TITLE: PHYSICAL AND STRUCTURAL GEOLOGY

COURSE CODE: 1GELTC0101

UNIT – 4

4.1 Elementary idea of types of deformation; Folds: Nomenclature and types of folds.

Deformation and its Types:

The term deformation is used in different ways by different people and under different circumstances. In most cases, particularly in the field, the term refers to the distortion (strain) that is expressed in a (deformed) rock. This is also what the word literally means: a change in form or shape. However, rock masses can be translated or rotated as rigid units during deformation, without any internal change in shape. If, during the period of motion, the distance between any two points in a body remains the same, the body is regarded as a rigid body. For instance, fault blocks can move during deformation without accumulating any internal distortion. Many structural geologists want to include such rigid displacements in the term deformation, and we refer to them as rigid body deformation (translation and rotation), as opposed to non-rigid body deformation (strain or distortion). Deformation is the transformation from an initial to a final geometry by means of rigid body translation, rigid body rotation, strain (distortion) and/or volume change.

Hence deformation can be divided into following types:

1. Rigid Body Deformation.
2. Non-rigid Body Deformation.

Rigid Body Deformation:

It includes translation and rotation.

- **a. Translation:** *Translation* is a motion in which any straight line through the body remains parallel to itself at all stages of the motion. As shown in Fig. 1 translation is not necessarily rectilinear motion.
- **b. Rotation:** A rigid body *rotation* is a motion in which there are always two points, within the body or in the extended part of a body, which remain motionless. The line which joins the two points is known as the *axis of rotation* (Fig. 6.2).

Non-rigid Body Deformation:

It includes Distortion and Dilation.

- **a. Distortion:** It involves change in the shape of the body after the application of stress as shown in figure 3.
- **b. Dilation:** It involves change in the volume of the body after the application of stress.

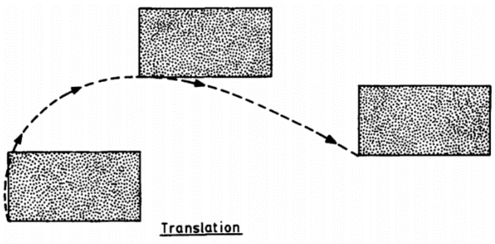

Figure 1

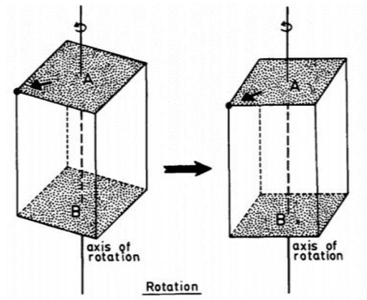

Figure 2

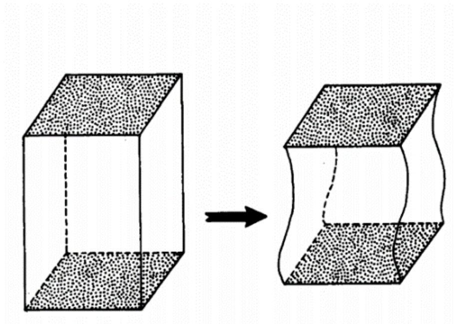

Figure 3

Folds: Nomenclature and types of folds:

A fold is a bend or a buckle in any of the pre-existing structure in a rock as a result of deformation. Folds are best displayed by structures that were formerly approximately planar, such as layering or bedding in sedimentary or igneous rocks, or foliation in metamorphic rocks. Some terms defining the various components of folds are shown in figure 4.

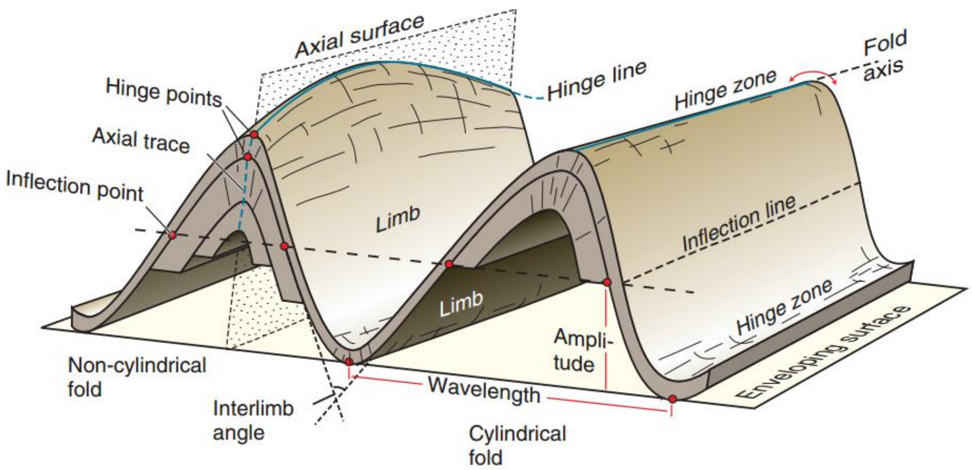

Figure 4

There is no hard and fast definition about the limits of a single fold. For most purposes it is convenient to define the lateral limits of a fold (Ramsay 1967) on a single surface by two consecutive lines of inflection.

In sections along a particular direction the trace of the folded surface appears as a straight line, while in all other sections the trace appears as a wavy line. This particular direction is called the *fold axis*. A fold axis may, then, be defined as a line which, moving parallel to itself, generates the folded surface. The fold axis is the most important structural element of a fold because the structures show the maximum continuity in this direction. A folded surface shows the maximum curvature in a plane perpendicular to the fold axis. Hence, the geometry of a cylindrical fold is best described by the orientation of the fold axis along with a description of the section perpendicular to the fold axis. Such a section is called a *transverse profile* or simply a profile.

A point which separates a convex and a concave segment of the wavy line is called an *inflection point*. In other words, the points of inflection separate, on the transverse profile, fold-segments of opposite senses of curvature. The line joining the corresponding inflection points of successive transverse sections is called the *inflection line*. As mentioned earlier, two adjoining inflection lines on a folded surface mark out the limits of a fold.

On the transverse section, the highest and the lowest points of a folded surface are known as the *crest point* and the *trough point* (Fig. 5). The line obtained by joining the corresponding crest points in serial cross sections of a fold is known as a *crest line* (Fig. 6). Similarly, we can define a *trough line* as a line which joins the lowest points of a fold. The point at which the folded surface shows the maximum, absolute value of curvature is a *hinge point* (Fig. 5). The line joining the corresponding points on successive profiles is the *hinge line* (Fig. 6) of the fold. For cylindrical folds the hinge line is parallel to the fold axis.

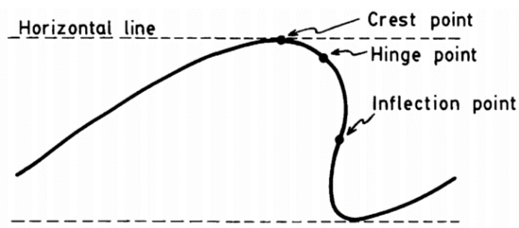

Figure 5

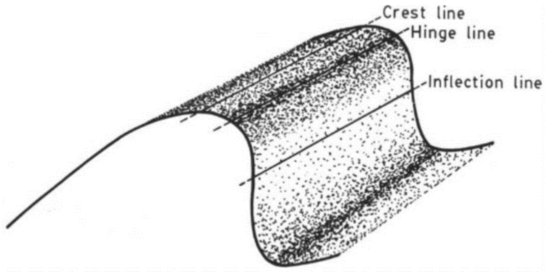

Figure 6

The surface which joins the adjoining inflection lines of a folded surface is called the *median surface* (Fig. 7). The two surfaces within which a train of folds rises and falls are known as *enveloping surfaces*. The *amplitude* (Fig. 8) of a fold may be defined as the distance between the median surface and the enveloping surface. For folds in which the lines of inflection are not well defined, the median surface may be taken as the surface equidistant from the two enveloping surfaces.

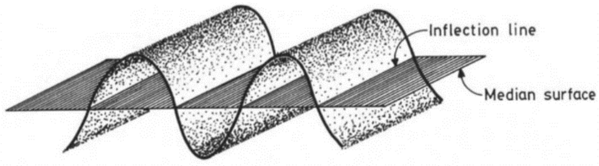

Figure 7

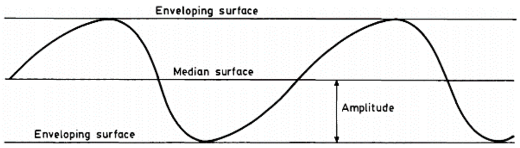

Figure 8

A *limb* of a fold may be defined as a segment of a fold between a hinge line and the adjacent inflection line (Fig. 9).

The *interlimb angle* of a fold (Fig. 10) is the angle subtended by the tangents at two adjacent inflection points.

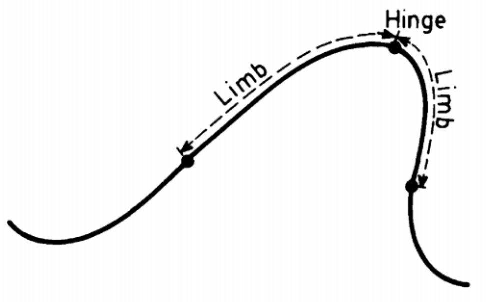

Figure 9

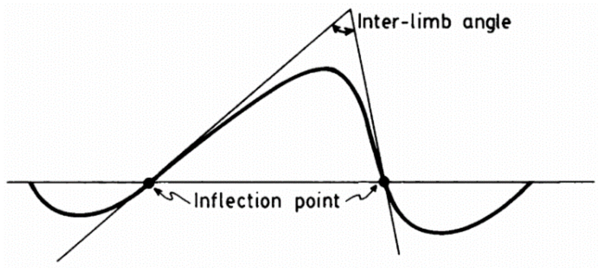

Figure 10

Types of Folds:

Many parameters are used to define the different types of folds, some of them are discussed below:

(a) Based on sense of curvature:

Antiform: a fold that closes upward (Fig. 11a).

Synform: a fold that closes downward (Fig. 11b).

Neutral fold: a fold that closes sidewise (Fig.11c).

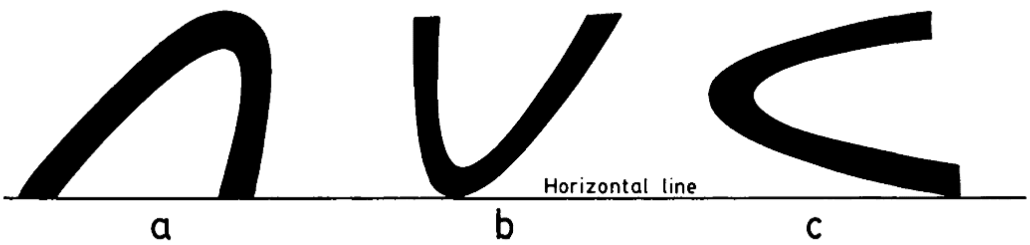

Figure 11

(b) Based on the plunge of the fold axis:

Horizontal fold: a fold whose axis is horizontal (Fig. 12a).

Plunging fold: a fold whose axis is inclined (Fig. 12b).

Vertical fold: a fold with vertical axis (Fig. 12c).

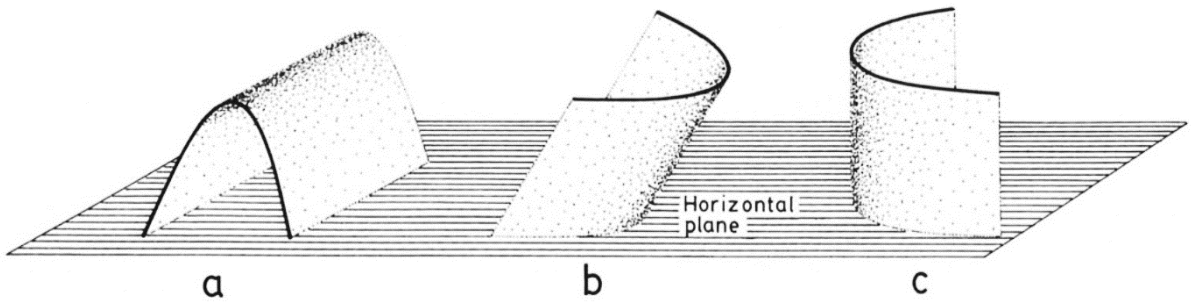

Figure 12

(c) Based on orientation of axial plane:

Upright fold: with vertical or nearly vertical axial plane (Fig. 13a).

Recumbent fold: with axial plane dipping at an angle of 10° or less (Fig. 13b).

Inclined fold: with inclined axial plane (Fig. 13c).

Reclined fold: inclined fold in which the pitch of the fold axis on the axial plane is between 80 and 100° (Fig. 13d).

Overturned fold: inclined fold in which both the limbs have the same sense of inclination (Fig. 13e).

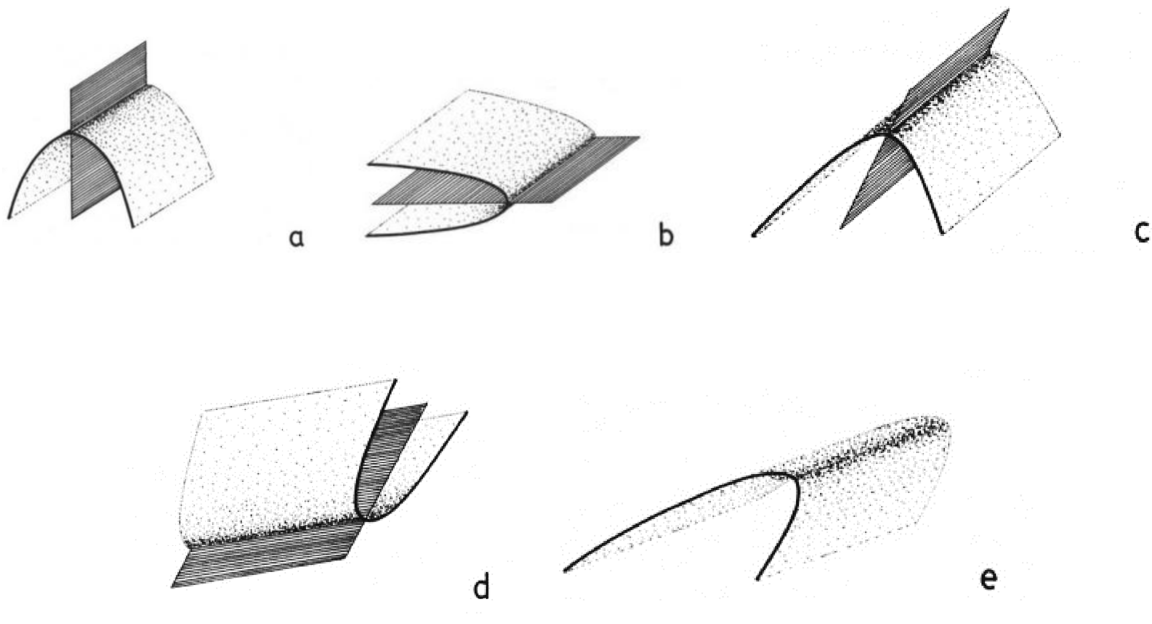

Figure 13

(d) Based on direction of younging relative to sense of fold closure:

Anticline: a fold in which direction of younging is away from the fold core (Fig. 14a).

Syncline: a fold in which direction of younging is towards the fold core (Fig. 14b).

Anticlinorium: a large anticline with many smaller folds on its back (Fig. 14c).

Synclinorium: a large syncline with many small folds on its back (Fig. 14c).

Synformal anticline: a fold that closes downward but with direction of younging away from the fold core (Fig. 14d).

Antiformal syncline: a fold that closes upward but in which the younging is towards the fold core (Fig. 14d).

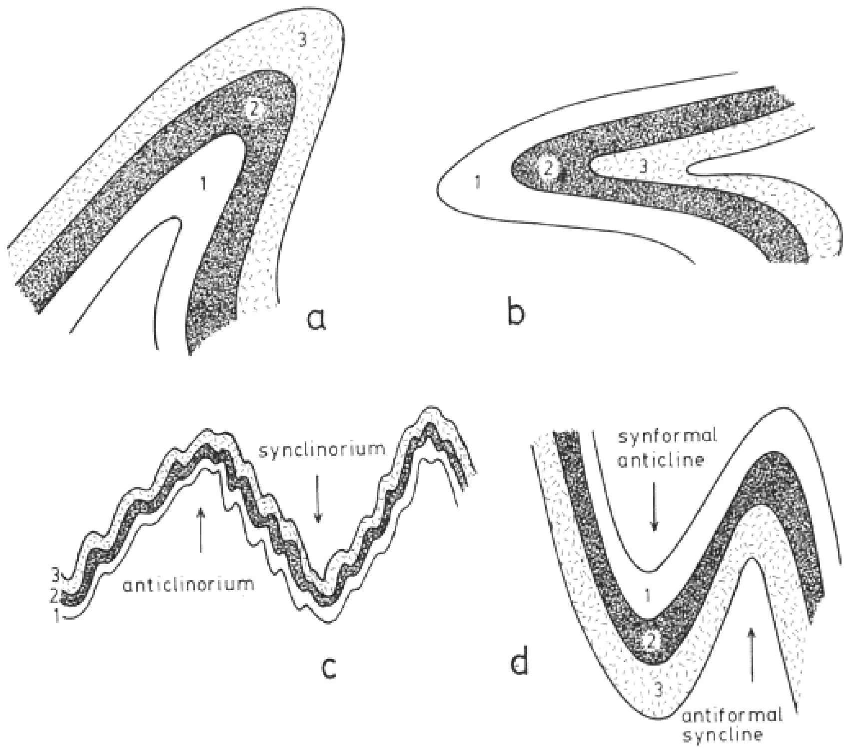

Figure 14

(e) Based on the symmetry of folds:

Symmetric fold: a fold in which the axial plane is a plane of symmetry (Fig. 15a).

Asymmetric folds: a fold in which the axial plane is not a plane of symmetry (Fig. 15b).

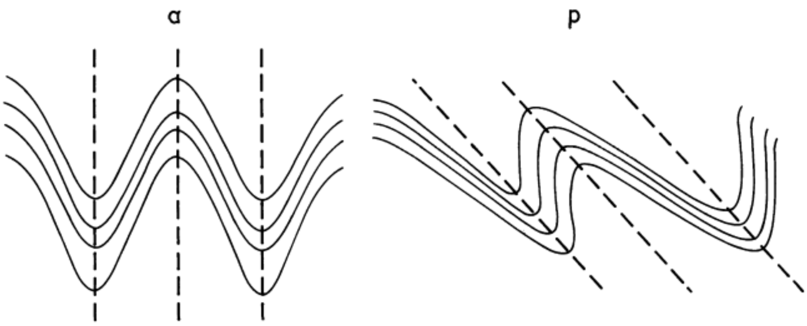

Figure 15

(f) Based on the nature of the hinge line:

Cylindrical fold: a fold which can be generated by moving a line parallel to itself. A cylindrical fold has a rectilinear hinge line parallel to the fold axis.

Non-cylindrical fold: a fold which cannot be generated by moving a line parallel to itself. The hinge line is either curved or the fold is conical.

(g) Based on interlimb angle:

Gentle fold: with interlimb angle between 180 and 120°.

Open fold: with interlimb angle between 120 and 70°.

Close fold: with interlimb angle between 70 and 30°.

Tight fold: with interlimb angle less than 30° and greater than 0°.

Isoclinal fold: with sub-parallel limbs (Fig. 16).

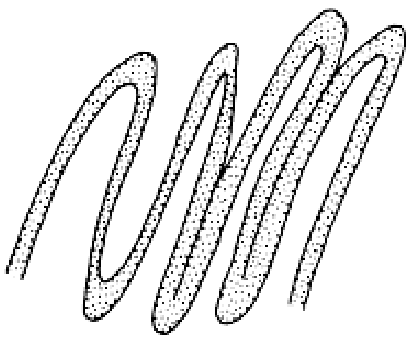

Figure 16

4.2 <u>Faults: Nomenclature, Geometrical and Genetic Classification, Normal, Thrust and Slip Faults.</u>

A fault is a fracture in earth materials along which the opposite sides have been relatively displaced parallel to the plane of movement. The surface along which movement takes place is known as the fault plane or fault surface. Movement may occur on a number of closely spaced faults within a fault zone rather than a discrete surface. Fault lengths may vary from few centimetres to hundreds of kilometres.

<u>Nomenclature of Faults:</u>

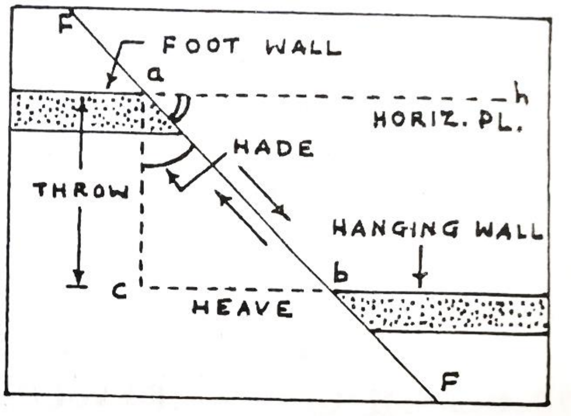

Figure 1

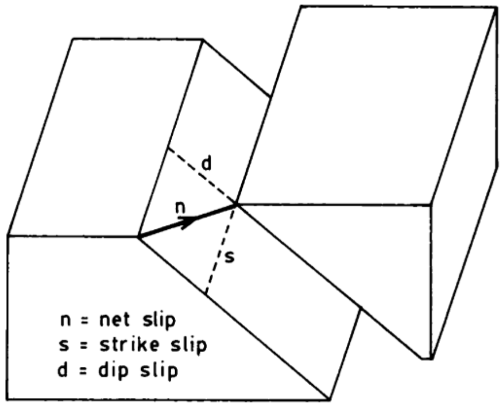

Figure 2

Hade is the angle of inclination of a fault plane with respect to vertical plane (Fig. 1).

Dip Amount is the angle of inclination of a fault plane with respect to horizontal plane (Fig. 1).

Dip Direction is the direction in which the fault plane is dipping.

Strike is the orientation of the line formed by the intersection of fault plane and the horizontal plane with respect to the North direction.

Throw is the vertical component of the displacement along the fault surface (Fig. 1).

Heave is the horizontal component of the displacement along the fault surface (Fig. 1).

Net Slip is the total displacement measured along the fault surface. It is measured between the two points which were originally in contact (Fig 2). The movement along the fault surface can be resolved into two components **Dip Slip** (slip component parallel to dip) and **Strike Slip** (slip component parallel to strike) (Fig 2).

Fault scarp is the cliff formed initially along the up-thrown side of the fault.

The trace of the fault on the earth's surface is the ***fault line***. If a fault is not vertical the side above the fault plane is called the ***hanging wall*** and the side below the fault plane is called the ***foot wall*** (Fig. 1). A fault surface may be curved or planar. Curved faults are known as ***listric faults.***

Classification of Faults:

Faults can be classified on the basis of their geometry or their genesis.

(A) Geometric Classification:

Geometrically faults can be classified on the following five basis:

1. Classification based on the Rake of Net Slip:

On this basis faults can be classified into following three categories:

a) Strike Slip Fault is one in which the net slip is parallel to the strike of the fault and there is no dip slip component (Fig 3). The rake of the net slip is therefore zero.

b) Dip Slip Fault is one in which the net slip is up or down parallel to the dip of the fault and there is no strike slip component (Fig 4). The rake of the net slip is therefore 90^0.

c) Diagonal/Oblique Slip Fault is one in which the net slip is diagonally up or down the fault plane and there is both dip slip and strike slip components (Fig 5). The rake of the net slip is therefore greater than zero but less than 90^0.

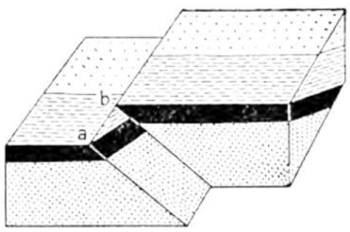

Figure 3

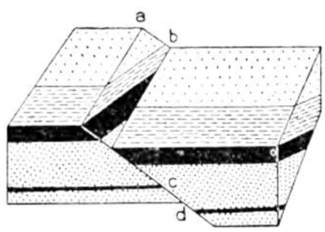

Figure 4

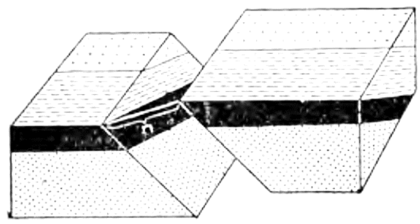

Figure 5

2. Classification based on Attitude of fault relative to attitude of adjacent beds:

On this basis faults can be classified into following categories:

a) Strike Fault is one that strikes essentially parallel to the strike of the adjacent rocks (Fig. 6). The strike of the adjacent rocks is ordinarily measured on the bedding, but if the bedding is absent, the strike may be measured on the schistosity of metamorphic rocks or on the flow structure of igneous rocks.

b) Dip Fault strikes essentially parallel to the direction *of* dip of the adjacent beds; that is, its strike is perpendicular to the strike of the adjacent beds (Fig. 7).

c) Diagonal/Oblique Fault is one that strikes obliquely or diagonally to the strike of the adjacent rocks (Fig. 8).

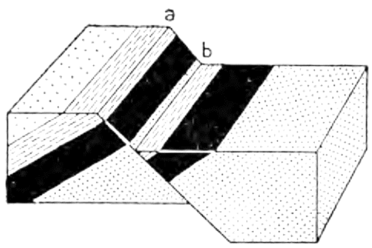

Figure 6

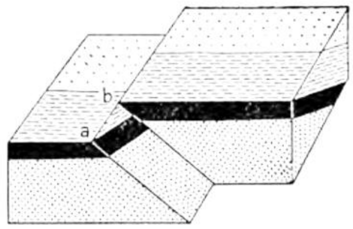

Figure 7

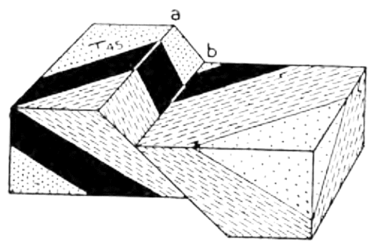

Figure 8

3. Classification based on Fault Pattern:

A third geometrical classification is based on the pattern shown by the faults. Following are some of the important faults in this category:

a) Parallel Faults have essentially the same dip and strike, and thus belong to a set of *parallel faults (Fig. 9A).* If the strikes are the same but the dips differ, the faults are assigned to two or more sets of parallel faults.

b) En echelon faults are relatively short faults that overlap each other (Fig. 9B).

c) Peripheral faults are circular or arcuate faults that bound a circular area or part of a circular area (Fig. 9C).

d) Radial Faults belong to a system of faults that radiate out from a point (Fig. 9D).

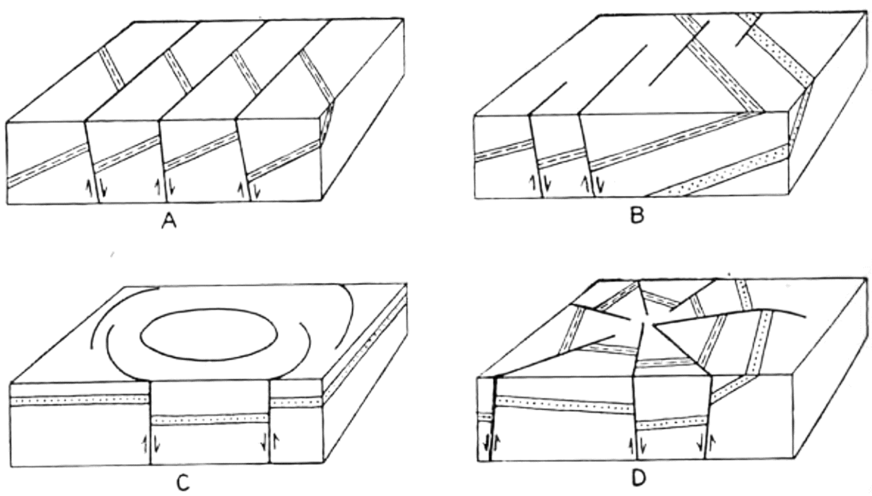

Figure 9

4. **Classification based on value of Dip of Fault:**

The fourth geometrical classification is based on the angle of dip of the fault.

a) **High Angle Faults** are those that dip greater than 45 degrees.

b) **Low Angle Faults** are those that dip less than 45 degrees.

5. Classification based upon Apparent Movement:

A fifth geometrical classification is based upon the apparent movement in vertical sections at right angles to the fault.

a) A Normal fault is one in which the hanging wall has apparently gone down relative to the footwall (Fig. 10).

b) A reverse fault is one in which the hanging wall has apparently gone up relative to the footwall (Fig. 11).

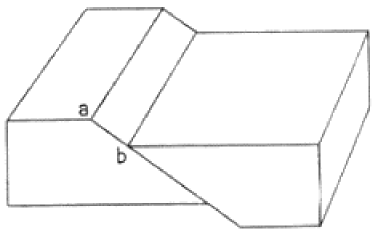

Figure 10

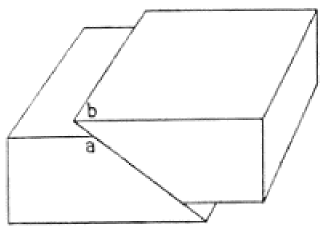

Figure 11

(B) Genetic Classification:

Genetically faults can be classified on the following two basis:

1. Classification based on relative movements:

The most satisfactory genetic classification that can be established at present is based on the nature of the relative movement along the fault.

a) Thrust Fault or thrust is a fault along which the hanging wall has moved up relative to the Footwall, generally at very low angle and blocks moved large distance along it (Fig. 11). These represent the shortening of the Earth's crust.

b) Gravity Fault *is* a fault along which the hanging wall has moved down relative to the footwall (Fig. 10). They indicate the lengthening of the Earth's crust.

c) Strike Slip Faults are those faults along which the displacement has been essentially parallel to the strike of the fault. The term Wrench Fault is also used for this type of fault if the dip is nearly vertical. A strike slip fault is said to be **Sinistral or Left-handed strike-slip fault** if the block on the opposite side of the fault is moved left relative to the block on which the observer is standing. If the block on the opposite side of the fault is moved right relative to the block on which the observer is standing then it is said to be **Dextral or Right-handed strike slip fault**. (Fig. 12).

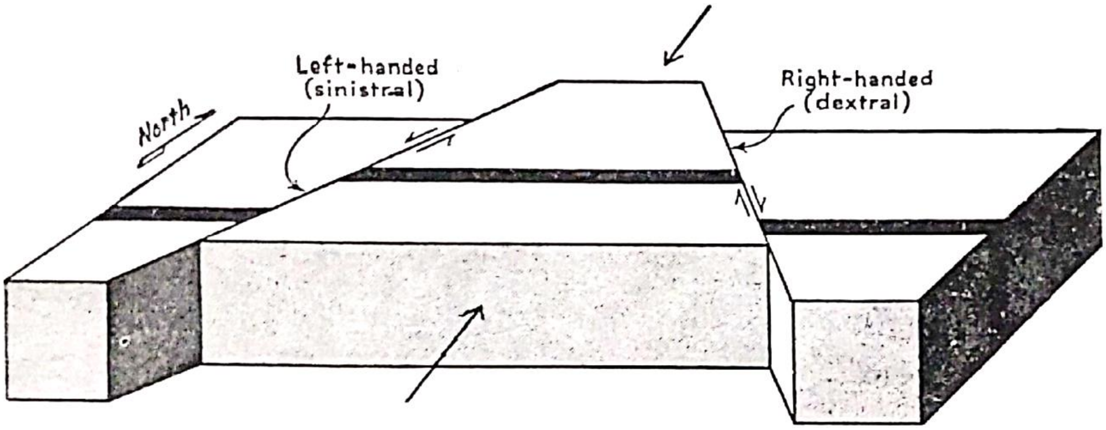

Figure 12

2. Classification based on Absolute Movements:

The classification outlined above is based on relative movements. A more elaborate classification would be based on absolute movements relative to some datum plane, such as sea level. Thus five kinds of gravity faults might be recognized:

(1) those in which the footwall stayed in place, but in which the hanging wall moved down;

(2) those in which the footwall moved up, while the hanging wall stayed still;

(3) those in which the hanging wall moved down and the footwall moved up;

(4) those in which both blocks moved down, but in which the hanging wall moved a greater amount ; and

(5) those in which both blocks moved up, but in which the hanging wall moved less than the footwall.

Similarly, five kinds of thrust faults might be established.

In most instances, however, data are not available to indicate the absolute movement of faults. Many attempts have been made to establish criteria, based on the pattern of the faults, the dip of the fault plane, or the comparative intensity of the deformation in the two blocks. Knowledge of that phase mechanics known as *Statics* indicates that such criteria is unreliable.

4.3 <u>Joints: Definition, types and significance.</u>

A joint is a break (fracture) of natural origin in the continuity of either a layer or body of rock that lacks any visible or measurable movement parallel to the surface (plane) of the fracture. Although they can occur singly, they most frequently occur as joint sets and systems. A ***joint set*** is a family of parallel, evenly spaced joints that can be identified through mapping and analysis of the orientations, spacing, and physical properties. A ***joint system*** consists of two or more intersecting joint sets.

Faults differ from joints in that they exhibit visible or measurable lateral movement between the opposite surfaces of the fracture. As a result, a joint may have been created by either strict movement of a rock layer or body perpendicular to the fracture or by varying degrees of lateral displacement parallel to the surface (plane) of the fracture that remains "invisible" at the scale of observation.

Joints are among the most universal geologic structures as they are found in most every exposure of rock. They vary greatly in appearance, dimensions, and arrangement, and occur in quite different tectonic environments. Often, the specific origin of the stresses that created certain joints and associated joint sets can be quite ambiguous, unclear, and sometimes controversial. The most prominent joints occur in the most well-consolidated, lithified, and highly competent rocks, such as sandstone, limestone, quartzite, and granite. Joints may be open fractures or filled by various materials. Joints infilled by precipitated minerals are called **veins** and joints filled by solidified magma are called **dikes**.

Types of Joints

Joints are classified either by the processes responsible for their formation or their geometry.

A. Classification of joints by geometry

In terms of geometry, three major types of joints, Non-systematic joints, Systematic joints, and Columnar jointing are recognized.

1. Nonsystematic joints

Nonsystematic joints are joints that are so irregular in form, spacing, and orientation that they cannot be readily grouped into distinctive, through-going joint sets.

2. Systematic joints

Systematic joints are planar, parallel, joints that can be traced for some distance, and occur at regularly, evenly spaced distances on the order centimeters, meters, tens of meters, or even hundreds of meters. The joints may be classified on the basis of their attitude relative to the bedding or some similar structure in the beds that they cut as follows:

a) Strike Joints are those which strike parallel or essentially parallel to the strike of the bedding of a sedimentary rock, the schistosity of a schist, or the gneissic structure of a gneiss. In Fig. 1, in which the bedding is shown in solid black, *BDEF* and *MNO* are strike joints.

b) Dip joints are those that strike parallel or essentially parallel to the direction in which the bedding, schistosity, or *gneissic* structure *dips*. In Fig. 1, *ABCD* and *GHI* are dip joints.

c) Oblique or diagonal joints are those striking in a direction that *lies* between the strike and direction of dip of the associated rocks. In Fig. 1, *PQR* and *STU* are oblique joints.

d) Bedding joints are parallel to the bedding of the associated sedimentary rocks. In Fig. 1, *JKL* is a. bedding joint.

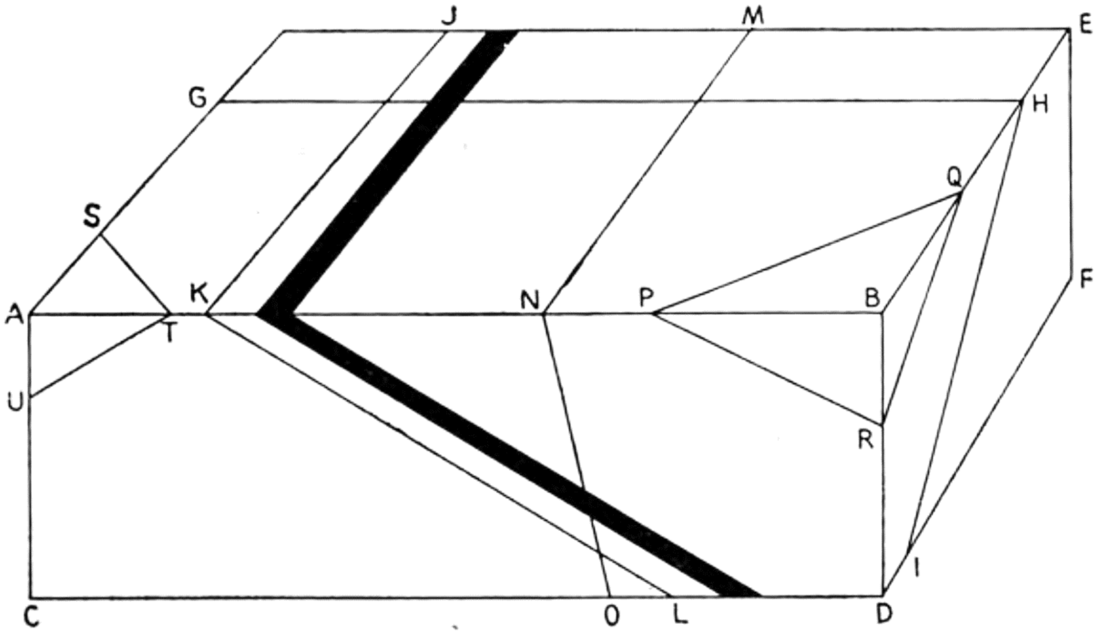

Figure 1

3. Columnar jointing

Columnar jointing is a distinctive type of joints that join together at triple junctions either at or about 120° angles. These joints split a rock body into long, prisms or columns. Typically, such columns are hexagonal, although 3-, 4-, 5- and 7-sided columns are relatively common. The diameter of these prismatic columns range from a few centimeters to several metres. They are often oriented perpendicular to either the upper surface and base of lava flows and the contact of the tabular igneous bodies with the surrounding rock (Fig. 2). This type of jointing is typical of thick lava flows and shallow dikes and sills. **Columnar jointing** is also known as either *columnar structure*, *prismatic joints*, or *prismatic jointing*.

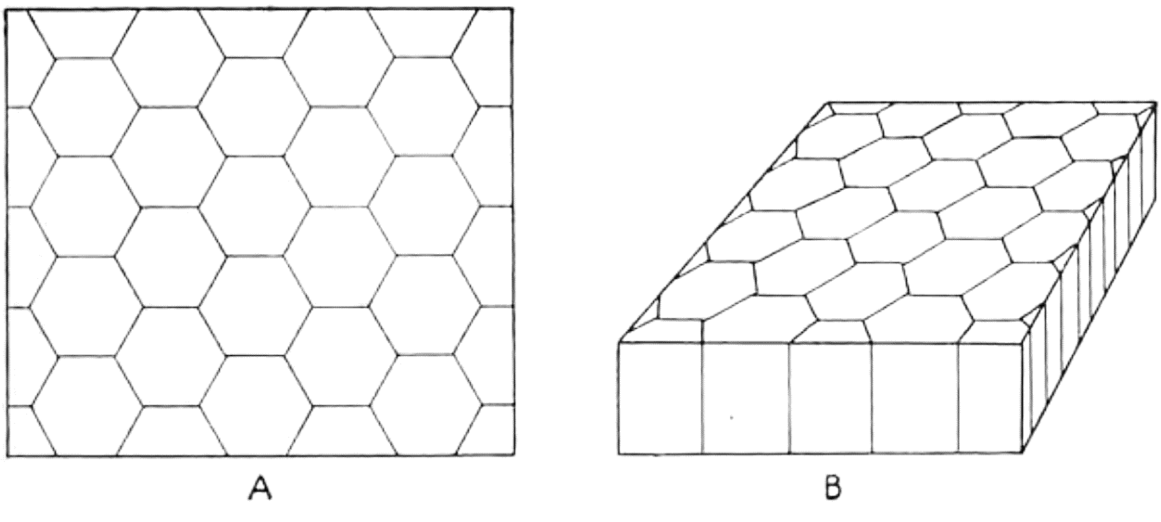

Figure 2: A. Upper Surface of Sheet, B. Block Diagram of Sheet.

B. Types of Joints with respect to Formation

Joints can also be classified according to their origin. On the basis of their origin, joints have been divided into a number of different types that include tectonic, hydraulic, exfoliation, unloading (release), and cooling joints.

1. Tectonic joints

Tectonic joints are joints that formed when the relative displacement of the joint walls is normal to its plane as the result of brittle deformation of bedrock in response to regional or local tectonic deformation of bedrock. Such joints form when directed tectonic stress causes the tensile strength of bedrock to be exceeded as the result of the stretching of rock layers under conditions of elevated pore fluid pressure and directed tectonic stress. Tectonic joints often reflect local tectonic stresses associated with local folding and faulting. Tectonic joints occur as both non-systematic and systematic joints, including orthogonal and conjugate joint sets.

2. Hydraulic joints

Hydraulic joints are joints thought to have formed when pore fluid pressure became elevated as a result of vertical gravitational loading. In simple terms, the accumulation of either sediments, volcanic, or other material causes an increase in the pore pressure of groundwater and other fluids in the underlying rock when they cannot move either laterally of vertically in response to this pressure. This also causes an increase in pore pressure in pre-existing cracks that increases the tensile stress on them perpendicular to the minimum principal stress (the direction in which the rock is being stretched). If the tensile stress exceeds the magnitude of the least principal compressive stress the rock will fail in a brittle manner and these cracks propagate in a process called hydraulic fracturing. Hydraulic joints occur as both non-systematic and systematic joints.

3. Exfoliation joints

Exfoliation joints are sets of flat-lying, curved, and large joints that are restricted to massively exposed rock faces in deeply eroded landscape. **Exfoliation jointing** consists of fan-shaped fractures varying from a few meters to tens of meters in size that lie sub-parallel to the topography.

4. Unloading joints

Unloading joints or *release joints* are joints formed near the surface during uplift and erosion. As bedded sedimentary rocks are brought closer to the surface during uplift and erosion, they cool, contract and become relaxed elastically. This causes stress build up that eventually exceeds the tensile strength of the bedrock and results in the formation of jointing. In the case of unloading joints, compressive stress is released either along pre-existing structural elements (such as cleavage) or perpendicular to the former direction of tectonic compression.

5. Cooling joints

Cooling joints are columnar joints that result from the cooling of either lava from the exposed surface of a lava lake or flood basalt flow or the sides of a tabular igneous, typically basaltic, intrusion. They exhibit a pattern of joints that join together at triple junctions either at or about 120° angles. They split a rock body into long, prisms or columns that are typically hexagonal, although 3-, 4-, 5- and 7-sided columns are relatively common.

Significance of joints

Joints have a profound control on weathering and erosion of bedrock. As a result, they exert a strong control on how topography and morphology of landscapes develop. Understanding the local and regional distribution, physical character, and origin of joints is a significant part of understanding the geology and geomorphology of an area.

Joints often impart a well-develop fracture-induced permeability to bedrock. As a result, joints strongly influence, even control, the natural circulation of fluids, e.g. groundwater and pollutants within aquifers; petroleum in reservoirs and hydrothermal circulation at depth. Thus, joints are important to the economic and safe development of petroleum, hydrothermal, and groundwater resources and the subject of intensive research relative to the development of these resources.

Also, regional and local joint systems exert a very strong control on how ore-forming (hydrothermal) fluids, consisting largely of H_2O, CO_2, and NaCl, that formed most of Earth's ore deposits circulated within the Earth crust. As a result, understanding their genesis, structure, chronology, and distribution is an important part of finding and profitably developing ore deposits of various types.

Finally, joints often form discontinuities that may have a large influence on the mechanical behaviour (strength, deformation, etc.) of soil and rock masses in, for example, tunnel, foundation, or slope construction. As a result, joints are an important part of geotechnical engineering in practice and research.

4.4 <u>Lineation: definition, Types, origin.</u>

A lineation is a fabric element in which one dimension is considerably longer than the other two dimensions.

A large number of nontectonic or primary linear structures occur in both undeformed and deformed rocks. Ropy lava, flow lineations and columns in columnar basalts in igneous rocks, and long axes of aligned non-spherical pebbles, groove marks and aligned fossils in sedimentary rocks are some examples. In our context we are concerned with linear structures resulting from deformation.

The fabric elements constituting tectonic linear structures include elongated physical objects, such as strained mineral aggregates or conglomerate pebbles, lines of intersection between two sets of planar structures, and geometrically defined linear features such as fold hinge lines and crenulation axes. A distinction is made between **penetrative lineations**, which build up a linear fabric or L-fabric, **surface lineations**, which are restricted to a surface (e.g. slickenlines), and **non-physical, geometric lineations** such as fold axes and intersection lineations.

<u>Types and their origin:</u>

Some common types of lineation are discussed below:

1. Mineral lineations

A penetrative linear fabric is typically made up of aligned prismatic minerals such as amphibole needles in an amphibolite, or elongated minerals and mineral aggregates such as quartz–feldspar aggregates in gneiss (Figure 1). Mineral lineations can form by several processes: Minerals and mineral aggregates can form a linear fabric by means of recrystallization, dissolution/ precipitation or rigid rotation.

Cataclasis, pressure solution and recrystallization all contribute to change the shape of minerals and mineral aggregates during deformation.

Stretching of minerals and mineral aggregates into a penetrative stretching lineation forms the most common type of lineation in deformed metamorphic rocks.

Rodding describes elongated mineral aggregates that are easily distinguished from the rest of the rock. Quartz rods are common in micaschists and gneisses where striped quartz objects occur as rods or cigars in the host rock. Rods are often considered as stretching lineations, but are commonly influenced by other structure-forming processes.

2. Intersection lineations

Many deformed rocks host more than one set of planar structures. A combination of bedding and cleavage is a common example. In most cases such planar structures intersect, and the line of intersection is regarded as an intersection lineation. Where the first tectonic cleavage (S_1) cuts the primary layering or bedding (S_0), the resulting intersection lineation (L_1) appears on the bedding planes, as shown in Figure 2.

Intersection lineations formed by the intersection of two tectonic foliations are also common. In most cases intersection lineations are related to folding, with the lineation running parallel to the axial trace and the hinge line.

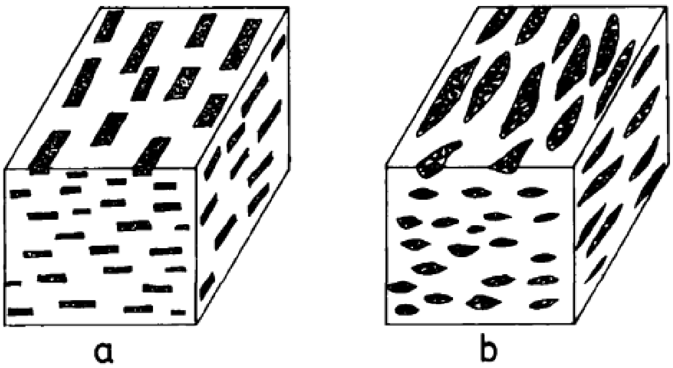

Figure 1: (a) Lineation marked by parallel orientation of mineral grains,

(b) Preferred orientation of elongated cluster of aggregates**.**

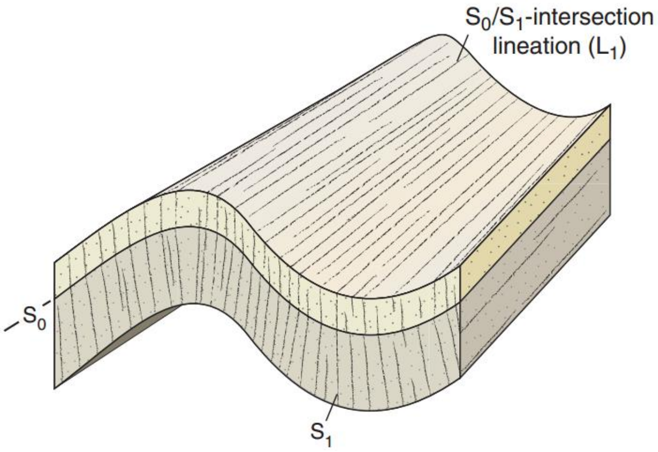

Figure 2: Intersection lineations appearing on bedding or foliation surfaces that are intersected by a later foliation.

3. Fold axes and crenulation lineations:

Fold axes are generally regarded as linear structures. Some rocks have a high enough density of parallel fold axes that they constitute a fabric. This is often the case with phyllosilicate-rich metamorphic rocks, where small-scale folds or crenulations constitute a crenulation lineation. Crenulation lineations are thus composed of numerous millimetre to centimeter-scale fold hinges of low-amplitude folds. They are commonly seen in multiply deformed phyllites, schists and in micaceous layers in quartz-schists, mylonites and gneisses.

4. Boudinage

Boudins are competent rock layers that have been stretched into segments (Figure 4). Individual boudins are commonly much longer in one dimension than the other two and thus define a lineation.

When occurring in folded layers, boudins typically appear on the limbs of the fold with their long axes oriented in the direction of the fold axis (Figure 5). Boudins are restricted to competent layers and therefore more restricted in occurrence than most other lineations.

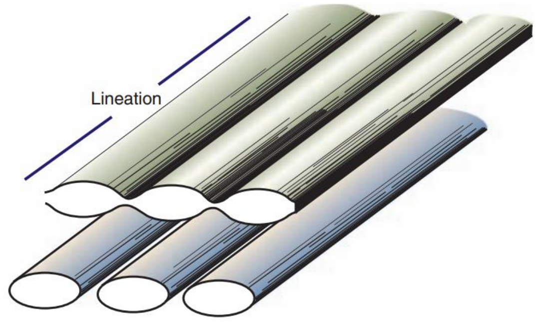

Figure 4: Cylindrical pinch-and-swell structures (above) and boudins (below) represent linear elements in many deformed rocks.

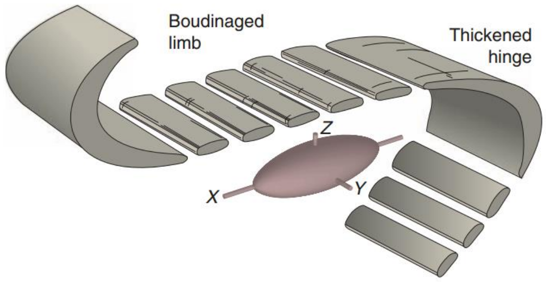

Figure 5: Common connection between folding and boudinage. The fold hinges are thickened while the limbs are extended and boudinaged. The strain ellipse is indicated.

5. Mullions

Mullion is the name that structural geologists use for linear deformation structures that are restricted to the interface between a competent and an incompetent rock. The term mullion has been used in several different ways in the literature, ranging from striations on fault surfaces (fault mullions) to layer-interface structures formed during layer-parallel extension as well as contraction. We will relate the term to layer-interface structures where the viscosity contrast is significant. In such cases the cusp shapes of mullions always point into the more competent rock, i.e. the one with the higher viscosity at the time of deformation (Figure 6). A common place to find mullion structures in metamorphic rocks is at the boundary between quartzite and phyllite or micaschist.

6. Pencil structures

The formation of pencil structures occurs as a result of discrete interference between compaction cleavage and a subsequent tectonic cleavage, or between two equally developed tectonic cleavages. Pencil structures have a preferred orientation and form a lineation in unmetamorphosed and very low grade metamorphic rocks.

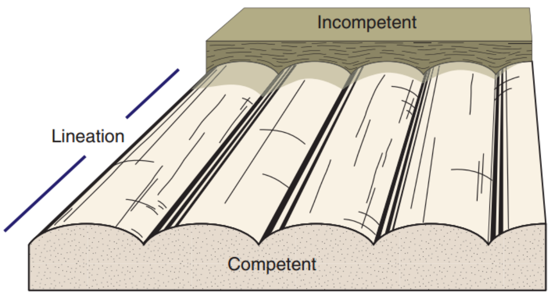

Figure 6: Mullion structures form lineations at the interface between rocks of significantly different competence (viscosity).

7. Fibre Lineation

Mineral lineations in the brittle regime tend to be restricted to fiber lineations, where minerals have grown in a preferred direction on fractures. The growth of minerals on fractures usually requires that the fractures open to some extent, either as true extension fractures or as shear fractures with a component of extension. Furthermore, the minerals must grow in a preferred direction for a lineation to be defined. Minerals such as quartz, antigorite, actinolite, gypsum and anhydrite may appear fibrous on fractures.

8 Striations or slickenlines

Striations or slickenlines are lineations found on shear fractures and form by physical abrasion of hanging-wall objects into the footwall or vice versa. The smooth and striated slip surface itself is called a slickenside. **Slickensides** tend to be shiny, polished surfaces coated by a 1 mm thick layer of crushed, cohesive fault rock. Hard objects or asperities can carve out linear tracks or grooves known as fault grooves. The term groove lineation can be used for this type of slickenlines. There are two principal types of slickenlines: those that form by mechanical abrasion (striations) and those formed by fibrous growth (slip fiber lineations).

9. Intersection lineations

Intersection lineations are found on fractures where the main slip plane is intersected by secondary fractures such as Riedel fractures or tensile fractures. The lines of intersection typically (but not necessarily) form a high angle to the slip direction, in marked contrast to striae and mineral lineations that tend to parallel the slip direction.

4.5 Foliations: definition; types and origin.

Foliation

Foliation (derived from the Latin word folium, meaning leaf) is generally used for any fabric-forming planar or curviplanar structure in a metamorphic rock, but may also include primary sedimentary bedding or magmatic layering. Some geologists prefer to reserve the term foliation for planar structures formed by tectonic strain, but it is now common to include depositional bedding and other primary planar structures in the definition of this term. It is important to make a clear distinction between the **primary foliations** that form during the deposition of sediments and formation of magmatic rocks, and **secondary foliations** such as axial plane cleavages in metamorphic rocks. Primary foliations are bedding in sedimentary rocks, flow banding in lavas and magmatic layering in intrusive rocks. Secondary foliations are products of stress and strain and most are tectonic foliations because they form in response to tectonic stress. The most important example of a non-tectonic secondary foliation is one resulting from compaction. In structural geology we tend to restrict the term foliation to planar structures formed by deformation, and a tentative classification scheme for such structures is shown in Figure 1.

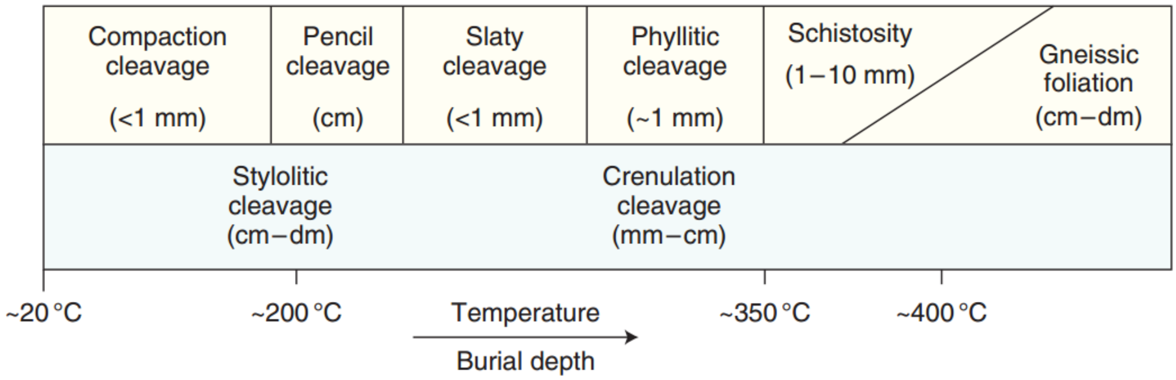

Figure 1: Schematic overview of important cleavage and foliation types, arranged according to burial depth or temperature and with an indication of the spacing of foliation domains. Temperatures indicated are very approximate.

A tectonic foliation is a planar structure formed by tectonic processes, and includes cleavages, schistosity and mylonitic foliations. Even if parallel fractures are distributed throughout a hand sample they may lack the cohesion that is a second characteristic of foliations. Although foliated rocks typically split along the foliation, force is required to overcome that cohesion. A foliated rock is by definition cohesive, although rocks may split preferentially along the foliation.

Cleavage

Rock cleavage is a set of closely spaced planar parallel secondary fabric elements that impart a mechanical anisotropy to the rock and do not cause an apparent loss of cohesion in the rock (Dennis *in* Bayly *et al*. 1977). Cleavage is a (large) subgroup of foliation – not all foliated rocks split preferentially along the foliation.

The cleaved rocks generally show a domainal structure, with *cleavage domains* and *microlithons*. In the cleavage domain the original fabric of the rock has been strongly altered. In the microlithons the original fabric has undergone little or no alteration (right side of Figure 2).

Cleavage and foliation are penetrative at the scale of a hand sample, but the spacing of the planar elements varies. If the distance is greater than 1 mm and distinguishable in the hand sample as individual surfaces or zones, the cleavage is designated a spaced cleavage (left side of Fig. 2). The structure is a continuous cleavage if the spacing of the planar elements is 1 mm or less (right side of Figure 2). Rock cleavage should not be confused with mineral cleavage, which is the tendency of a mineral to break along specific crystallographic planes.

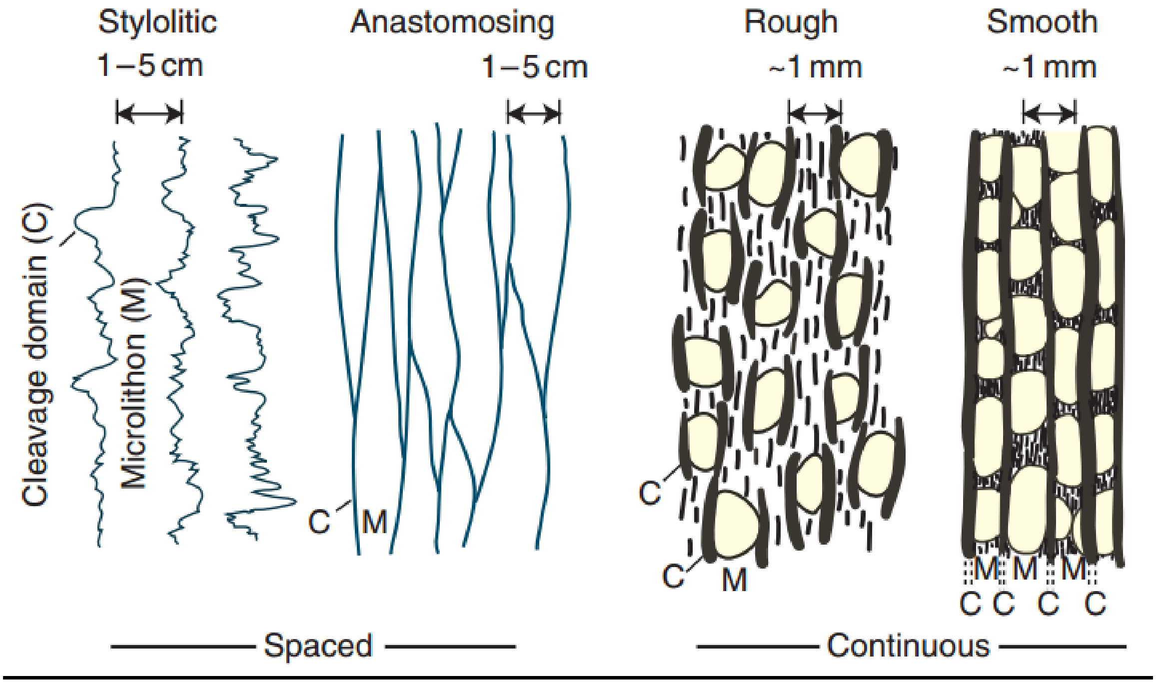

Figure 2: Disjunctive cleavage types. Stylolitic (limestones) and anastomosing (sandstones) cleavages are usually spaced, while continuous cleavages in more fine-grained rocks are separated into rough and smooth variants, where the rough cleavage can develop into the smooth version. All disjunctive cleavages are domainal, and the cleavage domains (C) are separated by undeformed rock called microlithons (M).

Types of Foliation or Cleavage and their Origin:

There are many types of cleavages and a rich terminology is available. To efficiently deal with cleavages and foliations it is useful to keep an eye on crustal depth and lithology. Crustal depth is related to temperature (and pressure), and with increasing temperature we first obtain increasing mobility of minerals and at yet higher temperatures the possibility that minerals will recrystallize. Around 350–375 ^{0}C we leave the realm of cleavage and enter that of schistosity and mylonitic foliations. Lithology and mineralogy are important because different minerals react differently to stress and temperature. Phyllosilicates are particularly important in cleavage development. In general, if there are no phyllosilicates in the rock there will not be a very strong cleavage or schistosity. Cleavage formation in calcareous rocks is controlled by the mobility of carbonate and the easy formation of stylolites. Cleavage is the low-temperature version of foliation and is best developed in rocks with abundant platy minerals.

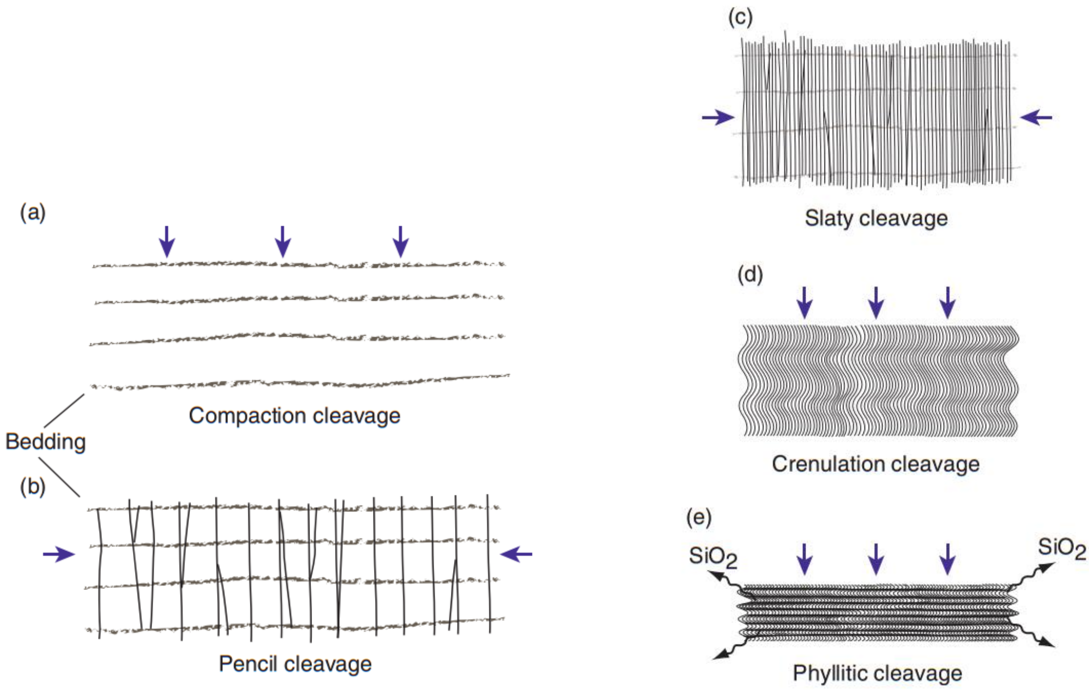

Figure 3: Theoretical cleavage development in a mudstone.

1. Compaction cleavage

The first secondary foliation forming in sedimentary rocks is related to their compaction history. Reorientation of mineral grains and collapse of pore space result in accentuation and reworking of the primary foliation (bedding). For a clay or claystone, the result is a shale with a marked compaction cleavage (Figure 3a). In this process there is also dissolution going on, and in some quartzites we can find pressure solution seams. Such structures are much more common in limestone, in which dissolution of carbonate produces subhorizontal and irregular seams

where quartz or carbonate has been dissolved and where clay and other residual minerals are concentrated. The seams are stylolites or pressure solution seams, and the foliation can be called a stylolitic cleavage (Figure 2, left), which is a type of (pressure) solution cleavage.

The spacing of the seams in calcareous rocks is usually several centimeters, and the cleavage is therefore a widely spaced cleavage. In fact, the stylolitic surfaces may be too far apart to define a cleavage. In contrast, the compaction cleavage in shale is recognizable under the microscope and therefore a continuous cleavage. These non-tectonic cleavages are usually regarded as S0 foliations.

2. Pencil Cleavage

A tectonic foliation commonly results when a sedimentary rock is exposed to tectonic stress that leads to progressive horizontal shortening of sedimentary beds – a condition typical of the foreland regions of orogenic belts. Pressure solution is important when shales are exposed to tectonic stress. In this case extensive dissolution of quartz causes concentration and reorientation of clay minerals. At some point the secondary cleavage will be as pronounced as the primary one, and clay minerals will be equally well oriented along S1 and S0. The shale will now fracture along both S1 and S0 into pencil-shaped fragments, which explains why the cleavage is known as pencil cleavage (Figure 3b).

3. Slaty Cleavage:

If the tectonic shortening persists, it will eventually dominate over the compactional cleavage. More and more clay grains become reoriented into a vertical orientation as quartz grains are being dissolved and removed. Microfolding of the clay grains may also occur. The result is a continuous cleavage that totally dominates the structure and texture of the rock. The rock is now a slate and its foliation is known as slaty cleavage (Figure 3c).

The formation of slaty cleavage occurs while the metamorphic grade is very low, so that recrystallization of clay minerals into new mica grains appears to have just started. A close look at a well-developed slaty cleavage reveals that a change has taken place in terms of mineral distribution. There are now domains dominated by quartz and feldspar, known as QF-domains, that separate M-domains rich in phyllosilicate minerals. that separate M-domains rich in phyllosilicate minerals. The letters Q, F and M relate to quartz, feldspar and mica respectively.

It was once thought that slatycleavage formed by physical grain rotation. We now know that so-called wet diffusion or pressure solution is what chiefly produces the domainal structure that characterizes slaty cleavage. Grains of quartz and feldspar are dissolved perpendicular to the orientation of the cleavage and achieve lensoid shapes (disk shapes in three dimensions). Where this happens, phyllosilicates are concentrated and M-domains form.

4. Phyllitic cleavage

New phyllosilicate minerals grow at the expense of clay minerals in shales and slates when they enter the field of greenschist facies metamorphism. A phyllite forms and the cleavage changes into a phyllitic cleavage (Figures 3e). The newly formed mica grains are thus parallel and a phyllitic cleavage is established. The cleavage is still a continuous one, and the development of QF- and M-domains is more pronounced than for slaty cleavage.

5. Schistosity

When original claystone reaches upper greenschist facies and perhaps lower amphibolite facies, the mica grains grow larger and become easily visible in a hand sample. At the same time, the foliation becomes less planar, wrapping around quartz–feldspar aggregates and strong metamorphic minerals such as garnet, kyanite and amphibole. The foliation is no longer called a cleavage but a schistosity, and the rock is a schist.

Schistosity is also found in quartz-rich rocks such as quartz schists and sheared granites. Here the M- and QF-domains are on the millimeter or even centimetre scale and they appear more regular and planar than for micaschists. This is why quartz schists and sheared granites split so easily into slabs that can be used for various building purposes. In summary, while wet diffusion (solution) and grain reorientation dominate the formation of slaty cleavage, recrystallization is more important during the formation of schistosity.

6. Crenulation cleavage

An already established tectonic foliation can be affected by a later cleavage (S2 or higher) if the orientation of the stress field changes locally or regionally at some point during the deformation, or if a later cleavage-forming deformation phase occurs. Because cleavages tend to form perpendicular to the maximum shortening direction (X), a new cleavage will form that overprints the preexisting one. In many cases this occurs by folding the previous foliation into a series of microfolds, in which case the cleavage is called a crenulation cleavage.

Crenulation cleavage is restricted to lithologies with a pre-existing well-developed foliation that at least partly is defined by phyllosilicate minerals. It is commonly seen in micaceous layers while absent in neighboring mica-poor layers.

7. Axial plane cleavage

A close geometric relation between cleavages and folds is seen in most cases. It is clear that the two types of structures commonly form simultaneously. Geometrically a cleavage splits the fold more or less along the axial surface, particularly near the hinge zone. Where a cleavage parallels the axial surface, the cleavage is called axial plane cleavage.

Interestingly, if we study cleavage–fold relations in detail we may see a difference in orientation between the axial plane and the cleavage. In fact, the orientation of the cleavage may be seen to vary from layer to layer. The variations occur across layers of contrasting competence or viscosity and the phenomenon is called cleavage refraction (Figure 4). The higher the contrast in competency, the more pronounced the refraction.

8. Transected folds and Cleavage

In most cases the theoretical axial surface has more or less the same orientation as the axial plane cleavage. Less commonly there is a marked difference between the orientations of cleavage and axial surface (Figure 5), even where the folding and the cleavage are genetically related and where there is no refraction due to rheologically contrasting layers. In such cases the cleavage transects not only the axial surface but also the fold hinge (Figure 12.20). Such cleavage is called transecting cleavage, and the folds are referred to as transected folds.

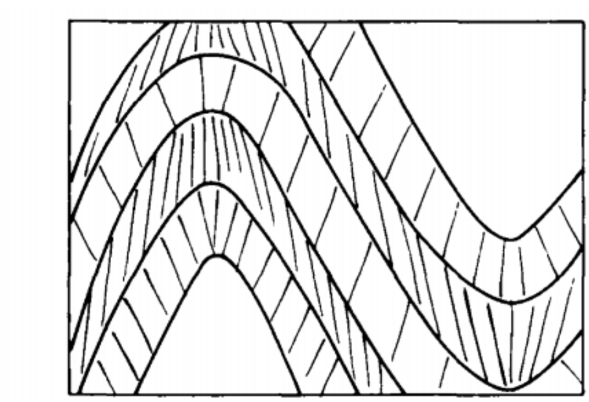

Figure 4

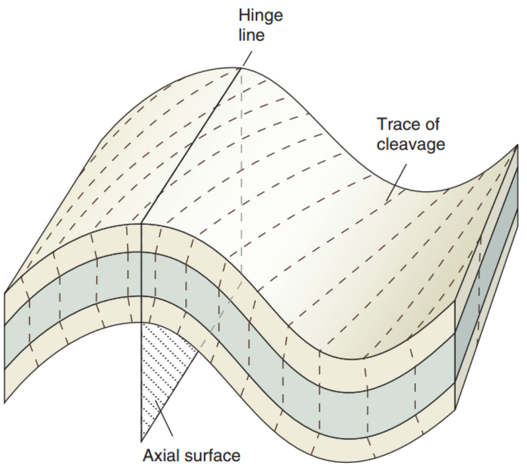

Figure 5