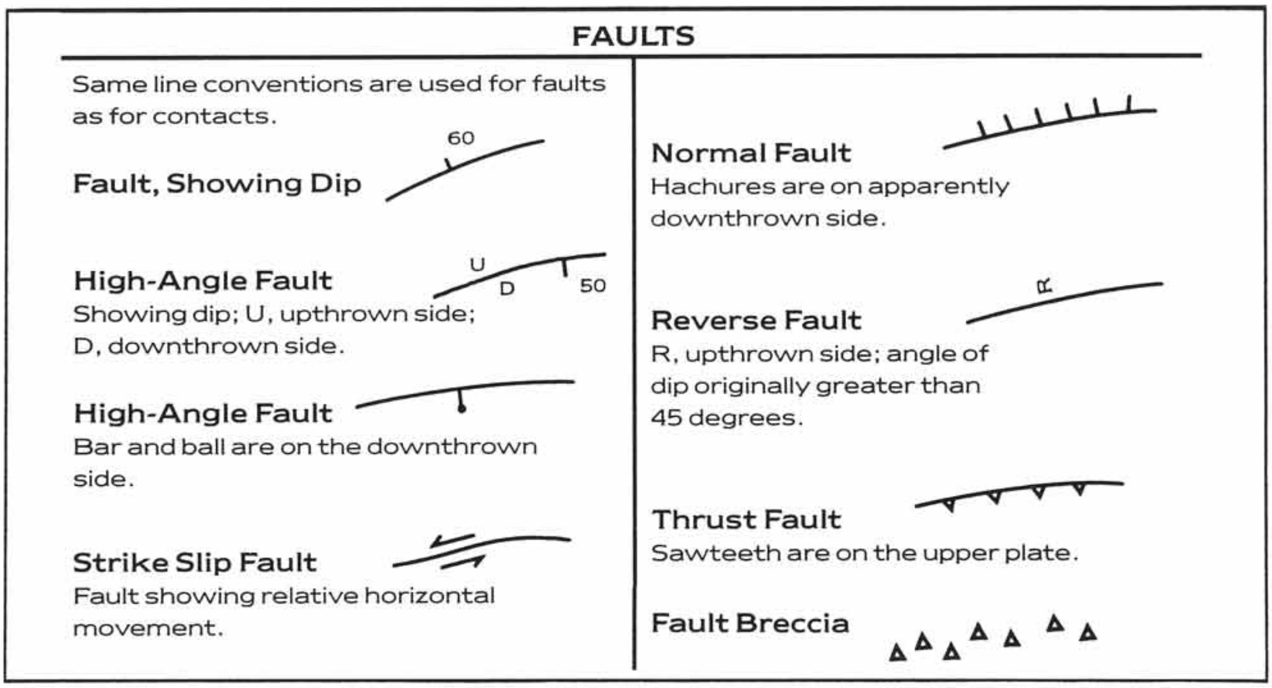


Figure 11-24: Common map symbols for indicating fault elements.

□Exercise 11-13: Examine the map pattern of Figure 11-25. A NNW-SSE striking fault divides the map into a west and east part. a) Concentrate first on the west part of the map, and determine the structure of the sandstone formation. b) What is the dip of the fault plane? c) Determine the azimuth and dip of the sandstone formation to the east of the fault. d) Determine the dip separation of the fault (see, also, section 11-2 and Fig. 11-12). e) Assuming only dip-slip has occurred, did the east wall move up or down relative to the west wall? f) Determine the strike separation. g) Assuming only strike-slip occurred, is the sense of shear sinistral or dextral?

discussed in chapter five. Figure 11-25 is a map of a sandstone formation, transected by a fault. For this simple structure, the exact amount of fault separation can be determined by the construction of structure contours, as elaborated in exercise 11-13. However, if no further information is available, the same fault separation can be due to either dip-slip alone, strike-slip alone, or a combination of both in oblique slip.

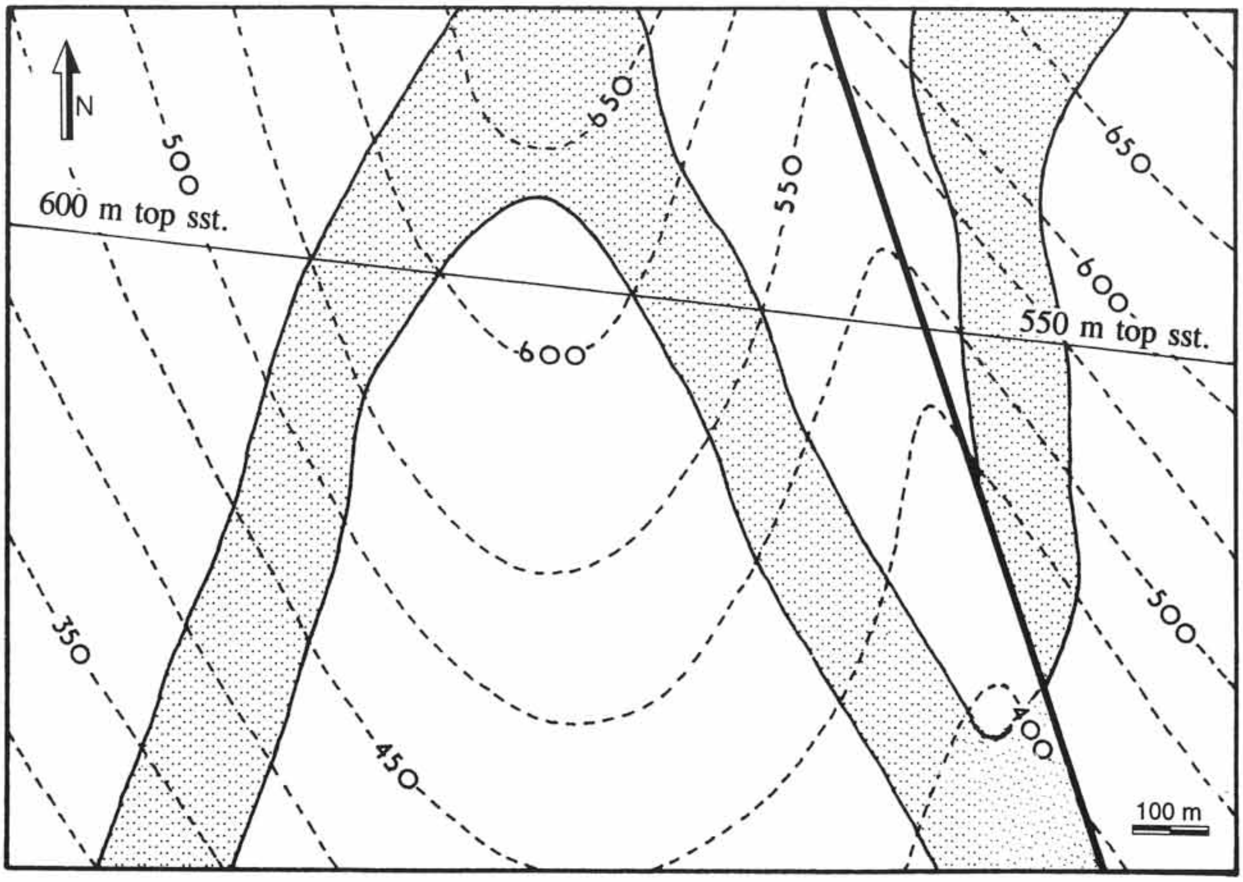


Figure 11-25: Outcrop pattern of faulted sandstone formation on topographic base map. See exercise 11-13.