4 Structural Geology

Introduction :

Rocks constituting the Earth`s crust have varying mechanical properties that get modified with increase in pressure and temperature as we go deeper within the Earth. The rocks are subjected to stress due to tectonic forces which cause their deformation. The driving force for tectonic activity is derived from convection within the upper mantle and the heat released from the core of the Earth. Deformation of rocks results into different structural features such as folds, faults, joints etc. The study of these structural features constitutes structural geology.

Stress and Strain :

Stress-Strain is the pressure applied to rocks and is expressed as force per unit area (F/A)

Rocks can be subjected to different kinds of stresses, such as:

a) **Lithostatic stress :** Rocks beneath the Earth's surface experience equal pressure exerted on them from all directions because of the weight of the overlying rocks. It is like the hydrostatic stress (water pressure) that a person feels pressing all around their body when diving deep into the water (fig. 4.1).

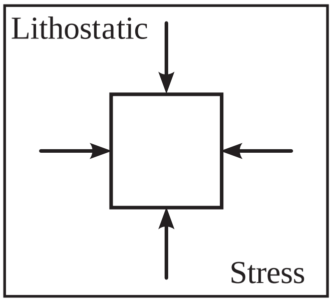


Fig. 4.1 : Depiction of lithostatic stress

b) **Directional stress :** In many cases, rocks may experience an additional, unequal stress due to tectonic forces. Three basic types of differential stresses are : (fig. 4.2)

(i) Tensional stress (stretching/ extension)

(ii) Compressional stress (squeezing)

(iii) Shearing stress

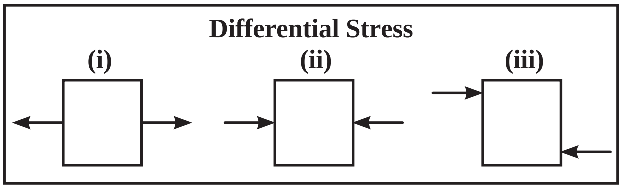


Fig. 4.2 : Types of directional stresses

Strain :

Strain is the deformation of rocks in response to stress.

Types of Deformation :

Four basic types of deformation are described as follows :

1) **Elastic deformation :** For small directional stresses, less than the yield strength, rock deforms like a spring as described by Hooke's Law. It changes shape by a very small amount in response to the stress, but the deformation is not permanent. If the stress is be released, the rock returns to its original shape (fig. 4.3).

2) **Plastic deformation :** Rocks undergo plastic deformation and flow when the differential stress applied is stronger than their yield strength. This occurs in the lower continental crust and in the mantle (fig. 4.3).

3) **Brittle deformation :** Near the Earth's surface, rock behaves in its familiar brittle fashion. If the differential stress applied is greater than the rock's yield strength, the rock breaks, i.e. it fractures or fails with the development of weak zone/ plane (fig. 4.4).

4) **Ductile deformation :** At depths greater than 10 kms, the enormous lithostatic stress makes it nearly impossible to produce a fracture or crack, as the high temperature makes the rock softer, less brittle and more malleable (fig. 4.4).

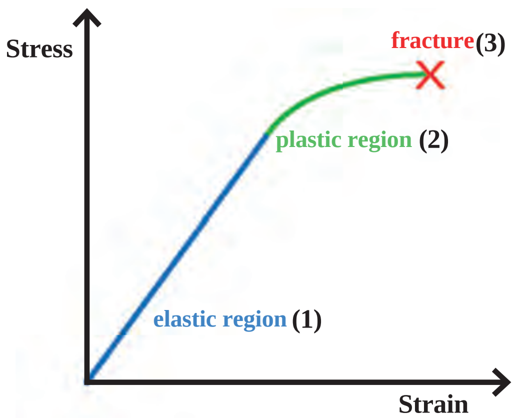


Fig. 4.3 Fig exhibiting stress strain relationship in rocks : With increasing stress, the rocks undergo: 1. elastic deformation 2. plastic deformation and 3. fracture

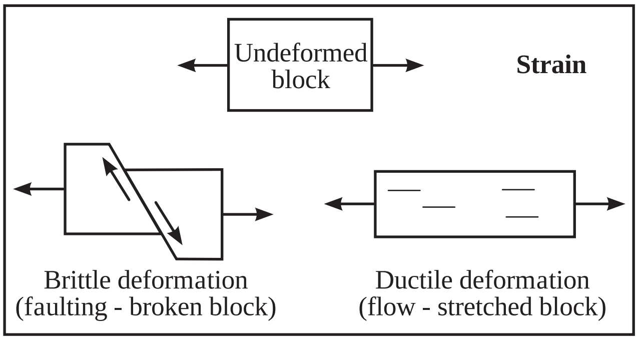


Fig. 4.4 : Brittle and ductile deformation

Measuring the attitude of beds :

The simplest form of deformation that is exhibited in any region, is tilting of initially horizontal sedimentary beds. The amount of tilting may vary within wide limits. The position of the bed on the ground surface is expressed as its attitude. This attitude of the beds can be quantified by their Strike and Dip.

The study of structural Geology requires measurement and documentation of the geometric features. The most common tool to measure strike and dip of an inclined bed is the compass or Brunton and/ or Clinometer compass.

Strike and Dip of Beds :

Any geological formation exposed on the surface is called an outcrop. Outcrops help geologists in examining and measuring the structural characteristics of rock beds and describing their orientation or position in space. Strike and dip refer to the orientation or attitude of a geologic feature. (fig. 4.5)

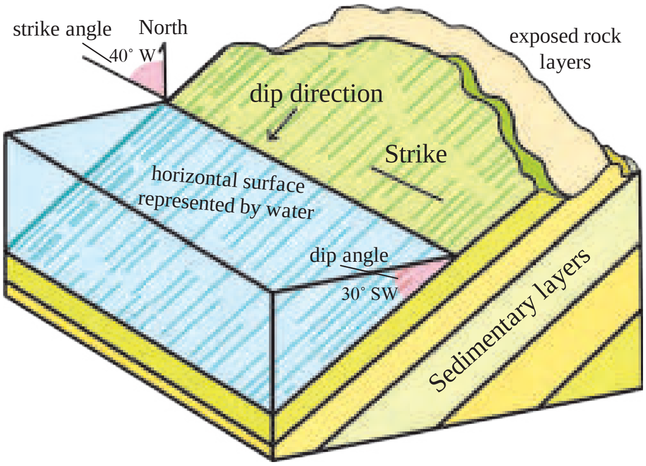


Fig. 4.5 : Attitude of beds

Strike refers to the direction of a horizontal line on any inclined plane such as a bed, fault plane, or any other planar feature. The strike direction is the direction of the line of intersection of that feature with a horizontal plane.

Dip literally means slope or inclination.

In structural geology, dip is expressed both as a direction and its amount or angle.

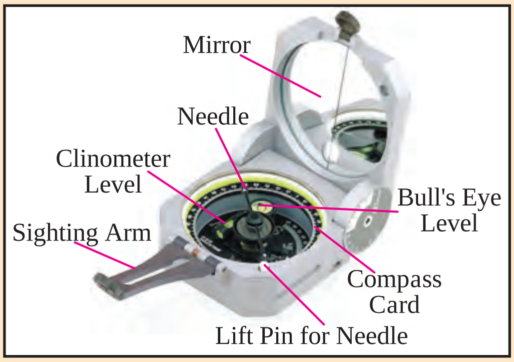
Dip direction is the direction along which maximum inclination of the bedding plane occurs. It is measured in a direction which is 90° to the strike direction. This is called the true dip.

The amount of dip or angle of dip gives the steepest angle of descent of a tilted bed or feature relative to a horizontal plane. This is given in degrees (0°-90°) and the direction in which the bed is dipping.

Do you know?

A Brunton compass, properly known as the Brunton Pocket Transit, is a precision compass made by Brunton, Inc. of Riverton, Wyoming. The Pocket Transit may be adjusted for declination angle according to one's location on the Earth. It is used to get directional degree measurements (azimuth) through use of the Earth's magnetic field. Holding the compass at waist-height, the user looks down into the mirror and lines up the target, needle, and guide line that is on the mirror. Once all three are lined up and the compass is level, the reading for that azimuth can be made. Arguably the most frequent use for the Brunton in the field is the calculation of the strike and dip of geological features (faults, contacts, foliation, sedimentary strata, etc.). Strike is measured by leveling (with the bull's eye level) the compass along the plane being measured. Dip is taken by laying the side of the compass perpendicular to the strike measurement and rotating horizontal level until the bubble is stable and the reading has been made. If field conditions allow, additional features of the compass allow users to measure such geological attributes from a distance.

As with most traditional compasses, directional measurements are made in reference to the Earth's magnetic field. Thus, measurements are sensitive to magnetic interference. For example, if the user is near an outcrop that contains magnetite or some other iron-bearing material, compass readings can be affected anywhere from several inches from the outcrop to tens of yards away (depending on the strength of the magnetic field). Since they are measured with a rotating level, dip measurements are unaffected by magnetic interference.



Apparent Dip and True Dip :

The dip angle and amount measured in a direction other than perpendicular the strike direction is called apparent dip. True dip is always greater than apparent dip. The apparent dip of the inclined bed will vary according to the direction in which it is measured, being zero parallel to strike and increasing in other directions till it is equal to the true dip when the direction of measurement is perpendicular to the strike. Table 4.1 describes the relationship between the orientation of the bed in relation to strike and dip.

Table 4.1 : Orientation of the bed in relation to strike and dip

Orientation of bed	Strike Direction	Dip Direction	Dip Amount (Angle)
Horizontal	Absent	Absent	Zero
Vertical	Present	Absent	90°
Inclined	Present	Present	$>0°$ and $<90°$

Folds, faults, joints and unconformities :

Structural deformation or defects are represented by folds, faults, joints etc.

These are internal features exhibited by rocks as a resulting due to tectonic disturbances.

Folds :

When a set of layers are subjected to compressive forces, they bend upward or downward. Such bends in rocks are called folds. These bends or curves are a result of permanent deformation due to tectonic forces. Folds may occur singly, isolated or as extensive fold trains of different sizes. A set of folds distributed on a regional scale constitutes a fold belt, a common feature in orogenic zones.

Parts or Elements of a fold :

Different parts of a fold can be described as follows :

Axial plane : An imaginary plane that divides the fold as symmetrically as possible.

Axis or Hinge : It is an imaginary line along which the bedding plane has suffered maximum bending or curvature .It may or may not coincide with the axial plane.

Crest : The convex or the up-arched part of the fold.

Trough : The concave or the down-arched part of the fold.

Limbs or Flanks : The sides of a fold. In a series of folds, it is the part between the crest of one fold and the trough of the adjacent fold.

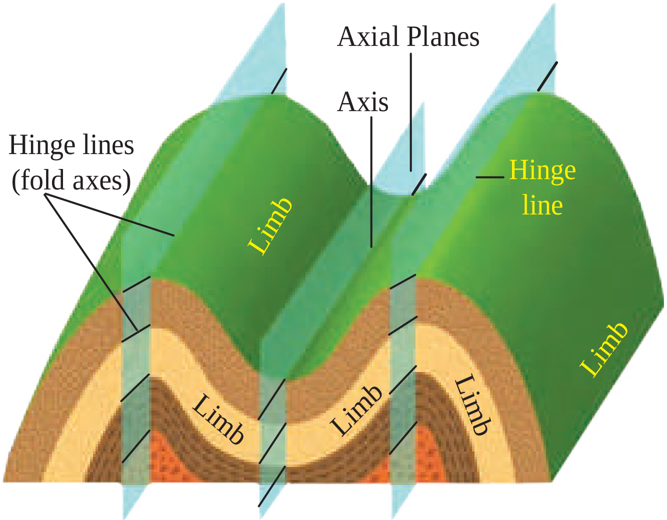


Fig. 4.6 : parts/ elements of a fold

Types of Folds :

1) **Anticline :** The name is derived from Greek term meaning 'opposite inclined'. Shape of this fold is convex upwards. The limbs of the anticline dip away from each other with reference to its axial plane. In such a fold, the older beds occur towards the core or centre of curvature (fig. 4.6).

2) **Syncline :** The name is derived from the Greek term meaning 'together inclined'. Syncline is opposite of anticline. Shape of the fold is convex downwards. The limbs of the syncline dip towards each other with reference to its axial plane. In this fold, the younger beds occur towards the core or centre of curvature (fig. 4.6).

3) **Symmetrical Folds :** The axial plane is vertical and divides the fold into two equal halves in such a way that one half is the mirror image of the other. In such folds, the two limbs dip by the same angle on either side of the axial plane. The compressive forces acting on the beds from either side are equal (fig. 4.7).

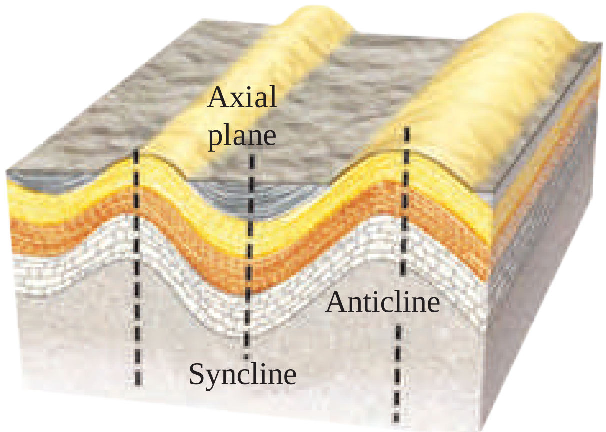


Fig. 4.7 : Symmetrical folds (anticline and syncline)

Symmetrical Folds are of two types :

Symmetrical Anticline : The axial plane is vertical and the two limbs dip away from each other by the same angle.

Symmetrical Syncline : The axial plane is vertical and the two limbs dip towards each other by the same angle.

4) **Asymmetrical Folds :** The axial plane is inclined. In such folds, the two limbs dip at different angles on either side of the axial plane. The unequal angles of dip imply that the forces acting on the beds from the two sides were unequal (fig. 4.8).

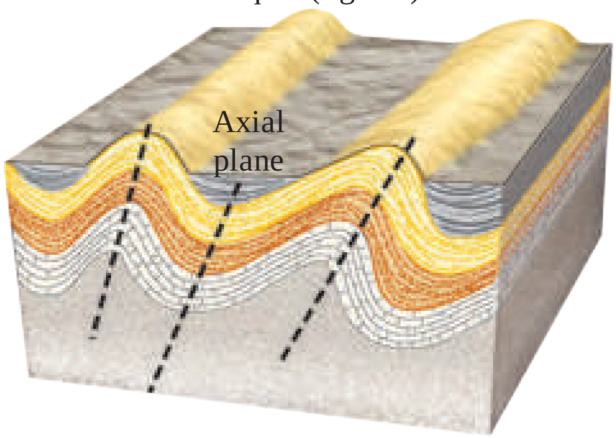


Fig. 4.8: Asymmetrical folds (anticline and syncline)

Asymmetrical folds may be two types:

Asymmetrical Anticline : The axial plane is inclined and the two limbs dip away from each other by different angles.

Asymmetrical Syncline : The axial plane is inclined and the two limbs dip towards each other by different angles.

Significance of Folds :

1) **Mountain building :** Folds result in the most stable features like mountains. Folds can give rise to valleys, hills and long mountains ranges. The great, lofty mountains like the Himalayas in India are fold mountains.

2) **Groundwater occurrence :** In terms of ground water occurrence, synclines sometimes furnish favourable conditions to tap enormous quantities of ground water. Thus, some artesian springs and wells, which are good sources of groundwater owe their origin to synclinal structures.

3) **Oil and Gas deposits :** Occurrence of important oil and gas deposits of the world are associated with anticlinal folds which serve as good structural traps of these valuable and strategic deposits (fig. 4.9).

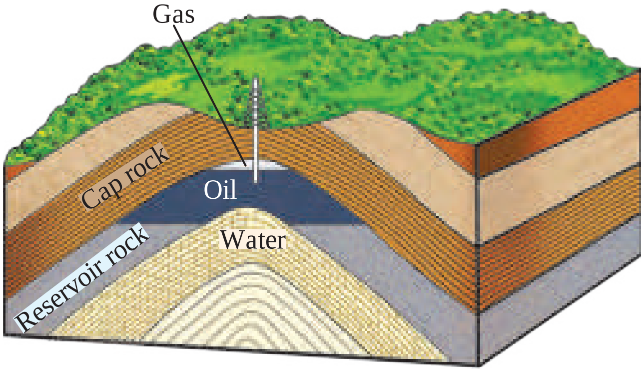


Fig. 4.9 : Anticlinal trap

Do you know?

Mumbai High Field

Bombay High (now Mumbai High) is an offshore oilfield located in the Arabian Sea, approximately 160 km west of the Mumbai coast. Discovered in 1974, by the Russian and Indian oil exploration team from seismic exploration vessel Academic Arkhangelsky while mapping the Gulf of Khambhat between 1964 and 1967. The field started production in 1976 and is operated by Oil and Natural Gas Corporation (ONGC).

Every oil resource rock requires Structural traps which are mainly salt domes, coral reefs, fault traps and fold traps. In case of Bombay High, the structure is a north-northwest to south-southeast trending doubly plunging Anticline with a faulted east limb, 65 km long and 23 km wide and is the most probable reason for calling it 'Bombay High'.

The oil field consists of two blocks named Mumbai High North (MHN) and Mumbai High South (MHS). The blocks were divided based on shale barrier assisting in independent exploitation of reserves at the north and south fields of Mumbai High.

The discovery of Bombay High with subsequent other discoveries of oil and gas fields in western offshore changed the oil scenario of India.

Faults :

Fault is a planar fracture in a volume of rock across which there has been significant displacement along the fracture as a result of Earth movements. (fig. 4.10). Energy release associated with rapid movement on active faults is the main cause of earthquakes.

Fig. 4.10 : Displacement along a fault

Parts or Elements of a Fault :

The different parts of a fault are:

1) **Fault Plane :** This is the plane along which the adjacent blocks are relatively displaced. In other words, this is the fractured surface on either side of which the rocks have moved past one another (FFF) (fig. 4.11). Its intersection with the horizontal plane gives the strike of the fault (ss). The direction (d) along which the fault plane has the maximum slope is its true dip amount.(θ)

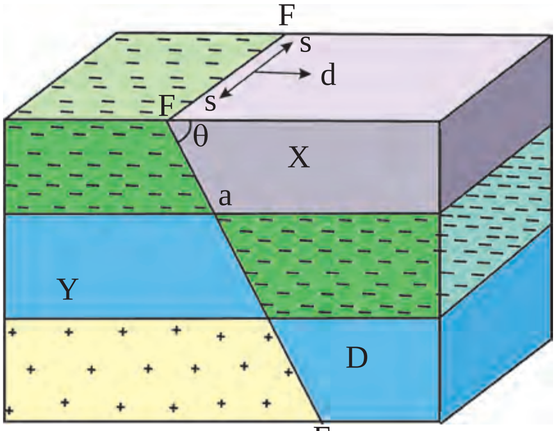


Fig. 4.11 : Parts of a Fault

2) **Foot wall and Hanging wall :** In an inclined fault, the faulted block which lies below the fault plane is called the footwall (Y) and the other block which rests above the fault plane is called hanging wall (X) (fig. 4.12).

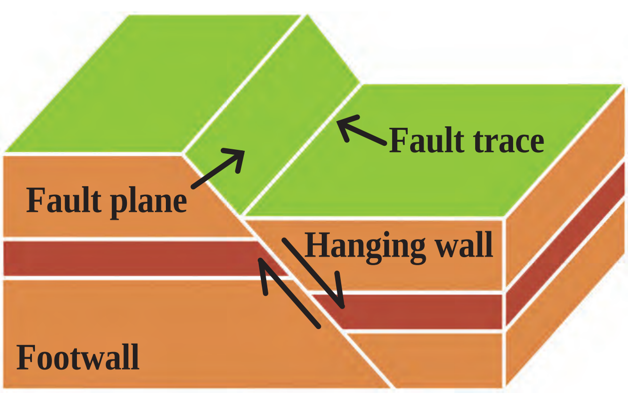
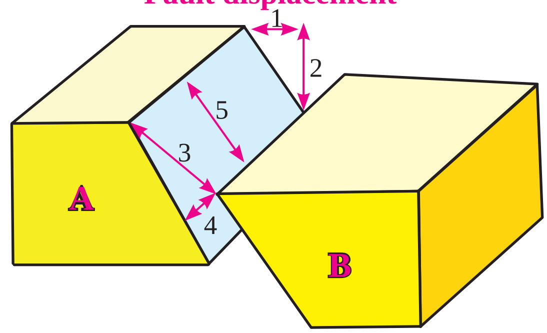


Fig.4.12 : Foot wall and hanging wall

Measurement of movement along fault plane :

1) **Slip :** The displacement that occurs during faulting is called the slip. The total displacement is known as the net slip. This may be along the strike (strike slip) or the dip direction (dip slip) or along both (fig. 4.13).

2) **Heave and Throw :** The horizontal component of displacement is called 'heave' and the vertical component of displacement is called 'throw' of the fault (fig. 4.13).



1-Heave 2-Throw 3-Slip 4-Strike slip 5-Dip slip

Fig. 4.13 : Components of displacement along a fault

Types of Faults :

Faults are classified on the basis of relative movement of footwall and hanging wall.

1) **Normal Faults :** In a Normal fault or Gravity fault, hanging wall is displaced down with reference to the footwall. These terms are very appropriate because the hanging wall is normally expected to move down along the slope of the fault plane, under the influence of gravity. Normal faults have dips greater than 45°. Lengthening and extension of the crust occurs in normal faults. They result from strong tensional forces (fig. 4.14).

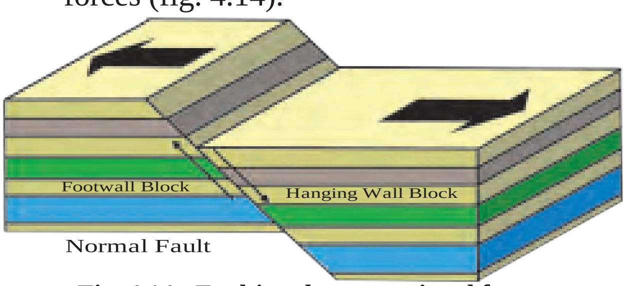


Fig. 4.14 : Faulting due to tensional forces

2) **Reverse Faults :** Hanging wall block moves up relative to the footwall. Reverse faults have dips greater than 45°. Shortening of the crust occurs in case of reverse faults. They result from strong compressional forces (fig. 4.15).

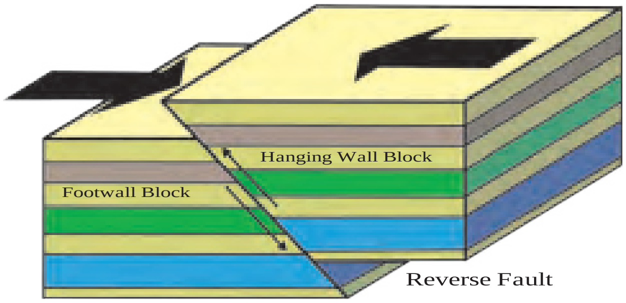


Fig. 4.15 : Faulting due to compressional forces

Thrust Faults :

A special case of reverse faults is the thrust Fault. Thrust faults are characterised by low dip angles (less than 45°) (fig. 4.16).

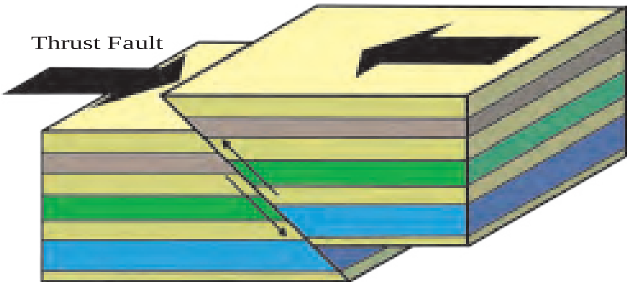


Fig. 4.16 : Thrust fault

3) **Strike Slip Faults :** In this type of fault, the blocks slide past each other along the direction of strike. This fault is also called lateral fault, trans-current fault, wrench fault or tear fault (fig. 4.17).

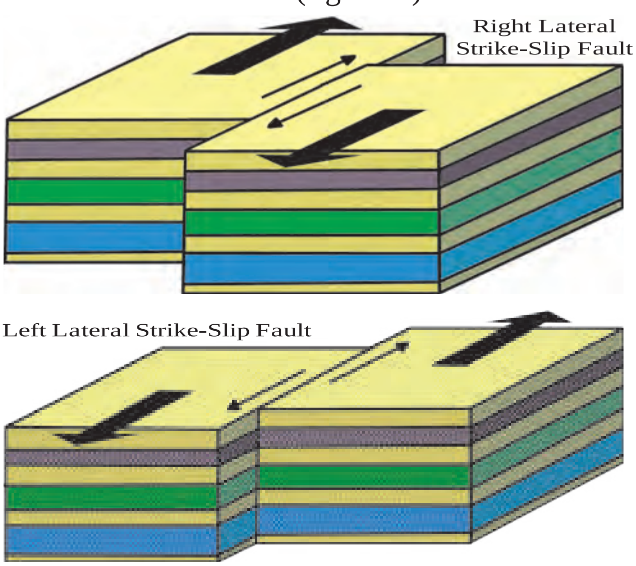


Fig. 4.17 : Strike slip fault

4) **Step Faults :** When a set of parallel normal faults occur at regular intervals, they give a step-like appearance and are called step faults (fig. 4.18).

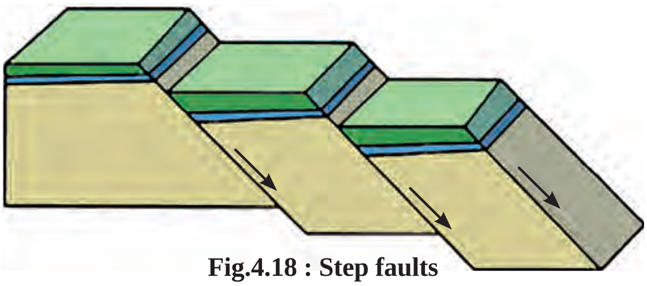


Fig.4.18 : Step faults

5) **Horst and Graben :** When normal faults with mutually diverging or converging fault planes occur, then a few wedge-shaped blocks called 'horsts' are displaced upwards and other blocks called 'grabens' are displaced downwards (fig. 4.19).

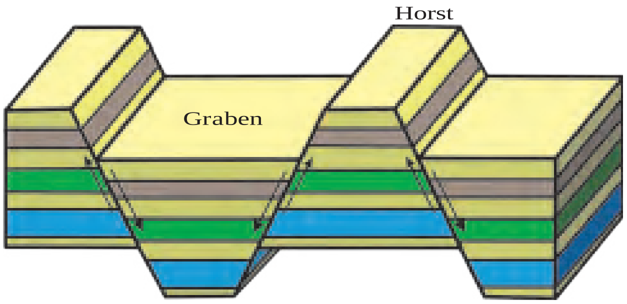


Fig. 4.19 : Horst and Graben

Horst and Graben of large magnitudes result in the formation of block mountains and rift valleys respectively.

Significance of Faults :

Faults are important due to their various disastrous as well as useful effects.

These can be briefly given as follows :

(i) Faults cause considerable damage to rocks and are therefore real hazards in mining and engineering works.

(ii) Fault breccia and fault gouge (pulverized rocks) have low strength and are poor foundation materials.

(iii) Earthquakes and landslides are likely to be triggered by faults.

(iv) It is necessary to have knowledge of the faults as they are conducive to earthquakes. This helps in proper designing of large civil structures for e.g. dams tunnels etc. to prevent them from damage.

(v) Many fault zones are most suitable sites for mineralization of gold, silver, copper etc.

(vi) Faults may create lakes, swamps, marshy zones, hot water springs etc. These hot water springs are good sources of geothermal energy.

(vii) Some fault zones form potential oil traps.

Joints :

Joints are fractures found in all types of rocks. They are cracks or openings along which there is no displacement parallel to the joint plane. The presence of joints divides the rocks into a number of parts or blocks. Though joints may be described as mere cracks in rocks, they differ mutually. Joints, like cleavages of minerals, occur oriented in a definite direction and as sets (fig. 4.20).

Fig. 4.20 : Geological outcrop showing joints

Types of Joints :

1) **Strike Joints :** Joint is parallel to the strike of adjacent beds (fig. 4.21).

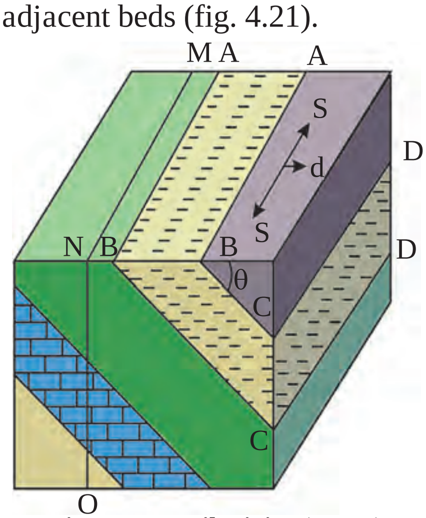


Fig. 4.21 : Strike joint (MNO)

2) **Dip Joints :** Joint is parallel to the dip direction of adjacent beds (fig. 4.22).

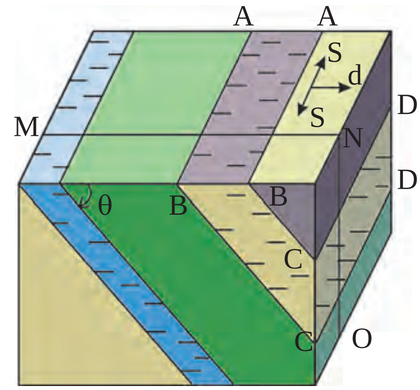


Fig. 4.22 : Dip joint (MNO)

3) **Diagonal Joints :** Joint is oblique to the strike and dip direction of the adjacent beds (fig. 4.23)

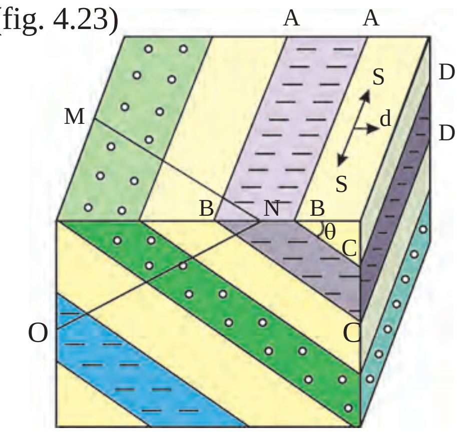


Fig 4.23 : Oblique joint(MNO)

4) **Bedding Joints :** Joint is parallel to the bedding plane (fig. 4.24).

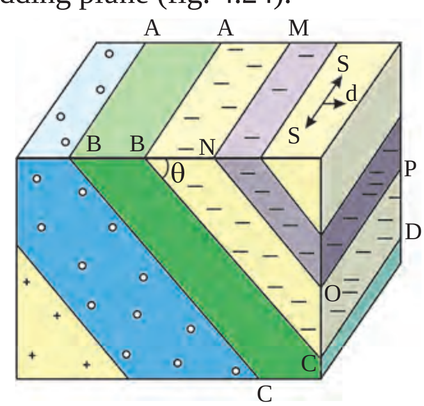


Fig 4.24 : Bedding Joint (MNOP)

5) **Columnar Joints :** Columnar joints are sets of intersecting closely spaced fractures. They occur in many types of igneous rocks and form as the rock cools and contracts. Columnar joints can occur in cooling lava flows as well as in some shallow intrusions (fig. 4.25).

These columns can vary from few

centimetres to few metres in diameter, and can be several hundred metres in height. They are typically parallel and straight, but can also be curved and vary in dimension. The number of sides of the individual columns can vary from 3 to 8.

Most commonly, columnar joints are observed in basalts. Figure explains the genesis or mode of formation of columnar joints.

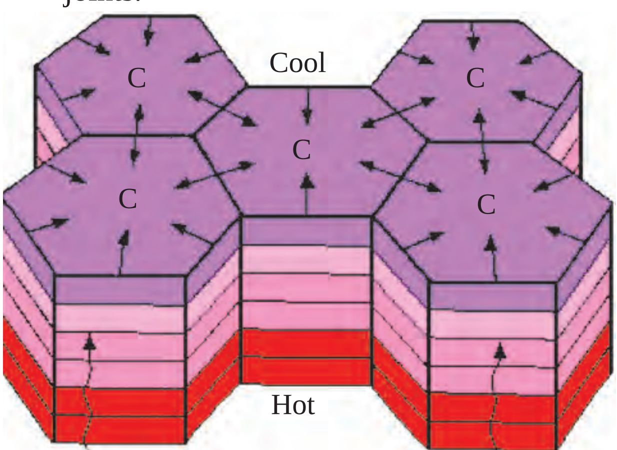


Fig. 4.25 : Columnar joints

When lava cools it contracts, giving rise to the formation of cracks or fractures. If contraction occurs at centres which are equally spaced, then polygonal fracture pattern develops. If the cooling centres are not evenly spaced, then other geometries of fractures, such as 5-sided or 7-sided columns may occur. e.g., columnar joints in basalts of Naldurga Fort, Osmanabad, Panhala Fort, Kolhapur, Gilbert Hill, Mumbai, St. Mary's island in Arabian sea off the coast of Malpe in Udupi, Karnataka, India (fig. 4.26).

Fig. 4.26 : Columnar joints at St. Mary's island Malpe in Udupi, Karnataka, India

Columnar joints are not restricted to basalt. This structure can also form in other types of rocks that undergo cooling and contraction e.g columns in rhyolite at Utan in Thane district.

Significance of Joints :

From the civil engineering point of view, joints are important because they split the rocks into a number of blocks, which in turn reduce the competence of rock mass, increase their porosity and permeability and make them susceptible to quick decay and weathering.

Occurrence of joints increases the ground water potential in any place. The area affected by joints can be easily improved by suitable methods such as cement grouting or plugging.

Unconformities :

Unconformities are a product of diastorphism and involve tectonic activity in the form of upliftment and subsidence of landmass. When sediments are deposited continuously, without any major break, they are said to be conformable. All the beds belonging to a conformable set possess the same strike, dip direction and dip amount. On the other hand, if a major break occurs in sedimentation between two sets of conformable beds, it is termed as an unconformity. Thus, an unconformity is a contact between two rock units that are unconformable with each other. An unconformity, typically, is a buried erosional surface that represents a break in the geologic record. An expected age of layer or layers of rocks is/are missing due to erosion and some period in geologic time is not represented. This is known as a hiatus.

Types of Unconformities :

Different types of unconformities can be recognised as follows :

1) **Angular Unconformity :** When the younger beds and the older set of strata are not mutually parallel, then the unconformity is called an angular unconformity. In such a case, beds of one set occur with a greater tilt or folding (fig. 4.27 and fig. 4.28).

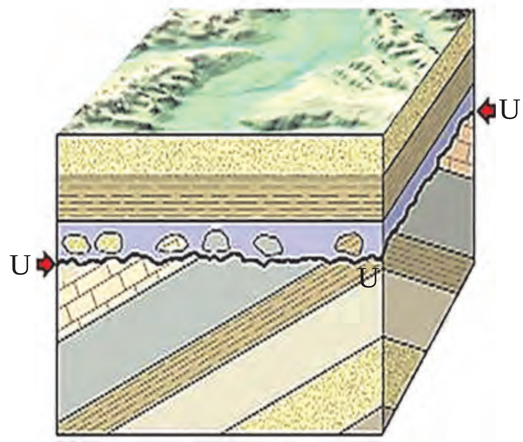


Fig. 4.27 : Angular unconformity

Fig. 4.28 : Field example of angular unconformity

Hutton's angular unconformity at Siccar Point where 345-million-year-old Devonian Old Red Sandstone overlies 425-million-year-old Silurian greywacke.

2) **Disconformity :** Disconformities are usually erosional contacts that separate parallel bedding planes of the upper and lower rock units. Since disconformities are hard to recognize in a layered sedimentary rock sequence, they are often discovered when the fossils in the upper and lower rock units are studied.

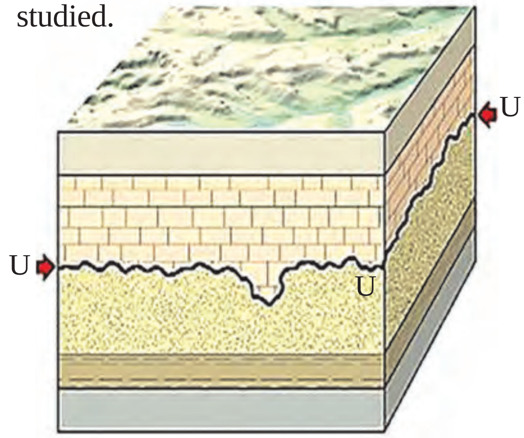


Fig. 4.29 : Disconformity

Fig. 4.30 : Field example of Disconformity

A gap in the fossil record indicates a gap in deposition. Disconformities are usually a result of erosion, but can occasionally represent periods of non –deposition (fig. 4.29 and fig. 4.30).

Disconformity between sedimentary rocks in California, with conglomerate deposited upon an erosion surface on the underlying rocks.

3) **Nonconformity :** When the underlying older formation is represented by igneous or metamorphic rocks and the overlying younger formation is made up of sedimentary rocks, the unconformity is called non-conformity. A nonconformity suggests that a period of long-term uplift, weathering and erosion occurred to expose the older, deeper rock at the surface before it is finally buried by the younger rocks above it. A nonconformity is the old erosional surface on the underlying rock (fig. 4.31 and fig. 4.32).

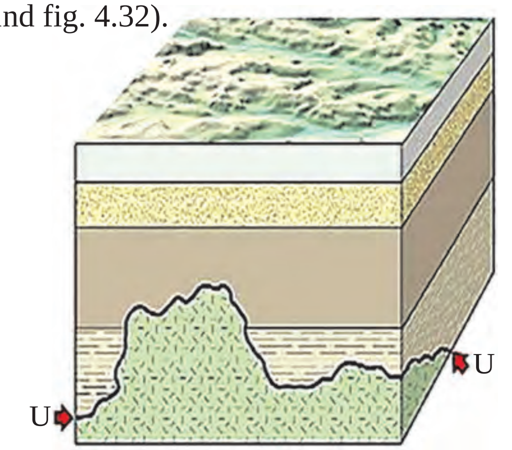


Fig. 4.31: Nonconformity

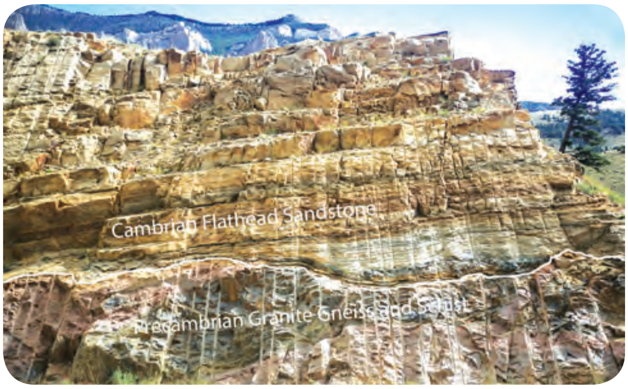


Fig. 4.32 : Nonconformity at yellow stone highway Wyoming

Significance of unconformities :

1) An unconformity represents a gap, break or interval in deposition of beds and forms a record of a gap in time.
2) Recognition of unconformities is useful for subdividing stratigraphic units, determining the timing of tectonic activity, correlating certain stratigraphic boundaries, interpreting sea-level changes etc.
3) In certain situations, an unconformity produces oil traps and aquifers.
4) Unconformities help in visualizing and in reconstructing palaeogeography of a region.
5) Unconformities are favourable sites for mineralization (e.g., uranium, aluminium, phosphates and gold).
6) It is an important structure that affects site conditions for engineering works. It generally forms a weak zone.

Application of Structural Geology :

- In Engineering geology and geotechnology : Problems such as construction of bridges, dams, power plants, highways, airports and issues related to building foundations.
- In Environmental geology : Problems such as land use, planning, earthquake hazard, volcanic hazard, distribution of groundwater.
- In Petroleum and mining geology : Understanding geometric techniques, projection of faults, geologic contacts, trends of regional processes that control the concentration of minerals and hydrocarbons.

Summary :

This chapter deals with the study and interpretation of different structural features like folds, faults, joints, unconformities, etc. found within rocks which constitute the Earth's crust. It helps to interpret their mode and mechanism of formation. This study is used as a framework to analyze and understand global, regional and local scale features. It is of prime importance in the fields of Economic Geology, both, Petroleum Geology and Mining Geology and has varied applications in Geotechnical Investigations and Engineering Geology. Environmental geologists and Hydro geologists apply this knowledge in the selection of suitable geological sites.

EXERCISE

Q. 1. Select and write the correct answer :

1) The direction of a line formed due to intersection of an inclined bed with the horizontal plane is called……..

   a) Strike b) dip c) hade d) heave

2) An imaginary plane that divides the fold into two equal halves is known as……..

   a) Axis b) Axial plane
   c) Fault plane d) Crest

3) An anticline is a fold that is……..

   a) Concave upwards and has its youngest bed at the core
   b) Convex upwards and has its youngest bed at the core
   c) Concave upwards and has its oldest bed at the core
   d) Convex upwards and has its oldest bed at the core

4) In an asymmetrical syncline, the two limbs……..

a) Dip towards each other by the same angle

b) Dip away from each other by the same angle

c) Dip towards each other by different angles

d) Dip away from each other by different angles

5) A fracture along which there has been slipping of displacement of rocks is called a ………

a) Joint b) Unconformity

c) Fault d) Fold

6) A type of fault in which the hanging wall block has been displaced upwards with respect to the footwall block is called ……

a) Graben b) Normal fault.

c) Horst d) Reverse fault

7) An unconformity in which the older bed is made up of igneous or metamorphic rocks is called……….

a) Conformity b) Nonconformity

c) Angular unconformity

d) Disconformity

Q. 2. Match the following :

1) a) throw — i) hanging wall displaced upwards

b) Normal fault — ii) Horizontal displacement.

c) Heave — iii) Footwall displaced upwards.

d) Reverse fault — iv) Vertical displacement

1) a-i, b-iv, c-iii, d-ii

2) a-iv, b-iii, c- ii, d-i

3) a-iii, b-ii, c-I, d-iv

4) a-ii, b-i, c-iv, d- ii

2) a) anticline — i) limbs dip by equal angle

b) Asymmetrical fold — ii) Convex downwards

c) Syncline — iii) Convex upward

d) Symmetrical — iv) Limbs dip by unequal angles

1) a-i, b-ii, c-iv, d-iii

2) a-ii, b-iii, c-I, d-iv

3) a-iii, b- iv, c-ii, d- i

4) a-iv, b-iv, c-iii, d- ii

3) a) Angular unconformity — i) surface of erosion or non deposition.

b) Nonconformity — ii) older series parallel to younger series.

c) Unconformity — iii) older series not parallel to younger series.

d) Disconformity — iv) older bed made up of plutonic igneous rocks.

1) a-i b-ii c-iii d-iv

2) a-iv b-i c-ii d-iii

3) a-ii b-iii c-iv d-i

4) a-iii b-iv c-i d-ii

Q. 2. Answer the following :

1) How will you explain the terms strike and dip of beds?

2) Differentiate between true dip and apparent dip of a bed of a bed? Explain with a suitable diagram.

3) Which are the different parts of a fold? Describe with a neatly labelled diagram.

4) Explain the characteristics of an anticline/ syncline with a neatly labelled diagrams.

5) Which are the different types of folds> Describe with neatly labelled diagrams.

6) Describe the different parts of fault with neatly labelled diagram.

7) Differentiate between Normal and Reverse faults?

8) Which are the different types of joints?

Q. 4. Answer in detail :

1) Differentiate between Symmetrical fold and an Asymmetrical fold?

2) Explain the different types of faults with neatly labelled diagrams.

3) What are columnar joints? How are they formed?

4) What is an unconformity? Discuss its process of formation.

5) Differentiate between a Disconformity and Nonconformity?