—8

Folds, faults and Other Structural Features of Rocks

8.1. General Introduction

The rocks of the Earth's crust are generally unstable, and are subjected to a number of forces operating within the Earth's body. Due to these forces, which may operate either during or after the formation of the rocks, the rocks may undergo deformation to varying degrees, depending upon the intensity and type of the forces, and rigidity of the rocks.

These deformational forces, for example, may tilt the initially horizontal rock layers into some inclination with the horizontal. In more acute cases, the beds may even be pushed into nearly vertical positions. The rocks, may, thus, be thrown into undulations or flexures or bends, called folds, which may be simple or complex in nature.

In certain cases, the rock bodies may get fractured, producing cracks or joints. In still other cases, such fractures may result in dislocation of the two fractured blocks of the rock, along the fractured surface, so that one block *moves* past the other. Such fractured surfaces, along which displacements have taken place, are called *faults.* These make the rocks extremely unstable and risky from stability point of view.

Sometimes, the stratified rocks may exhibit prominent lines of demarcation between the lower layers and the upper layers, thus indicating that a time gap had occurred during the formation of these two sets of rocks. This time interval must have passed after the formation of the lower layers, which might have got eroded to some extent by erosion, and the second set of layers getting deposited afterwards. The rocks above and below such demarcation lines or surfaces, will thus, represent their respective depositions under different geological conditions and at different geological times. Such a junction or surface of erosion, and break in deposition, is called an **unconformity**. Since the unconformities are directly associated with the position or *attitude** of the rocks, it constitute an important rock structure.

Besides these major structures (*i.e. folds, faults, joints* and *unconformities*), there are certain other minor structures like *inliers outliers, and overlap*, which are also associated with the attitude and disposition of the rocks, and are formed due to additional effects of erosion and deposition, etc. All these major and minor rock structures shall be discussed in the following pages of this chapter.

8.2. Attitude of Beds

As pointed out earlier, *attitude* refers to the three dimensional orientation or positioning of a given geological feature, such as a bed, a joint, a fold, etc. The attitude of a planar geological feature like a rock bed or a joint or a fold is defined by their *strike* and *dip*.

8.2.1. Strike. When a bedding plane (or a joint plane, or a fault plane) is cut by a horizontal plane, a line of intersection will be obtained at the surface. This direction is known as the *strike*, or the *direction of the strike*, or the *line of the strike*, as shown in Fig. 8.1.

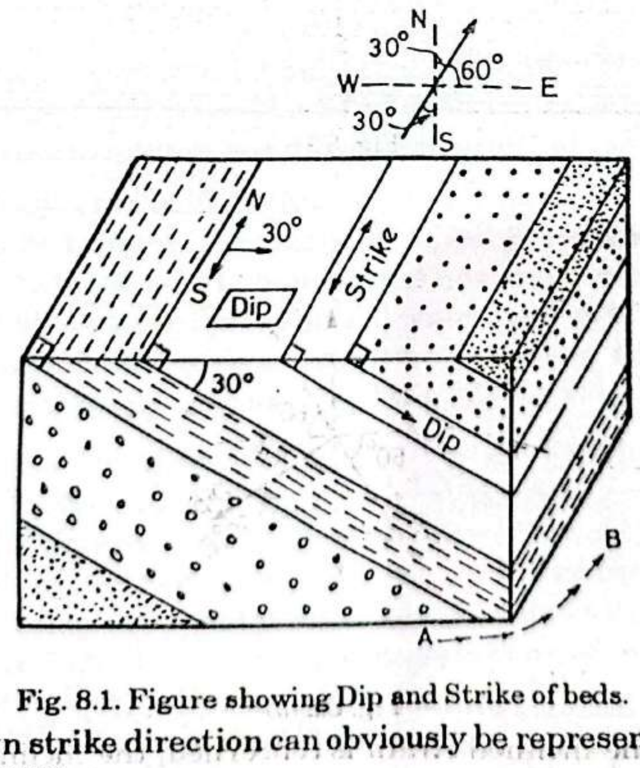


Fig. 8.1. Figure showing Dip and Strike of beds.

The shown strike direction can obviously be represented as N 30° E or as S 30° W.

*the three dimensional orientation of a given sequence of rocks is called the attitude of the rocks.

8.2.2. Dip. The dip direction is the direction along which the inclination of the bedding plane occurs. The dip amount is the angle of inclination between the bedding plane and a horizontal plane. The dip of a bed is therefore expressed in terms of the angle in degrees which the bed line makes with the horizontal line, and the direction with respect to north, south, east and west, in which the bed is inclined. Say for example in Fig. 8.1, the beds are inclined at 30° to the horizontal, and their dip may be expressed as S 60° E ; when the strike direction is N 30° E as shown in Fig. 8.2 (*a*) ; or S 60° W as shown in Fig. 8.2 (*b*).

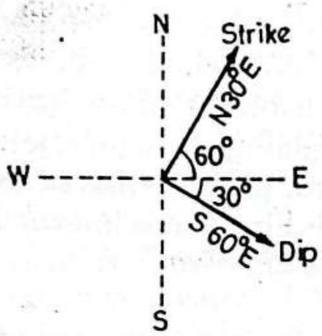


Fig. 8.2 (*a*)

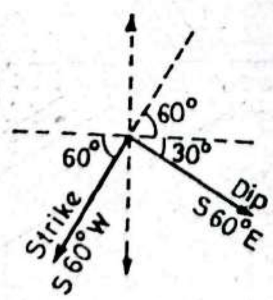


Fig. 8.2 (*b*)

As far as the inclined strata is concerned, the inclination of the bedding planes will be maximum in a direction perpendicular to the strike direction, and this is called the true dip direction or simply dip direction, and the amount of inclination along this direction is

called the **true dip** amount or simply as dip amount. Close observations will reveal that this dip amount gradually decreases on either side of the true dip direction, when we move towards the strike direction.

To illustrate this, let us for example, first assume that the observer is situated at A (located due south) in Fig. 8.1. This observer will find the beds with maximum angle of inclination of 30°, which is *the inclination of the beds in a direction at right angles to the strike and hence represents the true dip*. But if the observer moves towards the position B (located due east), the bedding inclination observed appears to be decreasing, untill at B it becomes zero, as the beds appear to be in a horizontal position. All such inclinations will be known as **apparent dips**.

The true dip and apparent dip values are infact related to each other by the equation :

$$\tan \alpha = \tan \beta \cos \gamma \qquad \text{...(8.1)}$$

where β = angle of true dip

α = angle of apparent dip

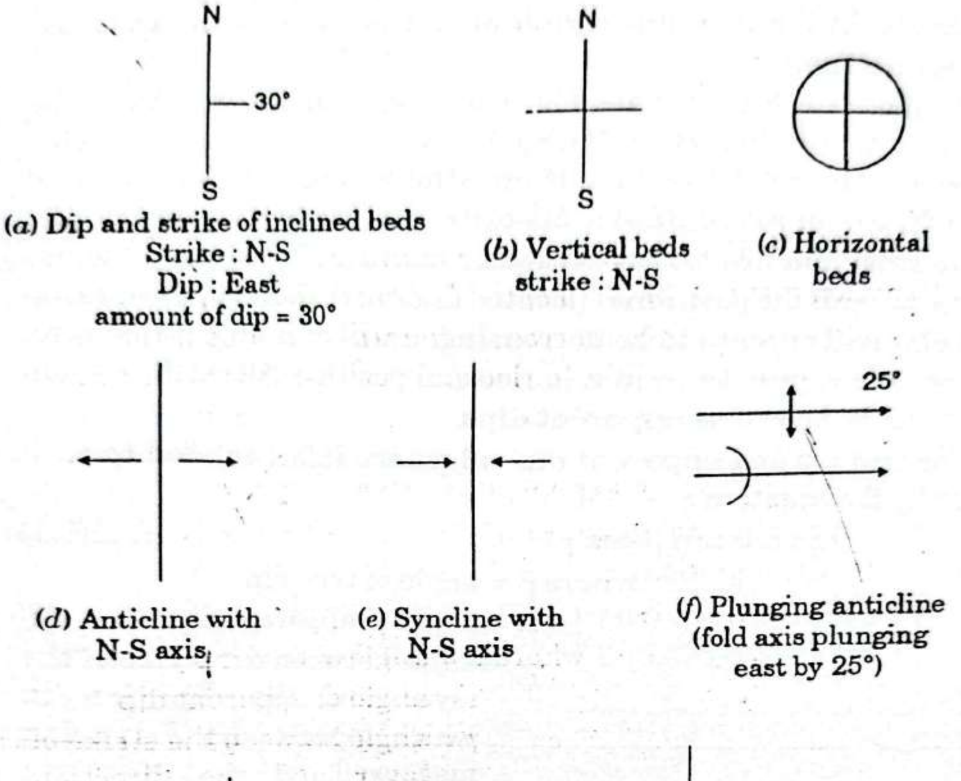
γ = angle between the strike of the layer and the direction in which apparent dip (β) is being measured.

For *vertical beds*, there can be only strike direction but no dip direction, and the dip amount will be 90°. For *horizontal beds*, there can be neither strike direction nor dip (direction and amount).

In the attitude symbol, a slightly elongated straight line represents the strike direction and a small perpendicular side line drawn at the middle shows the dip direction and the numerical value given in degrees, refers to the true dip amount, as shown in Fig. 8.3, which shows some commonly adopted symbols for indicating the *strike direction, dip direction, dip amount* and other structures.

8.2.3. Measurement of Strike and Dip in the Field. The dip and strike of beds can be easily measured in the field from their exposures called *outcrops*. **Outcrops**, infact, are those sections on the Earth's crust, where *the solid rocks are exposed at the ground surface*, without being covered by any unconsolidated alluvium or soil layers (Refer Fig. 8.4). Such exposed sections of rocks are generally found, forming sides of valleys or caps of hills.

The dip and strike of an exposed bed in the field can be measured in degrees by an instrument, known as a *clinometer*, which consists of a pendulum with a graduated arc. The directions of the dip and



(*a*) Dip and strike of inclined beds
Strike : N-S
Dip : East
amount of dip = 30°

(*b*) Vertical beds
strike : N-S

(*c*) Horizontal beds

(*d*) Anticline with N-S axis

(*e*) Syncline with N-S axis

(*f*) Plunging anticline (fold axis plunging east by 25°)

(*g*) Plunging syncline (fold axis plunging east by 25°)

(*h*) Dip and strike of foliation

(*i*) Dip and strike of inclined joints

(*j*) Vertical joints

(*k*) Horizontal joints

Fig. 8.3. Symbols of some common geological structures.

strike can be measured similarly by a *compass*. For the sake of convenience, a clinometer as well as a compass are both combined together, as to form an instrument known as *clinometer-compass*.

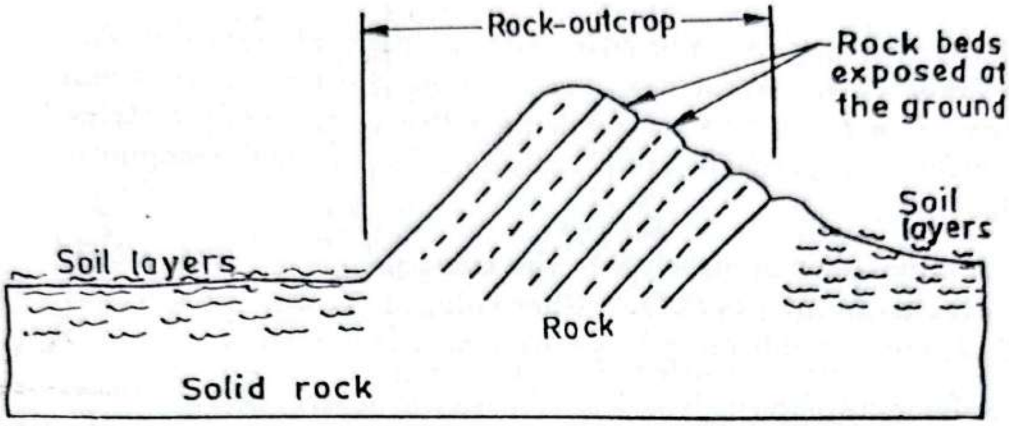


Fig. 8.4. A rock *Outcrop* showing bedding.

The clinometer of this instrument will help in measuring the amount of the dip and strike ; while the compass will help in measuring their directions with respect to north, south, east and west.

The **clinometer compass** (Fig. 8.5) differs rather from an ordinary compass in the following manner.

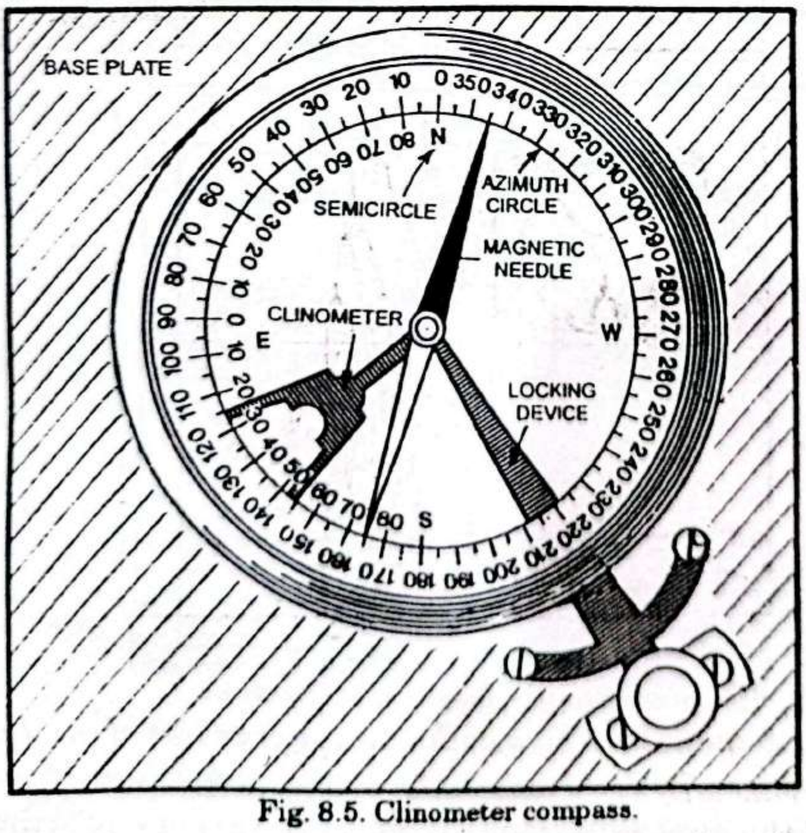


Fig. 8.5. Clinometer compass.

(*i*) This compass is usually fixed to a rectangular plate made of cast iron or plastic, in such a way that the 0°—180° diameter, *i.e.*, North-South direction, is parallel to the length (*i.e.*, longer side of the rectangular plate).

(*ii*) The divisions on the circle from 0 to 360° go anticlockwise. The signs for East and West are thus the opposite from the normal compass. This is done so, as to calculate the azimuth of the strike directly from the position of the North-pointing end of the magnetic needle.

(*iii*) A clinometer is attached to the compass needle with a half circle divided from 0° to 90° on either side, as shown. The angle of the dip is measured from by its position on the half circle.

The elements of the beds of a rock strata are determined in 4 steps by this instrument, as explained below :

(*a*) The *direction or line of the strike* is first determined on a cleared patch of the bed (Fig. 8.6). For doing so, the long side of the compass is applied (held) to the plane of the bed, so that the clinometer registers zero. A line drawn along the long side of the plate indicates the direction of the strike.

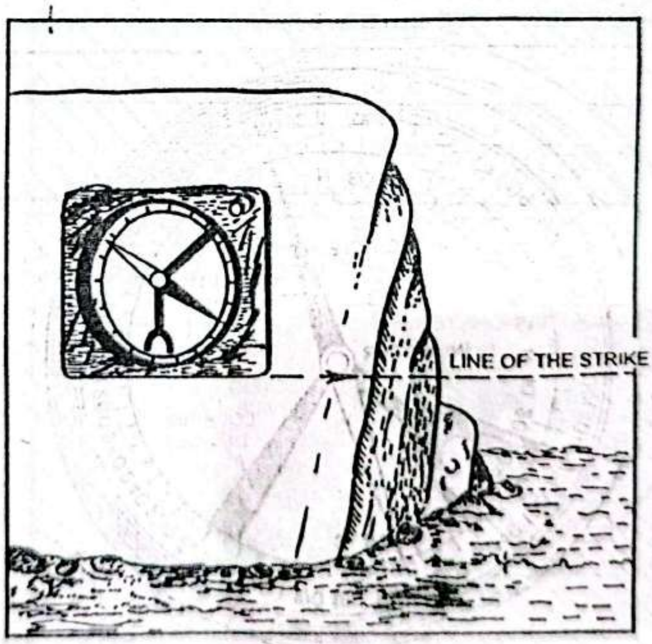


Fig. 8.6. Determining the direction of the strike.

(*b*) Having determined the strike, *the direction or line of the dip* is determined (Fig. 8.7). For doing that, the compass is turned, so that the clinometer gives a maximum reading. A line parallel to the long side of the compass will then indicate the direction of the dip. In all these cases, it must be noted that the line of the dip of the bed is always perpendicular to that of the strike. The angle of the dip is of then determined immediately (when it is small).

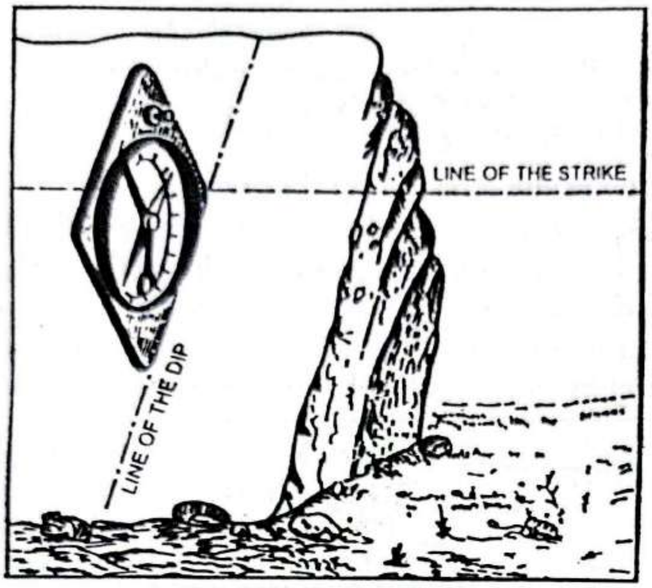


Fig. 8.7. Determining the dip and angle of dip of a bed.

(c) To determine the azimuth of the dip of the bed (Fig. 8.7), the compass is applied to the strike, so that the south end is pressed against the bed and the north end is pointed down the dip. The compass is then brought to the horizontal position. When it has been so fixed, the locking device is released and the needle allowed to

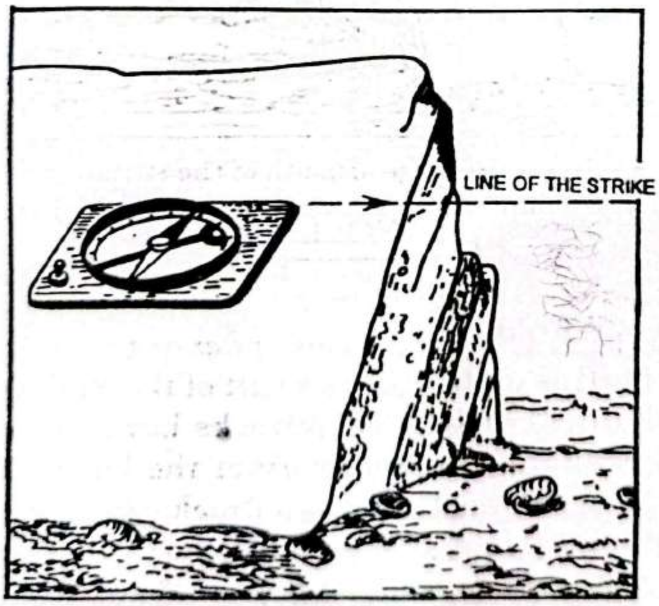


Fig. 8.8. Determining the azimuth of the dip of a bed.

settle ; the azimuth of the dip is read from the graduated circle (according to the direction of the black, north-seeking end of the pointer).

(d) Knowing the azimuth of the dip of bed, there is no need to further measure the azimuth of the strike ; as it can be easily calculated by adding or subtracting 90° to the measured azimuth of the dip. For example, if the azimuth of the dip is S 60° E, the azimuth of the strike will be S 60° W or N 30° E.

Sometimes however, you may be required to measure the azimuth of strike by the compass itself to counter check your dip measurements. For this measurement, the long side of the compass is applied (as shown in Fig. 8.9) to the strike and the azimuth is read from the graduated circle. The reverse bearing can be calculated from this reading by adding 180° to the measured azimuth.

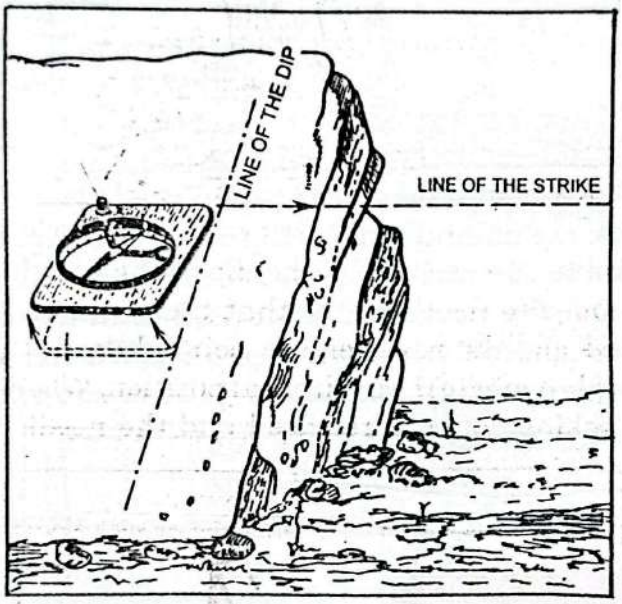


Fig. 8.9. Determining the azimuth of the strike of the bed.

FOLDS

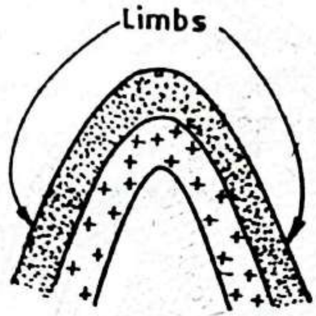
8.3. Definition of a Fold

Folds may be defined as undulations or *bends* that are developed in the rocks of the Earth's crust, as a result of the stresses (commonly lateral compression) to which these rocks have been subjected to, from time to time in the past history of the Earth. These bends, called folds, may develop in any type of rock, but are best displayed by the stratified rocks such as, sedimentary or volcanic rocks or their metamorphosed equivalents. These folds may be of different shapes-starting from simple up and down warpings to complicated geometrical patterns. In lateral extent, they may range from several kilometres to only a few metres or even a few centimetres. The extent of folding undergone by the rocks and their ultimate folded shapes depend upon the intensity, magnitude, type, and duration of the *rock folding forces* acting within the Earth, as also upon the type and nature of the rocks withstanding those forces.

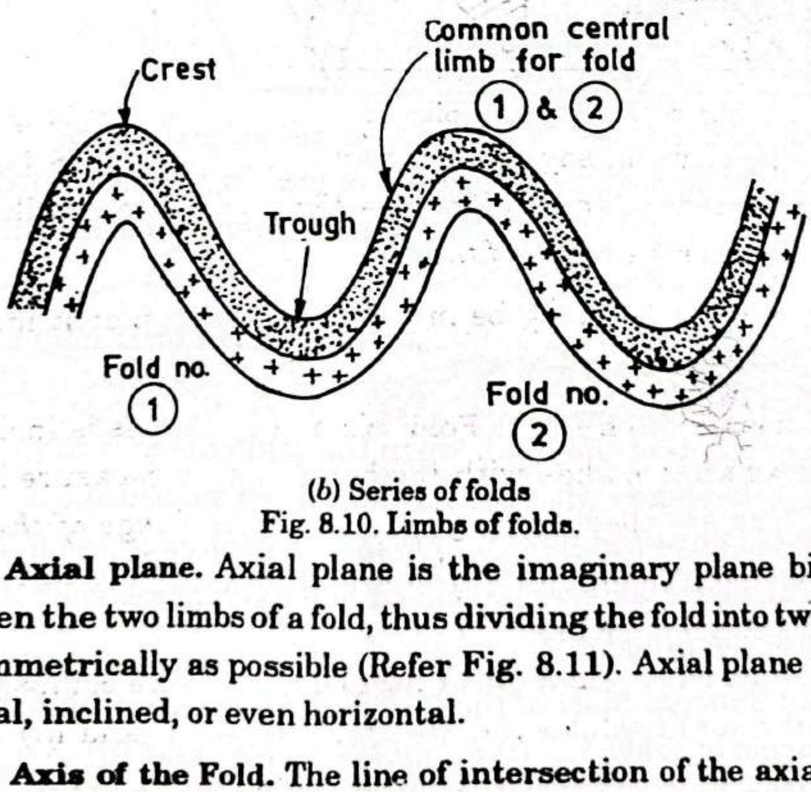
8.4. Parts of a Fold and Connected Terminology

The various parts of a fold, and the terms generally used in describing them are explained below w.r.to the vertical cross-sections of the folds or the folded area.

(*i*) **Limbs.** Limbs are the sides of a fold. An individual fold will have two limbs ; whereas, in a series of folds, the central limb is *common* to any two adjacent folds (Refer Fig. 8.10).



(*a*) Single fold



(*b*) Series of folds

Fig. 8.10. Limbs of folds.

(*ii*) **Axial plane. Axial plane is the imaginary plane bisecting between the two limbs of a fold, thus dividing the fold into two parts, as symmetrically as possible (Refer Fig. 8.11). Axial plane may be vertical, inclined, or even horizontal.**

(*iii*) Axis of the Fold. The line of intersection of the axial plane with any bed of the fold, is termed as the *axis of the fold* or *fold axis*. Hence, if a folded sequence is composed of a number of beds, it will have a number of intersections with the axial plane ; or in other words, equal number of axes. But since all these axes are essentially

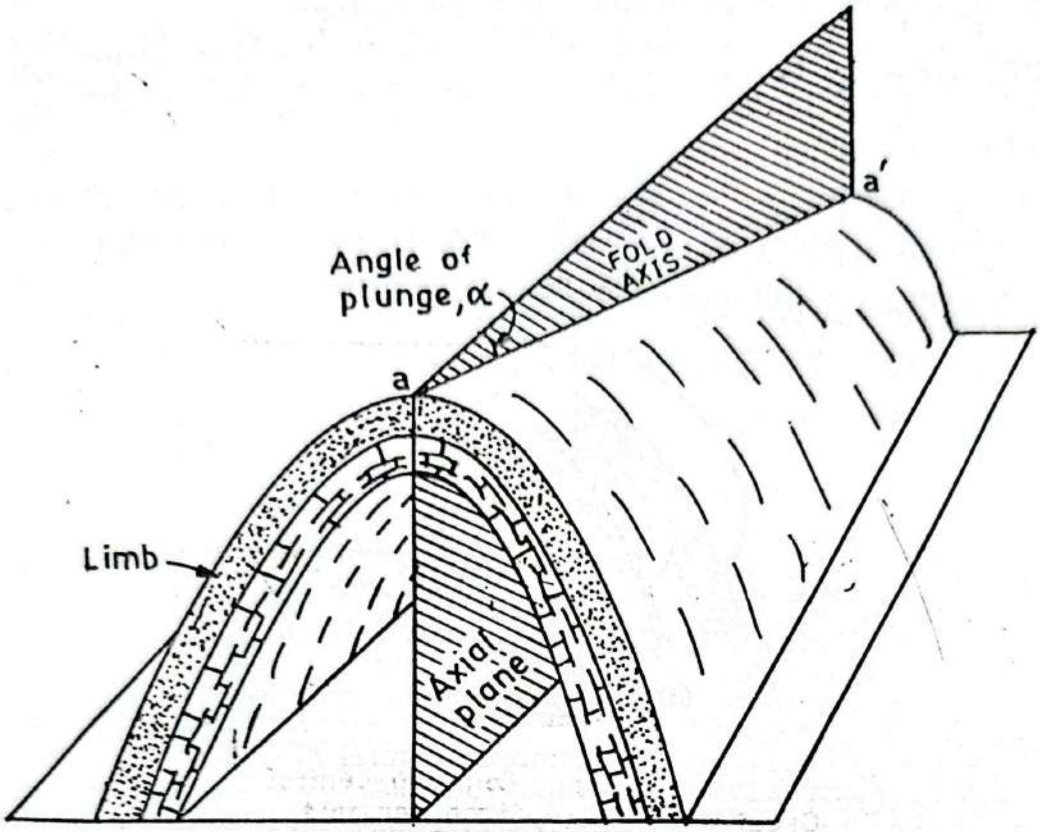


Fig. 8.11. Figure showing axial plane, fold axis, and anlge of plunge.

parallel, one of them, say the top most one (*aa'* in Fig. 8.11) will represent the general trend of inter-section, and hence is called the axis of the fold or the *hinge of the fold.*

The axis of the fold may be in horizontal position or it may be inclined.

(*iv*) **Plunge or Pitch of the Fold.** When the fold axis is inclined, the angle which it makes with the horizontal, as measured in a vertical plane, is called the *angle of plunge, or plunge of the fold* (Refer Fig. 8.11). Such folds with inclined fold axes are known as *plunging folds* or *pitching folds.*

(*v*) **Crest and Trough.** Most of the folded rocks are composed of two general forms of folds, *i.e.* (*i*) *up folded* bends, and (*ii*) *down folded* bends. The line running through the highest points in an up-arched fold defines the *crest* ; and a corresponding line running through the lowest points on the same bed, in a down-arched fold, is called the *trough* (Refer Fig. 8.12). The crest or trough may or may not coincide with the axis of the fold.

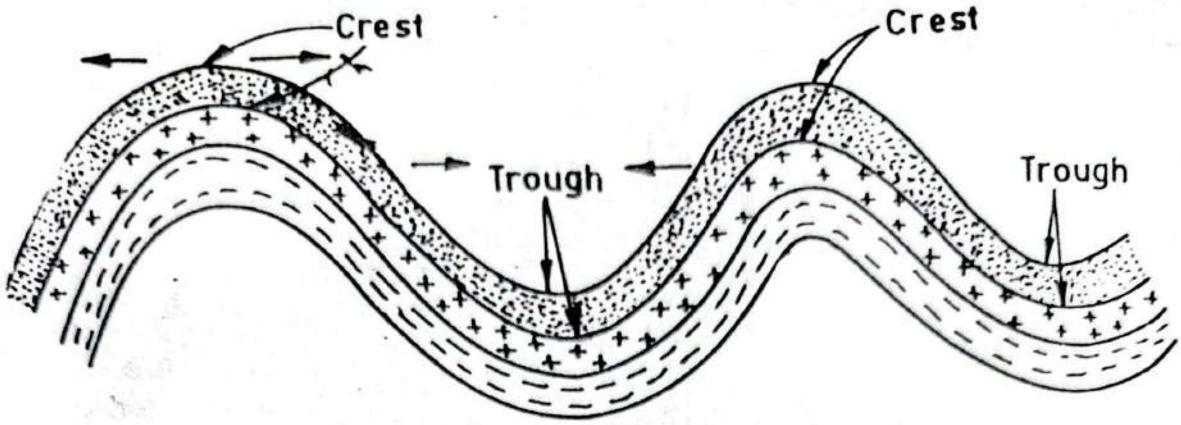
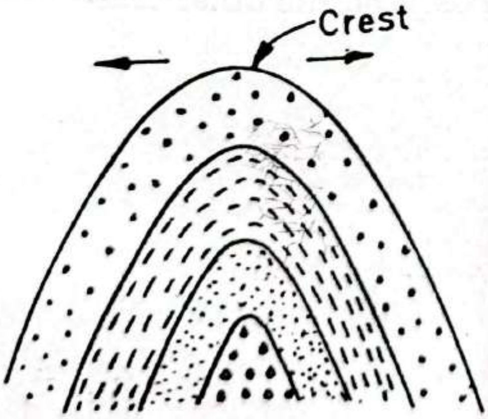
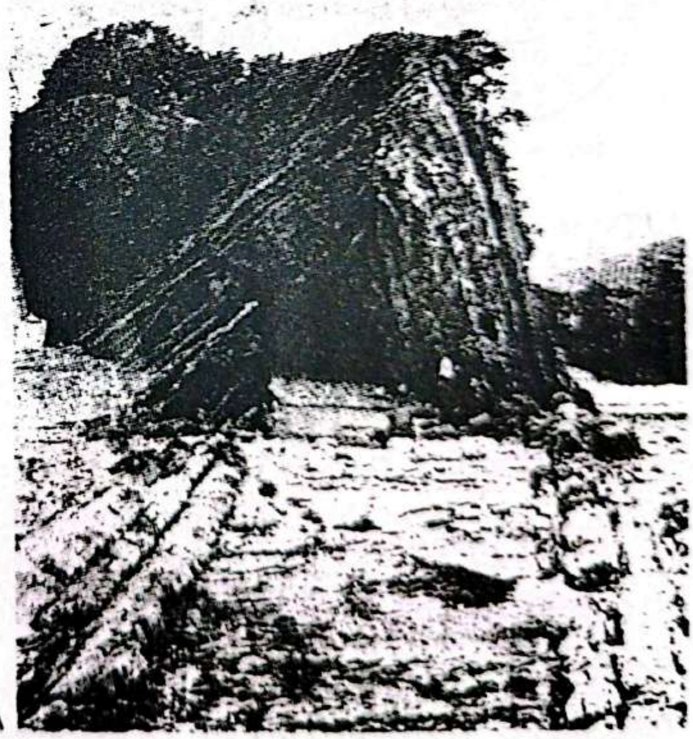


Fig. 8.12. Crest and Trough of folds.

(iv) **Anticline and Syncline.** When the beds are upfolded into an arch-like structure, it is called an *anticline* or an *anticline fold.* In such folds, the beds on either side are *inclined away* from the crest, and that is why the name *anti-cline* [Refer Fig. 8.13 (*a*) and (*b*)].



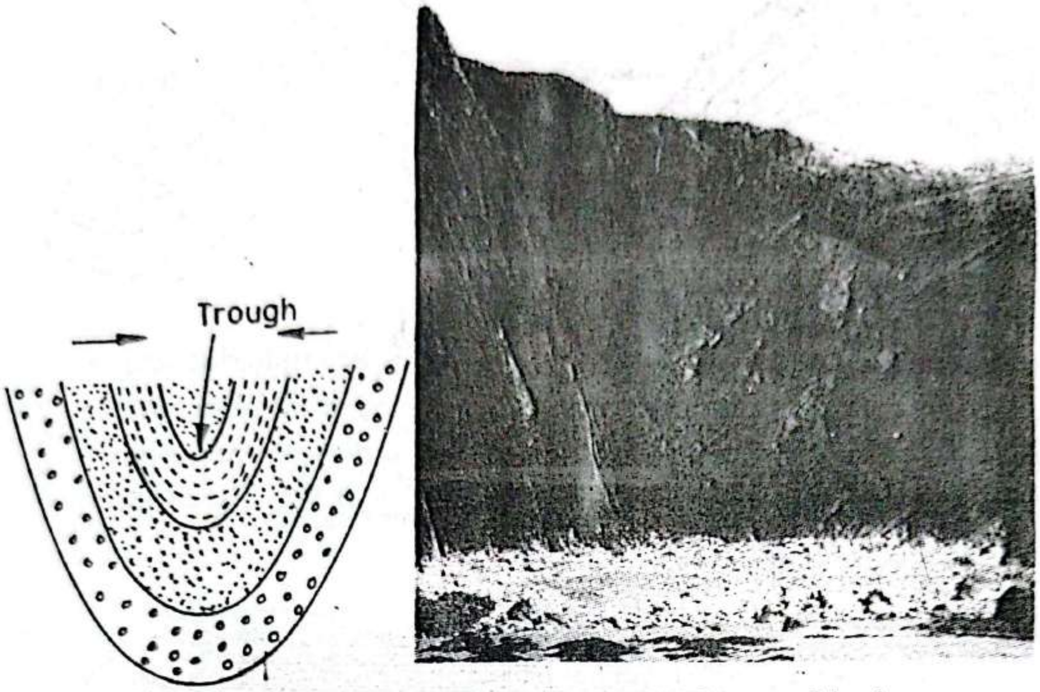
(*a*) Sectional elevation



(*b*) Photographic view

Fig. 8.13. Anticline folds.

Conversely, when the beds are down-folded into a trough like form, the structure is called a *syncline*, because in this case the beds on either side *'incline together'* towards the keel [Refer Fig. 8.14 (*a*) and (*b*)].



(a) Sectional elevation (b) Photographic view

Fig. 8.14. Syncline folds.

8.5. Types of Folds and their Classifications

Besides the major classification of folds as *anticlines* and *synclines*, of which most of the folded rocks are composed of, the other classifications may be :

1. On the basis of *position of axial plane* ;
2. On the basis of *degree of compression of the beds* ;
3. On the basis of *their mode of occurrence* ;
4. On the basis of their *position of fold axis* ;
5. On the basis of their *behaviour with depth* ; and
6. Other *miscellaneous* folds.

All the different types of folds, based on such classifications, are briefly described below :

8.5.1. Classification of Folds on the basis of Position of Axial Plane. Based on the position of the axial plane and the limbs, the following types of folds are recognised :

(*i*) **Symmetrical folds.** A symmetrical fold is that in which the axial plane is *essentially vertical*. Obviously, in such a fold, the two limbs will have the same angle of dip in *opposite directions* (Refer Fig. 8.15).

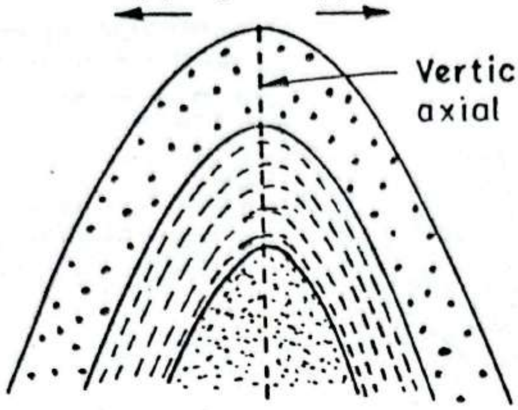


Fig. 8.15. Symmetrical (anticline) fold.

(*ii*) **Asymmetrical Folds.** The fold in which the axial plane is not vertical but is inclined, is called an asymmetrical fold. The two limbs of such a fold will obviously have different angles of dip, in normal *opposite directions* of course (Refer Fig. 8.16). The symmetrical as well as asymmetrical folds will separately remain as *anticlines* or synclines, depending upon whether it is *upfolding* or *downfolding*, respectively.

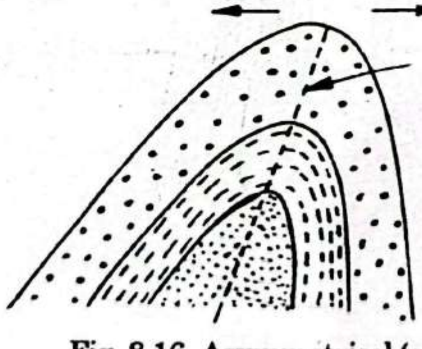


Fig. 8.16. Asymmetrical (antiline) fold.

(*iii*) **Overturned folds.** An overturned fold is a severely folded fold, in which the axial plane gets so much inclined that the two limbs of the fold dip in the *same general direction*. The amount of dip of the two limbs may not necessarily be the same. (Refer Fig. 8.17). In such folds, the folding is so severe that one of the two limbs comes to occupy the present up side down position, after having suffered a rotation through more than 90°. This limb is called the ***reversed limb*** ; and other normal limb with right side up, is called the ***normal limb***. The reversed limb in also called the *inverted* or ***overturned limb***.

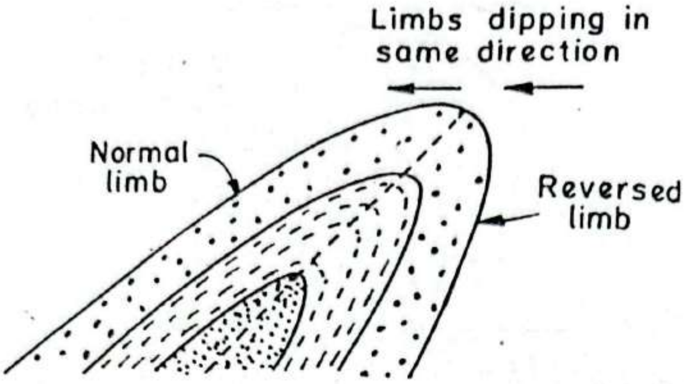


Fig. 8.17. Overturned fold.

In certain more severe cases, both the limbs of a fold may get overturned because of very high compression from opposite sides, resulting in bringing the limbs so close to each other, that the usual dip conditions get reversed. In other words, the anticlinal limbs will dip towards each other, and synclinal limbs dipping away from each other. Such a completely abnormal fold is called a **fan fold** (Refer Fig. 8.18)

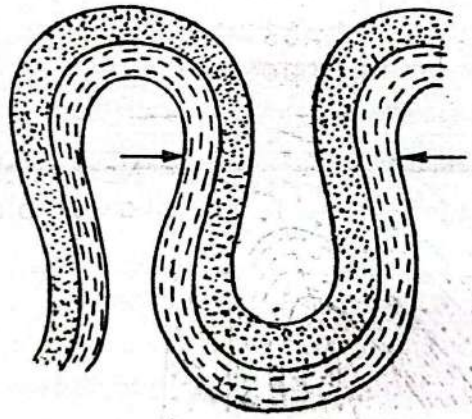


Fig. 8.18. Fan folds.

(*iv*) Recumbent Folds. These are extreme types of overturned folds, in which the axial plane acquires an almost horizontal position. In such folds, obviously, one limb lies vertically above the other. The overlying limb is right-side-up, and so called the normal limb ; while the underlying limb is up-side-down, and called the overturned or inverted limb (Refer Fig. 8.19).

(*v*) Isoclinal Folds. Isoclinal folds are those in which the limbs are dipping essentially in the same direction and at equal angles, so that their axial planes are essentially parallel (Refer Fig. 8.20). These folds may be vertical, inclined, or even horizontal, and are respec-

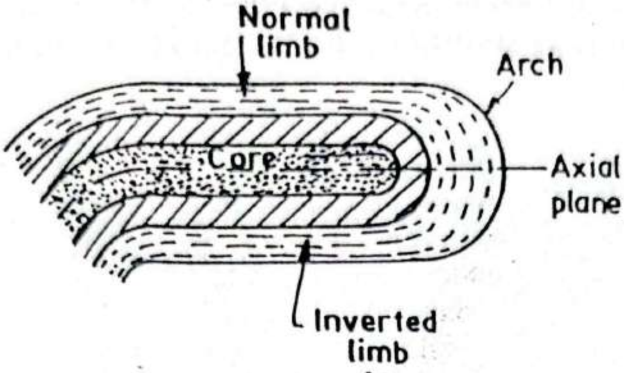
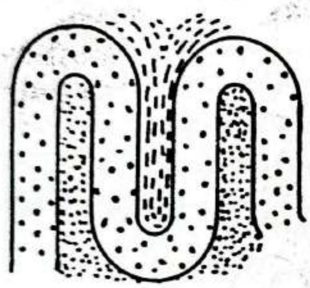
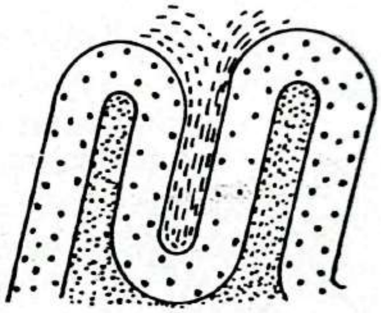


Fig. 8.19. Recumbent fold.

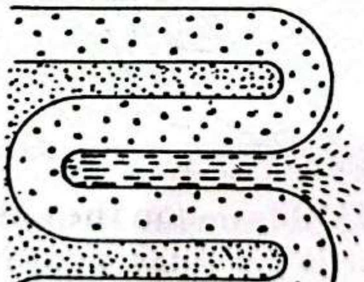
tively called, *vertical isoclinal folds, inclined isoclinal folds,* and *recumbent isoclinal folds*, as shown in Fig. 8.20 (*a*), (*b*) and (*c*).



(*a*) Vertical Isoclinal fold



(*b*) Inclined isoclinal folds



(*c*) Recumbent isoclinal folds

Fig. 8.20. Isoclinal folds.

8.5.2. Classification of Folds on the basis of Degree of Compression of the Beds. During folding, the beds may get compressed either slightly or severally. In the first case, when they are compressed to a lesser or extent, the rock layers may not undergo any variation in the thickness of the constituent beds ; whereas, in the case of severe compression, the beds may get *thinner at the limbs and thicker at the crests and troughs*. The former type of folds, where the thickness of bed is the same throughout its fold layer, is called an open fold ; and the latter one, where the thickness is more at trough and crest than at the limbs, is called a **closed fold.** (Refer Figs. 8.21 and 8.22).

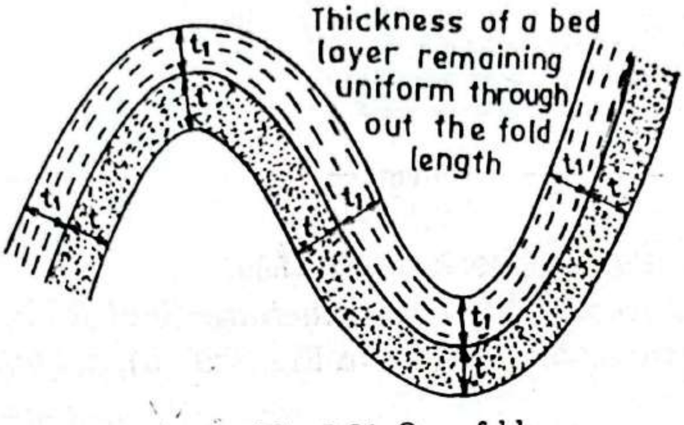


Fig. 8.21. Open folds.

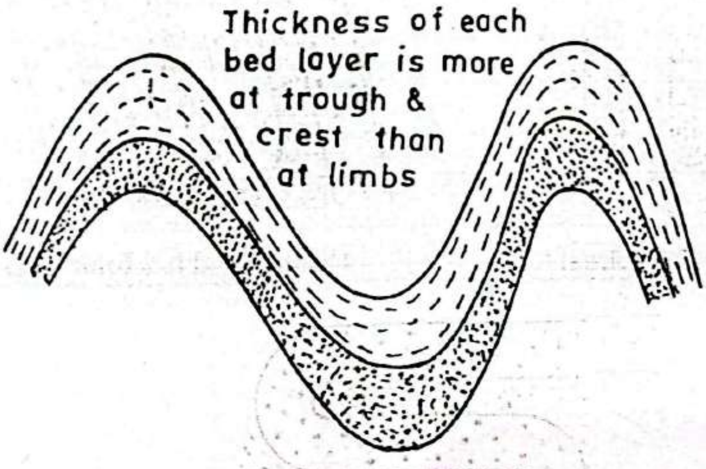


Fig. 8.22. Closed folds.

8.5.3. Classification of Folds on the basis of Their Mode of Occurrence. Folds, generally donot occur singularly, but, infact they often form a group in which individul members exhibit many similarities as well as dissimilarities. The common types of folds recognised on this basis are given below :

(*i*) Anticlinorium and Synclinorium Folds. An Anticlinorium fold is a large anticline which is further thrown into smaller folds, as shown in Fig. 8.23. Similarly, a synclinorium is a large syncline further consisting of smaller folds, as shown in Fig. 8.24. Both these types of folds are very large in size, running several kilometres across, and their limbs are locally warped into numerous small scale folds of various types.

Fig. 8.23. Anticlinorium.

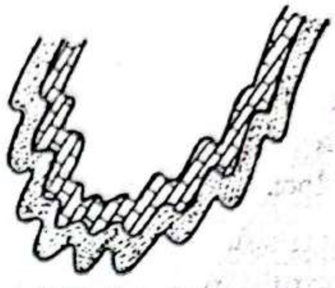
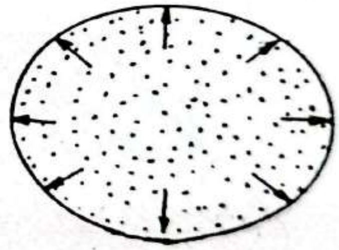


Fig. 8.24. Synclinorium.

Geanticlines and Geosynclines are the terms, which are used for similar folds of much larger size, running in scores of kilometres, and affecting a region as a whole. Geosynclines, as pointed out in a previous chapter, form important basins for sediment deposition, which on further lifting, form fold mountains.

(*ii*) **Domes and Basins.** A *dome* is a special type of anticline in which the beds dip away from the central point, in all directions, as shown in Fig. 8.25. A *basin* is a special type of syncline in which the

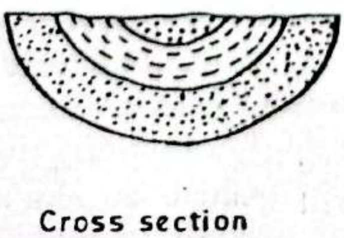
Cross section



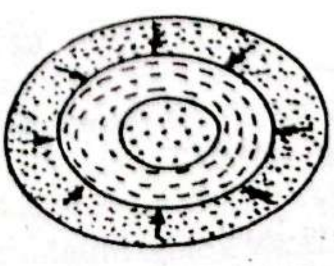
Plan

Fig. 8.25. Dome.

beds dip towards the central point, from all directions, as shown in Fig. 8.26. In outline, domes and basins are generally oval or nearly circular in shape.



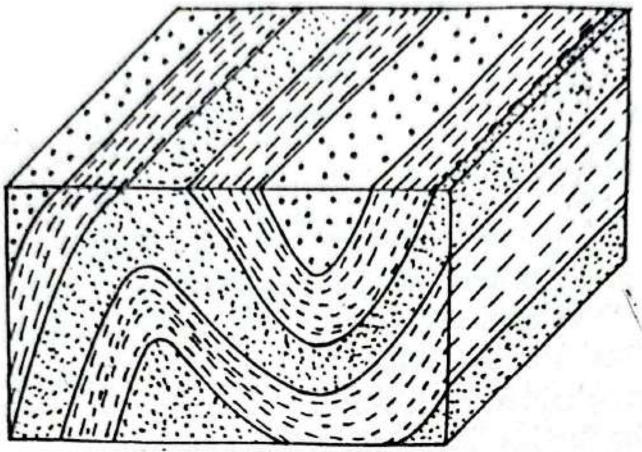
Cross section



Plan

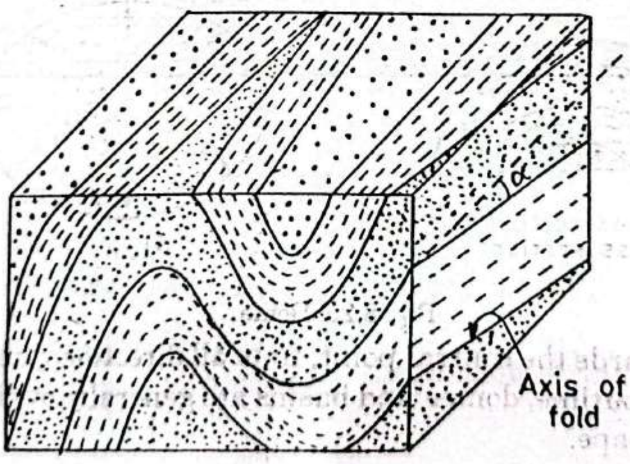
Fig. 8.26. Basin.

8.5.4. Classification of Folds on the basis of the Position of Fold Axis. As pointed out earlier, the fold axis may either be horizontal or may be inclined. When the fold axis is horizontal, it is called a **Non plunging fold** ; and when the axis is inclined to the



(a) Non-plunging fold

horizontal, it is called a **Plunging fold** (Refer Fig. 8.27). The angle of inclination being called as the *angle of plunge* (α), as defined earlier.



(b) Plunging fold
Fig. 8.27

8.5.5. Classification of Folds on the Basis of Their Behaviour with Depth. The following three types of folds are generally recognised on this basis :

(*i*) **Similar Folds.** Similar folds are those in which the shapes of the folds remain the same with any amount of depth. In such folds, however, the *thickening* at *axial regions* (*i.e.* at crests and troughs) and thinning of the limbs, will take place, as shown in Fig. 8.28.

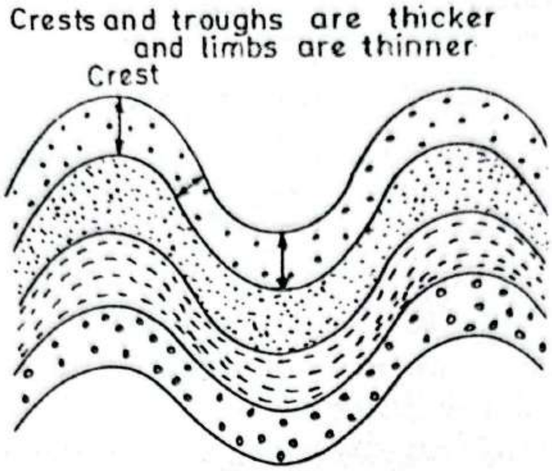


Fig. 8.28. Similar folds.

Such type of folding involves the plastic movement of material from the limbs to the axial regions, and hence are characteristic of *zone of rock flowage*.

(*ii*) **Parallel Folds.** Parallel folds are those in which the shape of the folds varies with depth, but the thickness of the folded bed layers remains more or less the same (Refer **Fig.** 8.23). In such folds, the anticlines become sharp and sharper with depth ; whereas, the synclines become broad and broader with depth, as shown in Fig. 8.29.

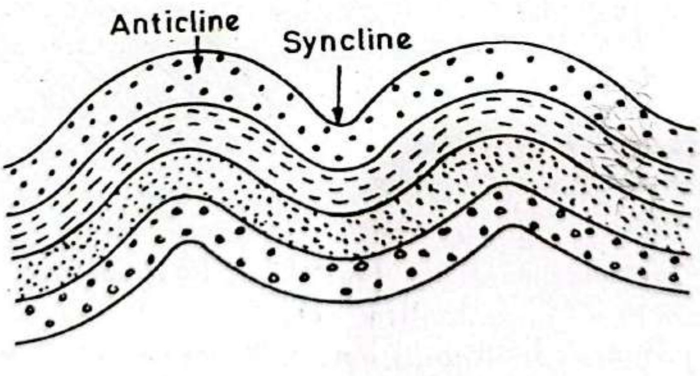


Fig. 8.29. Parallel folds.

(*iii*) **Supratenuous Folds.** These folds are developed when sedimentation accompanies the folding process in rocks. These folds exhibit *thinning* and thickening at the *crests* and the troughs, respectively (Refer Fig. 8.30). In such supratenuous folds, therefore, anticlinal ridges will be thinner due to erosion or lesser deposition of sediments ; and the synclinal troughs would be thicker due to large scale gradual accumulation of sediments in sinking basins.

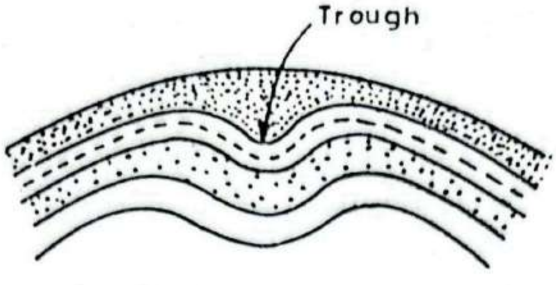
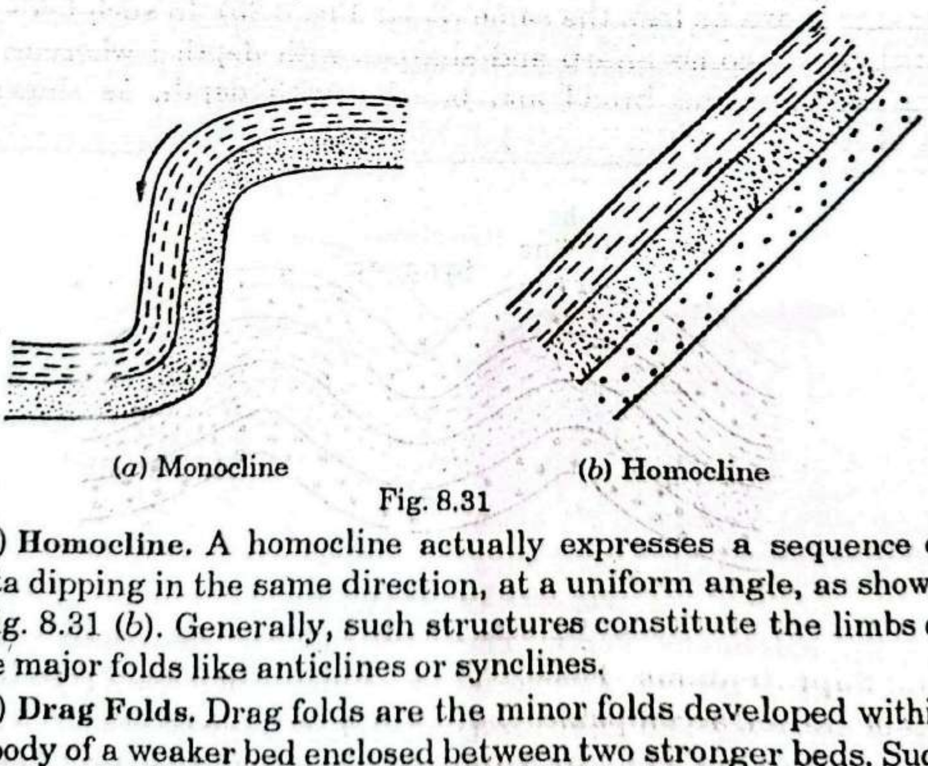


Fig. 8.30. Supratenous folds.

8.5.6. Other Miscellaneous Folds. Besides the above described types, there are a few other types of folded structures, like *monocline, homocline, drag folds,* and *chevron folds,* which can be treated as special types of folds and are mentioned here.

(*i*) **Monocline.** Monocline is a local warping in which the otherwise horizontal strata, exhibit an abruptly steep inclination. This inclination of a monocline may sometimes become enormous (*i.e.* almost vertical from horizontal) so that a large difference of elevation between the strata on either side of the bend is introduced. [Refer Fig. 8.31 (*a*)].



(*a*) Monocline (*b*) Homocline

Fig. 8.31

(*ii*) **Homocline.** A homocline actually expresses a sequence of strata dipping in the same direction, at a uniform angle, as shown in Fig. 8.31 (*b*). Generally, such structures constitute the limbs of some major folds like anticlines or synclines.

(*iii*) **Drag Folds.** Drag folds are the minor folds developed within the body of a weaker bed enclosed between two stronger beds. Such folds are developed due to the dragging effects, when the stronger beds happen to slide past the sandwitched weaker bed, in opposite directions, during any major folding operations (Refer Fig. 8.32). The weaker bed is called the *incompetent bed*, and the stronger beds are called the *competent beds.*

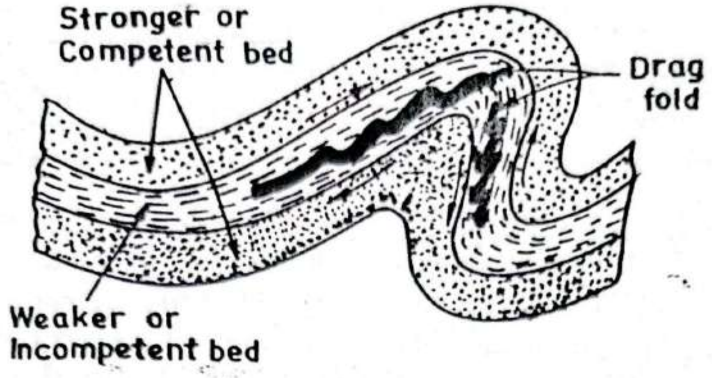


Fig. 8.32. Drag folds.

(*iv*) **Chevron Folds.** Mostly, the folds are rounded along their axial parts. However, sometimes when the axial parts are not rounded and remain pointed, then they are called *Chevron folds* (Refer Fig. 8.33).

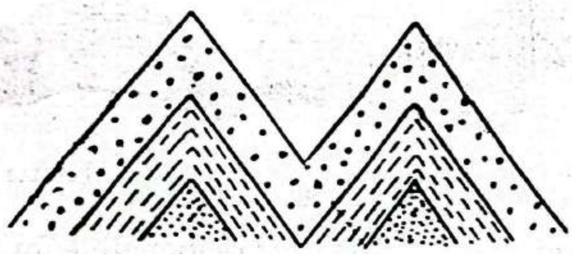


Fig. 8.33. Chevron folds.

8.6. Causes of Folding

Folding of rocks may be caused by numerous factors or causes, which may be divided into two main types, *i.e.*

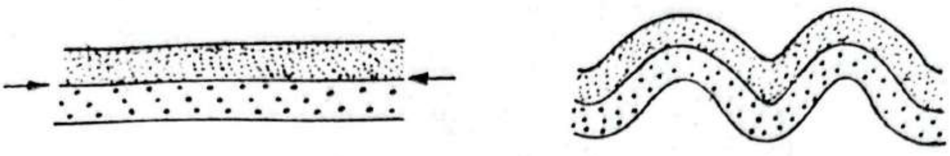
(1) *Tectonic causes* ; and

(2) *Non-tectonic causes*.

8.6.1. Tectonic Causes of Folding. Tectonic causes are those which are produced due to the forces operating within the Earth's crust, such as : (*i*) *lateral compression* caused by shrinkage ; (*ii*) *igneous instructions* ; and *salt instructions* ; etc. These forces are briefly described below :

(*i*) **Lateral Compression.** As pointed out earlier (in chapter 6), it is believed that stresses are developed within the Earth's crust due to *shrinkage*, resulting from the *differential cooling** of the initial hot molten Earth. These compressional stresses developed by shrinkage, are thought to be primarily responsible for throwing the rocks of the crust into undulations and warps (*i.e.* folds) of the severest types, as shown in Fig. 8.34.

**i.e.* the top crust getting cooled rapidly, and the inner part loosing heat subsequently.



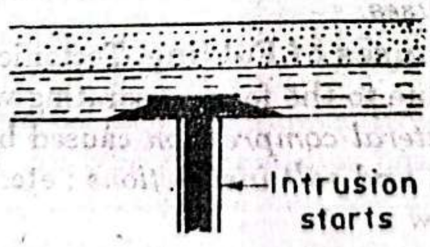
(a) Rocks before folding (b) Rocks after folding
Fig. 8.34. Lateral compression resulting in folding.

When the solid crustal rocks are subjected to such compressional stresses, larger and major folds are developed, and it is known as *flexuer folding*. Whereas, when the pressurised rocks are plastic or viscous, the compression is not fully transmitted, as the material flows only locally, forming buckles or folds of minor nature, only at local places (Refer Fig. 8.35). This is called *flow folding*.

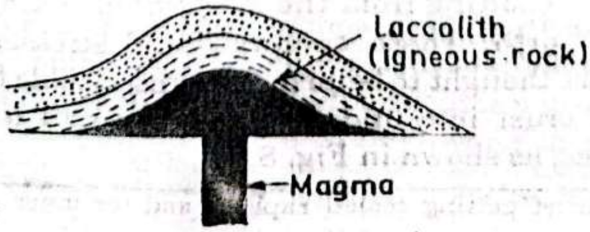
(a) Viscous mass before folding (b) After folding
Fig. 8.35. Flow folding.

Besides such compressional forces responsible for folding, certain people believe, that *shearing stresses* are also developed inside the Earth's crust, which are responsible for causing folding. It is assumed, that in such *shear folding*, huge sized upper blocks move against the lower blocks, exerting dragging effects on them, and thus cause them to buckle, forming folds.

(*ii*) **Igneous Intrusions.** Intrusions of magma from beneath may



(a) before folding



(b) after folding
Fig 8.36. Folding due to intrusion of magma.

result in the folding of the overlying strata, as shown in Fig. 8.36. The anticlinal folds may, thus develop easily during the formation of *laccoliths*.

(*iii*) **Salt Intrusious.** The upward movements of salt bodies under pressure (*i.e.* intrusions) from beneath, may also result in the arching up of the strata above, as shown in Fig. 8.37.

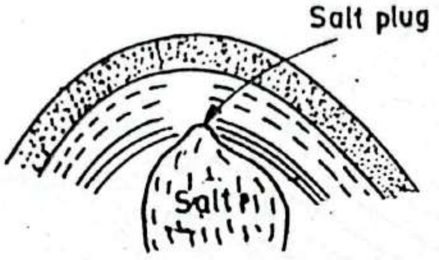


Fig. 8.37. Folding due to intrusion of salt plug or salt dome.

8.6.2. Non-Tectonic Causes of Folding. These include all those rock-folding effects which are effective over the ground surface, resulting mainly under the influence of gravitational force. A few of these causes include : (*i*) *land sliding* ; (*ii*) *creeping* ; (*iii*) *differential compaction* ; (*iv*) *isostatic settling* ; (*v*) subsidence *into solution* cavities ; and (*vi*) *glaciation* ; etc., as explained below :

(*i*) **Landsliding.** Landsliding may sometimes produce folding, when large parts of rock beds slide down the slopes, and get buckled up or folded because of compression produced during their coming to rest. (Refer Fig. 8.38). These are very minor and local folding effects.

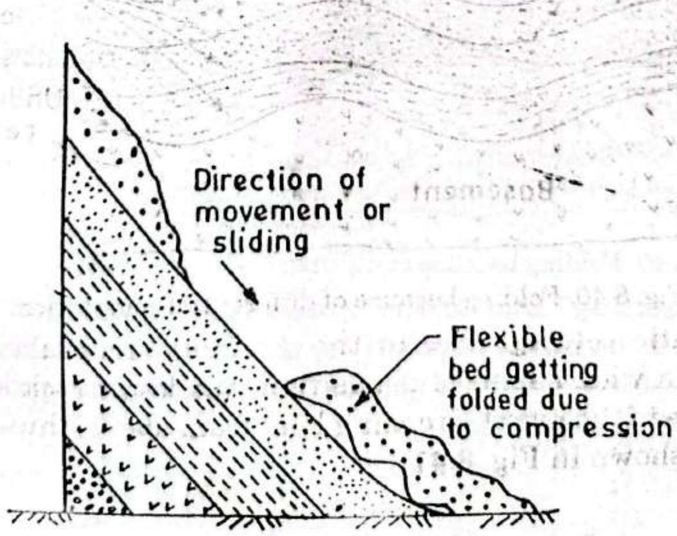


Fig. 8.38. Folding of a flexible bed by landsliding.

(*ii*) **Creeping.** The slow movement or creeping along hill slopes may result in the bending of the weak beds. Rocks like Shales, which are very weak and plastic, may undergo this type of folding. Refer Fig. 8.39. The folding effects, so produced, are very minor and local.

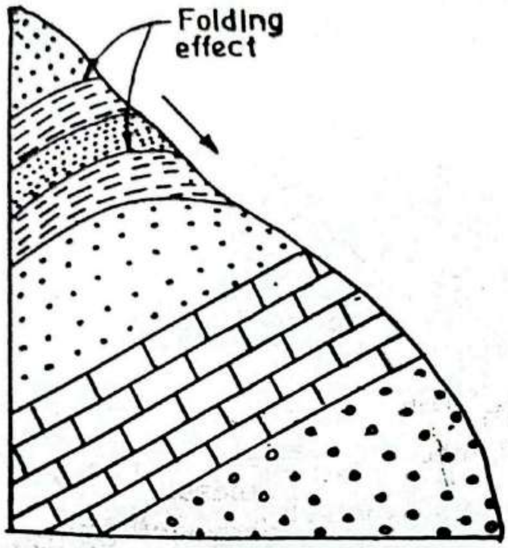


Fig. 8.39. Folding due to creeping along slopes.

(*iii*) **Differential compaction.** During the formation of sediementary rocks, if the underlying substratum is of an undulating relief, the deposited sediments may also acquire similar undulations (folding) on compaction, as shown in Fig. 8.40.

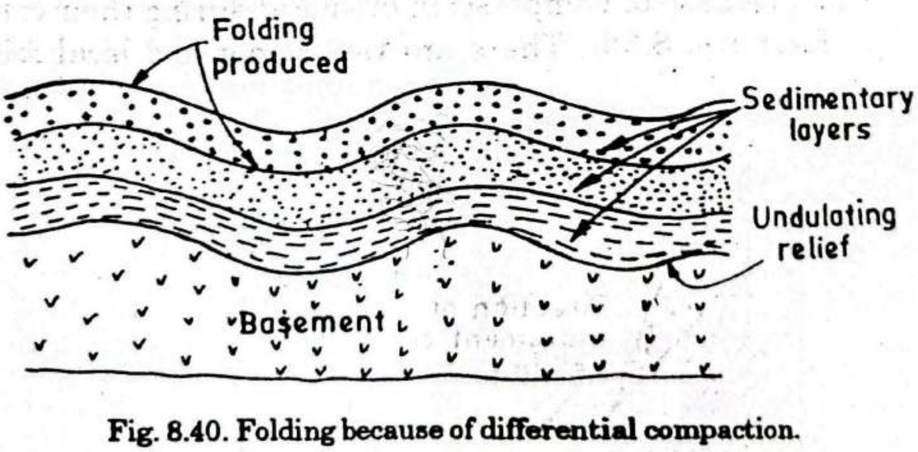
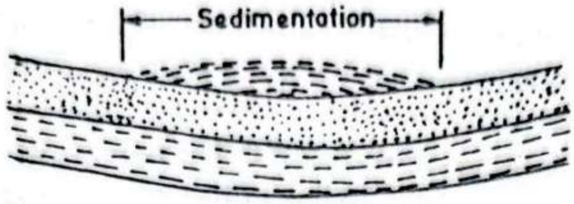
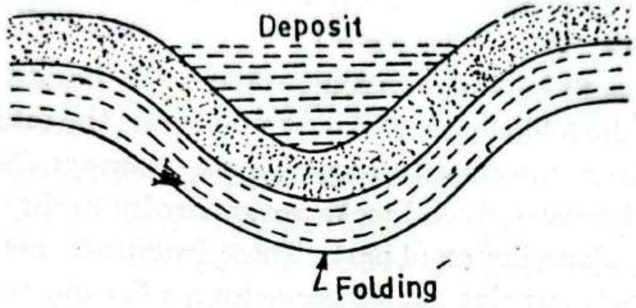


Fig. 8.40. Folding because of differential compaction.

(*iv*) **Isostatic setting.** Due to the gradual accumulation of the sediments in wide basins of deposition, the lower rock layers may get bent due to the ever increasing load from above, thus producing folding, as shown in Fig. 8.41.



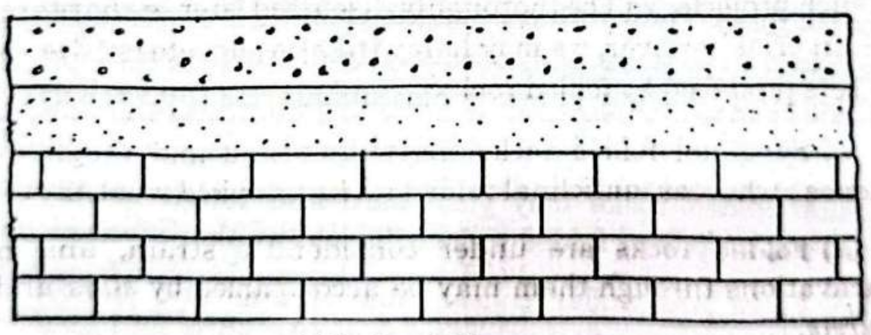
(a) before folding



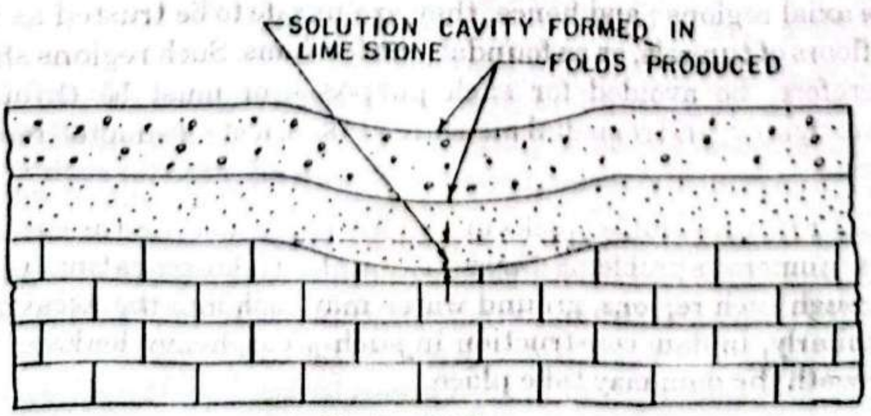
(b) after folding

Fig. 8.41. Folding due to isostatic settling.

(v) **Subsidence into solution cavities.** Solution of some part of an



(a) before folding



(b) after folding

Fig. 8.42. Folding due to subsidence in solution cavities.

underlying formation may result in the subsidence of the overlying beds, thus producing folding effects in these upper layers, as shown in Fig. 8.42.

(*vi*) **Glaciation.** The dragging effect caused by the moving glaciers may sometimes cause warping and folding of the weaker rocks in the glacial valley, thus causing folding.

8.7. Engineering Considerations Involved in Dealing with Folded Rocks

A civil engineer has to be very cautious, while he is handling or excavting through the folded rocks, because whenever, the folds are disturbed, they release the stored energy and may damage the site in various ways. Moreover, folded rocks are generally highly fractured, particularly along the axial parts. These fractures, not only make the rocks *weak*, but also act as channel-ways for the surface waters to percolate through them. Hence, for all major projects, like construction of tunnels, site selection for dams and reservoirs, construction of highways, etc. *due consideration* must be given to the presence of folds. Their influence on the stability and economy of such projects, will be thoroughly discussed later in chapters 14 to 16. In brief however, we may herewith also summarise the various effects produced by folded rocks.

(*i*) Synclinal folded rocks may yield hard and tough quality stones ; whereas, anticlinal folded rocks will yield weaker stones.

(*ii*) Folded rocks are under considerable strain, and hence, excavations through them may be accompanied by *slips* and *rock bursts.*

(*iii*) folded rocks are generally shatterd and weak, particularly in the axial regions ; and hence, they are unsafe to be trusted as roofs or floors of tunnels, or as foundations for dams. Such regions should therefore, be avoided for such purposes, or must be throughly investigated, and remedial measures taken, if at all adopted for such uses.

(*iv*) Fractured folded rocks are highly permeable, and as such may pose numerous problems. Say for example, while excavating tunnels through such regions, ground water may rush into the excavation. Similarly, in dam construction in such areas, heavy leakage from beneath the dam may take place.

(*v*) Since the folded rocks offer great prospects for ground water, they become quite important for engineers searching for water supplies. Infact, artesian conditions are developed only when aquifers are folded (or inclined) as synclines, and are enclosed between top and bottom impervious layers.

(*vi*) The anticlinal folds provide good prospects for stored petroleum ; and hence in oil exploration, folds must not be over looked. Note. For detailed information of this point, please refer chapter 13 on "Economic Mineral Deposits".

FAULTS

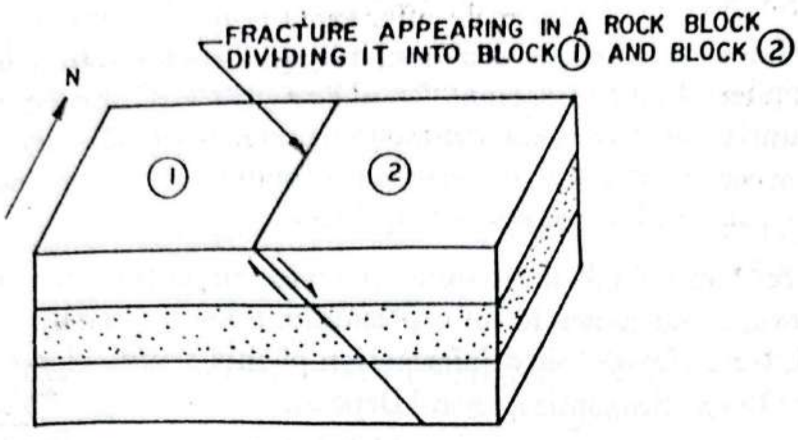
8.8. Definition of Faults and Faulting

It was pointed out earlier that due to the stresses developed within the Earth's crust, the rock formation of the Earth may either get folded or fractured. Folding is generally favoured by the development of compressional stresses within the crust ; whereas, *fracturing* is favoured by the *shearing stresses.* Thus, when such internal shearing stresses exceed the shearing resistance of the rocks (which happens generally with brittle rocks), fracturing does occur. Such fracturing may sometimes be severe, and may result in the dislocation of the fractured rock blocks *along* the *fracture surface,* so that one block moves past the other. Such a rock fracture or *a fracture surface along which relative movement between the fractured parts occurs,* is called a *fault* [Refer Fig. 8.43 (*a*) and (*b*)] ; and the phenomenon of development of such fractures and occurrence of the relative displacement of blocks, is known as *faulting.*

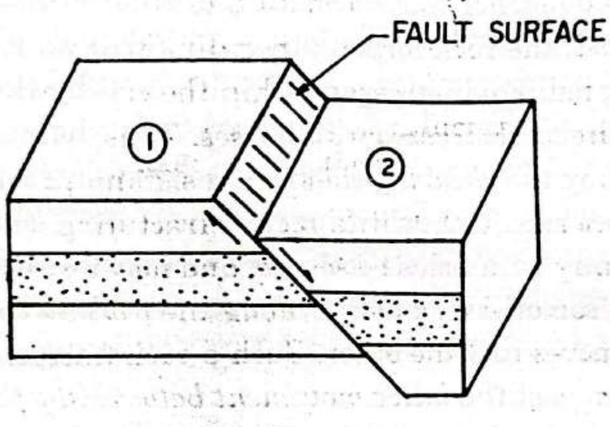
Depending upon the nature and magnitude of stresses and the type of the rocks, the rock bodies may get fractured into different parts (in block), and the relative displacement of blocks may occur for different distances, varying from a few centimetres to many metres. Moreover, this displacement may occur in any direction.

Some faults, even large ones, are clear sharp knife like breaks. Other faults, because of the frictional effects of the rock masses sliding over one another, break or crack (*i.e. brecciate*) the rock on either side of rupture. Still other faults pulverize the rock in the *fault zone** to clay like powder, called *gouge.* Conventionally, the

*The *terms fault zone* or *shear zone* are often applied to closely spaced sub parallel structures along which there has occurred distributive movement.



(*a*) Conditions before faulting. Only a rupture, shown, developed in a block of the crust.



(*b*) Conditions after faulting. Displacement occurring along the fracture surface.

Fig. 8.43: Development of a fault.

surface of rupture along which relative movements have taken place, are known as *fault planes*, but strictly speaking, they are termed as *fault surfaces* because most of the fault surfaces are warped or curved and irregular in detail. The movement on the fault surface may be in any dirction ; and the total displacement on many faults is a cumulative result of intermittent dislocations. Indeed, spasmodic movements along many faults are continuing even to the present ; the displacements along the San Andreas Rift, being the witness within the present century.

A fault is considered as live, if displacements have occurred along it within the recent historic time ; whereas, a fault on which no recent slippage has taken place is considered as *dead*.

8.9. Fault Terminology

The following terminology is frequently used in describing the parts and dispositions of different types of faults :

(*i*) **Fault plane.** The surface along which fracture occurs in the rock body ; and there occurs a relative movement between the so formed rock-parts, is termed as *fault plane* or *fault surface.* Refer Fig. 8.44 (*a*) and (*b*). This surface, may either be exceptionally smooth or much uneven, and it may be in a horizontal, vertical or inclined position.

(*ii*) **Fault trace or Fault outcrop or Fault line.** This may be defined as the line of intersection of a fault plane with the *ground surface*, or with any artificial surface of reference, such as the floor of the tunnel.

(*iii*) **Dip and Strike of the fault.** The inclination of the fault plane, with the horizontal is called the '*dip of the fault*'. It is represented in degrees, and indicates the direction with respect to north, south, east or west. The direction perpendicular to the dip direction is nothing but the '*strike of the fault*' (Refer Fig. 8.44 (*b*)].

(*iv*) **Hade.** Hade is the angle which the fault plane makes with the

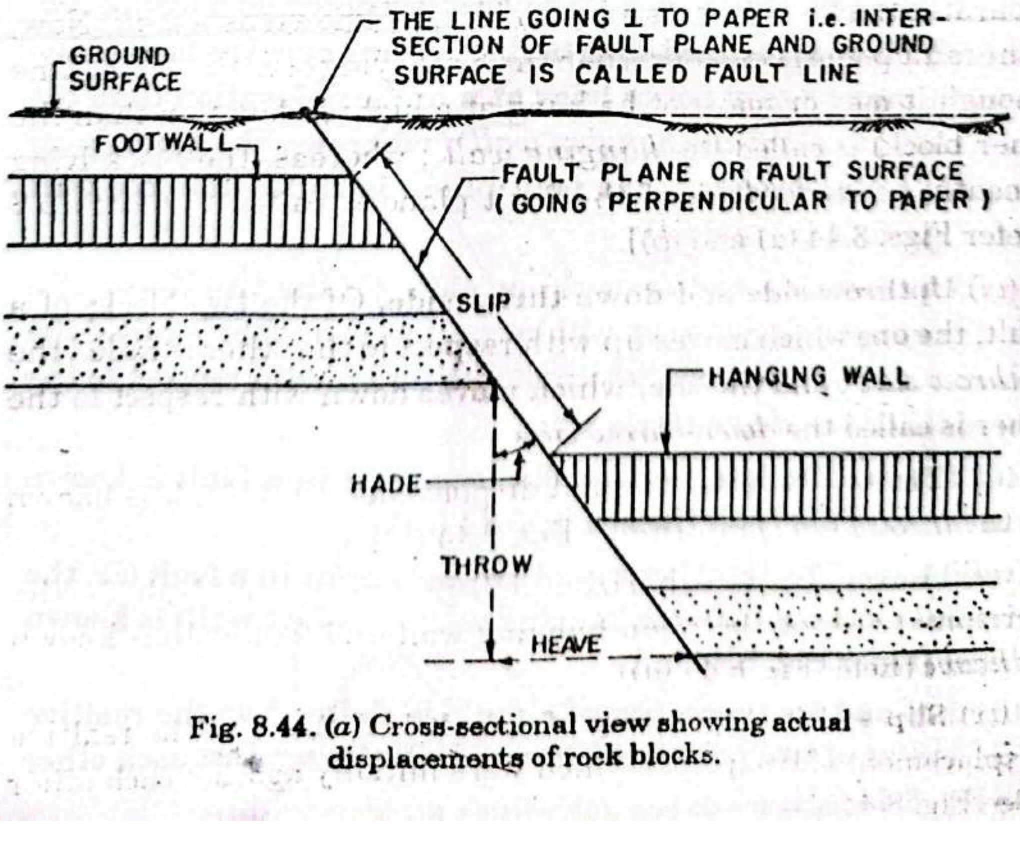
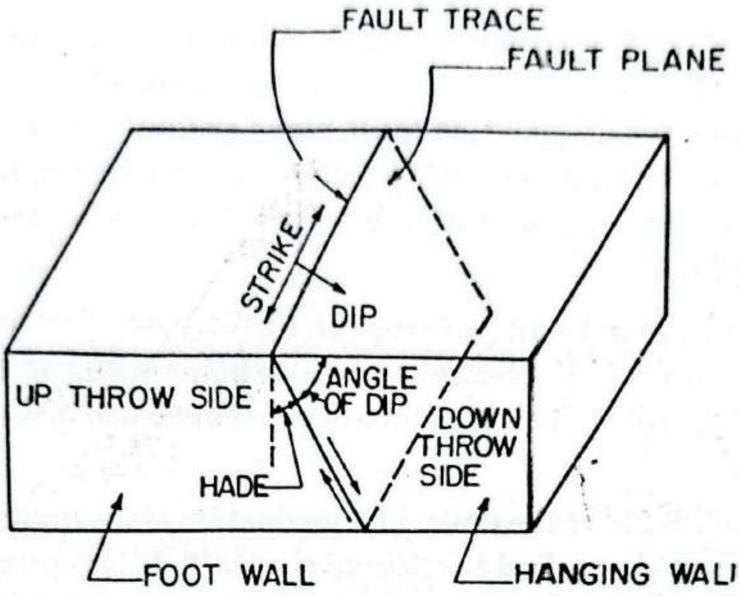


Fig. 8.44. (*a*) Cross-sectional view showing actual displacements of rock blocks.

vertical, as shown in Fig. 8.44 (*a*) and (*b*). **Hade, thus, equals 90° minus the dip of the fault.**



(*b*) Block diagram without showing the actual movement between the blocks.

Fig. 8.44. Fault Terminology explained with reference to a normal faulting in horizontal beds.

(*v*) **Hanging wall and Footwall.** As you know, a fault plane separates the two blocks, and each block is known as a *wall*. Now, if the fault plane is inclined, then the block lying *over* the fault plane (though it may or may not be lying at a higher elevation than the other block) is called the *hanging wall* ; whereas, the block lying beneath, *i.e. underdside* of the fault plane is called the *foot wall* [Refer Figs. 8.44 (*a*) and (*b*)].

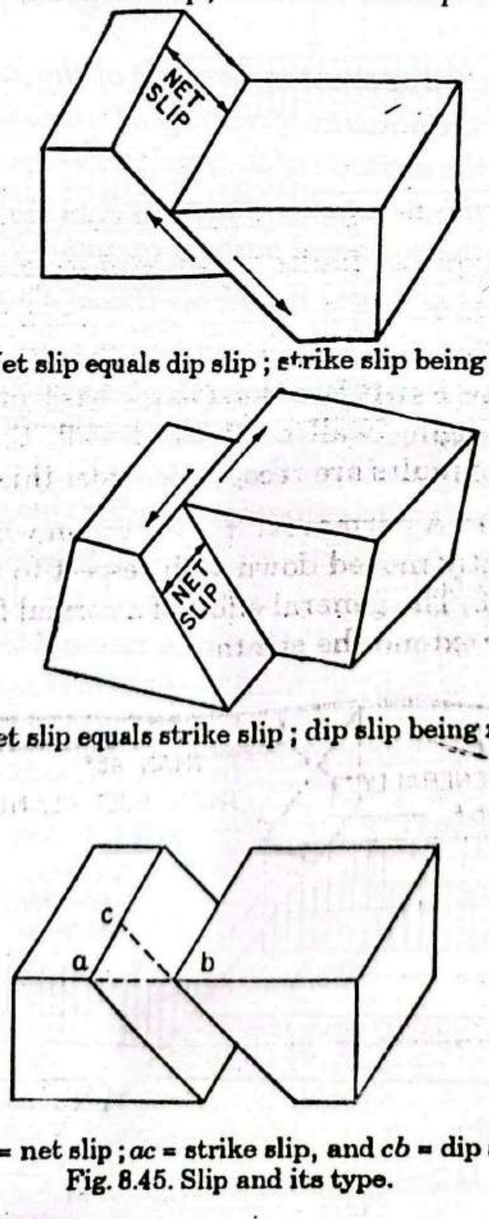
(*vi*) **Upthrow side and down-throw side.** Of the two blocks of a fault, the one which moves up with respect to the other is called the *upthrow side* ; and the one, which moves down with respect to the other is called the *down-throw side*.

(*vii*) **Throw.** The total vertical displacement in a fault is known as the *throw of the fault* [Refer Fig. 8.44 (*a*)].

(*viii*) **Heave.** The total horizontal displacement in a fault (*i.e.* the horizontal distance between hanging wall and foot wall) is known as *heave* [Refer Fig. 8.44 (*a*)].

(*ix*) **Slip and its types.** Slip of a fault is defined as the realtive displacement of two points which were initially against each other [See Fig. 8.44 (*a*)].

Further, the maximum displacement is known as *Net slip* ; displacement along the strike of the fault plane is known as *Strike slip* ; and the displacement along the dip of the fault plane is known as *Dip slip*. Say for example, in Fig. 8.45 (*a*), the displacement is shown only along the dip of the fault ; and hence in this case, the net slip is equal to the dip slip, while strike slip is zero. In Fig. 8.45 (*b*), the displacement is shown only along the strike of the fault, and hence in this case, the net slip is equal to the strike slip, and dip slip is zero. In Fig. 8.45 (*c*), the displacement is shown in a direction other than the dip strike direction ; and hence in such a case, the maximum displacement *ab* will be the *net dip*, which has two components, *i.e. ac*—the *strike slip*, and *cb*—the *dip slip*.



(*a*) Net slip equals dip slip ; strike slip being zero.

(*b*) Net slip equals strike slip ; dip slip being zero.

(*c*) *ab* = net slip ; *ac* = strike slip, and *cb* = dip slip.

Fig. 8.45. Slip and its type.

(*x*) **Slicken sides.** The moving blocks in a faulting, may cause a lot of scratching on one another along the fault plane. Due to this scratching, sometimes, *striations* or *grooves* may be produced. Such striated or grooved surfaces produced by faulting are called *slicken sides*. Slicken sides are important evidence of faulting and are even helpful in indicating the *direction of movement* of blocks during faulting, which is indicated by the ridges or irregularities (sometimes diffcult to notice) running across the striations.

8.10. Types of Faults and their Classifications

Various important types of faults may be classified on the following basis :

(1) on the basis of *the apparent movement of the fault blocks* ;

(2) on the basis of *the amount of the dip of the fault* ;

(3) on the basis of *the attitude of the fault* ;

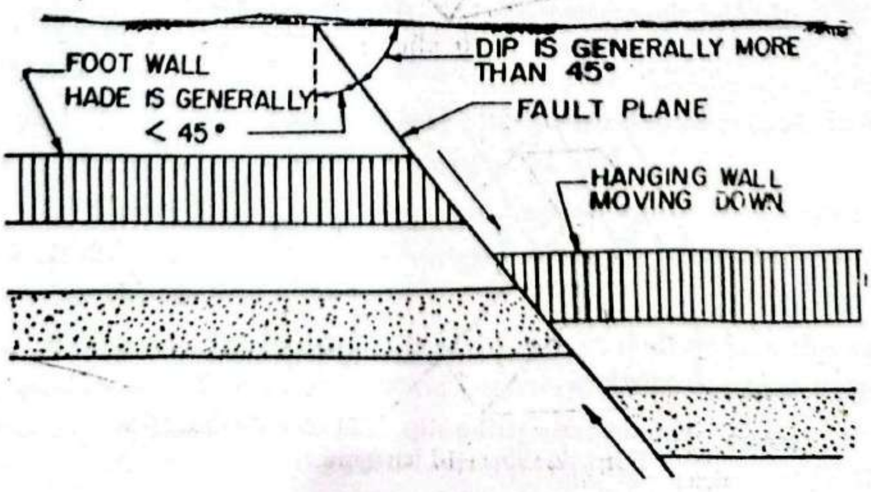
(4) on the basis of *the direction of the net slip* ; and

(5) on the basis of their *general pattern* or mode of occurrence.

The different types of faults based on these classifications are given below :

8.10.1. Classification of Faults on the basis of the Apparent Movement of the Fault Blocks. On the basis of the up or down motion of the hanging wall or the foot wall, the following two important types of faults are recognised under this classification :

(*i*) **Normal fault.** A normal fault is the one in which the *hanging wall* has apparently moved down with respect to the *foot-wall*, as shown in Fig. 8.46. The general effect of a normal fault on the beds is to pull apart or extend the strata.



These normal faults in which the hanging wall has actually gone down relative to foot wall are known as **gravity faults**. The fault planes of majority of normal faults dip more than 45° (*i.e.* angle of hade > 45°), although less steep normal faults are also known.

(*ii*) **Thrust fault.** A *thrust fault* or a *thrust* is one in which the hanging wall has apparently *moved* up with respect to the foot wall, as shown in Fig. 8.47. The general effect of a thrust fault is to *shorten* the rock strata, as against their extension in a normal fault.

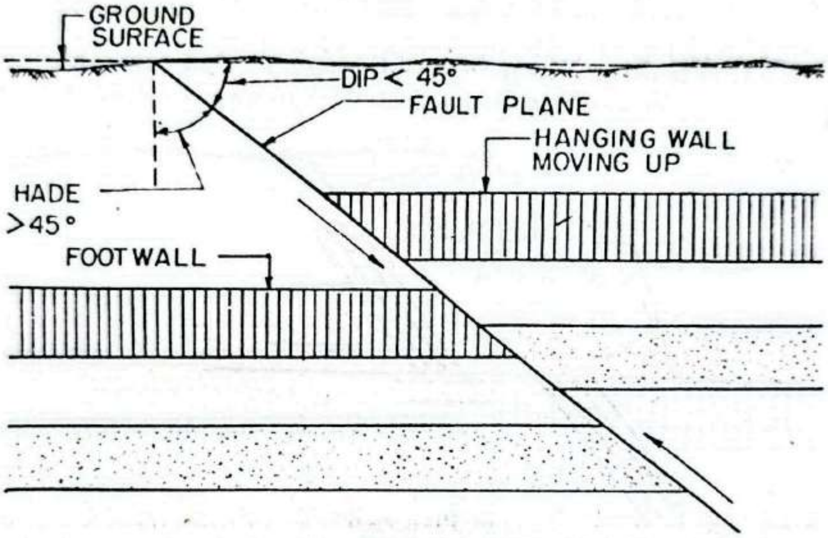


Fig. 8.47. Thrust fault.

In thrust faults, three categories are generally recognised on the basis of their dips. A **reverse fault** is that thrust which dips more than 45° ; a **thrust fault** is that thrust which dips less than 45° ; and an **overthrust fault** is the one which dips less than about 10° and has a large net slip.

(*iii*) **Transcurrent fault** or **Tear fault** or **Transverse fault.** It is that fault inwhich the blocks have moved against each other in an essentially *horizontal direction*, as shown in Fig. 8.48.

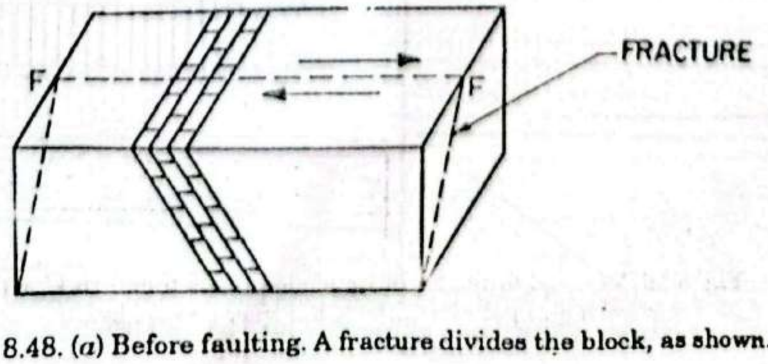
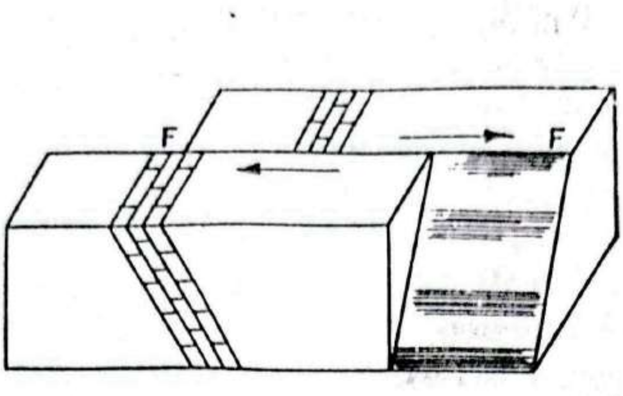
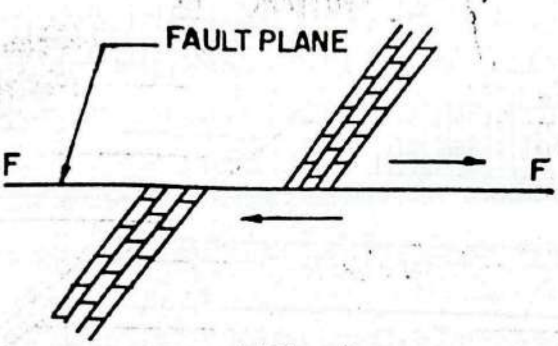


Fig. 8.48. (*a*) Before faulting. A fracture divides the block, as shown.



(b) After faulting. The movement taking place horizontally in the directions indicated by arrows.



(c) Plan view

Fig. 8.48. Transcurrent or Tear fault.

(iv) **Vertical fault.** That fault in which the fault plane is vertical, and the resulting movement of blocks is also in vertical direction, is termed as *vertical fault*. In such a fault, since neither of the blocks hangs over the other, there is no hanging wall or footwall as such.

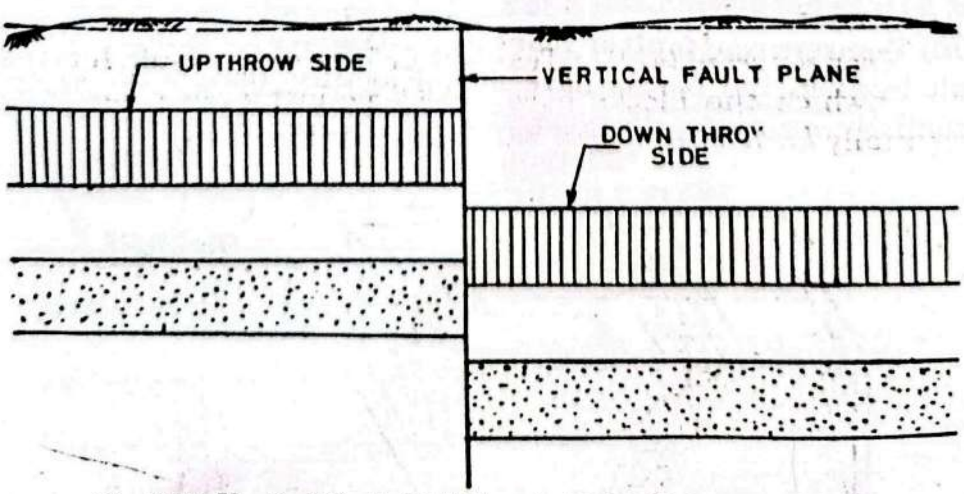


Fig. 8.49. Vertical fault. Right hand side block (eastern block) shown going down, although it may go up also.

The blocks on either side of the fault can move up or down w.r.to the other. Say for example in Fig. 8.49, the right hand side block is shown as moving down, although it can move up also.

Evidently, in a vertical fault, there is no dissimilarity in the look or orientation in space of the two blocks, as occurs in an inclined fault.

8.10.2. Classification of Faults based on the Amount of the Dip of the Fault. Based upon the amount of the dip of the fault, two important types of faults are generally recognised.

(*i*) **High angle faults.** These are those faults in which the fault plane dips steeply, at angles more than 45°, as generally happens in normal faults. Refer Fig. 8.50.

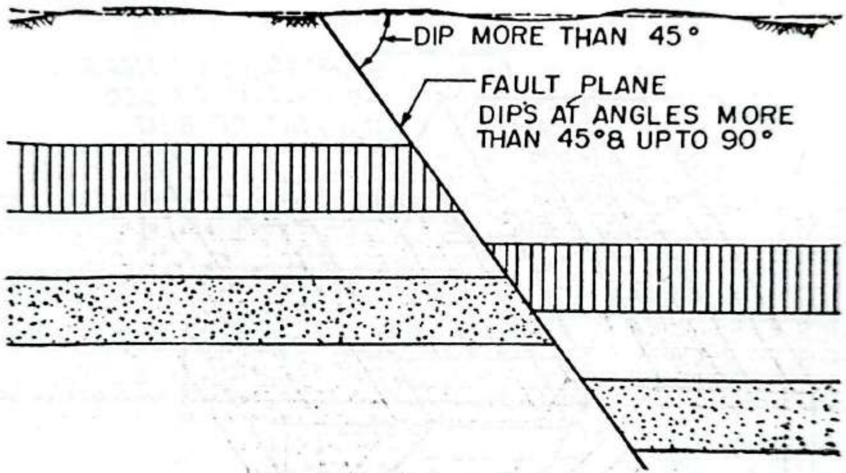


Fig. 8.50. High angle fault.

(*ii*) **Low angle faults.** These are those faults in which the fault plane dips gently at angles less than 45°, as generally happens in thrust faults. Refer Fig. 8.51.

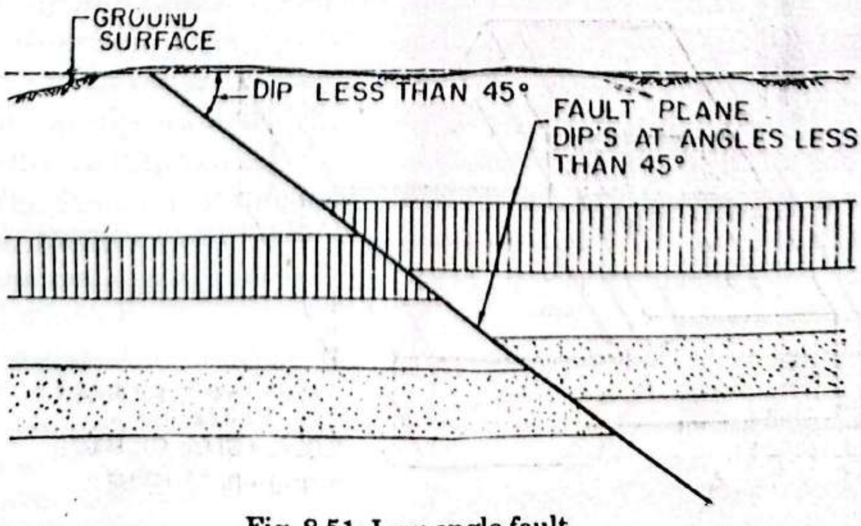


Fig. 8.51. Low angle fault.

8.10.3. Classification of Faults on the basis of the Attitude of the Fault. The relationship between the attitude (*i.e.* dip and strike) of the fault plane, and the attitude of the adjacent beds, has been used in describing many types of faults. *This relationship refers merely to the relations as observed in plan—that is on the geological map.* On this basis, there are three possibilities ; *i.e.* the fault plane may strike (*i*) parallel to, or (*ii*) normal to ; or (*iii*) obliquely to the strike of the regional beds. Depending on these three possibilities, we can have three types of faults, *i.e., strike fault*; *dip fault* ; and *oblique fault*, as given below :

(*i*) **Strike fault.** A strike fault is that in which the strike direction of the fault plane is essentially parallel to the strike direction of the

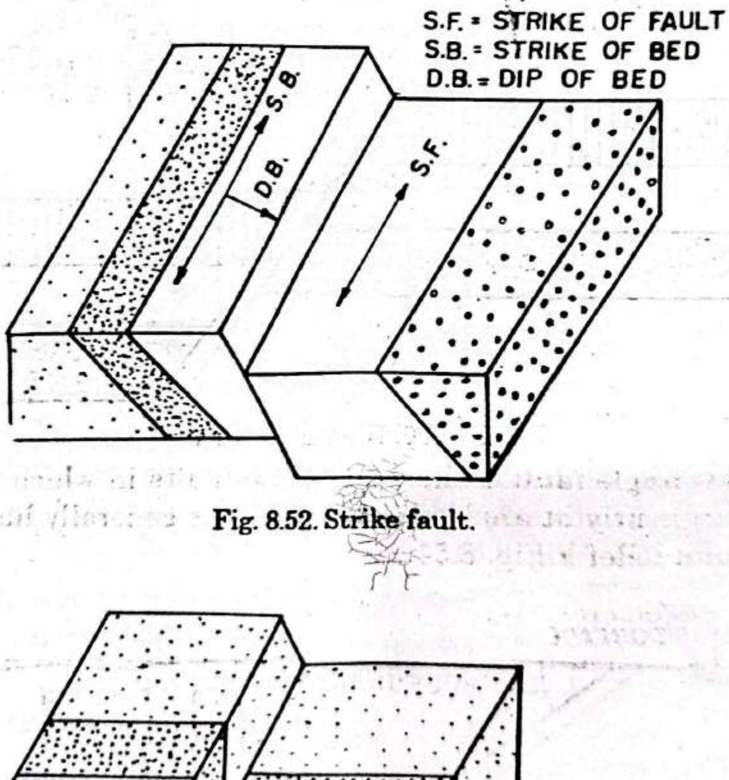


Fig. 8.52. Strike fault.

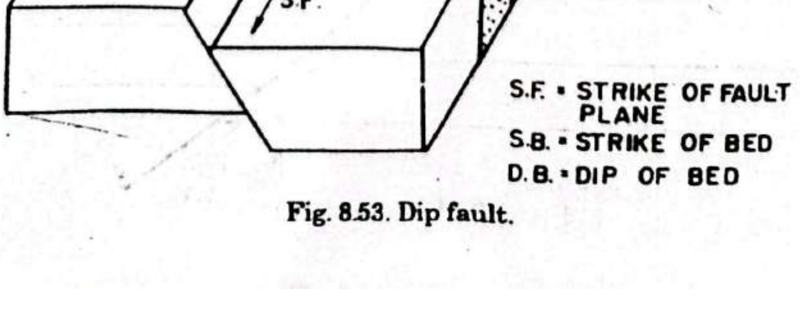


Fig. 8.53. Dip fault.

adjacent beds. In other words, the *fault strikes* along the strike of the disrupted beds. Refer Fig. 8.52.

(*ii*) **Dip fault.** A dip fault is that in which the strike of the fault plane is essentially normal (perpendicular) to the strike of the adjacent beds, as shown in Fig. 8.53. Such a fault, therefore, strikes parallel to the direction of dip of the adjacent beds.

(*iii*) **Oblique fault.** An *oblique* or *diagonal fault* is that in which the fault plane strikes the beds neither parallelly nor normally, but strikes obliquely or diagonally. And hence, the strike of the fault is neither along the dip nor is along the strike of the beds. Refer Fig. 8.54

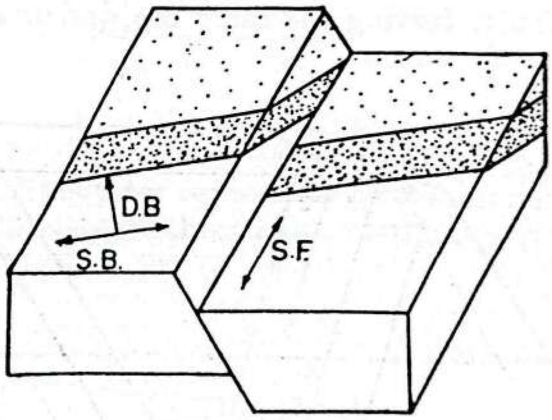


Fig. 8.54. Oblique fault.

8.10.4. Classification of Faults based on the direction of the Net Slip of the Fault. On this basis, the following three types of faults are recognised :

(*i*) **Dip Slip faults.** These are those faults in which the net slip is in the direction of the dip of the fault. In other words, in such faults, displacement takes place only along the dip of the fault, and net slip equals dip slip, as strike slip being zero. [Refer Fig. 8.45 (*a*)].

(*ii*) **Strike Slip faults.** These are those faults in which the net slip is in the direction of the strike of the fault. In other words, in such faults, displacement takes place only along the strike of the fault, and the net slip equals the strike slip as dip slip being zero. Refer Fig. 8.45 (*b*).

There are two common types of strike slip faults ; as indicated below :

(*a*) **Wrench fault** is a *strike-slip fault* in which the dip of the fault plane is very steep, nearly vertical, and in their general behaviour, they are *transverse* to the regional structures. They are also called *tear faults* or *transverse faults*.

(*b*) **Rift fault** is also a strike slip fault, which, unlike the *wrench fault*, is *parallel* to the regional structures. When an exceptionally large block subsides between the two such parallel faults, a *rift valley* is produced.

(*iii*) **Oblique Slip faults.** These are those faults in which the net slip is neither along the dip nor along the strike of the fault, rather it is oblique. Refer Fig. 8.45 (*c*).

8.10.5. Classification of Faults on the basis of their General Patterns or Mode of Occurrence. In their actual existence, the faults may exhibit a variety of relations with each other, and also with the surrounding region ; thus forming some typical general patterns. Depending on such patterns or their mode of occurrence, faults may be divided into the following important types.

(*i*) **Parallel faults.** This term is used to express the occurrence of a number of faults having the same dip and strike, as shown in Fig. 8.55.

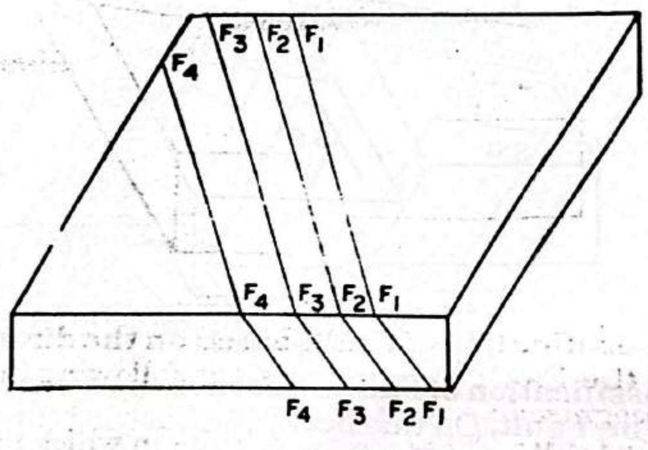


Fig. 8.55. Parallel faults.

(*ii*) **Radial faults.** These comprise a group of faults that are

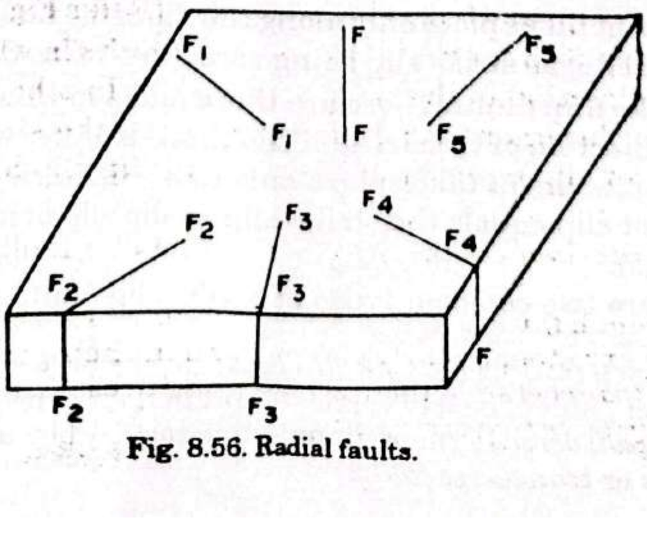


Fig. 8.56. Radial faults.

arranged in a radial manner. Consequently, these faults appear to be radiating from a common point. Refer Fig. 8.56.

(*iii*) **Enchelon faults.** This term is used to express a group of faults that overlap one another, as shown in Fig. 8.57.

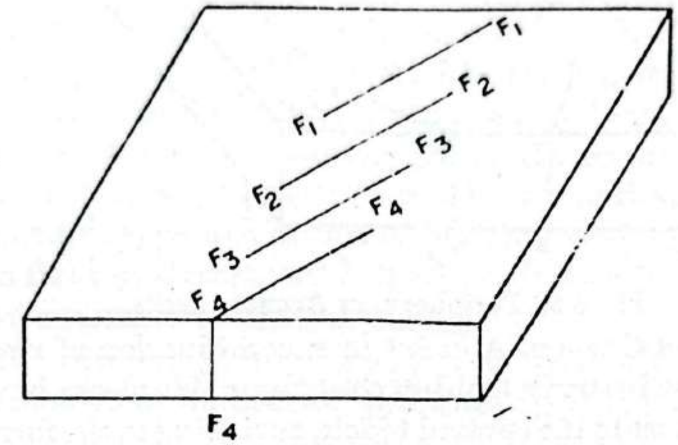


Fig. 8.57. Enchelon faults.

(*iv*) **Step faults.** This term represents a combination of parallel faults, in which the beds are thrown into step-like arrangement, as shown in Fig. 8.58.

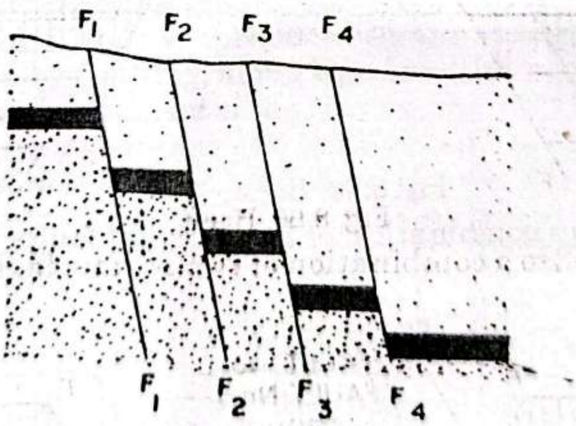


Fig. 8.58. Step faults.

(*v*) **Peripheral faults.** When in a given region, the faults are curved or *arcuate*, and they are arranged in a peripheral manner, enclosing a more or less circular area, as shown in Fig. 8.59, then this system of faults is known as *peripheral* or *arcuate faults*.

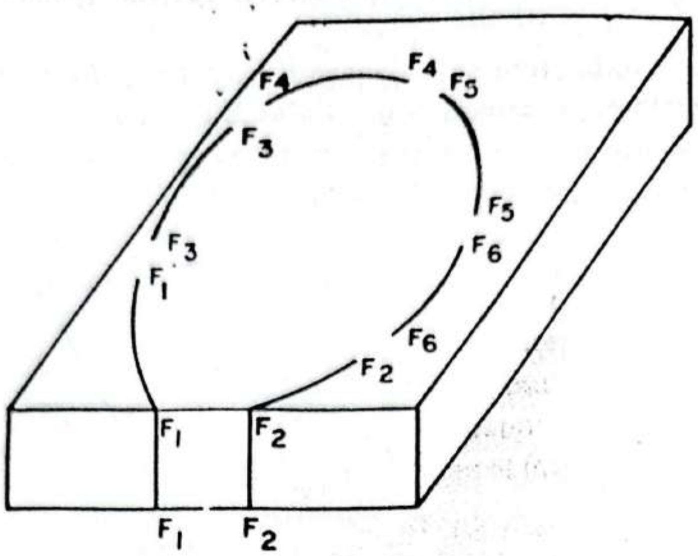


Fig. 8.59. Peripheral or Arcuate faults.

(*vi*) **Horst and Garben.** A *horst* is a combination of two normal faults, occurring in such a fashion that their side blocks have moved down with respect to the central block, resulting in the formation of a raised land mass, as shown in Fig. 8.60.

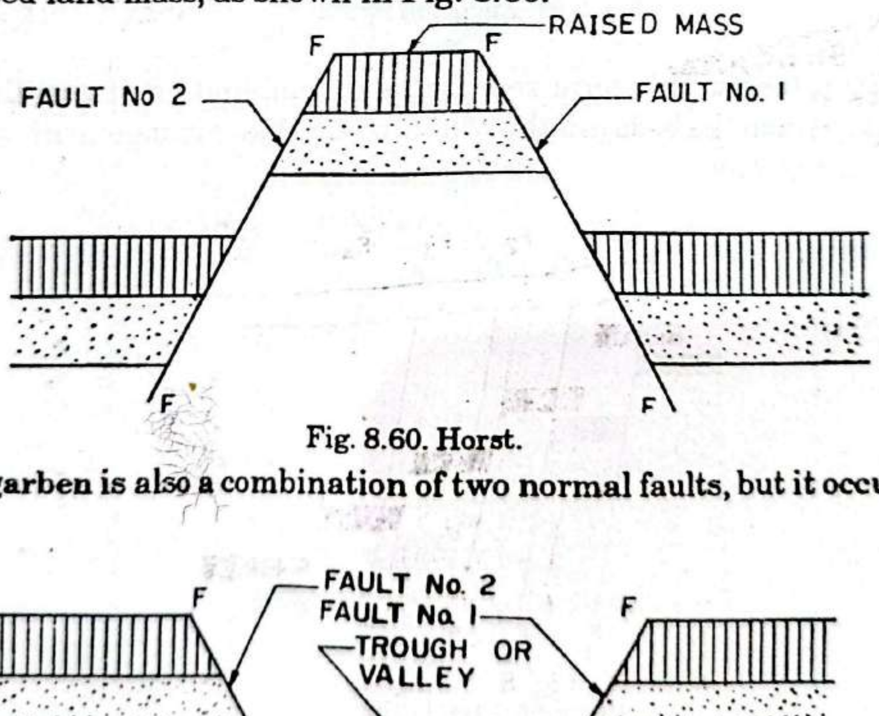


Fig. 8.60. Horst.

A garben is also a combination of two normal faults, but it occurs

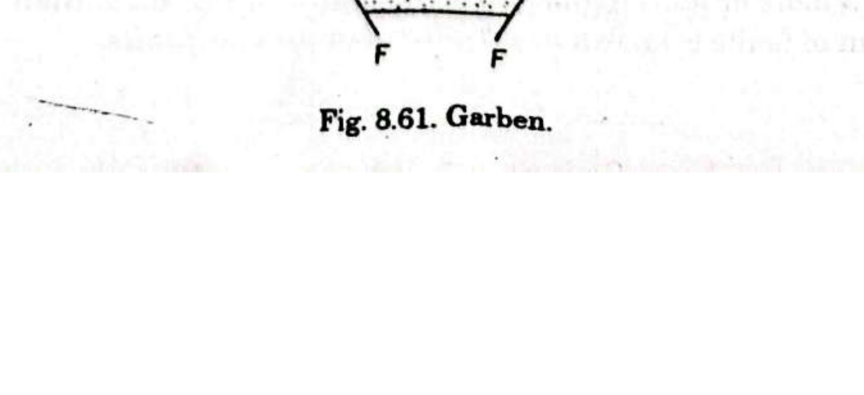


Fig. 8.61. Garben.

in such a way that the central block has moved down with respect to the side blocks, resulting in the formation of a trough or a valley, as shown in Fig. 8.61.

8.11. Recognition of Faulting in the Field

Faults are generally recognised in the field, not by direct observations in the field, but by drawing inference from the *lithological* and other *physiographical* evidences available in the given area. These evidences are the results of the effects produced by faulting ; and hence, if sufficient data is available regarding these effects, and if the data are interpreted properly, much can perhaps be known about the nature, type and extent of faulting in the given region. The various field evidences which help us in detecting faulting in the field, are summerised below :

8.11.1. Lithological Evidences for Recognition of Faults. A variety of lithological features are associated with faulting. Among the most significant of these features are :

(*i*) *slicken sides* ; (*ii*) *brecciation* and *gouge* ; (*iii*) *shear zones* ; (*iv*) *abnormal behaviour of strata*, such as (*a*) its abrupt termination, (*b*) repetition and omission, and (*c*) offset, etc. These features are briefly described below :

(*i*) **Presence of slicken sides.** A rock surface can be recognised in the field, as having been produced by faulting, if it is found polished, and contains striations or grooves. Such striations or grooves are called *slicken sides*. They are produced by the movement of the rock blocks, produced by faulting, along this fracture surface.

The direction of movement of the rock blocks, that has taken place in the past, can also be inferred to some extent, by the inspection of these striations, and by passing the hand over the surface to find the rough and smooth directions. A slicken-sided surface from which a determination of the direction of relative displacements can be

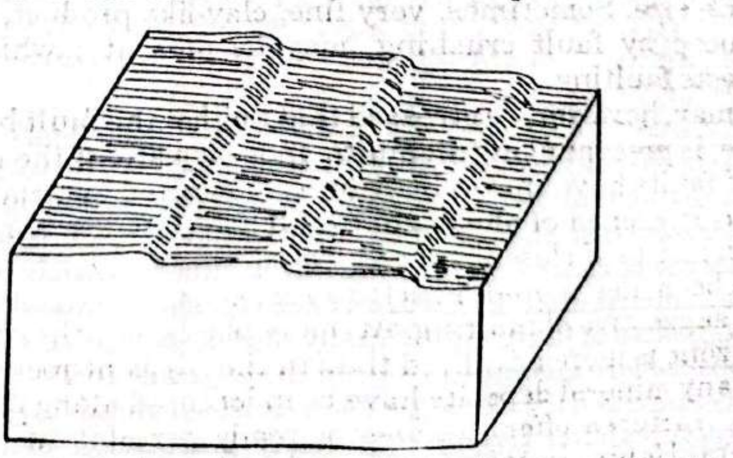


Fig. 8.62. Slicken-sided surface showing relative movement. Note the step-like surface, shown exaggerated in the figure.

made by this method, is shown in Fig. 8.62. A photoview of slicken sided surface is also shown in Fig. 8.63.

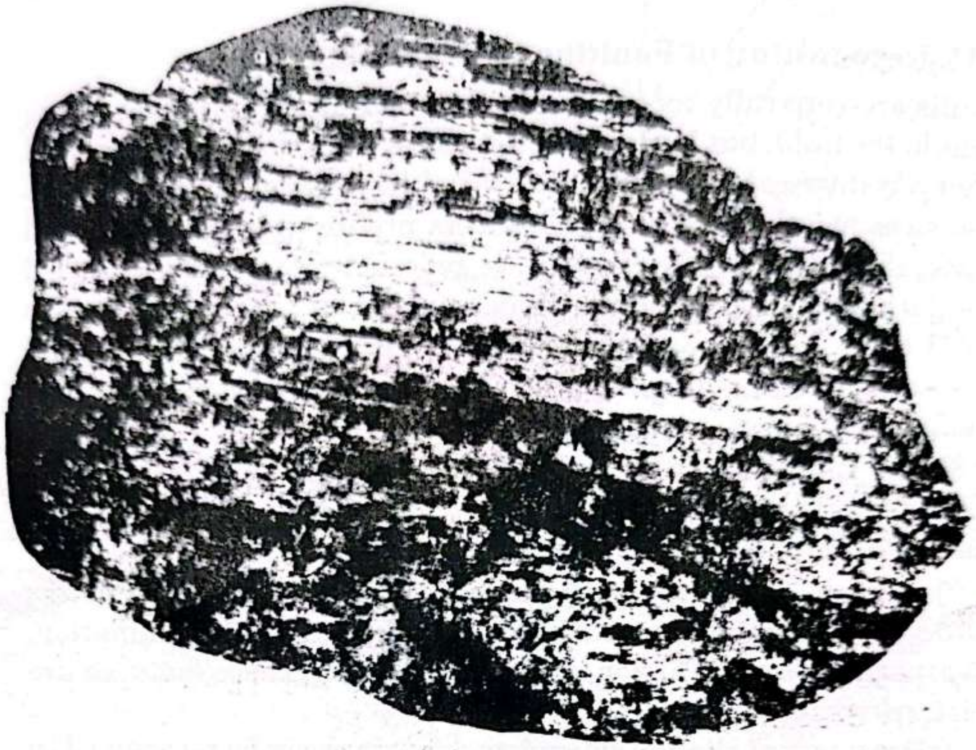


Fig. 8.63. A photoview of a Slicken-sided surface.

(*ii*) **Presence of brecciation and gouge.** Along some of the faults, the rocks may be highly fractured or even crushed to angular fragments, called *breccias*. The presence of an elongated zone of brecciation which transects bedding is, therefore, suggestive of faulting. These angular fragments or breccias are extremely variable in their dimensions. In some fault breccias, the fragments may be measured in a few metres ; and in others, perhaps in those originating at greater depths, these rock fragments may be of very minute size. Sometimes, very fine, clay-like product, called *gouge*, produced by fault crushing, may be present ; which of course, suggests faulting.

It may, however, be stressed that neither the fault breccia nor the gouge, is present along all faults. Indeed, many of the major investigated faults have shown little or no associated brecciation or gouge.

(*iii*) **Presence of shear zones.** Many faults are characterised by the presence of closely spaced fractures, among which movements have been distributed. Fracture zones (*i.e.* shear zones) are, therefore, suggestive of faulting. At many places, weathering along fracture zone is more advanced than in the adjacent rocks.

Many mineral deposits have been localised along faults, because such fractures offer avenues of ready percolation of circulating waters. Hence, in many ancient faults, such fractures have been completely sealed and healed by mineral fillings and replacements.

(iv) Abnormal behaviour or dislocation of strata. In any given region, if the rock strata are not found arranged in a normal sequence, it is indicative of some kind of geological disturbance, that had disturbed the rocks. The following abnormalities, if found in the behaviour of the existing rock strata, will be especially suggestive of faulting :

(a) *Abrupt termination of strata.* An abrupt termination of structures, such as, folds, beds, dykes, etc., along common line or zone, is suggestive of faulting. This is because, such a thing may happen during faulting due to breaking of the strata into blocks, and movement of the either block in a downward or lateral direction, causing such a break in the continuation of strata on either side of

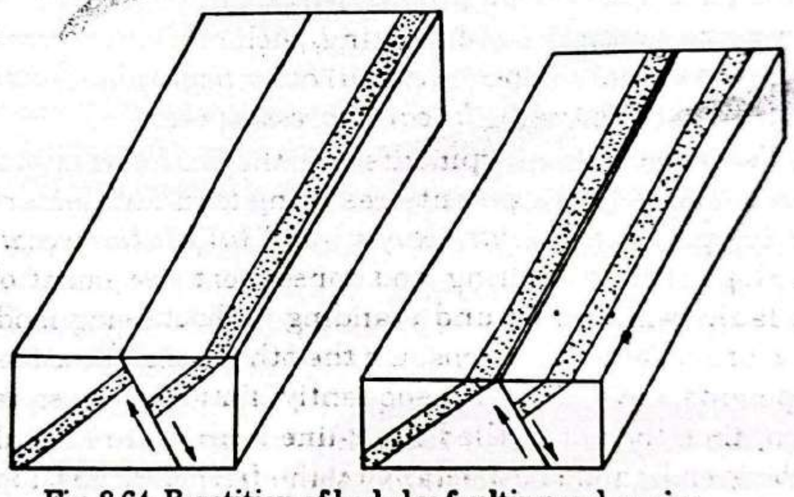


Fig. 8.64. Repetition of beds by faulting and erosion.

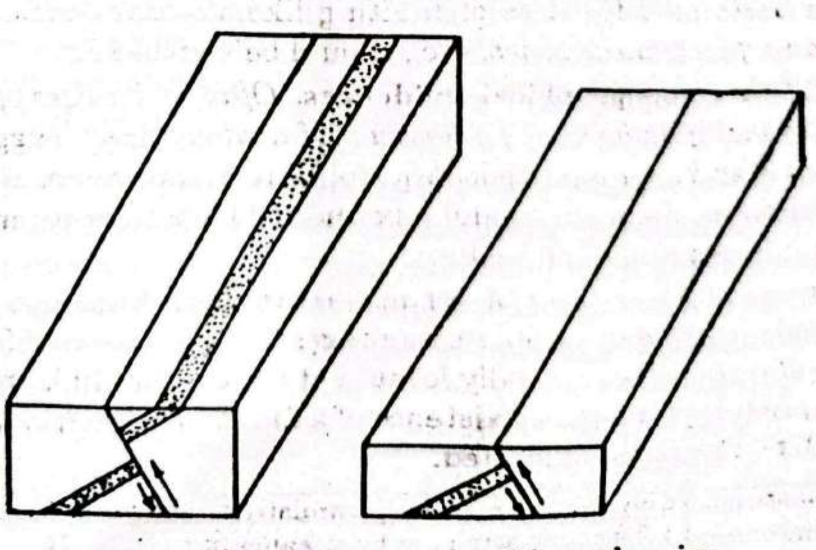


Fig. 8.65. Elimination of beds by faulting and erosion.

the fault plane. Sometimes, the two parts may still be visible after displacement, which is a conclusive evidence of faulting.

(*b*) *Repetition and Omission of strata*. The repetition or elimination of recognisable beds, often establishes the break in the continuity of the strata, thus indicating faulting (Refer Figs. 8.64 and 8.65).

(*c*) *Offsetted beds*. Disruption of beds due to faulting generally results in their displacement, which may be determined in terms of slips, separation, and offset. When such *displacement* is noticed, faulting is indicated.

8.11.2. Physiographical Evidences for Recognition of Faults. Landscape forms, or physiographic features, sometimes offer reliable indications of existing faults in a given region. Such features may either be seen in the field or recognised on maps or aerial photographs. Among the important physiographic features, which may be suggestive of faulting, include : (*i*) *escarpments* (*i.e.* sudden and unusual slopes) ; and (*ii*) *other topographic features like springs arranged linearly*, *linear depressions*, etc.

(*i*) **Escarpments.** Escarpments are the linear forms of abrupt increase of slope. Escarpments resulting from faulting are of two general types ; *i.e.* (*i*) *fault scarps* ; and (*ii*) *fault-line scarps*. The steep slopes left by faulting and consequent movement of blocks along faults which are found standing without being modified by erosion are called **fault scarps.** On the other hand, if the steep fault escarpments have been consequently flattened or softened by erosion, then they are called **fault-line scarps.** Care should, however, be exercised, and especially by the fresh geologists, to ensure that they do not misinterpret a *cliff** as a fault scarp. For this reason, other associated features of faulting like *dislocated beds, slicken sided surfaces, shear zones,* etc., should be searched for.

(*ii*) **Other topographical evidences.** *Offsets of ridges, parallel deflections of valleys, and reversals of drainage*, may suggest the presence and approximate location of a fault. The presence of linear depressions or shallow troughs bounded by fault scarps, may also indicate the presence of faults.

Presence of a number of springs arranged in a line (*i.e.* springs formed along a fault trace) is also suggestive of some recent faulting. If such springs are especially located at the base of a hill, and are of *hot spring* type, then the existence of a fault along the spring line is much more strongly indicated.

* Cliffs are formed in many ways, entirely unrelated to faulting, say for example, by marine erosion, by glacial action, or by stream cutting.

Sometimes, the local deviation of a stream from its main course may also be due to a fault cutting across it, and, thus, be indicative of faulting.

All such physiographic evidences may help a geologist in investigating the presence of a fault. It may, however, be emphasised that physiographic evidences of faulting, are seldom conclusive. The more recent the faulting, the better will be the available physiographic evidences. But for old faults, such evidences may not be available. In any case, taken in conjuction with other lithological evidences, physiographic evidences of faulting are quite helpful and significant.

8.12. Causes of Faulting

Faults are essentially the shear or sliding failures, resulting from tensional, compressional, or rotational stresses acting on the crustal rock masses. As pointed out earlier, the exact reason for the evolution of these internal forces or stresses, are not very well understood even uptill now. They may be due to the *shrinking Earth* ; or due to the *convection currents* produced in the Earth, or due to some other reasons, as discussed under various theories given in article 6.18.

Just as we are not sure regarding the origin of these internal forces, we are also not sure regarding the nature and magnitude of the forces involved in the development of different types of faults. What is known is mostly theoretical and suggestive of possibilities. Thus, the two important types of faults, are assumed to be formed as follows :

Normal faults or gravity faults are assumed to have been formed under the influence of *horizontal tension*, whereby the crust would rupture or fail along vertical or nearly vertical fractures. Such faults are, therefore, sometimes called as *tension faults*. Such tensile forces may also give rise to shear stresses along some rocks, causing shear fractures.

Thrust faults may be assumed to be originating from *compressive stresses*, which may throw the rocks into folds, and these intensely folded rocks getting fractured and faulted under *shear*, at a later date. These reverse faults are therefore, sometimes called *compressional faults*.

It may also be mentioned here that faults occur in abundance in volcanic areas and mountain zones, although however, they are found in plains and plateaus also.

8.13. Engineering Considerations Involved in Dealing with the Faulted Rocks

Faulted rocks generally offer unstable sites from engineering considerations, not only because there has been displacements along the fault(s) in the past, but also that *further fresh movements may take place at any time in future*. Thus, if a structure is constructed on such rocks, then any future movements along the fault plane(s) may endanger the stability of the structure, and thus causing it to collapse.

Hence, an engineer, as a general rule, must try to avoid locating any of his *major structures* on fault or rather even in its vicinity. This is much more necessary to follow in the region where fault(s) have been *active* in the recent past. Scattered projects like installation of electric or telegraphic poles may, however, be undertaken even in faulted regions, without much of a risk.

Nevertheless, sometimes, it becomes necessary for an engineer to design and construct even his major structures in moderately faulted regions. In such cases, *precautions* must be taken to avoid any major failures, either by *seismic effects* caused by movements along the faults, or due to *heavy leakage* that may take place through the faulted rocks. The improvement works in faulted rocks, such as excavation of weaker material from the fault zone and refilling or *grouting* it with cement concrete, etc. may therefore, become necessary. The *additional safety factors* in designs and constructions as discussed earlier under "Earthquakes", may also have to be adopted.

Note. More detailed description of the relationships of faults to the construction of individual major structures, like dams, reservoirs, tunnels, roads, etc. is discussed in chapters 14 to 16.

JOINTS

8.14. Joints, Their Definition, Nature, and Attitudes

Joints may be defined as *cracks* or *fractures* present in the body of a rock, along which there has been no relative movements as happen in the case of faults. These joints, thus, divide the rock into parts or blocks, but these blocks are not moved past each other, except for some slight opening in some cases.

These joints or cracks may be of small sizes extending only for a few centimetres in length, or may be extremely extensive. Moreover, the joints may be either *open* or *closed*. **Open joints** are those in which the blocks are separated or 'opened out' for some small widths in a direction at right angles to the fracture surface. In **Close joints**, however, there is no such separation.

Very commonly, the joints in the rocks develop, on some more or less regular fashions. They, thus, tend to develop mainly in *sets* or *groups* (a number of parallel joints constituting a *set* ; and a number of joint-sets with the same general trend, forming a *group* of joints or *joint system*). Moreover, a rock is generally traversed profusely by various joints, but some of them may be more prominent and well developed, extending continuously for considerable lengths, as compared to others. Such *prominent* joints are called **master joints** or **major joints.**

As in the case of beds or faults, the inclination of a joint plane with the horizontal is called the *dip of the joint*. It is expressed as the angle in degrees, and the direction with respect to north, south, east and west. The line along which the joint plane meets the surface is called the *strike of the joint*, the strike direction being perpendicular to the dip direction.

8.15. Classifications and Types of Joints

Joints may be classified into two major classifications, *i.e.*

(1) *geometrical* classification ; and

(2) *genetic* classification, as given below.

8.15.1. The Geometrical Classification of Joints. The geometrical classification of joints is based on the attitude of the joints with respect to that of the beds. Accordingly, we may have three types of joints, *i.e. strike joints, dip joints* and *oblique joints.*

(*i*) **Strike joints** are those in which the strike of the joints is parallel to the strike of the beds ; (*ii*) **Dip joints** are those in which

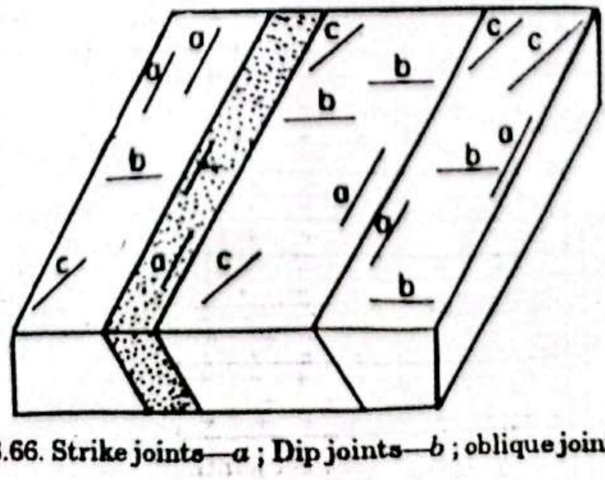


Fig. 8.66. Strike joints—*a* ; Dip joints—*b* ; oblique joints—*c*.

the strike of the joints is perpendicular to the strike of the beds (*i.e.* parallel to the dip of the beds), and (*iii*) **Oblique joints** are those in which the strike of the joints is neither parallel nor normal to the strike of the beds [Refer Fig. 8.66].

8.15.2. The Genetic Classification of Joints. Depending upon the cause of their origin, joints may be divided into (*i*) *Tension joints* and (*ii*) *Shear joints*, as given below :

(*i*) **Tension joints.** Tension joints are those which are formed due to tensile forces or stresses produced in the rocks, either during their formation or after their formation. The direction of such joints is always perpendicular to that of the force which tries to pull them apart. The important types of tension joints are : (*a*) *columnar joints* ; (*b*) *mud cracks* ; (*c*) *sheeting joints* ; and (*d*) *mural joints*.

(*a*) **Columnar joints**, as discussed earlier in article 4.7 (Fig. 4.10), are generally developed in igneous volcanic rocks, particularly Basalts. These joints are hexagonal in plan, and are produced in the body of the cooling magma, due to the contraction caused by cooling.

(*b*) **Mud cracks** are also tension joints, formed in a similar manner as columnar joints ; but here, the contraction occurs due to the drying of the mud. As the fine clayey mud dries, the tensile stresses operate from a number of centres within a plane, giving rise to cracks enclosing roughly polygonal areas, as shown earlier in Fig. 4.18. These cracks are wider at the surface, and narrows down with depth. They are generally developed in fine textured sedimentary rocks, especially clays.

(*c*) **Sheet joints**, as discussed earlier in article 4.7.2, are the *horizontal* joints developed in massive igneous rocks, especially Granites. These horizontal joints are closely spaced in the upper layers, and become progressively farther apart with depth. They divide the rocks into sheets, as shown in Fig. 8.67. To some extent,

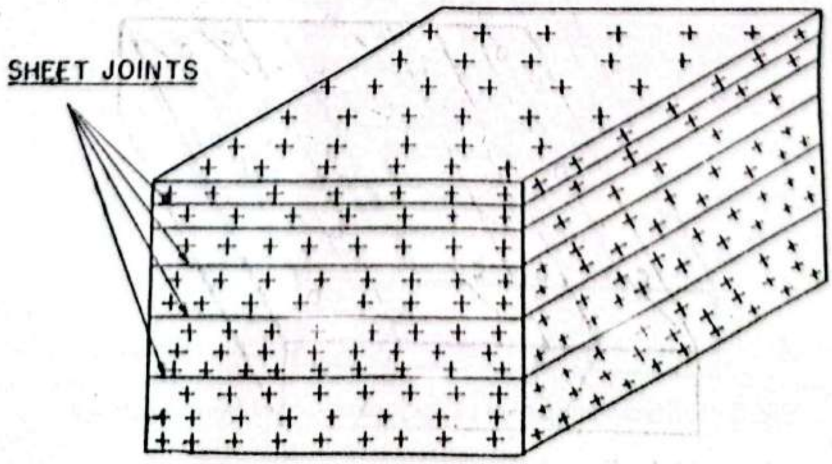


Fig. 8.67. Sheet jointing.

these joints might develop by temperature changes, but are largely developed due to the expansion of the overlying body of the rock is removed by erosion.

(*d*) **Mural joints.** These are three sets of joints, mutually perpendicular (two sets of vertical joints and one set of horizontal joints) to one another, developed generally in igneous rocks, such as Granites. The spacing between the joints is more or less equal, so that the rock is split into cubical blocks, or *murals*.

Besides these four types of tension joints, tension joints are also developed during folding of the rocks. The axial parts of folds, along which beds are bent, are subjected to tension, resulting in the development of such joints (Refer Fig. 8.68).

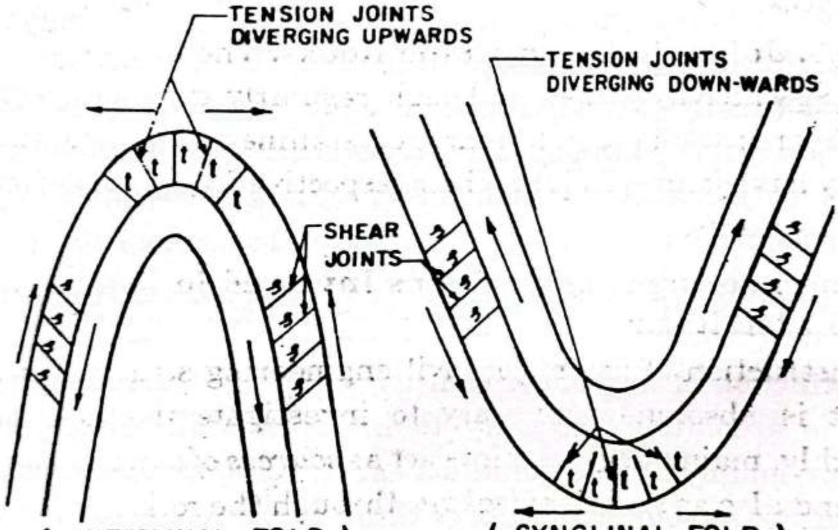


Fig. 8.68. Joints in folded rocks. *t* represents tension joints, and *s* represents shear joints.

(*ii*) **Shear Joints.** Shear joints are formed by the shearing stresses, which tend to slide (or actually slide) one part of the rock against the other. Such joints are thus, developed during folding or faulting. The joints developed in the limbs of the folds are, thus, developed in this fashion, and are called shear joints. (Refer Fig. 8.68).

8.16. Joints in Different Rocks

The joints developed in three different types of rocks exhibit certain prominent characteristics, which are briefed below :

8.16.1. Joints in Igneous Rocks. Igneous rocks are joined to varying degrees, depending upon the conditions under which the magma has cooled down for their formations. Tension Joints are generally developed in igneous rocks due to contraction of magma or lava.

Columnar tension joints are commonly developed in volcanic igneous rocks like Basalts ; whereas, *Mural tension joints* are developed in massive *deep seated* igneous rocks like Granites. *Sheeting tension joints* are also sometimes developed in Granites, which make this rock look like a bedded sedimentary formation.

8.16.2. Joints in Sedimentary Rocks. Generally, two sets of joints, more or less perpendicular to each other, and also to the bedding of the rock, are developed in sedimentary rocks.

In folded sedimentary rocks, *tension joints* are developed near the axial parts, and *shear joints* are developed in the body of the folds (*i.e.* limbs). Fine-grained sedimentary rocks like clays may develop *mud cracks*.

8.16.3. Joints in Metamorphic Rocks. These rocks are also sometimes heavily jointed, although regularly exhibited jointing patterns are rather poor. The coarse crystalline rocks like Gneisses, etc. may have joints similar to their respective igneous or sedimentary equivalents.

8.17. Engineering Considerations Involved in Dealing with Jointed Rocks

For construction of any major civil engineering structure in any area, it is absolutely necessary to investigate the rock joints thoroughly, mainly because joints act as *sources of weakness* for the rocks, and also as *sources of leakage* through the rocks.

Hence, if the proposed foundation rocks for a dam or a reservoir happens to be heavily jointed, and if the water-table of the region is low, then the leakage from the reservoir to the underground may be very heavy, finally resulting in abandoning the proposed site, and to choose better one. Similarly, in construction of tunnels, if the roof or the side rocks, are highly fractured or jointed, the ground water may seep into the tunnel, thus creating acute water troubles, in addition to its becoming unstable or unsafe structurally.

The joints in rocks play a very important role in landslides in hilly regions, because they serve as *slip surfaces*. For example, joints dipping towards the hill slope may allow the overlying, unsupported mass of rock to slide down, causing a landslide. Hence, the occurrence and orientation of joints, and their possibilities of lubrications, must be investigated, as they may lead to landslides from under the highway, or along the proposed engineering structure.

The effects of joints on the proposed structure should, therefore, be thoroughly considered, and remedial measures undertaken, before the actual construction of the structure. *Treatment of joints* will differ in different projects. Say for example, when leakage is to be avoided, grouting of joints is generally adopted. Similarly, when the jointed rocks offer instability or unsafety, as in the case of heavily jointed roofs of tunnels, lining of tunnels may become necessary. In case of landslides, jointing factor becomes difficult to control; but steps should be taken to reduce their chances of getting lubricated.

In addition to all these engineering problems, study of joints becomes important in quarrying and mining operations. In quarrying of stones, joints may help in making quarrying easier, if quarrying is done along them. But this may reduce the sizes of the quarried stones, which may then be limited by the spacing between the joints. Too much jointing may spoil the stones to such an extent that it may be left unusable as dimension stones, and may have to be used only as crushed stone.

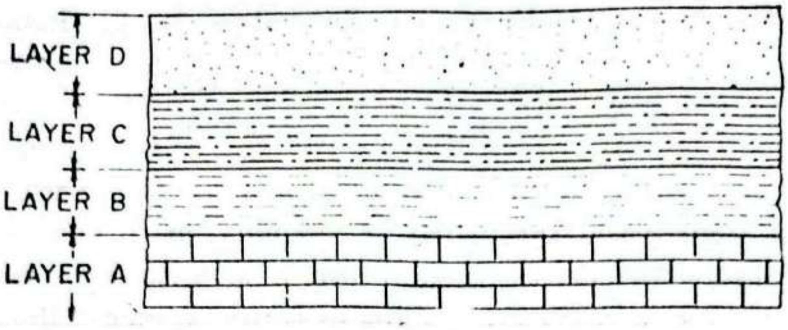
OTHER STRUCTURAL FEATURES OF ROCKS

Besides the major structural features like *folds, faults*, and *joints*, certain other structures like *unconformities, inliers and outliers, overlaps,* etc., need attention. They are also briefly described in the following pages.

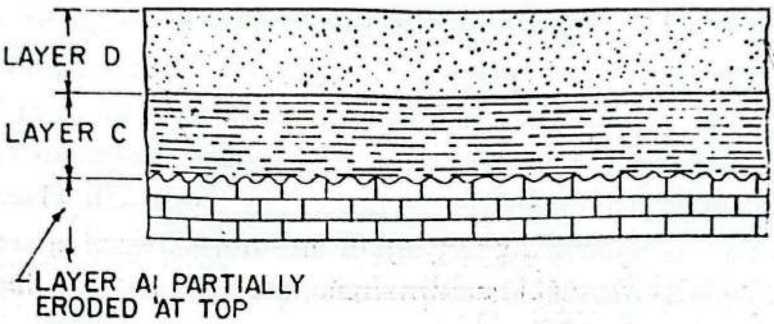
8.18. Unconformities

8.18.1. Definition and Formation of Unconformities. As pointed out earlier, an unconformity is defined as *a surface of erosion or non-deposition occurring within a sequence of stratified rocks,* and thus, separating the underlying *older* formations from the overlying *newer* formations. An unconformity, thus indicates a gap or time interval that has occurred during the formation of these two sets of rocks, and thus helps in determining the geological history (*i.e.* stratigraphy) of the rocks.

If the deposition of stratified rocks continues *uninterruptedly* for a considerable time, then layer after layer will get deposited, one above the other, forming a *sequence* of rocks. Such a sequence of rocks, the formation of which was continuous and not interrupted by any break in deposition, is called *conformable sequence*, [Refer Fig. 8.69 (*a*). But, however, suppose in any other case, if the process



(*a*) Conformable rock sequence—Continuous deposition of layers without any break in the process of deposition.



(*b*) Unconformable rock sequence—Layer B is missing and layer A is also partially eroded at top in this sequence, as compared to the one given in Fig. (*a*) above.

Fig. 8.69. Conformable and Unconformable rock sequence.

of deposition was *interrupted*, and the already deposited rocks exposed to erosion, then a few of the top layers may get eroded. If this is again followed by further deposition, during which new beds are deposited over the eroded surface, then the sequence of the rocks so formed will not be conformable. It contains prominent surface which demarcates the formation of lower layers and upper layers, under different geological conditions, and at different geological times. Such a surface is an unconformity [Refer Fig. 8.69 (*b*)].

8.18.2. Types of Unconformities. Besides distinguishing them as *local* or *regional unconformities*, depending upon whether they are limited to a small local area or are wide spread over a wider region, we may classify them into the following three important types :

(1) *Angular unconformity* ;

(2) *Disconformity* ; and

(3) *Non-Conformity.*

8.18.2.1 Angular Unconformity. It is that unconformity in which the beds on either side of the unconformity are not parallel. The lower older beds may be steeply inclined, or even folded and faulted ;

whereas, the upper younger beds are either horizontal or gently inclined. Refer Fig. 8.70.

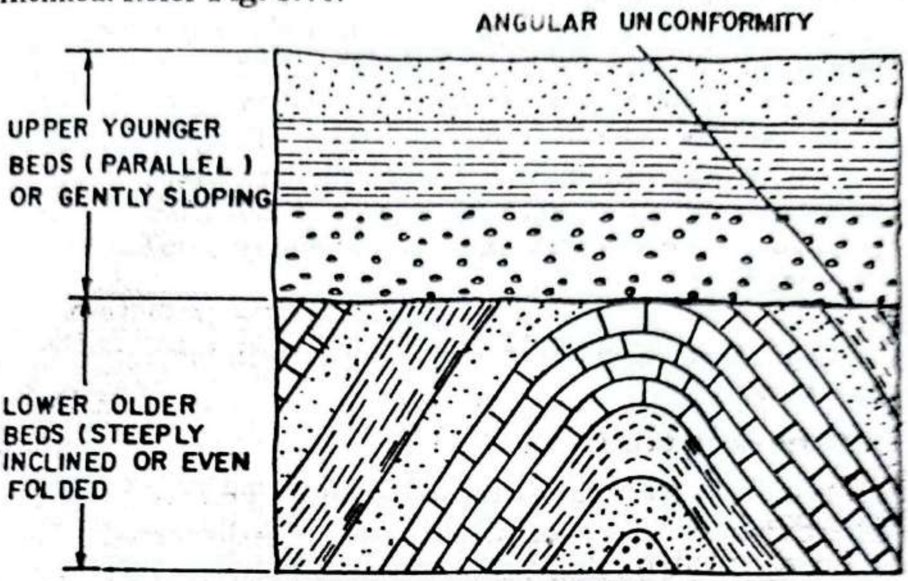


Fig. 8.70. Angular Unconformity.

8.18.2.2 Disconformity. It is that unconformity, in which the beds on either side of the unconformity are more or less parallel. No tilting or folding of lower strata is thus, indicated in such cases. Refer Fig. 8.69 (*b*).

8.18.2.3 Non-conformity. This term is used to represent the surface of contact between the lower older igneous rocks, and the upper younger sedimentary or volcanic rocks. Hence, an unconformity in which the lower rocks are igneous rock masses like Granites, is called a non-conformity. Refer Fig. 8.71.

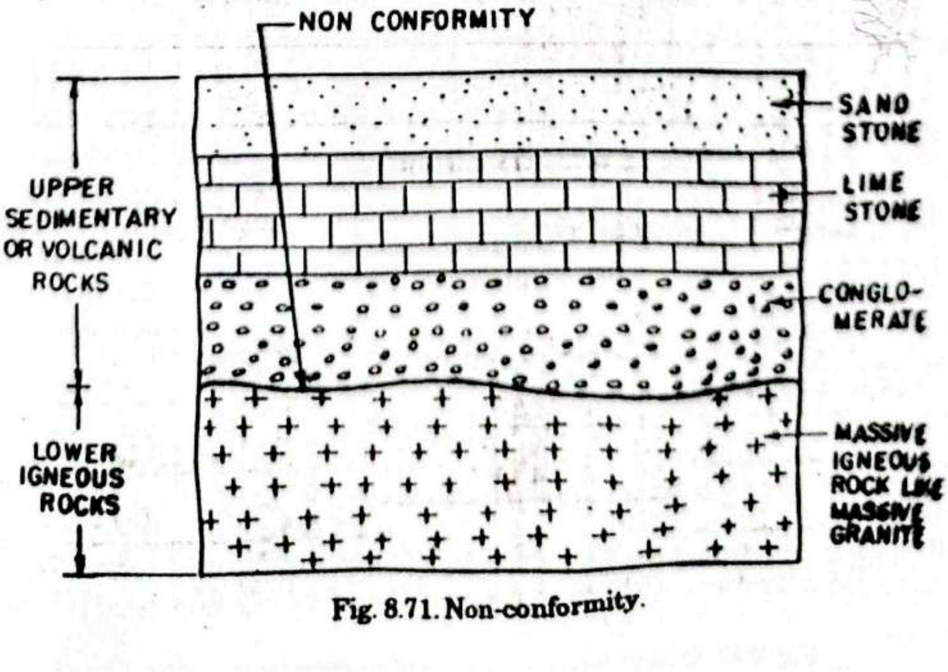


Fig. 8.71. Non-conformity.

8.18.3. Recognition of Unconformities in the Field. There are various indications by which an unconformity in a given sequence of rocks can be recognised in the field. Say for example, the arrangement of upper and lower beds (*i.e.* beds on either side of a contact surface suspected to be unconformity) may not be parallel, with the lower beds exhibiting pronounced titling. Secondly, an unconformity is generally indicated by the *presence of a layer of conglomerate just above the unconformity*. Such a conglomerate layer signifies shallow water conditions, and may help in recognising an unconformity.

Thirdly, *the presence of a layer of residual soil* (a product of weathering) *within a sequence of rocks,* offers reliable indication of an unconformity.

8.19. Outliers and Inliers

Outliers and inliers are the structural features, created because of the selective erosion of rocks in certain areas, as discussed below :

8.19.1. Outliers. An *outlier* is an isolated patch *or* outcrop of *younger* rock, surrounded on all sides by geologically older rocks. Such a feature may result due to *excessive erosion* (Fig. 8.72) ; or due to *garben faulting* followed by erosion ; (Fig. 8.73) ; or because of *folding* in *synclinal fashion* (Fig. 8.74).

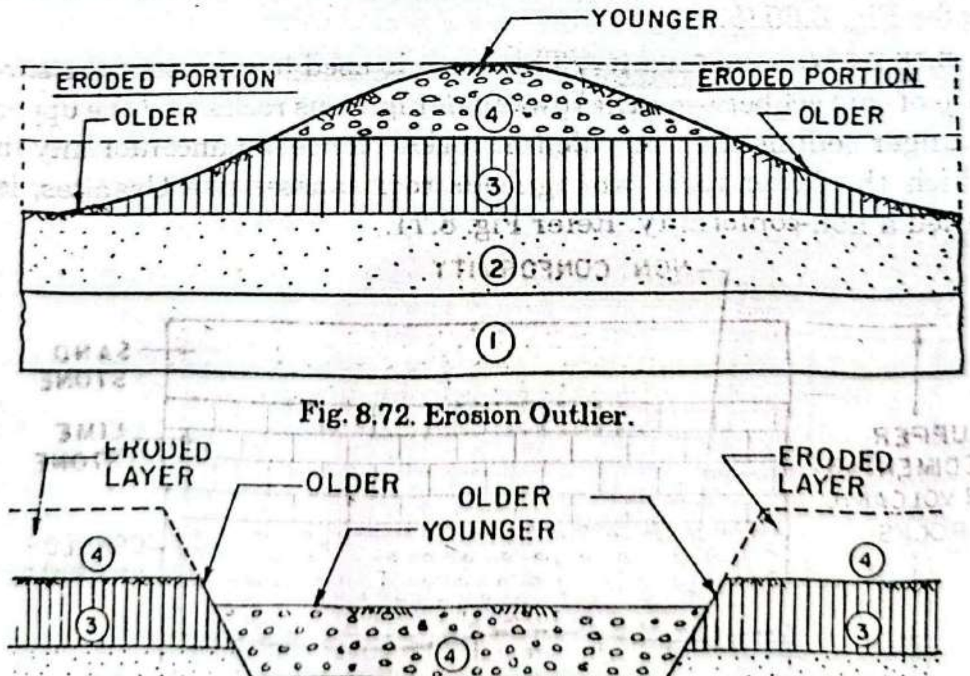


Fig. 8.72. Erosion Outlier.

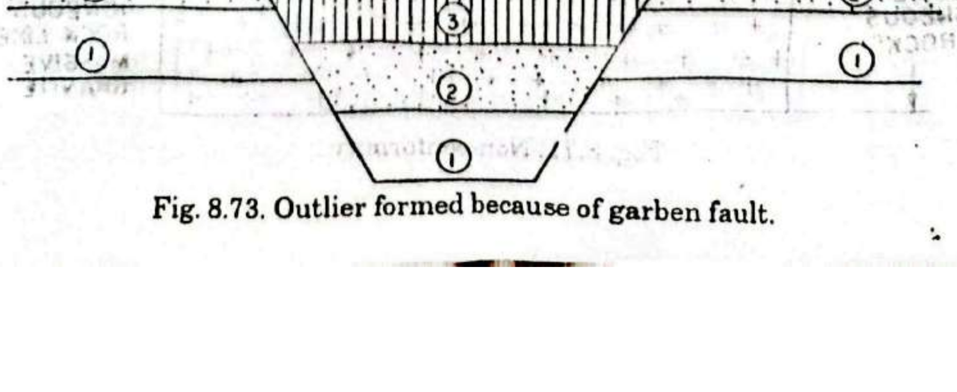


Fig. 8.73. Outlier formed because of garben fault.

The *erosion outlier* (Fig. 8.72) is formed when a patch of upper formation proves resistant to weathering, whereas it is easily eroded from the sides, exposing the underlying older formations.

In the case of faulted rocks, a *garben* gives rise to an outlier, where the raised side blocks after erosion, leave the older underlying beds surrounded by the younger beds of the central valley. (Refer Fig. 8.73).

In the case of folded rocks, a synclinal hill itself makes an outlier ; because, here the outcrop of overlying younger bed is surrounded by the underlying older bed (Refer Fig. 8.74).

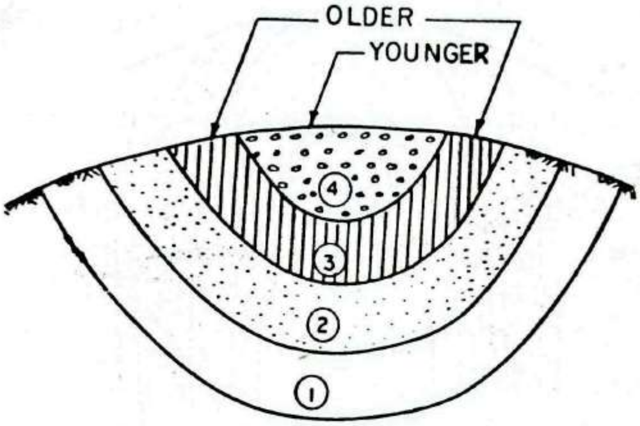


Fig. 8.74. Outlier formed because of a synclinal hill.

8.19.2. Inliers. These are the outcrops of *older rocks* surrounded on sides by younger rocks. They are, thus, the reverse of outliers. They are formed at those places, where erosion process is confined to younger strata, and ultimately succeeds in breaking through them, thereby exposing a part of the lower sequence of older rocks.

Valley formation is a common process of erosion, giving rise to inliers. As the valley floor is eroded, the underlying older beds are exposed, with younger ones surrounding them from the valley sides, as shown in Fig. 8.75.

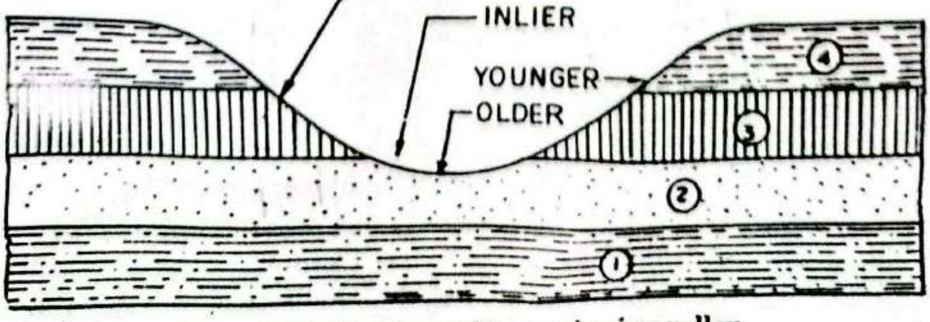
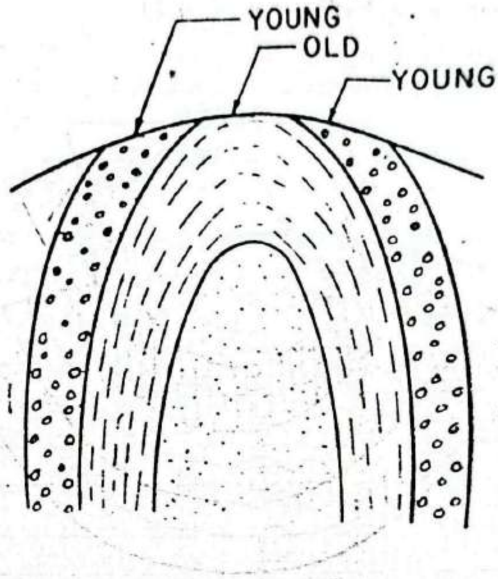


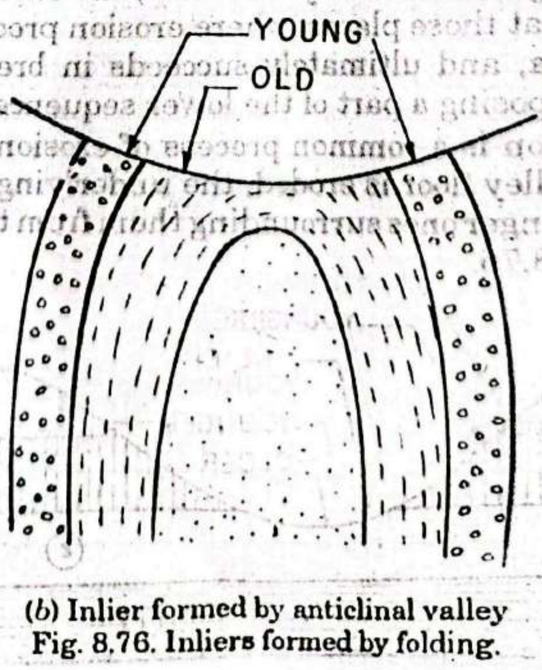
Fig. 8.75. Inlier formed by erosion in a valley.

Besides being chiefly formed by erosion, inliers like outliers, may also be formed by folding and faulting.

In the case of folded rock formations, an anticlinal hill or a valley may give rise to an inlier, as in both cases, the exposure contains older beds surrounded by comparatively younger beds, [Refer Figs. 8.76 (*a*) and (*b*)].



(*a*) Inlier formed by anticlinal hill.



(*b*) Inlier formed by anticlinal valley
Fig. 8.76. Inliers formed by folding.

In case of faulted rocks, a *horst* gives rise to an inlier ; wherein, the inner raised block, on erosion, exposes the older rocks surrounded by the younger rocks of the side blocks. (Refer Fig. 8.77).

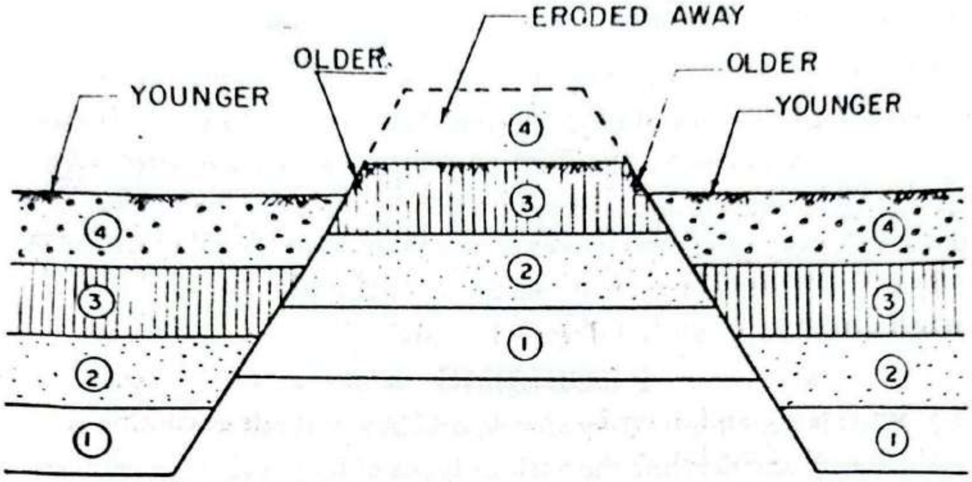


Fig. 8.77. Inlier formed by horst fault on erosion.

8.20. Overlaps

An overlap may be defined as a structural feature, in which every overlying (younger) bed extends, so as to overlap the underlying (older) bed, as shown in Fig. 8.78.

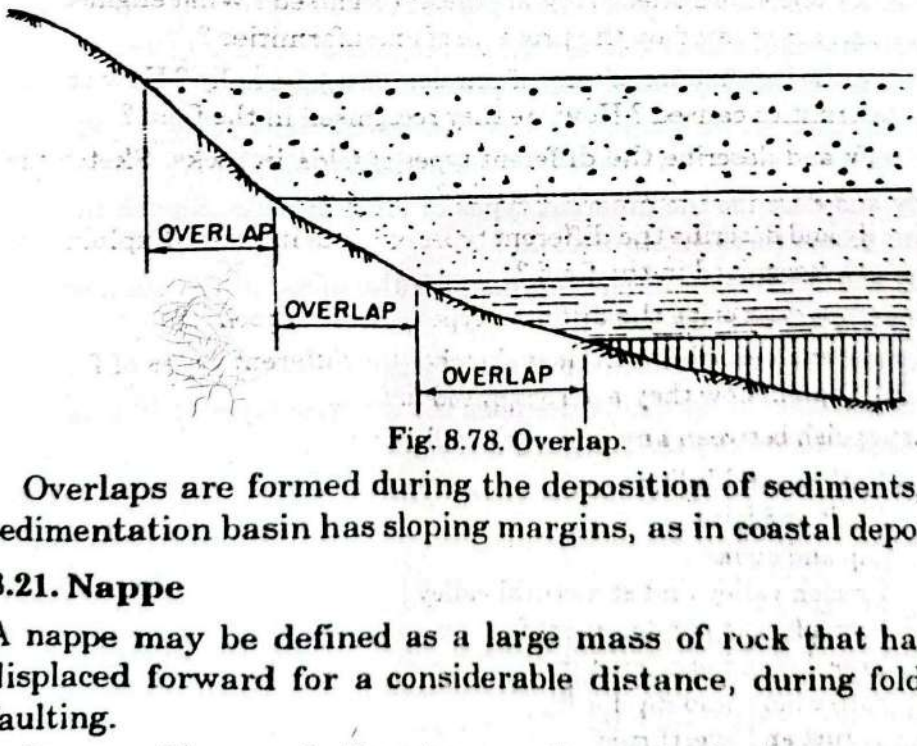


Fig. 8.78. Overlap.

Overlaps are formed during the deposition of sediments, if the sedimentation basin has sloping margins, as in coastal deposits.

8.21. Nappe

A nappe may be defined as a large mass of rock that has been displaced forward for a considerable distance, during folding or faulting.

In case of low angle thrust or overthrust faults, intense compression may result in the displacement of the hanging wall in the forward direction, over several kilometres distances, thus giving rise to the formation of what are known as *nappes*. Similarly, in the case of acute folding, giving rise to the formation of recumbent folds, there may be considerable displacement in the forward direction, extending upto several kilometres.

8.22. Klippe

A klippe is defined as an isolated erosional remnant of an over thrust sheet. During overthrust faulting, the hanging wall generally moves over the foot wall for considerable distances. Thus, a large sheet of thrusted rocks may get spread over other formations. Erosion of this overthrust sheet, may with the passage of time, leave behind only an isolated patch of it, called *clippe*.

PROBLEMS

1. (*a*) What is meant by folding of rock, and how is it produced ?
   (*b*) Classify and describe the various types of folds encountered in the crust of the Earth.
2. Discuss the topographical expression of different types of folds and faults. How do these topographical features control civil engineering construction works, such as tunnels, highways, dams, and reservoirs ?
3. What are the different types of faults, and how faults are distinguished from joints ? What are the problems of faults in civil engineering works ?
4. What are unconformities ? How are these recognised ? What engineering problems are created by the presence of unconformities ?
5. Discuss the importance of unconformities in stratigraphy ? How are the unconformities caused ? How are they recognised in the field ?
6. Classify and describe the different types of folds in rocks. Sketch the different geometric elements of a fold ?
7. Classify and describe the different types of faults in rocks. Explain how they are recognised in the field ?
8. Classify and describe the different types of joint in rock.
9. Classify and describe with neat sketches the different types of folds in rocks. Explain how they are recognised in field.
10. Distinguish between any four of the following :
    (*i*) Outliers and Inliers ;
    (*ii*) Fault and joint ;
    (*iii*) Dip and strike ;
    (*iv*) Erosion valley and structural valley ;
    (*v*) Disconformity and non-conformity ;
    (*vi*) True dip and apparent dip ;
    (*vii*) Strike fault and dip fault ;
    (*viii*) Thrust and overthrust.
11. Write notes on any four of the following :
    (*i*) Unconformity ;
    (*ii*) Recumbent fold ;
    (*iii*) Reverse fault ;