Chapter 4*

STRUCTURAL GEOLOGY

4.1 INTRODUCTION

Structural geology deals with rock features of the earth's crust. The geological structures formed during the deposition or implacement of rock are known as **primary structures**, and those formed later are called **secondary structures**.

4.2 DEFINITIONS

4.2.1 *Strike and Dip*

The **strike**, **dip**, and **dip direction** of a plane define its orientation in space (Fig. 4.1). Figure 4.1 shows that the strike of a plane is the direction (bearing) of a horizontal line contained in that plane and the dip is the line of maximum inclination which is perpendicular to the strike line. It is defined by angle and direction of maximum inclination. For simplicity, the dip and the dip direction are measured.

The **apparent dip** is the dip of any line on a plane other than the true dip and is always smaller than the true dip (Fig. 4.2). All beds have horizontal apparent dips in any vertical section parallel to their strike. Table 4.1 shows the calculation of true dip, given the apparent dip and the acute angle between the strike of the plane and the line of section.

Fig. 4.3 indicates different symbols used to represent strike and dip on a map.

4.2.2 *Trend and Plunge*

Trend and **plunge** define the attitude of a linear feature, such as a fold hinge, mineral lineation, or plane-plane intersection. **Trend** is the azimuth of the line, projected on the horizontal plane, and plunge is the angle between the line and its horizontal projection.

4.3 PRIMARY STRUCTURES

Primary structures include those features that are formed concurrently with rock formation. These include the sedimentary structures as well as flow contacts of volcanic rocks. The most important sedimentary structure is **bedding** which separates strata of different composition and texture. Other features, such as ripple marks, cross-bedding, and flute casts are related to bedding. These may affect the behaviour of the bedding surface due to their roughness or waviness. Generally, sediments are deposited horizontally. Subsequent tectonic movements cause these layers to be uplifted, titled, and warped (Fig. 4.4a).

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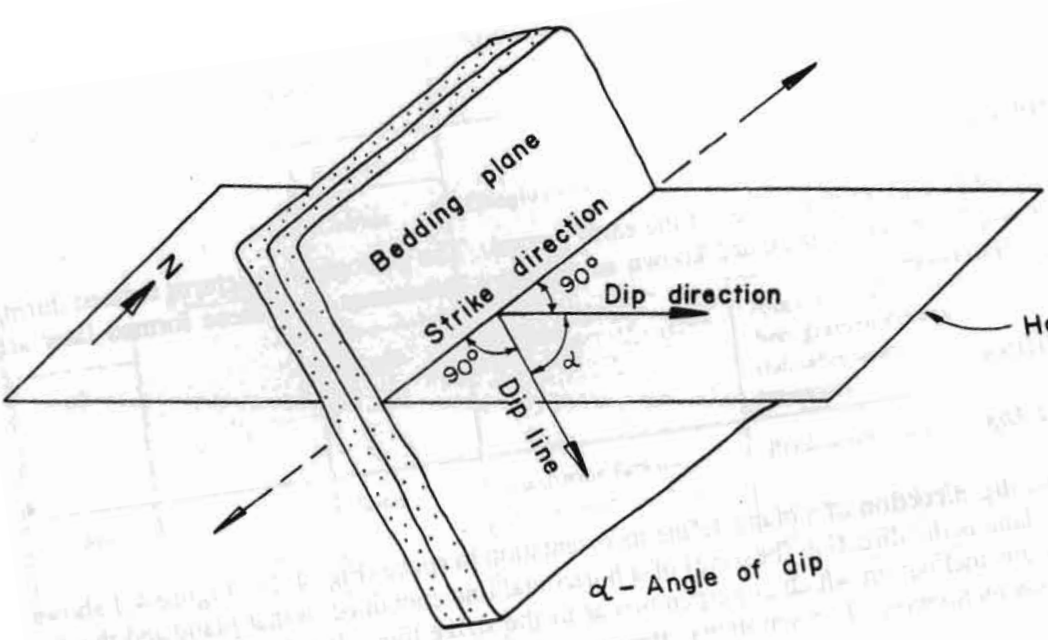


Fig. 4.1 Strike and dip of a plane

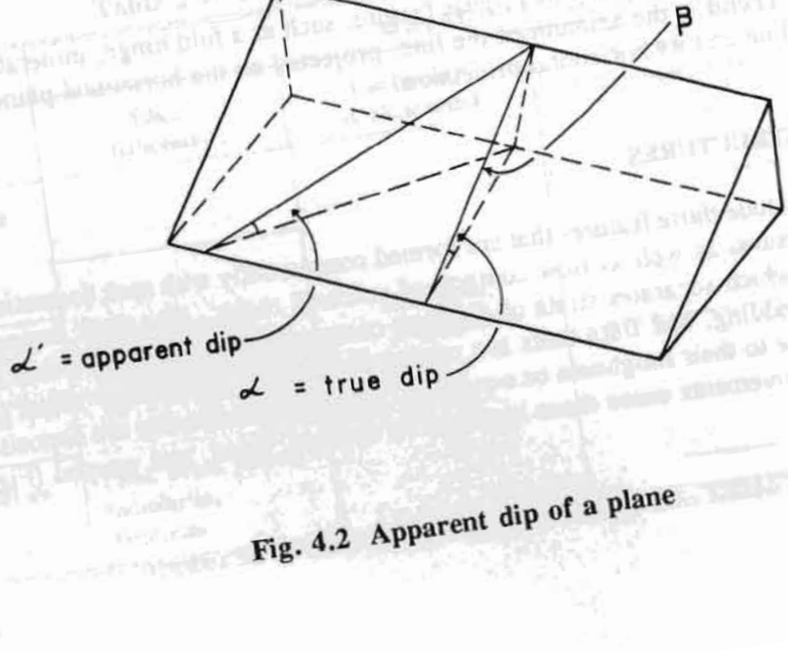
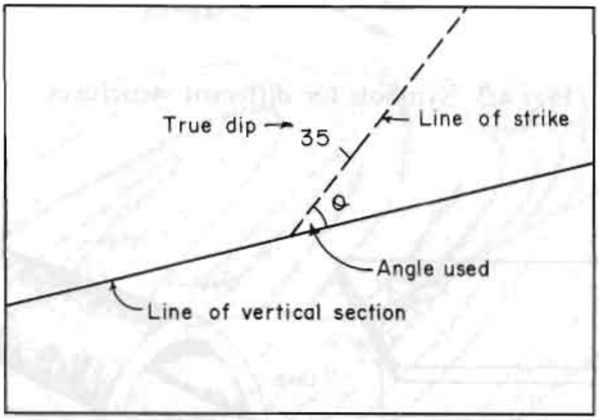


Fig. 4.2 Apparent dip of a plane

Table 4.1 Table for conversion of true dips to apparent dips

Tan A = Tan α. Sin Θ

A	=	apparent dip	(in degrees)
α	=	true dip	(in degrees)
Θ	=	angle between the line of cross-section and the strike line (degrees)	



True Dip α	ACUTE ANGLE Θ BETWEEN STRIKE AND LINE OF VERTICAL SECTION															
	2.5	5	10	15	20	25	30	35	40	45	50	55	60	65	70	80
5	0.0	0.5	1.0	1.5	2.0	2.0	2.5	3.0	3.0	3.5	4.0	4.0	4.5	4.5	5.0	5.0
10	0.5	1.0	2.0	2.5	3.5	4.0	5.0	6.0	6.5	7.0	8.0	8.0	8.5	9.0	9.5	10.0
15	1.0	1.5	3.0	4.0	5.0	6.5	8.0	9.0	10.0	11.0	11.5	12.5	13.0	13.5	14.0	15.0
20	1.0	2.0	3.5	5.5	7.0	9.0	10.0	12.0	13.0	14.5	15.5	16.5	17.5	18.0	19.0	20.0
25	1.0	2.0	4.5	7.0	9.0	11.0	13.0	15.0	17.0	18.0	20.0	21.0	22.0	23.0	24.0	25.0
30	1.5	3.0	6.0	8.0	11.0	14.0	16.0	18.5	20.5	22.0	24.0	25.0	26.5	27.5	28.5	29.5
35	2.0	3.5	7.0	10.5	13.5	16.5	19.5	22.0	24.0	26.5	28.0	30.0	31.0	32.5	33.5	35.5
40	2.0	4.0	8.0	12.0	16.0	19.5	23.0	26.0	28.5	30.5	33.0	34.0	36.0	37.0	38.5	39.5
45	2.5	5.0	10.0	14.5	19.0	23.0	26.5	30.0	33.0	35.0	37.0	39.0	41.0	42.0	33.0	44.5
50	3.0	6.0	11.5	17.0	22.0	27.0	31.0	34.5	37.5	40.0	42.5	44.0	46.0	47.0	48.0	49.5
55	4.0	7.0	14.0	20.0	26.0	31.0	35.5	39.5	42.5	45.0	47.5	49.5	51.0	52.5	53.5	54.5
60	4.5	8.5	16.5	24.0	30.5	36.0	41.0	45.0	48.0	51.0	53.0	55.0	56.0	57.5	58.5	59.5
65	5.5	10.5	20.5	29.0	36.0	42.0	47.0	51.0	54.0	36.5	58.5	60.0	62.0	63.0	63.5	64.5
70	6.5	13.0	25.5	35.0	43.0	49.0	54.0	57.5	60.5	63.0	64.5	66.0	67.0	68.0	69.0	69.5
75	9.0	18.0	33.0	44.0	52.0	57.5	62.0	65.0	67.5	69.0	70.5	72.0	73.0	73.5	74.0	75.0
80	13.5	26.5	44.5	56.0	63.0	67.5	70.5	73.0	74.5	76.0	77.0	78.0	78.5	79.0	79.5	80.0
85	26.0	45.0	63.5	71.5	75.5	78.0	80.0	81.5	82.0	83.0	83.5	84.0	84.0	84.5	84.5	85.0

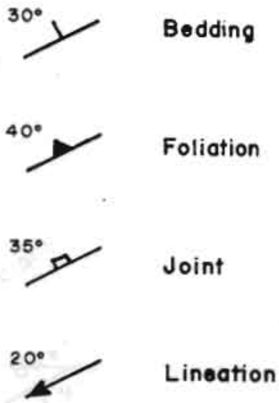


Fig. 4.3 Symbols for different structures

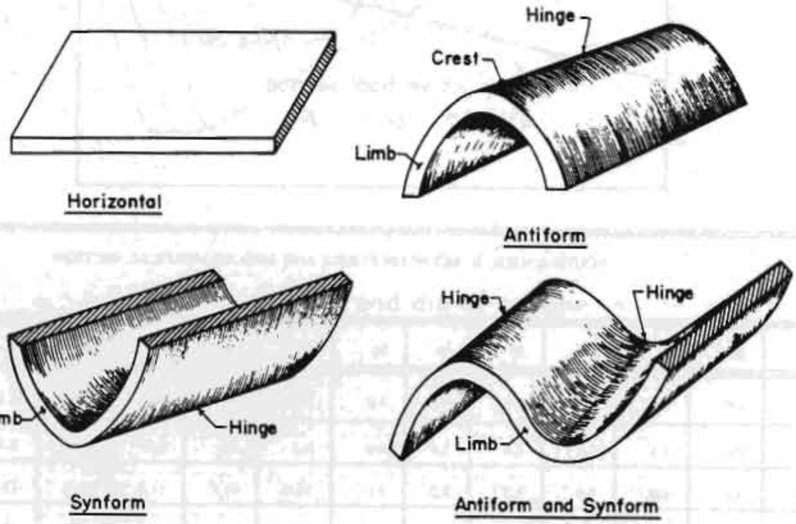


Fig. 4.4a Folded single layer

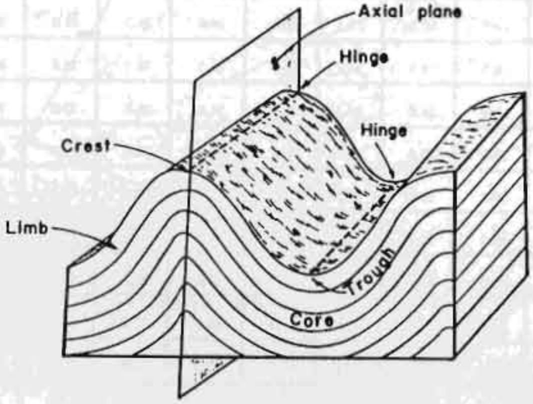


Fig. 4.4b Parts of a fold

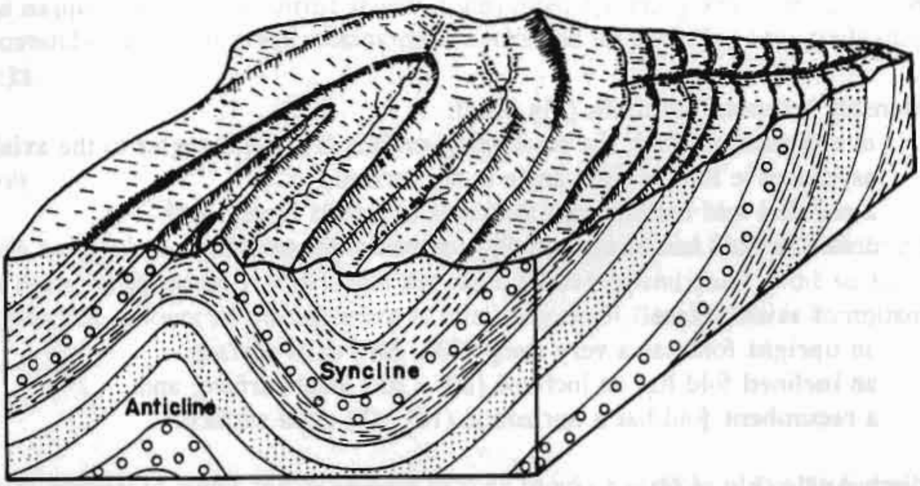


Fig. 4.5 Folded multilayers

4.4 SECONDARY OR TECTONIC STRUCTURES

4.4.1 *Folds*

A fold is a non-planar configuration of rocks resulting from deformation. When layers are subjected to stress they buckle or fold.

Parts of a Fold

A single fold can be divided into several important parts as follows (Fig 4.4a, 4.4b).

The hinge lines are lines along points of maximum curvature.
The axial plane (or axial surface) is the locus of hinge lines of beds in a fold.
The crest is the highest part of an antiform
The trough is the lowest part of a synform

Folds can be classified as **antiforms** and **synforms** (Fig 4.4a, 4.5). An antiform is a fold with limbs dipping away from each other. When rocks at the core are older than on the outside, this is called an **anticline** (Fig. 4.5). A synform is a fold with limbs dipping towards each other. A **syncline** contains younger rocks at its core (Fig. 4.5).

Geometry of Folds

Folds can have different shapes and orientations. Some important terms describing them are illustrated in Figure 4.6.

i. Relationship between fold limbs (Fig 4.6a):
   - in a **symmetric** fold, the enveloping surface is at right angles to the axial surface; in an **asymmetric** fold, a right angle is not formed,
   - a **parallel** fold has constant thickness of folded layers, and
   - a **similar** fold has a constant dip, vertically downwards.

ii. Inclination of axial surface
   - an **upright** fold has a very steep (90° - 80°) axial surface,
   - an **inclined** fold has an inclined (80° - 10°) axial surface, and
   - a **recumbent** fold has a horizontal (10° - 0°) axial surface.

iii. Interlimb Angle (Fig. 4.6b)

   The **interlimb** angle is the angle between the limbs of a fold.

   - an **isoclinal fold** has an interlimb angle of about 0°,
   - a **tight fold** has an interlimb angle of less than < 30°,
   - a **close fold** has an interlimb angle between 30°-70°,
   - an **open fold** has an interlimb angle between 70°-120°, and
   - a **gentle fold** has an interlimb angle between 120°-180°.

d. *Small-Scale Structures*

These are generally several millimeters to a few metres in scale and include cleavage, boudinage, and small-scale folds.

i. Cleavage

Cleavage consists of parallel to sub-parallel fractures often oriented normal to the principal stress. Although cleavage may fan out sometimes about the hinge of a fold, it is generally parallel to the hinge line. On the earth's surface, cleavage is more open in antiforms and closed in synforms (Fig. 3.9).

ii. Boudinage

Boudinage structure results from deformation of a hard or competent layer by stretching into sausage-like boudins. The intervening gaps are filled by incompetent material (refer to Fig. 3.9).

e. *Major Fold Structures*

These may cover several tens to hundreds of square kilometres in area.

In the *Himalaya* **nappe** structures or thrust-sheets, transported for many kilometres, are common (Fig. 4.7). These commonly have high-grade metamorphic rocks and they overlay low-grade metamorphic or sedimentary rocks.

4.4.2 ***Fractures***

When a rock fails by brittle deformation, it **fractures**. If one block moves laterally relative to the other, it is said to have failed by **faulting**. If movement has taken place perpendicular to the surface, it is known as a **joint**. In joints, the amount of displacement is relatively small (less than a few cm).

a. *Faults*

Faults are surfaces parallel to which the movement of rock blocks has taken place. They can be classified into **dip, strike**, and **oblique-slip faults**, depending upon the direction of movement (Fig. 4.8). Faults in which the movement is along the dip of the fault are **dip-slip faults**. The apparent vertical displacement of layers is known as the **vertical throw**. When the movement is parallel to the strike of the fault, the faults are called **strike-slip faults**. Faults in which movement is neither parallel to the strike, nor to the dip, are called **oblique-slip faults**. Dip-slip faults are either **normal** or **reverse**.

Normal faults are those where the **hangingwall** has moved down relative to the **footwall** (Fig 4.9a). This situation develops during the extension of a layer.

Reverse faults are those along which the footwall moves down relative to the hangingwall along a steeper inclined fault plane (Fig 4.9b). This results in a shortening of the horizontal extent of the rock formation. **Thrust** faults are reverse faults in which planes dip at less than 30°.

A thrust fault develops due to horizontal tectonic stresses. This results in great shortening of the layers, and the resulting **imbrication** appears in the stacking up of successive layers (Fig. 4.10). Nappes are thrust faults with large horizontal displacements. This phenomenon is in the *Himalaya* where complex thrust sheets are piled on top of each other successively giving rise to thrust faults such as the Main Central Thrust (MCT), Main Boundary Thrust (MBT), and large nappes.

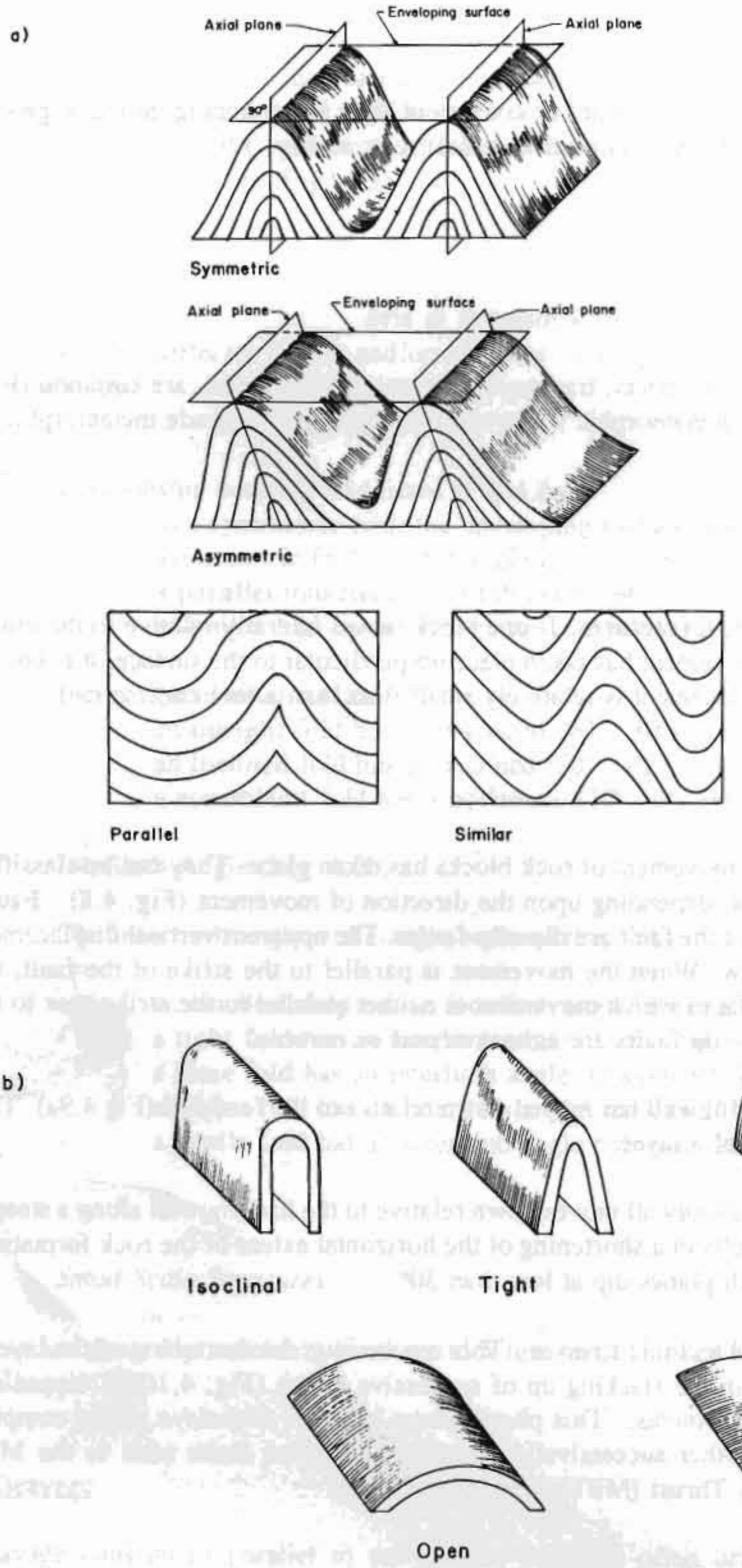


Fig. 4.6 Fold geometry

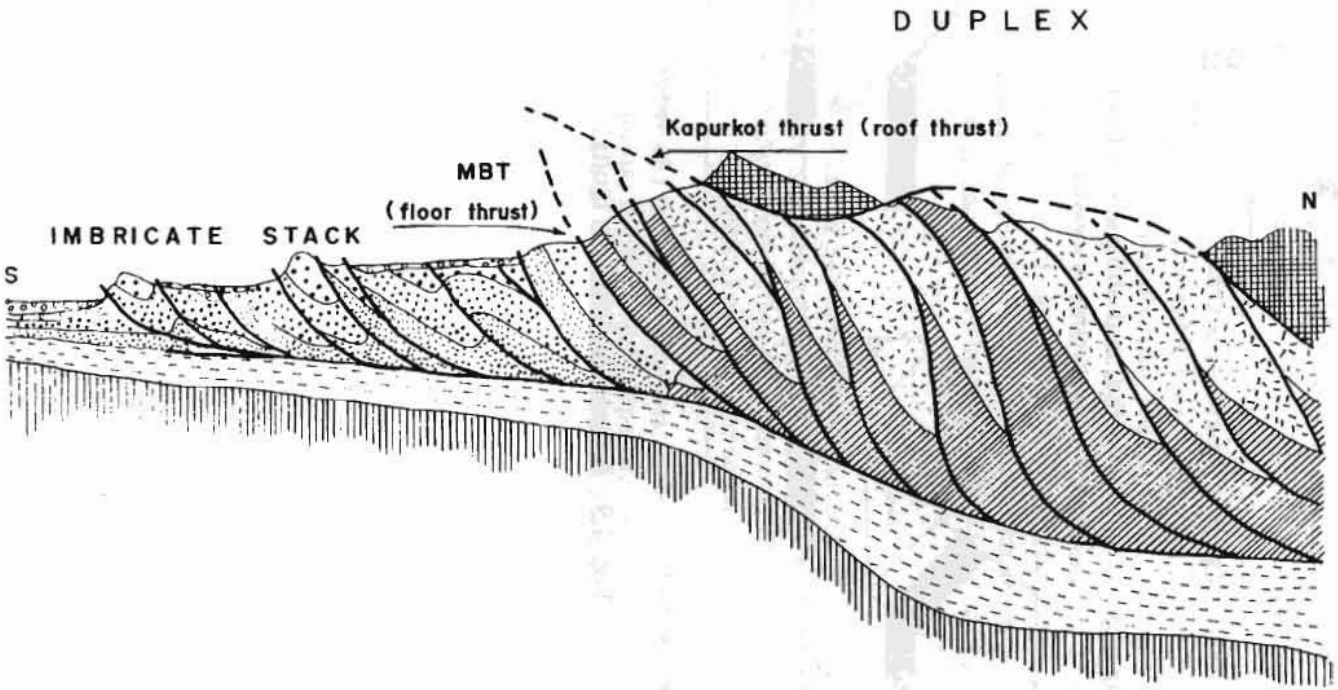


Fig. 4.7 Example of nappes in West-Central Nepal

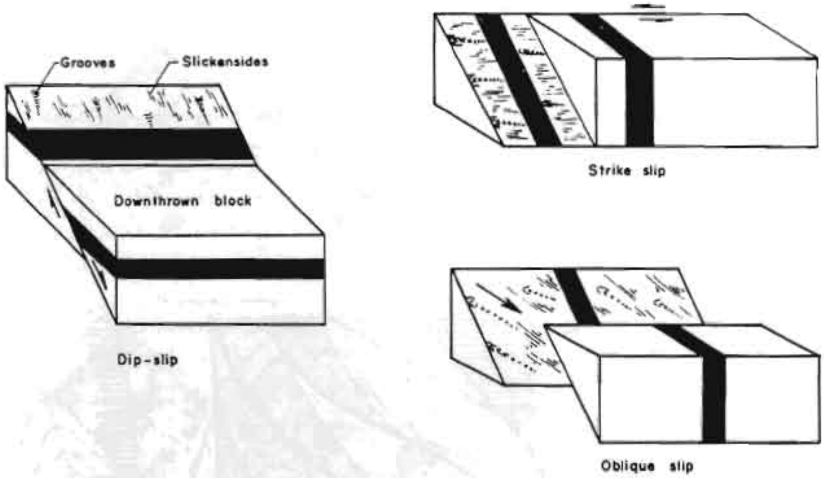


Fig. 4.8 **Dip, strike, and oblique slip faults**
Arrows show direction of movement.

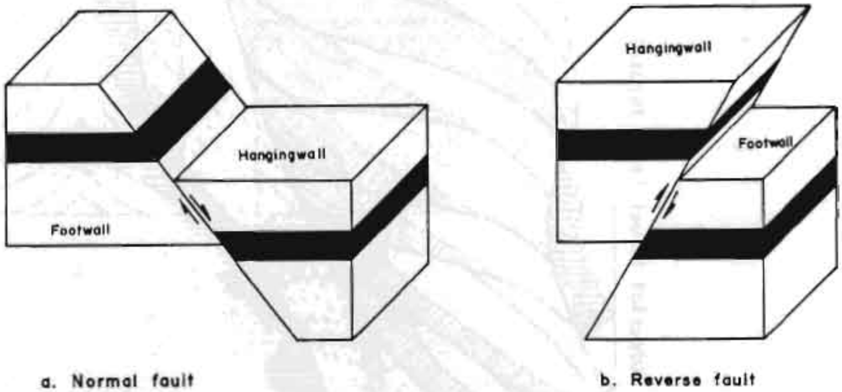


Fig. 4.9 Normal and reverse faults

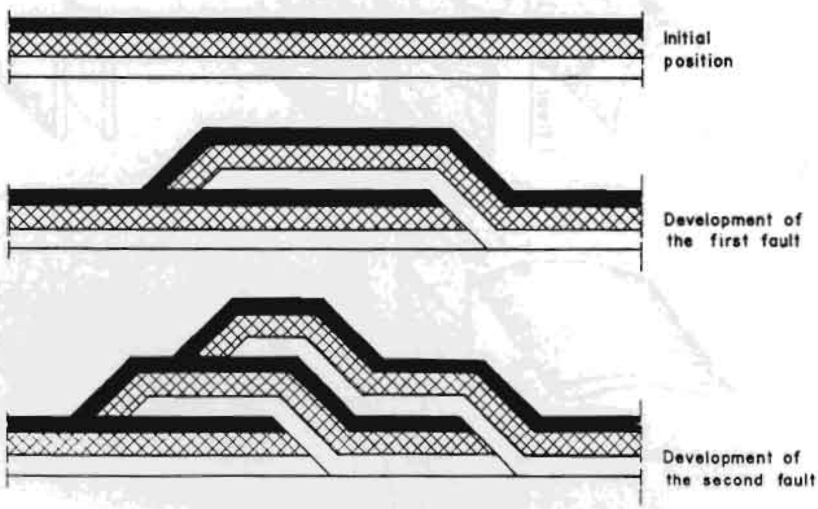


Fig. 4.10 Development of thrust faults and imbricate structure

iii. Engineering Considerations in Faulted Terrain

Faulted terrain is generally very friable and crushed. Because the faults may have tapped deep layers of the earth, hydrothermal fluids may have invaded them, resulting in further weakening of the rocks. The increased surface area of materials in fault zones makes these more susceptible to attack by rain, river, and frost action.

Fault zones can be recognized by several features.

1. **Breccia** - angular, crushed rock fragments.
2. **Gouge** - highly crushed, soft clayey mass.
3. **Slickensides** - smooth, polished hard surfaces, often with straight grooves.
4. **Mylonite** - fine-grained, sheared metamorphic rock.
5. **Cataclasite** - partially fused, dense metamorphic rock.

Construction on or near a fault is asking for trouble if due consideration is not given to their unstable nature. In the *Himalaya*, many faults are still active. Many of the region's largest landslides are located on or near fault zones. Earthquake-triggered landslides have also caused abundant damage in the region. In the *Himalaya* most of the historic earthquakes have epicentres located between the MCT and MBT.

b. *Joints*

Joints are surfaces along which no lateral movement has occurred and are found in practically all rocks. Commonly, they are found in **joint sets**, related by their orientation with respect to the stresses operating in an area. Because joints are relatively open, they are commonly filled with minerals. The infilling tends to reduce shearing resistance and cohesion along the joint surfaces. Some important joints are:

Joints in Folded Rocks: formed due to regional stresses. Some are parallel to the axial plane and are called **longitudinal** or **tension joints**. Joints formed perpendicular to the hinge line are called **transverse** or **dip joints**. Joints which are neither parallel to or perpendicular to the hinge line are called diagonal joints. **Conjugate joints** are sets of joints oriented roughly perpendicular to each other and are bisected by the principal stress (Fig. 4.11)

Columnar Joints in basaltic rocks give rise to a hexagonal pattern when these rocks contract on cooling at the earth's surface (Fig. 4.12).

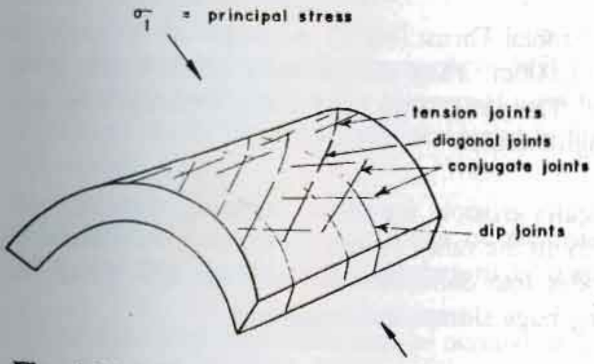


Fig. 4.11 Joints in folded rocks

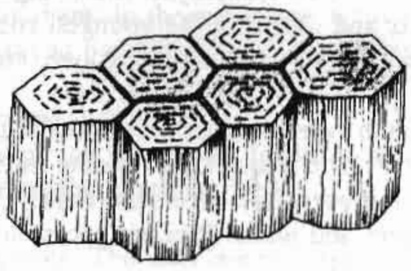


Fig. 4.12 Columnar joints in basalt