Lecture one

***Structural* Geology:** Deals with the *origin*, *geometry* and *kinematics of structures' formation*. It requires an ability to visualize objects in three dimensions Fig. (1-1).

Fig.(1-1)

Plate Tectonics: Deal specifically with plate generation, motion, and interaction Fig.(1-2).

Tectonic structures: are produced in rocks in response to stress generated by plate motion within the Earth. They include all kinds of faults, folds along with other structures. They make up the tectonic framework of the earth.

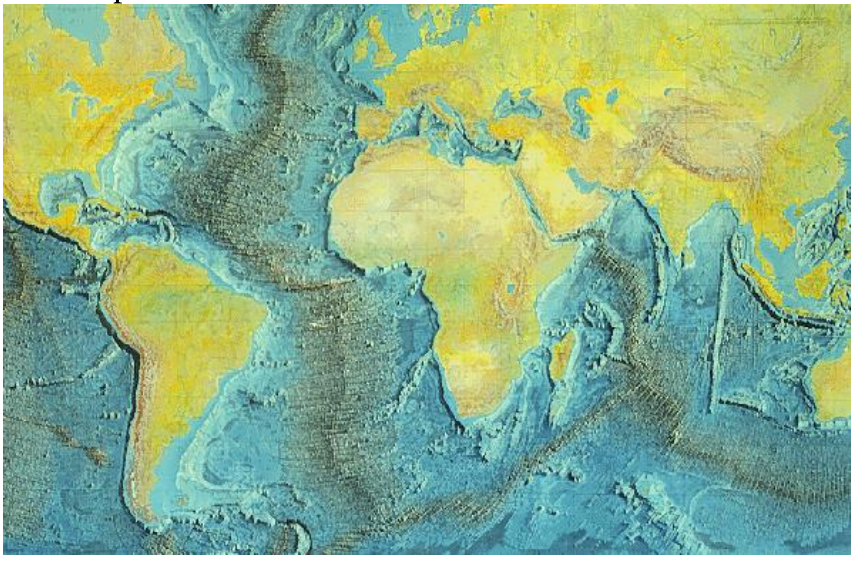


Fig.(1-2)

Structural Geology: Involve studying outcrop and microscopic size local structures such as: Non tectonic structures and Folds, faults, and other related structure Fig. (1-3).

Fig. (1-3)

Tectonics: involve the study of larger features, and regional structures such as: mountain ranges, parts of continents, trenches, island arcs, and oceanic ridges Fig(1-4).

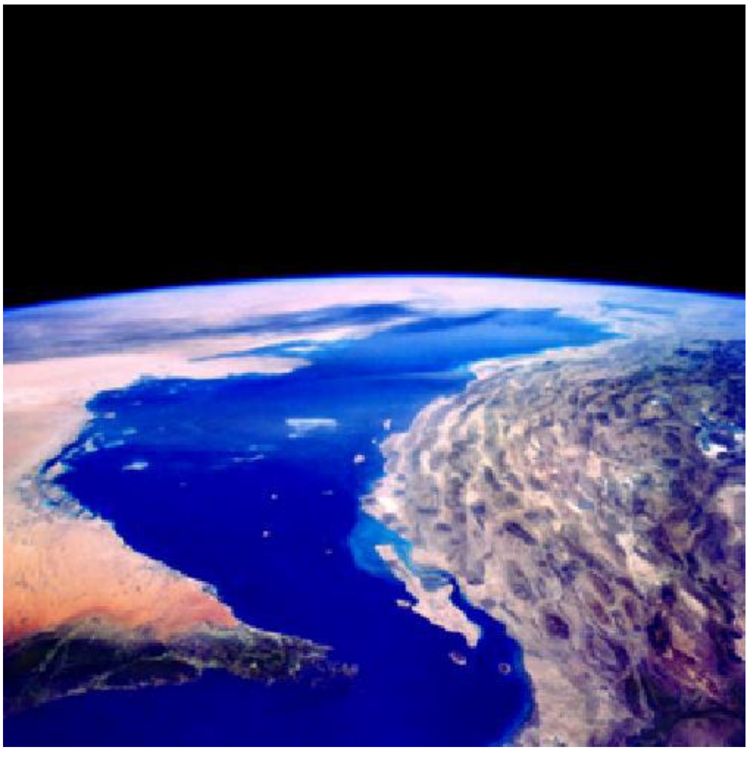


Fig.(1-4)

ROCK DEFORMATION

STRESS

Stress is a force exerted against an object. Tectonic forces exert different types of stress on rocks in different geologic environments. The first, called confining stress or confining pressure, occurs when rock or sediment is buried (Fig.1-5a).Confining pressure merely compresses rocks but does not distort them, because the compressive force acts equally in all directions, like water pressure on a fish. Burial pressure compacts sediment and is one step in the lithification of sedimentary rocks. Confining pressure also contributes to metamorphism during deep burial in sedimentary basins. In contrast, directed stress acts most strongly in one direction. Tectonic processes create three types of directed stress. Compressive stress squeezes rocks together in one direction. It frequently acts horizontally, shortening the distance parallel to the squeezing direction (Fig.1-5b). Compressive stress is common in convergent plate boundaries, where two plates converge and the rock crumples, just as car fenders crumple during a head-on collision. Extensional stress (often called tensional stress) pulls rock apart and is the opposite of tectonic compression (Fig.1-5c). Rocks at a divergent plate boundary stretch and pull apart because they are subject to extensional stress. Shear stress acts in parallel but opposite directions (Fig.1-5d). Shearing deforms rock by causing one part of a rock mass to slide past the other part, as in a transform fault or a transform plate boundary.

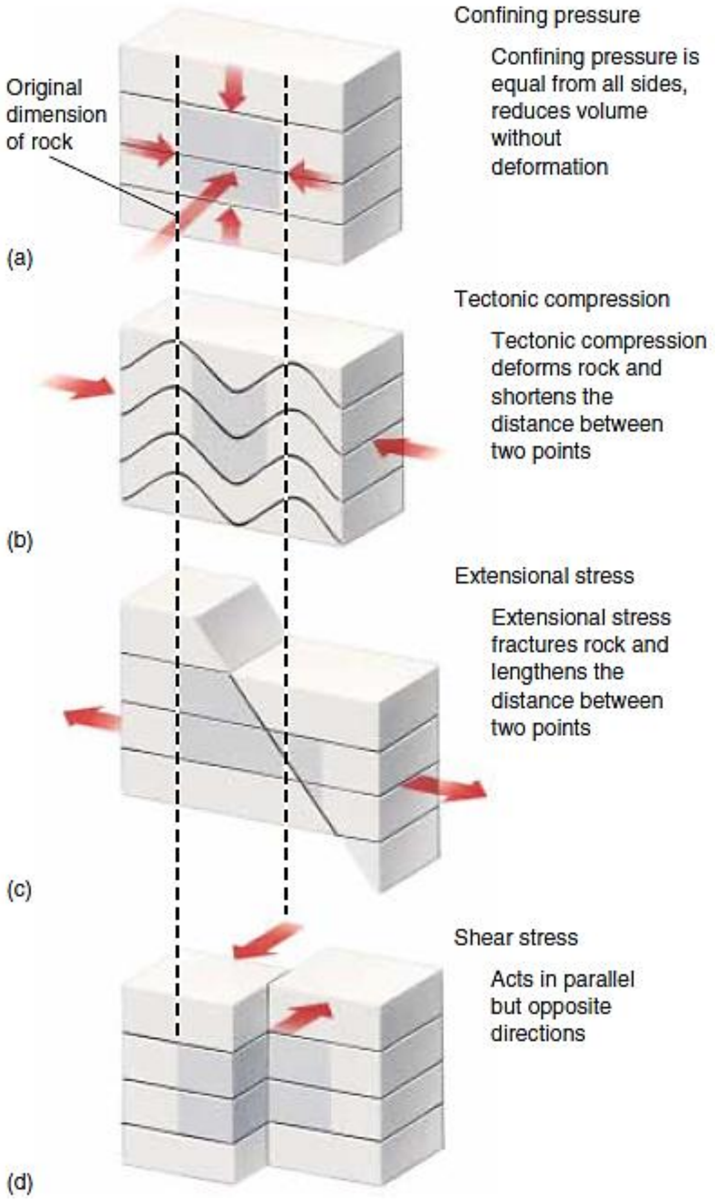


Figure (1-5) (a) Confining pressure acts equally on all sides of a rock. Thus, the rock is compressed much as a balloon is compressed if held under water. Rock volume decreases without deformation. (b) Tectonic compression shortens the distance parallel to the stress direction. Rocks fold or fracture to accommodate the shortening. (c) Extensional stress lengthens the distance parallel to the stress direction. Rocks commonly fracture to accommodate the stretching. (d) Shear stress deforms the rock parallel to the stress direction.

STRAIN

Strain is the deformation produced by stress. A rock responds to tectonic stress by elastic deformation, plastic deformation, or brittle fracture. An elastically deformed rock springs back to its original size and shape when the stress is removed. During plastic deformation, a rock deforms like putty and retains its new shape. In some cases a rock will deform plastically and then fracture (Fig. 1-6).

(Fig. 1-6)

Factors That Control Rock Behavior

Several factors control whether a rock responds to stress by elastic or plastic deformation or fails by brittle fracture:

1. The nature of the material. Think of a quartz crystal, a gold nugget, and a rubber ball. If you strike quartz with a hammer, it shatters. That is, it fails by brittle fracture. In contrast, if you strike the gold nugget, it deforms in a plastic manner; it flattens and stays flat. If you hit the rubber ball, it deforms elastically and rebounds immediately, sending the hammer flying back at you. Initially, all rocks react to stress by deforming elastically. Near the Earth's surface, where temperature and pressure are low, different types of rocks behave differently with continuing stress. Granite and quartzite tend to behave in a brittle manner. Other rocks, such as shale, limestone, and marble, have greater tendencies to deform plastically.
2. Temperature. The higher the temperature, the greater the tendency of a rock to behave in a plastic manner. It is difficult to bend an iron bar at room temperature, but if the bar is heated in a forge, it becomes plastic and bends easily.
3. Pressure. High confining pressure also favors plastic behavior. During burial, both temperature and pressure increase. Both factors promote plastic deformation, so deeply buried rocks have a greater tendency to bend and flow than shallow rocks.
4. Time. Stress applied over a long time, rather than suddenly, also favors plastic behavior. Marble park benches in New York City have sagged plastically under their own weight within 100 years. In contrast, rapidly applied stress, such as the blow of a hammer, to a marble bench causes brittle fracture.

Lecture two

GEOLOGIC STRUCTURES

Enormous compressive forces can develop at a convergent plate boundary, bending and fracturing rocks in the tectonically active region. In some cases the forces deform rocks tens or even hundreds of kilometers from the plate boundary. Because the same tectonic processes create great mountain chains, rocks in mountainous regions are commonly broken and bent. Tectonic forces also deform rocks at divergent and transform plate boundaries.

A geologic structure is any feature produced by rock deformation. Tectonic forces create three types of geologic structures: folds, faults, and joints.

FOLDS

A fold is a bend in rock (Fig. 1-7). Some folded rocks display little or no fracturing, indicating that the rocks deformed in a plastic manner.

Figure 1-7 A fold is a bend in rock. These are in quartzite in the Maria Mountains, California.

In other cases, folding occurs by a combination of plastic deformation and brittle fracture. Folds formed in this manner exhibit many tiny fractures. If you hold a sheet of clay between your hands and exert compressive stress, the clay deforms into a sequence of folds (Fig. 1-8). This demonstration illustrates three characteristics of folds:

Figure 1-8 Clay deforms into a sequence of folds when compressed

1. Folding usually results from compressive stress. For example, tightly folded rocks in the Himalayas indicate that the region was subjected to compressive stress.

2-Folding always shortens the horizontal distances in rock. Notice in Figure 1-9 that the distance between two points, A and A′, is shorter in the folded rock than it was before folding.

3-Folds usually occur as a repeating pattern of many folds as in the illustration using clay.

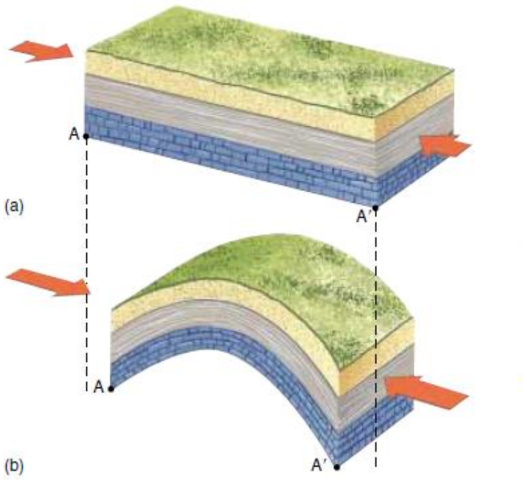


Figure 1-9 (a) Horizontally layered sedimentary rocks b) A fold in the same rocks. The forces that folded the rocks are shown by the arrows. Notice that points A and A′ are closer after folding.

Simple folds are divided into two types, that is, anticlines and synclines in the former, the beds are convex upwards, whereas in the latter, they are concave upwards. In the anticline when we move toward the core we can show the oldest rocks in contrary to the syncline we show the youngest rocks. The crestal line of an anticline is the line that joins the highest parts of the fold, whereas the trough line runs through the lowest parts of a syncline (Fig. 1.10a, b).

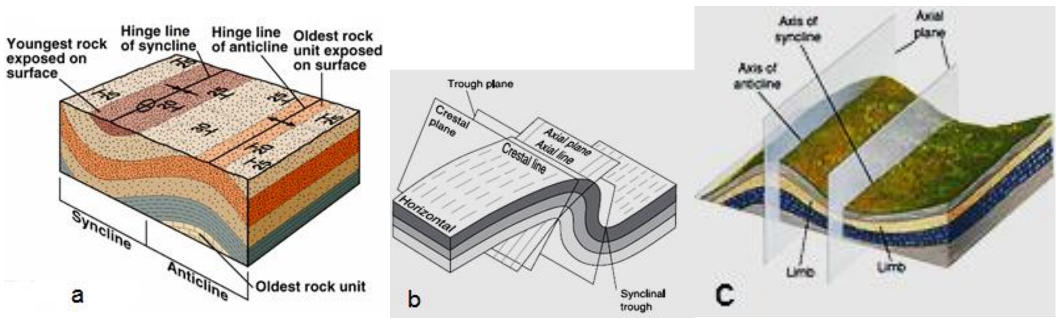


Figure 1-10 (a) symmetrical anticline and syncline, and the parts of a fold. (b) Asymmetrical anticline and syncline. (c) Axial plane of anticline and axial plane of syncline .

The hinge line of a fold is the line along which the greatest curvature exists and can be either straight or curved. However, the axial line is another term that has been used to describe the hinge line. The limb of a fold occurs between the hinges, all folds having two limbs. The axial plane of a fold is commonly regarded as the plane that bisects the fold and passes through the hinge line (Fig. 1.10c).

A fold arching upward is called an anticline and one arching downward is a syncline. The sides of a fold are called the limbs. Notice that a single limb is shared by an anticline–syncline pair. A line dividing the two limbs of a fold and running along the crest of an anticline or the trough of a syncline is the fold axis. The axial plane is an imaginary plane that runs through the axis and divides a fold as symmetrically as possible into two halves. In many folds, the axis is horizontal, as shown in Figure 1–10a, b. If you were to walk along the axis of a horizontal anticline, you would be walking on a level ridge.

In other folds, the axis is inclined or tipped at an angle called the plunge, as shown in Figure 1–11. A fold with a plunging axis is called a plunging fold. If you were to walk along the axis of a plunging fold, you would be traveling uphill or downhill along the axis. Even though an anticline is structurally a high point in a fold, anticlines do not always form topographic ridges. Conversely, synclines do not always form valleys Figure 1–11B .

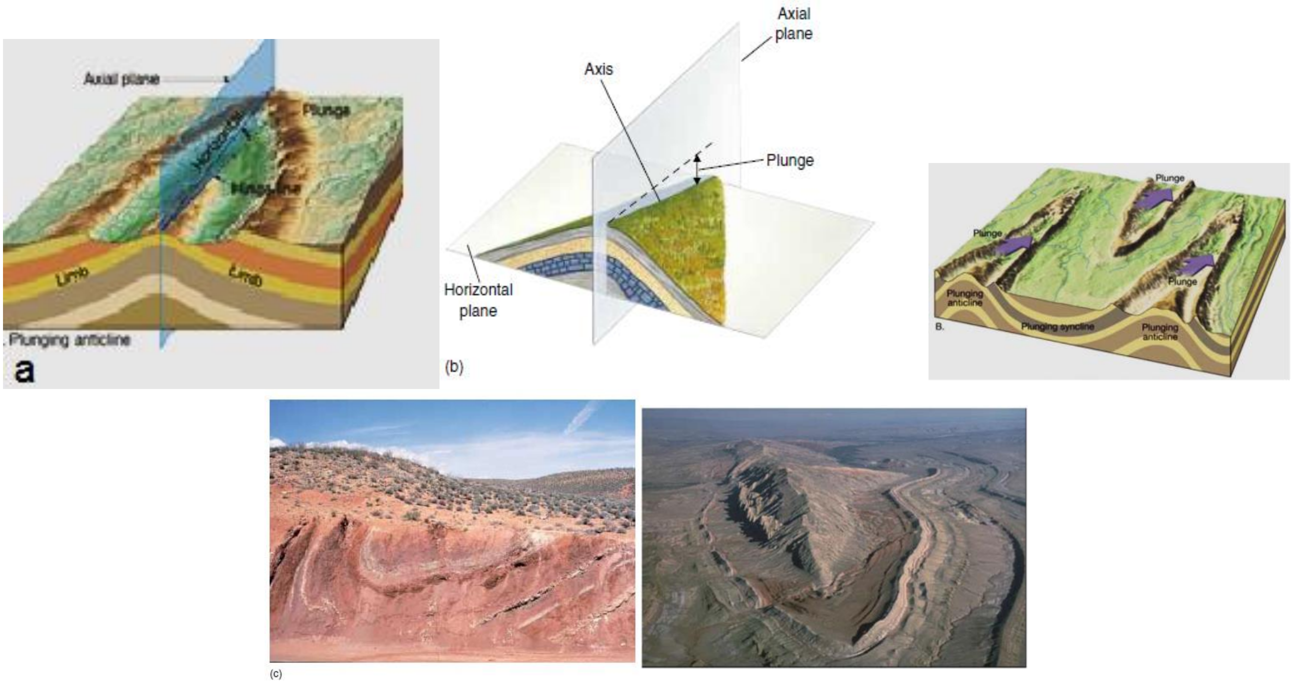
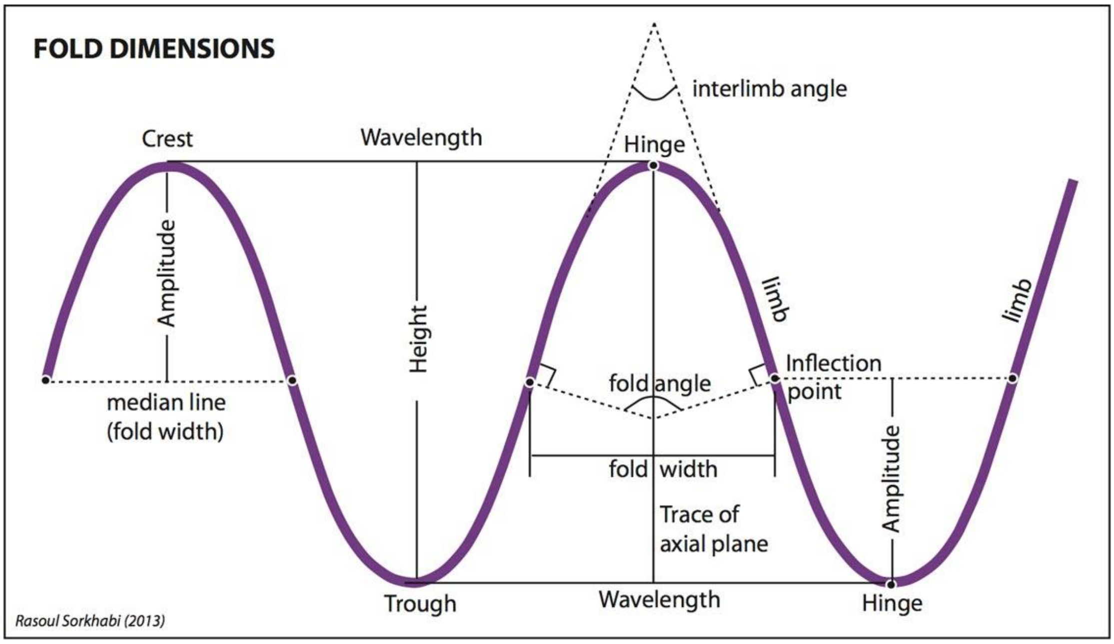


Figure 1-11 Plunging anticline and plunging syncline, figures and photos.

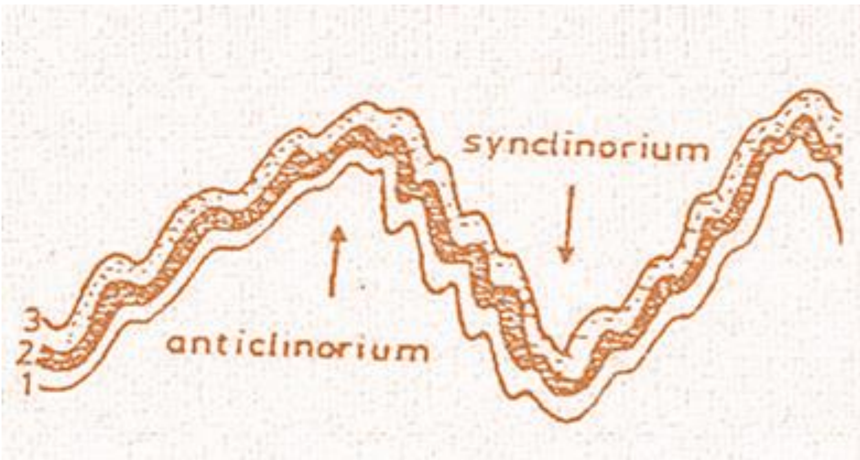
Landforms are created by combinations of tectonic and surface processes. The amplitude of a fold is defined as the vertical difference between the crest or the trough and the median line, whereas the wave length of a fold is the horizontal distance from crest to crest or trough to trough.

Fig 1-11 B, shows a syncline lies beneath the mountain peak and an anticline forms the low point, or saddle, in the Canadian Rockies, Alberta.



■Anticlinorium: A series of anticlines and synclines so arranged structurally that together they form a general arch or anticline.

■ Synclinorium: it called for the fold in which a number of small synclines are on the limb of a large syncline.



Lecture: 3

Types of Folding

Corresponding to the dip angle of the limb and the axial plane the folds are classified to four types, the first is **symmetrical** if both limbs are arranged equally about the axial plane so that the dips on opposing flanks are the same; otherwise they are **asymmetrical** (Fig. 1.12). In symmetrical folds, the axial plane is vertical, whereas it is inclined in asymmetrical folds. As folding movements become intensified, **overturned folds** are formed in which both limbs are inclined, together with the axial plane, in the same direction but at different angles (Fig. 1.12). In a **recumbent fold**, the beds have been completely overturned so that one limb is inverted, and the limbs, together with the axial plane, dip at a low angle to the same direction (Fig. 1.12).

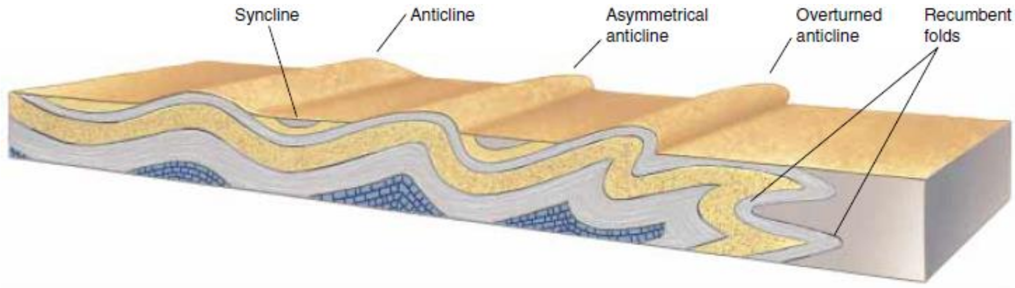


Figure 1-12 Cross-sectional view of five different kinds of folds. Folds can be symmetrical, as shown on the left, or asymmetrical, as shown in the center. If a fold has tilted beyond the perpendicular, it is overturned.

Parallel or concentric folds are those where the strata have been bent into more or less parallel curves in which the **thickness** of the individual beds remains the same. From Figure 1.13a, it can be observed that, because the thickness of the beds remains the same on folding, the shape of the folds changes with depth and, in fact, they fade out. Parallel folding occurs in competent (relatively strong) beds that may be interbedded with incompetent (relatively weak, plastic) strata, Fig. 1.13a and 1.13A.

Similar folds are those that retain their shape with depth. This is accomplished by flowage of material from the limbs into the crest and trough regions (Fig. 1.13b). Similar folds are developed in incompetent strata. However, true similar folds are rare in nature, for most change their shape to some degree along the axial plane. Most folds exhibit both the characteristics of parallel and similar folding Fig. 1.13 B.

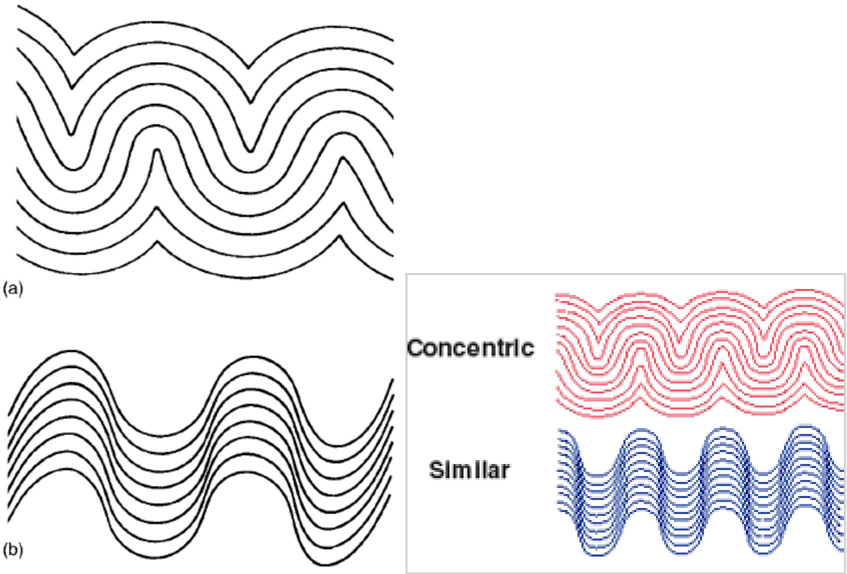


Figure 1.13 Shows (a) Parallel folding. (b) Similar folding.

Fig. 1.13 A. These are folds in Cretaceous strata exposed at Ernst Tinaja in Big Bend National Park. They show the disharmonic geometry and maintenance of bedding-perpendicular thickness that characterize a parallel fold style.

Fig. 1.13B. Shows photo of similar fold.

Several other common terms specify relative orientations of the limbs of the folds. A **homocline** comprises a surface, such as bedding, that has a uniform nonhorizontal attitude over a regional scale with no major fold hinge (Fig.1.14A). A **monocline** is a special type of fold with only one limb or a fold pair that has two long horizontal limbs connected by a relatively short inclined limb (Fig.1.14B). A monocline may develop where sedimentary rocks sag over an underlying fault (Fig.1.15). A **structural terrace** is a fold pair with two long planar inclined limbs connected by relatively short horizontal limb (Fig.1.14C). A **recumbent** fold in which one limb is overturned i.e. rotated more than 90º (Fig.1.14D).

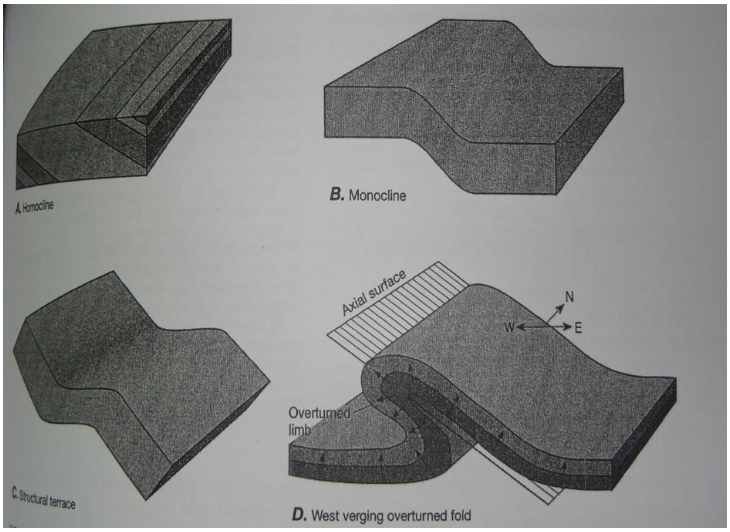
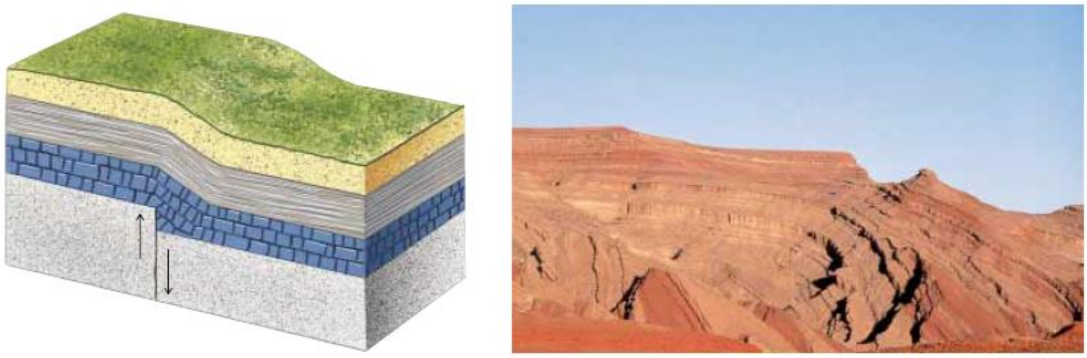


Fig. 1.14 Structural terms describing the orientation of fold limds.



(a) (b)

Figure 1–15 (a) A monocline formed where near-surface sedimentary rocks sag over a fault. (b) A monocline in southern Utah.

Zigzag or chevron folds have straight or nearly straight limbs with sharply curved or even pointed hinges (Fig. 1.16A and 1.17). Such folds possess features that are characteristic of both parallel and similar folds in that the strata in their limbs remain parallel, beds may be thinned but they never are thickened, and the pattern of the folding persists with depth.

Box fold is one in which the crest broad and flat; two hinges are present, one on either side of the flat crest (Fig. 15B).

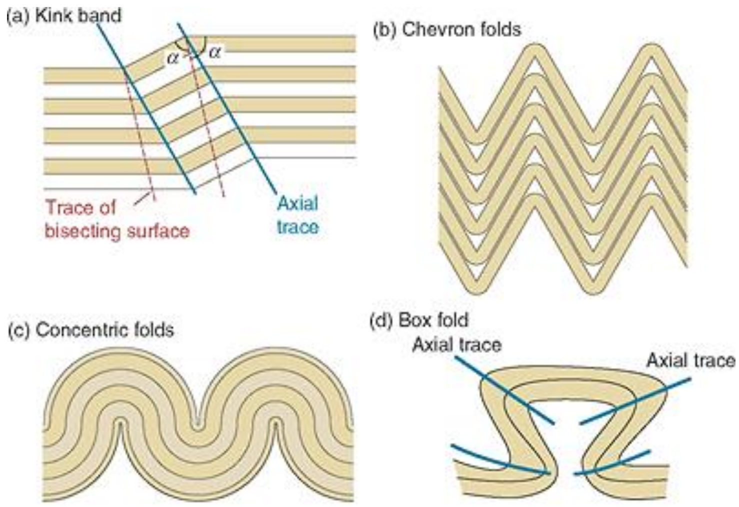
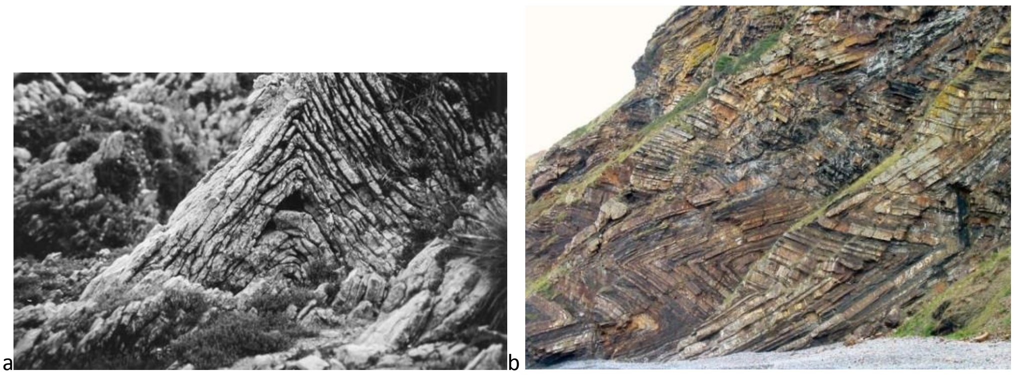


Fig. 16. Shows some varieties of folds. (A) Chevron fold. (B) Box fold.



a b

Fig.1.17(a) Chevron fold in limestone of Miocene age, Kaikuora, South Island, New Zealand, **b**, Chevron folds with flat-lying axial planes, Millook Haven, North Cornwall, UK

Fan fold is one in which both limbs are overturned (Fig.1.18A). In the anticlinal fan fold, the two limbs dip toward each other; in the synclinal fan fold, the two limb dip away from each other.
Kink bands are narrow bands, usually only a few inches or few feet wide, in which the beds assume a dip that is steeper or gentler than that in the adjacent beds (Fig.18B).

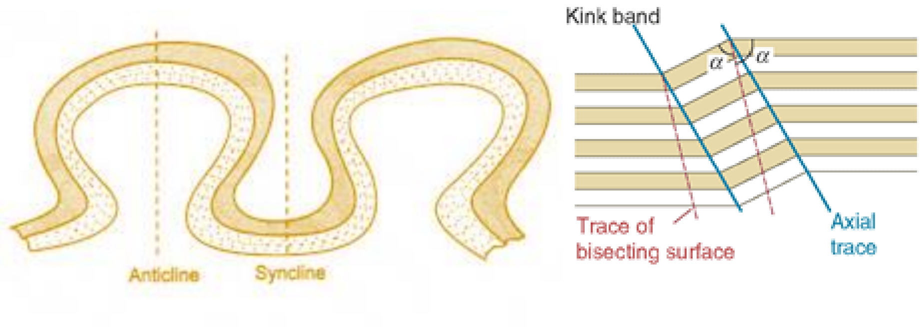
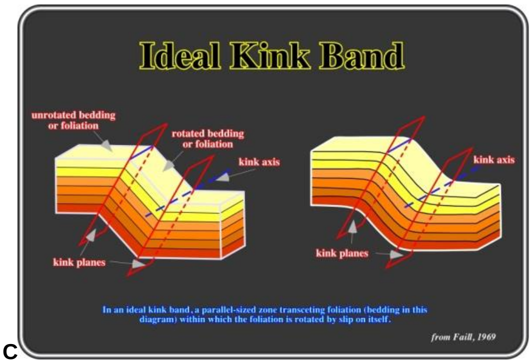


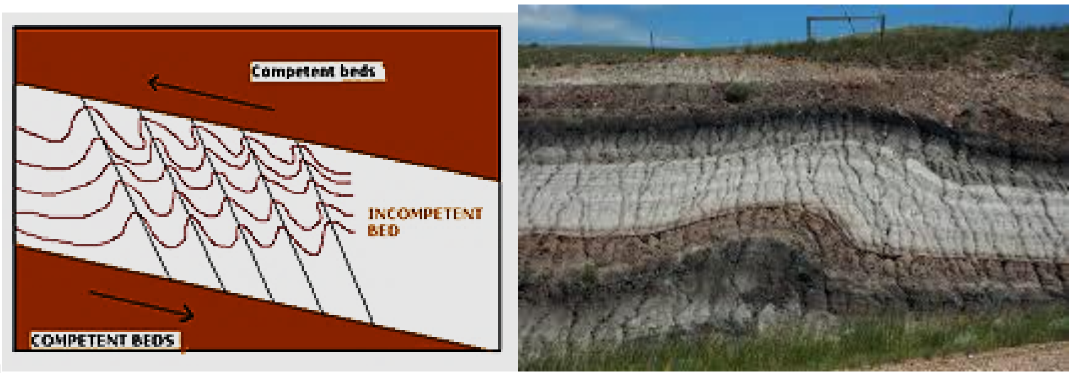
Fig.18. Shows some varieties of folds. of Fan fold
(B) Kink bands. A fracture may separate the kink band from the rest of beds.

C


D


Fig.18.C, modeling of kink band formation, D , photo of kink band figure.

Drag folds form when a competent (strong) bed slides past an incompetent (weak) bed, minor folds may form on the limbs of larger folds because of the slipping of beds past each other. The axial planes of the drag folds are not perpendicular to the bedding of the competent strata, but are inclined at an angle (Fig.1.19).



a b

Fig.1.19. a, Mechanism of drag folds resulting from shearing, b, photo of drag folds in incompetent bed.

Dome

A circular or elliptical anticlinal structure resemble inverted bowls is called a **dome**. Sedimentary layering dips away from the center of a dome in all directions (Fig. 1.20a). A similarly shaped where the sedimentary layers dip toward the center of the syncline is called a **basin (Fig. 1.20b)**. Domes and basins can be small structures only a few kilometers in diameter or less. Frequently, however, they are very large and are caused by broad upward or downward movement of the continental crust. The Black Hills of South Dakota are a large structural dome. The Michigan basin covers much of the state of Michigan, and the Williston basin covers much of eastern Montana, northeastern Wyoming, the western Dakotas, and southern Alberta and Saskatchewan.

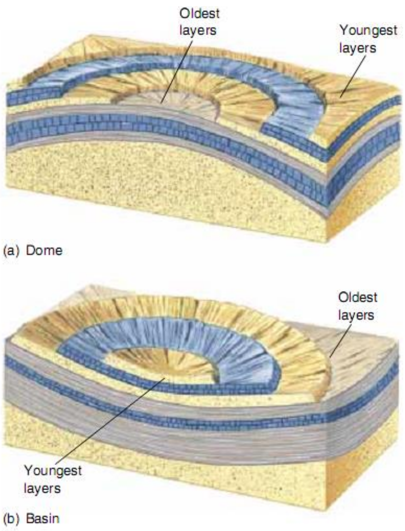


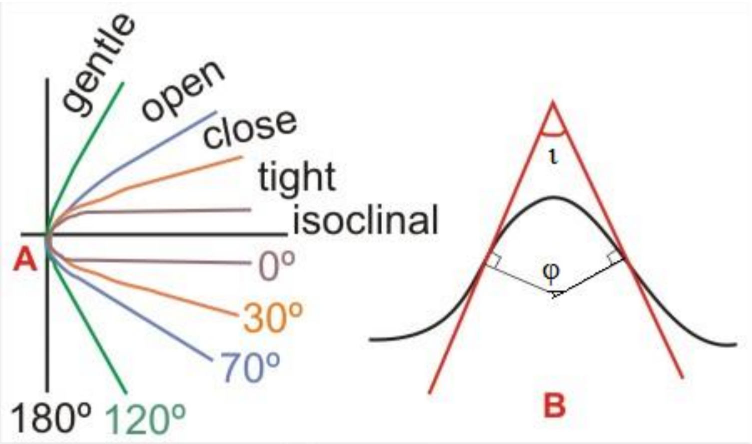
Figure 1.20 (a) Sedimentary layering dips away from a dome in all directions, and the outcrop pattern is circular or elliptical. (b) Layers dip toward the center of a basin.

Lecture: 4

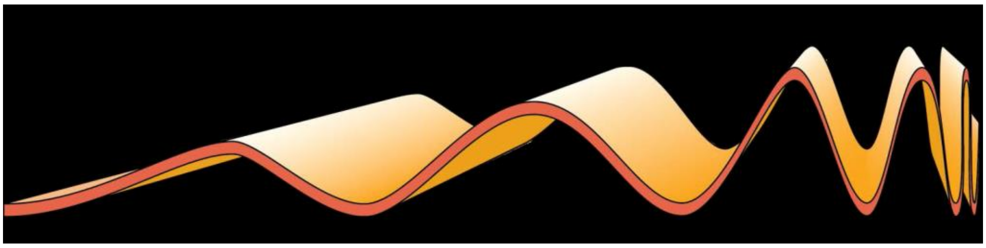
Fold Tightness

Fold tightness is *defined* by the interlimb angle (ι) or folding angle (φ).

The **inter-limb angle**, which is the angle measured between the two projected planes from the limbs of the fold, it is the angle subtended by the tangents at two adjacent inflection points, which may reflect the intensity of compression. And the **folding angle** φ is the angle between the normal to the folded surface constructed at the inflection points.



They can be used to assess the degree of closure of a fold. Seven degrees of closure can be distinguished based on the inter-limb angle. **Gentle folds** are those with an inter-limb angle greater than 120˚; **open folds**, the inter-limb angle is between 120˚ and 70˚; **close folds**, it is between 70˚ and 30˚; **tight folds** are those with an inter-limb angle of less than 30˚; **isoclinal folds**, the limbs are parallel and so the inter-limb angle is zero; **fan folds** the inter-limb angle is between 0˚ and -70˚ and finally **Involute folds** the inter-limb angle is between -70˚and -180˚ ,table 1.



Descriptive Term	Folding Angle ϕ°	Interlimb Angle $\imath^\circ$
Acute		
Gentle	$0 < \phi < 60$	$180 > \imath > 120$
Open	$60 \le \phi < 110$	$120 \ge \imath > 70$
Close	$110 \le \phi < 150$	$70 \ge \imath > 30$
Tight	$150 \le \phi < 180$	$30 \ge \imath > 0$
Isoclinal	$\phi = 180$	$\imath = 0$
Obtuse		
Fan	$180 < \phi \le 250$	$0 > \imath \ge -70$
Involute	$250 < \phi \le 360$	$-70 > \imath \ge -180$

Source: Modifidie after Fleuty 1964.

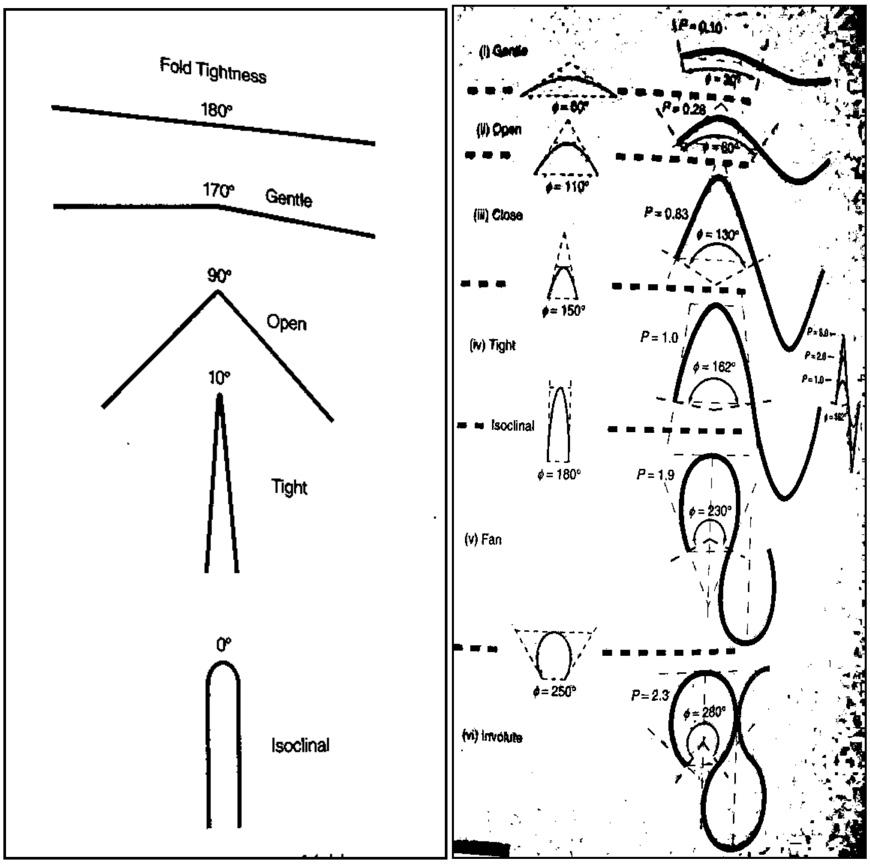


Fig.1.20. A. Old tightness classification. B. Modern tightness classification where **P=A/M**; is the ratio of the amplitude **A** of a fold measured along the axial surface, to the distance **M** measured between the adjacent inflection points that bound the fold.

Fold classification using Isogons

This method is based on the construction of dip isogons: line joining points of equal dip on either side of the folded layer. Using three geometric parameters are as follow (1) The dip isogons; (2) the orthogonal thickness $t\alpha$, which is the perpendicular distance between the two parallel tangents; (3) the axial trace thickness $T\alpha$, which is the distance between the two tangents measured parallel to the axial surface trace(Fig.1.21). The two measures of layer thickness $t\alpha$ and $T\alpha$ are related by

$t\alpha = T\alpha \cos\alpha$

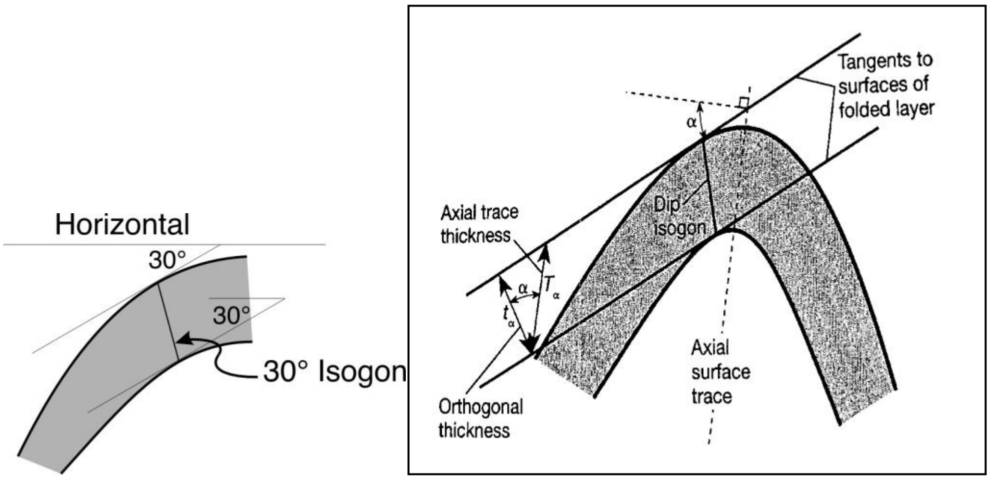


Fig.1.21 Definition of the layer inclination α, the dip isogons, the orthogonal thickness tα, the axial trace thickness Tα used to define the style of folded layer.

If the lines of dip isogons converge toward the inner side of the fold, that is convergent isogons; if they diverge toward the inner surface, that is the divergent isogons; and when they are parallel, that is parallel isogons.

Three classes of folds have been recognized (Fig.1.22):

Class 1, Convergent isogons imply that the inner arc curvature exceed that of the outer arc, which are subdivided in to three subclasses.

Sub-class 1A: strongly convergent

Sub-class 1B: parallel fold with isogons perpendicular to layering.

Sub-class 1C: weakly convergent.

Class 2, parallel isogons, and similar fold, the lines of isogons are parallel to the axial surface.

Class 3, Divergent isogons, imply that the outer arc curvature exceed that of the inner arc.

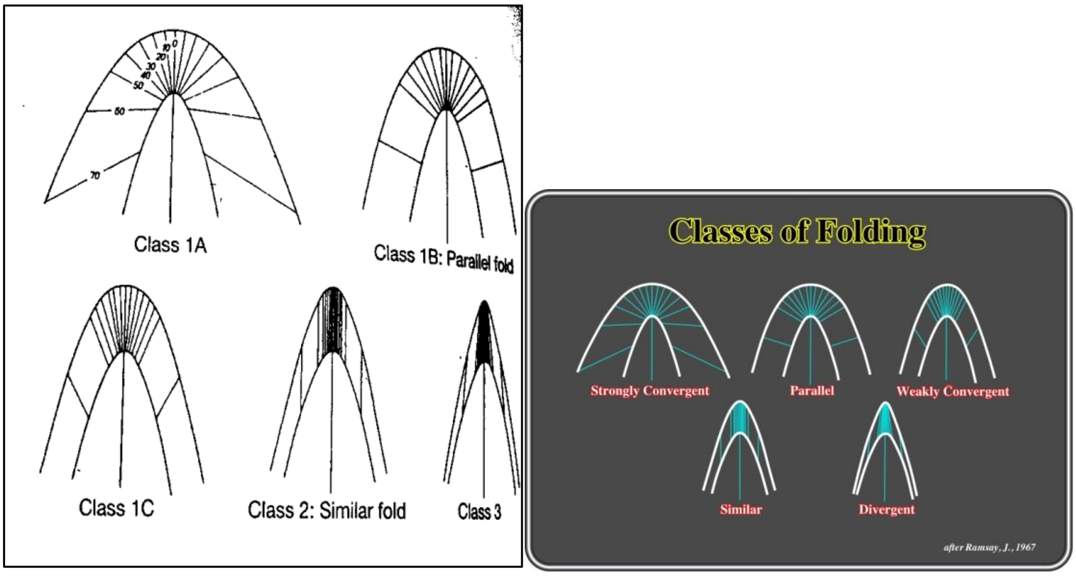


Fig.1.22. The dip isogon characteristics of the main fold classes.

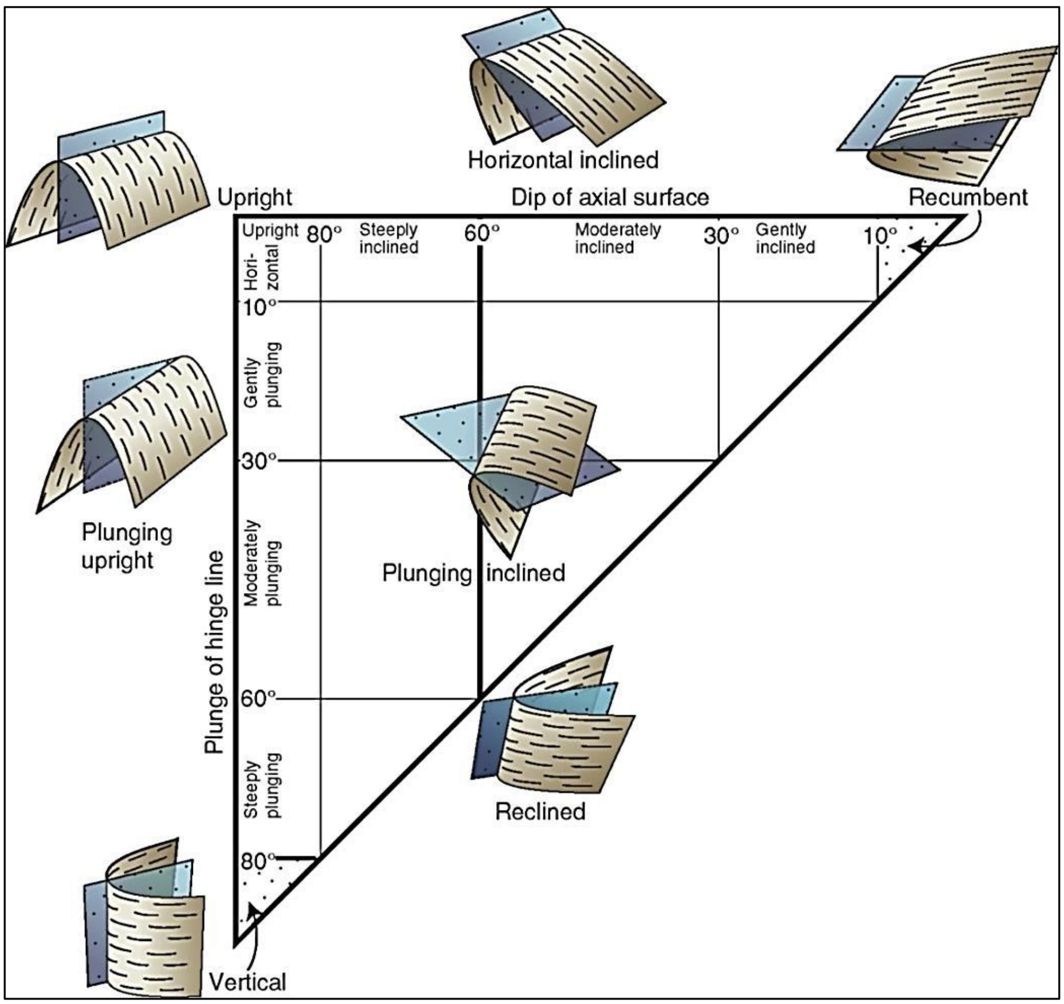
For class 1A folds, the orthogonal thickness tα and the axial trace thickness Tα increase from hinge to limb, for class1B folds, the orthogonal thickness is constant from hinge to limb and the axial trace thickness Tα increases from hinge to limb, these folds also are commonly referred to as parallel folds because tα is constant all around fold, and for class 1C folds, the orthogonal thickness decrease from hinge to limb and the axial trace thickness Tα increase from hinge to limb.

In class 2 and class 3 folds, the orthogonal thickness tα decrease from hinge to limb, but the axial trace thickness Tα, is constant in class 2 and decrease in class 3 folds from hinge to limb Fig. 1.23.

Lecture: 5

Classification of folds based on the orientation of hinge line and the axial surface

This type of folds classification depends on the combinations between the orientation of the hinge line and the axial surface orientation, as shown in table (2) and fig 1.24, when the axial surface is vertical, three types of hinge line orientations are formed as a **Horizontal normal**, **plunging normal** and **vertical**; when the axial surface is dipping, also three types are formed. They are **horizontal inclined**, **plunging inclined** and **reclined** and finally when the axial surface is horizontal, **recumbent fold** is formed.



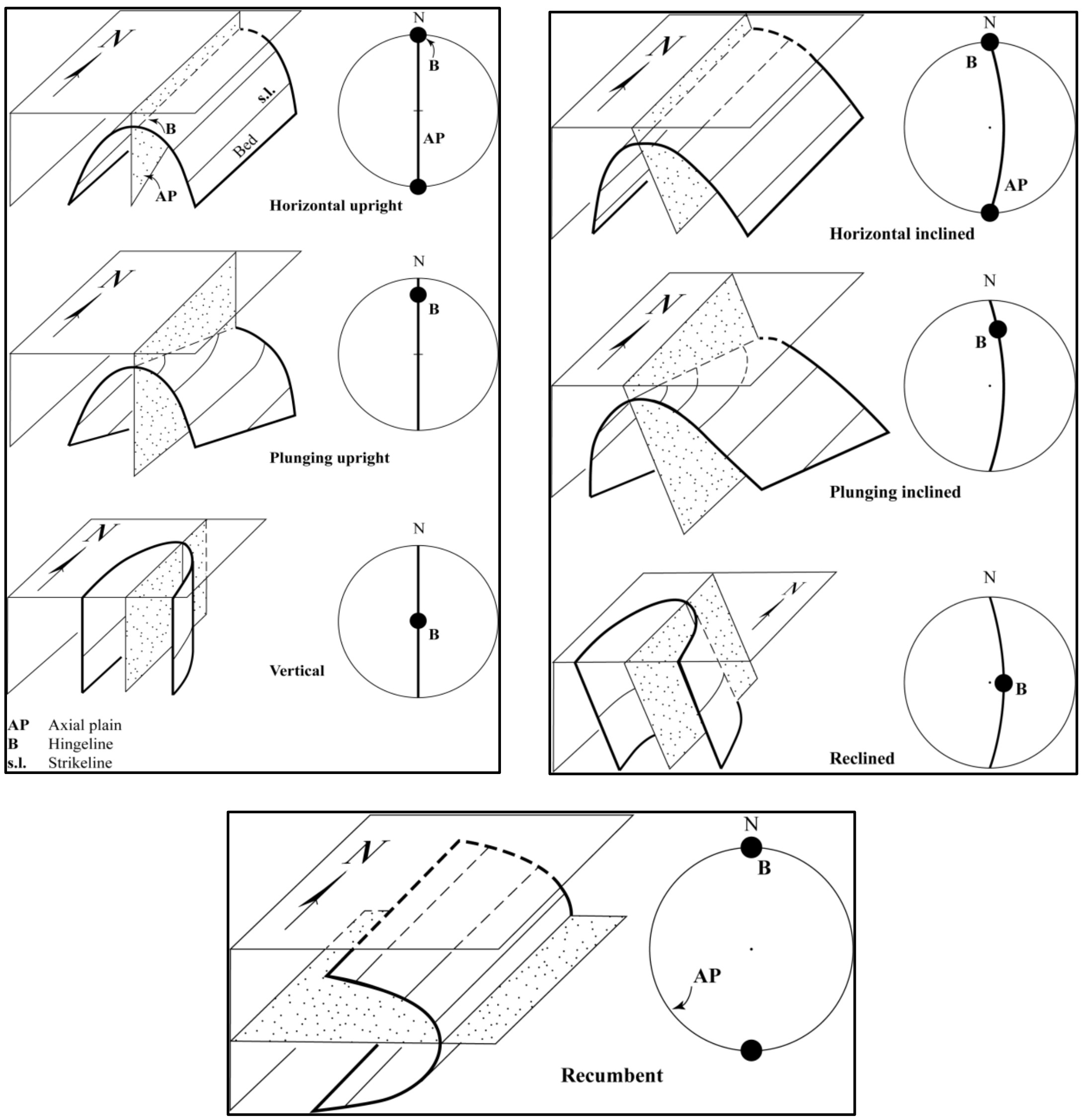


Fig.1.24.Shows the Classification of folds based on the orientation of axial surface and the orientation of hinge line.

Table 2: Classification of approximately plane cylindrical folds by orientation after Turner and Weiss(1963).

		Orientation of Hinge Line		
		Horizontal	plunging	vertical
Orientation of axial surface	vertical	Horizontal normal	plunging normal	vertical
	Dipping	Horizontal inclined	plunging inclined (strike of axial plane oblique to trend of fold axis)	
			Reclined (strike of axial plane perpendicular to trend of fold axis)	
	Horizontal	Recumbent		

Depending on the angle of dipping of the axial surface, it's classified to three types of folds as **recumbent**, **reclined** and **vertical** or **upright** and depending on the angle of plunging of the hinge line, it's classified to five types, as **horizontal**, **shallow**, **intermediate**, **steep** and **vertical**, table 3.

Table.2: classification of fold according orientation after
(Pluijm and Marshak, 2004).

Plunge of Hinge Line	**Dip of Axial Surface**
Horizontal: 0°–10°	Recumbent: 0°–10°
Shallow: 10°–30°	Inclined: 10°–70°
Intermediate: 30°–60°	Upright: 70°–90°
Steep: 60°–80°	
Vertical: 80°–90°	

Lecture: 6

Mechanics and causes of Folding

In general three types of folding are recognized, but the transition and combination are common. The types are (1) flexure folding, (2) shear folding, (3) flow folding

Kinematic analysis is the reconstruction of movements that take place during the deformation of rocks at all scales.

Folds may develop by a range of different mechanisms. These different mechanisms give rise to different deformation paths for different parts of the fold. Understanding the mechanism may enable you to predict the position of localization deformation (e.g. **hinge**, **limb** etc) and therefore may be useful in exploration.

1- **Flexural Folding** : can result from bending or buckling of single layer or multiple layers . Bending & buckling describe the different ways forces are applied to a layer.

A: Bending: Layer is folded by deflection in same direction as applied stress,
equal & opposite torques bend layer into a fold shape Fig.1.25-a. In pure bending, there is no net tension or compression averaged over the layer, either parallel or perpendicular to it. The vertical force acting upward in the middle of the layer could represent the uniform fluid pressure of an intrusive magma body applied over a segment of strata. The resulting uplift of the strata into a localized fold is called a **laccolith**. This vertical force could also represent the effect of a normal fault in basement rocks that bends the overlying strata into a **monoclinal fold** Fig1.26.

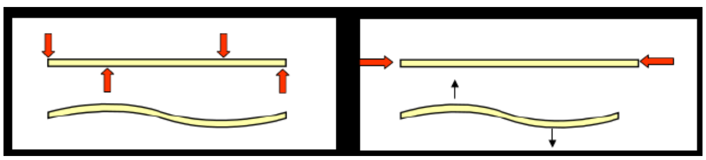


Fig.1.25, (a) **Bending: require opposite torques,** (b) **Buckling: Compressive stress acting parallel to the layer**

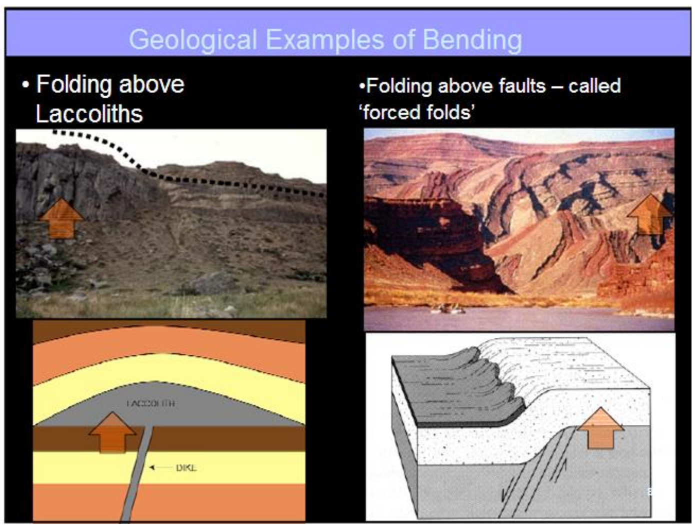


Fig.1.26

B: Buckling: result from the application of compressive stress **parallel** to a competent layer Fig1.25- b. Then the layer is folded by deflection normal to the shortening direction.

Net compression causes layer to buckle into a fold shape. Buckling applies to a single folded layer of finite thickness or to multiple layers with high cohesive strength between layers.

Buckling is what happens when you push on the ends of fairly rigid layer (put a piece of paper on a flat surface and push the edges towards one another) . The compressive force here is parallel to the bedding Fig.1.27. Buckling of a layer will produce parallel fold (class 1b) geometries Fig.1.28, since the thickness of the layer is unaffected. The important thing to realize is that the model predicts a characteristic pattern of strain.

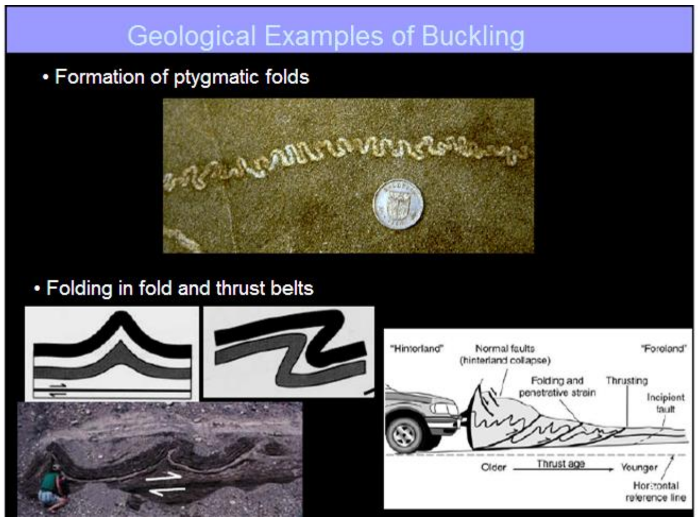


Fig.1.27

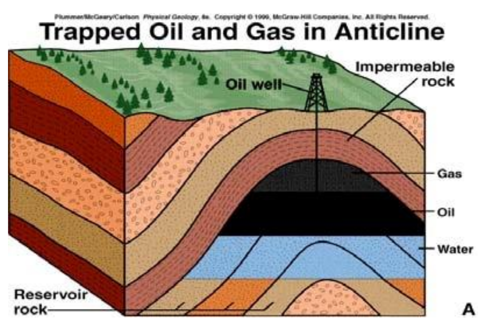
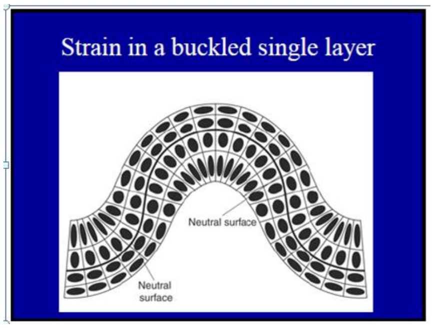


Fig.1.28. Shows trapped oil and gas in anticline, the fold is class1B.

Characteristic features of buckle folds: (1) the upper part of the layer folded anticlinally will be in extension, the lower half in compression. You can define a **neutral surface** that separates areas of compression and extension. On this surface, material points experience no strain. (2) Deformation occurs only by bending about the fold axis. Ideally, there is no extension parallel to the fold axis. That is, this is an example of **plane strain**. (3) Compressive and extensional strain increase with distance from the neutral surface. (4) There is no strain at inflection points of the limbs Fig.1.29. In the field we can show some indications of the buckling like the veins, normal faults, and others extension index on the convex side of the fold, and stylolites and reverse faults in its concave side Fig.1.30.



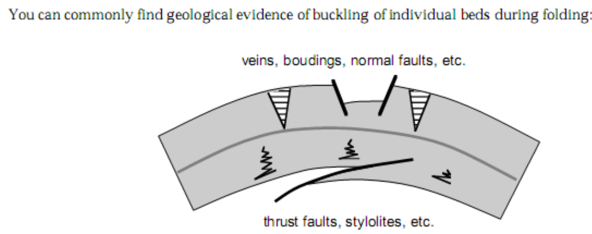


Fig.1.29 **Fig.1.30**

In the folding of sedimentary rocks, some formations are **competent**, whereas others are **incompetent**. Competency is a relative property. A **competence formation** is a strong and can transmit the compressive force much farther than a weak, **incompetent formation.** Many factors determine the competency of the rock, (1) crushing strength, the greater crushing strength will be the more competent in folding, as quartzite and marble are more competence than sandstone and limestone, and the shale is the weakest, (2) massiveness of the formation, in the same kind of rock (e.g. limestone), the thicker beds is more competent, (3) healing of fractures, the sandstone may be stronger than an adjacent limestone. But once the sandstone has broken, the fracture may heal with difficulty, whereas the rupture in the limestone may heal relatively rapidly, so the limestone is more competent than the sandstone.

C Passive folding, if layer rheology does not control the folding process, it is passive folding.

Kinematic Model:

A layer may respond to either bending or buckling load by orthogonal flexure or flexural slip or volume-loss flexure which are kinematic processes.

Lecture: 7

Brittle Deformation

Brittle deformation is simply the permanent change that occurs in a solid material (rocks) due to the growth of fractures and/ or sliding on fractures once they have formed. Brittle deformation occurs only when stresses exceed a critical value, and thus only after a rock has already undergone some elastic and/or plastic behavior.

Fracture: is a planar or curviplanar discontinuity forms as a result of brittle rock failure under relatively low pressure and temperature condition in the earth crust. These structural discontinuities are amongst the most common of all geological features: every outcrop and most cores exhibit some sort of fracturing. Fractures and other discontinuities affect nearly every petroleum reservoir, either by enhancing the production, or by causing problems for production.

Rock fractures range in size from microcracks (fraction of mm) to faults which extend for hundreds of kilometers.

Fracture is a discontinuity across which cohesion (C_o) is lost.

A fracture dose not extend infinitely in all direction, some fracture intersect the surface of a body of rock, whereas others terminate within the body. The line representing the intersection of the fracture with the surface of a rock body is the fracture trace and the separating the region of the rock that has fractured from nonfractured regions is the fracture front. The point at which the fracture trace terminate on the surface of the rock is the fracture tip, Fig(1-34).

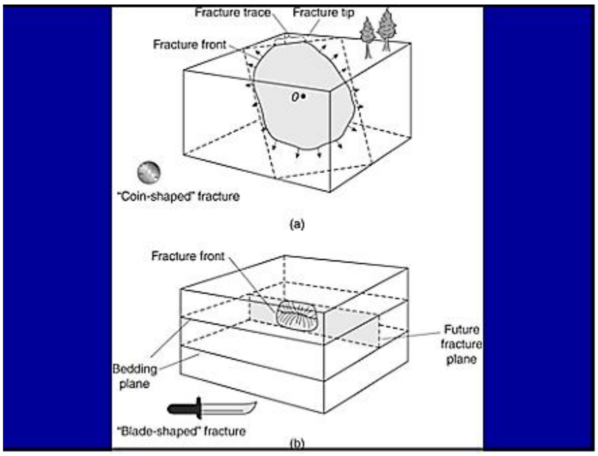


Fig. (1.34)

Joints: are defined as dry fractures of geologic origin along which no appreciable displacement has occurred. Joints (also termed extensional fractures) are planes of separation on which no shear displacement has taken place. The two walls of the resulting opening typically remain in tight (matching) contact. Joints may result from regional tectonics (i.e. the compressive stresses in front of a mountain belt), folding (due to curvature of bedding), faulting, or internal stress release during uplift or cooling.. In sedimentary rocks these joints are usually perpendicular or parallel to the bedding plane. In volcanic rocks, the contraction of the rock during cooling forms joints that isolate prisms perpendicular to the gradient of temperature. Joint growth is controlled by the mechanical layer thickness of the deforming rock. The aperture of a joint is the space between its two walls measured perpendicularly to the mean plane. Apertures can be open (resulting in permeability enhancement) or occluded by mineral cement (resulting in permeability reduction). A joint with a large aperture (> few mm) is a fissure.

Why are the Joints important?

- Provide fracture porosity/permeability - hydrologic modeling, mineralization.
- Important geomorphic control, contributing to drainage (e.g. trellis), lineaments.
- At deeper levels joints exert a control on the migration of geological fluids: water, petroleum and gas.

Spacing :the sizes and spacing (the average orthogonal distance between neighbouring fracture planes) are essential characteristics of joint sets.

Joint sets and systems: Joints are ubiquitous features of rock exposures and often form families of straight to curviplanar fractures typically perpendicular to the layer boundaries in sedimentary rocks. A set is a group of joints with similar orientation and morphology. Several sets usually occur at the same place with no apparent interaction, giving exposures a blocky or fragmented appearance. Two or more sets of joints present together in an exposure compose a joint system. Joint sets in systems commonly intersect at constant dihedral angles. They are conjugate for dihedral angles from 30 to 60°, orthogonal when the dihedral angle is nearly 90°.

- Systematic joints are characterised by a roughly planar geometry; they have relatively long traces and typically form sets of approximately parallel and almost equally spaced joints.
- Non-systematic joints are usually short, curved and irregularly spaced. They usually terminate against systematic joints.

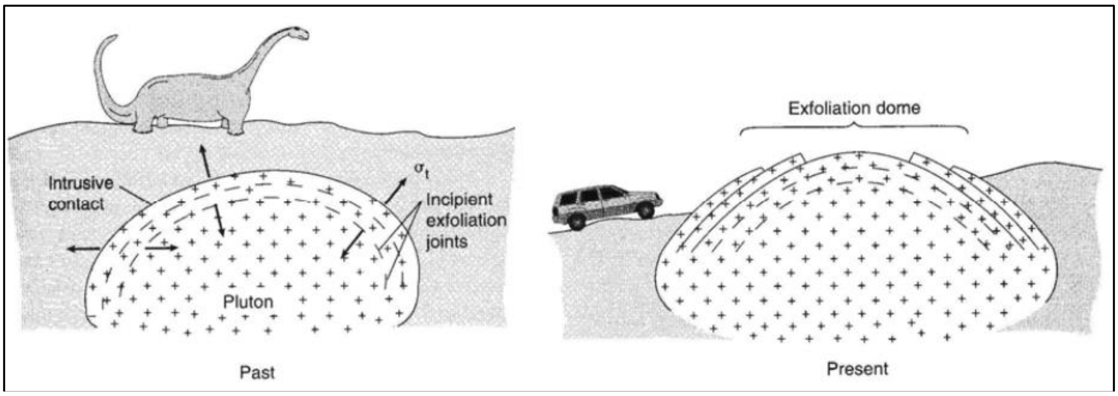
Joints are sometimes farther classified as extension joints and shear joints, as a subdivision based on the angular relations of crossing joints. Because no movement normal or parallel to the joint walls can be observed. Although individual joint fractures may be quite short (1-10m), in certain regions it is found that master joints run for very long distances. Many of the striking lineaments seen on air photographs are master joints rather than the major faults.

Thus, the main types of joint are:
Tectonic joints; breaks formed from the tensile stresses accompanying uplift or lateral stretching, or from the effects of regional tectonic compression. They commonly occur as planar, rough-surfaced sets of intersecting joints, with one or two of the sets usually dominating in persistence (Fig.1.35).

Fig. 1-35 Note how the rock is broken into rectangular blocks, a common phenomenon when two orthogonal (at right angles) joint sets exist. Also note how the one set of joints truncates against the continuous joint running from side to side in the image. If this relationship is consistent, the continuous joint is the longitudinal joint, which is interpreted to have formed **before** the cross joints that truncate against it. Finally note that some fractures that can not be assigned to one of the two orthogonal sets exist. It is not uncommon at all that a rock body can have three or more joint sets developed within it.

Sheeting joints or Exfoliation joints; a set of joints developed more or less parallel to the surface of the ground, especially in plutonic igneous intrusions such as granite; probably as a result of the unloading of the rock mass when the cover is eroded away. It appears that sheeting joints form where horizontal stress is greater than the vertical load.

Breaks developed as a product of exfoliation; the breaking or splitting off from bare rock surfaces by the action of chemical or physical forces, such as differential expansion and contracting during heating and cooling over the daily temperature range (Fig. 1-36).



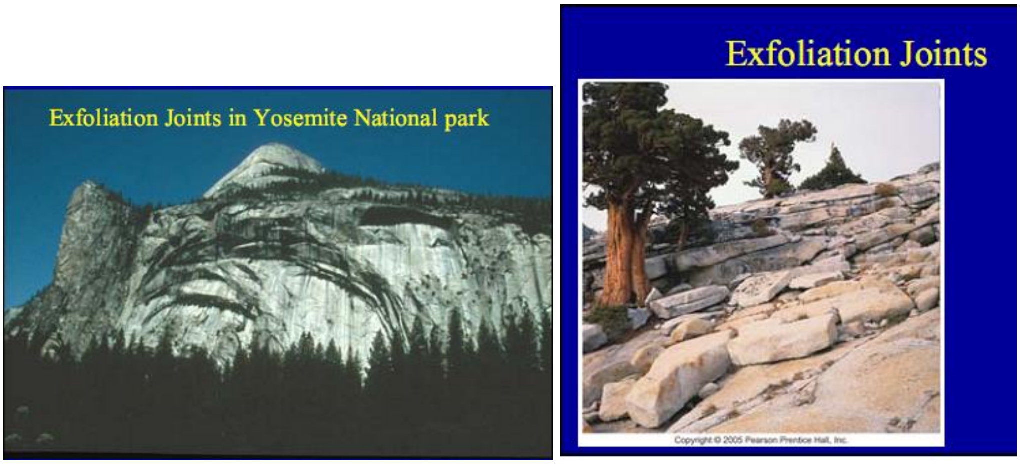


Fig. (1-36). Shows sheeting and exfoliation joints.

Cooling joints, are extensional fractures characteristic of shallow tabular igneous intrusion, dykes or sills or thick extrusive flows. The fractures separate the rock into roughly hexagonal or pentagonal columns, which are often oriented perpendicular to the contact of the igneous body with the surrounding rock (Fig.1-37).

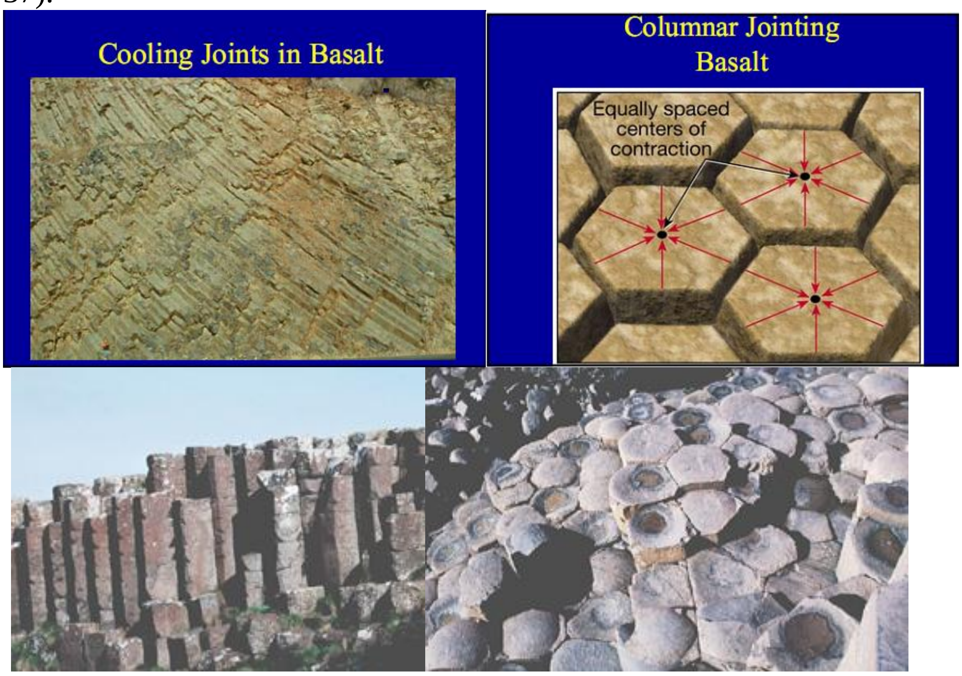


Fig.(1-37)

Classification of the joints

A-Joint classification with respect to bedding plane:

1): **Strike joint** : is the joint that the strike of the joint parallel to the strike of the bed.

2):**dip joint :** Strike of the joint parallel to the dip direction of the bed.

3):**bedding joint :** The strike and dip of the bed coincide with the strike and dip of the joint.

4): **diagonal joint:** there are no coherency neither in strike nor dip between bed and joint Fig.(1-38).

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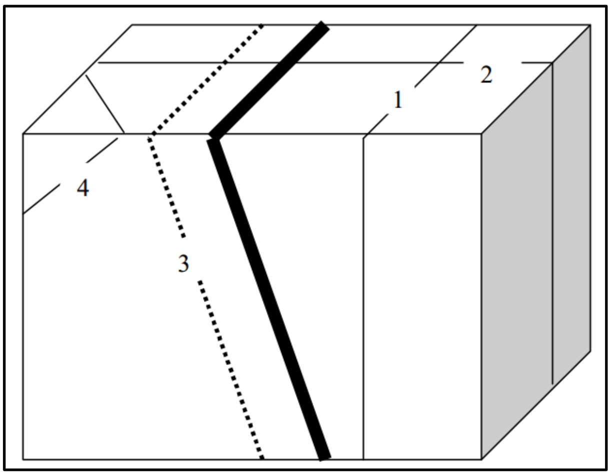


Fig.(1-38).

B-Geometrical classification of the joints:

This classification is depend up on arbitrary three geometrical axes (three tectonic axes) a, b,c axes by (Turner & Weiss).

The perpendicular tectonic axes (a), (b), and (c) are used for the classification of various fracture types. And these axes are geometrically related to the hinge lines of the anticline and bedding planes. The tectonic axis (a) is perpendicular to the fold hinge line (in the state that the hinge line is horizontal), tectonic axis (b) is parallel to the hinge line, (c) axis is perpendicular to (a,b) plane so it's perpendicular to the bedding plane. Fractures are either parallel to two of the tectonic axes or one tectonic axis or cut the three (a, b and c) Fig.(1-39).

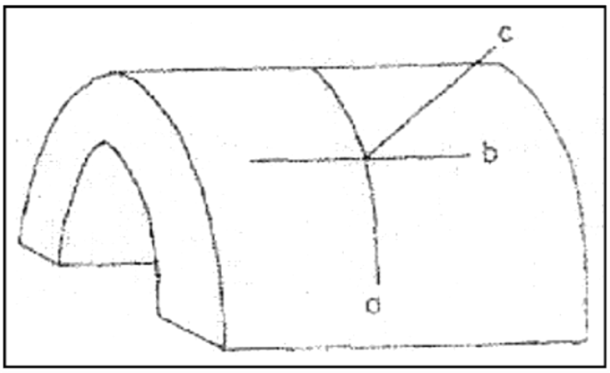


Fig.(1-39)

1-ab set fractures:

The planes of these fractures are parallel to both (a) and (b) axes and perpendicular to (c) axis. This set includes all the planes parallel to bedding plane and usually intersected by other sets.

2-ac set fractures:

The planes of this set of fractures are parallel to tectonic axes (a) and (c) and perpendicular to (b) axis. This set is perpendicular to the hinge line of the fold.

3-bc set fractures:

The planes of this set of fractures are parallel to tectonic axes (b) and (c) and perpendicular to (a) axis. Also they are normal to subnormal to the bedding planes. If we matching this geometrical classification of joint as above we conclude that: Dip joint represent ac joint, strike joint represent bc joint and bedding joint represent ab joint. All these joints represent tension joints (Fig.1.40).

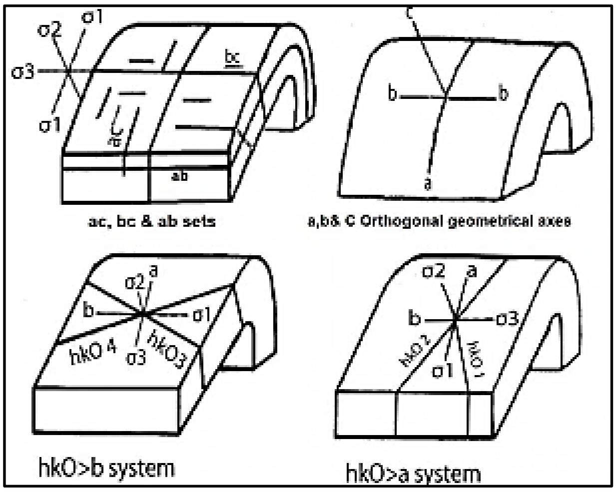


Fig. (1.40): Geometrical classification of the joints with respect to three orthogonal geometrical axes after (Hancock, 1985).

Conjugate joints

This type of classification depend on the orientation of the joint with respect to the three axis (a, b, and c), when the joint crossing all the three axes is designated **hkl** (Fig.1.41), when the joint Parallel to each of the axes it replaced by letter **(O)**, when it's parallel to a-axis as **Okl**: (Okl acute angle about (b) subsystem:The tectonic axis (c) bisects the obtuse and acute angle between the two sets, whereas the tectonic axis (b) bisects the acute angle, Okl acute angle about (c) subsystem: The two planes of this subsystem intersect and forming an acute angle with the tectonic axis (c) and obtuse angle with (b) Fig. (1 .42). When it's parallel to b-axis as hOl: (hOl acute angle about (a) subsystem:The two sets of this subsystem intersect the tectonic axes (c) and (a) and make an obtuse and acute angles around each of them respectively, hOl acute about (c) subsystem: This subsystem is also consisting of two conjugate shears trending parallel to the tectonic axis (b). The tectonic axis (a) bisects the obtuse angle between the two sets of this subsystem, whereas the tectonic axis (c) bisects the acute angle Fig. (1 .42). And when it's parallel to c-axis as hkO (: hkO acute angle about (a) subsystem: This subsystem consists of intersecting two sets, the tectonic axis (a) bisects the acute angle between them, whereas the tectonic axis (b) bisects the obtuse angle, hkO acute angle about (b) subsystem: This subsystem consists of intersecting two sets, the tectonic axis (b) bisects the acute angle between them, Whereas the tectonic axis (a) bisects the obtuse angle) Fig. (1 .40). All these joints represent Shear joints.

a b c

h k l

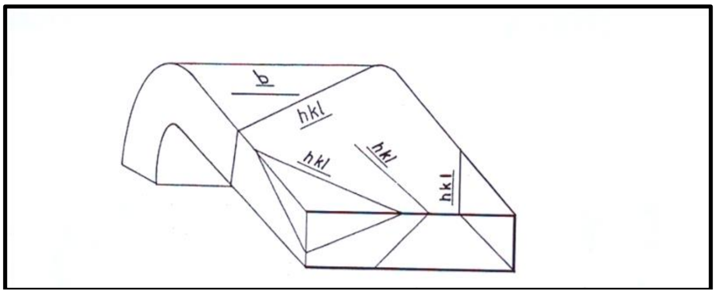


Fig. (1 .41): Geometrical classification of the joint (hkl) with respect to three orthogonal geometrical axes after (Hancock, 1985).

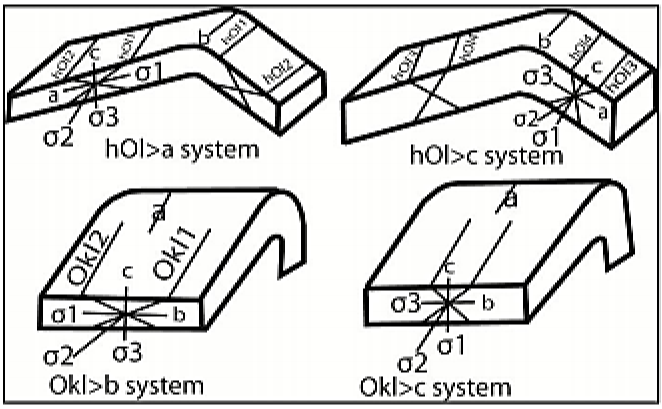


Fig.(1.42): Geometrical classification of the joints with respect to three orthogonal geometrical axes after (Hancock, 1985).

Lecture: 8

Veins: are dilated fractures filled with oriented crystal fibres or non-oriented mineral deposits (typically quartz, calcite or carbonates) Fig. 1.43. Such secondary crystallizations have been transported into and then deposited or precipitated along the fracture from solutions under favourable conditions of temperature and pressure. Veins are thus taken as evidence for movement of fluids along fractures. They occur in rocks of all types and metamorphic grades with thickness from less than a millimetre to several meters.

Fig.(1.43):Veins filled by calcite material.

Faults: Are fractures that have appreciable movement parallel to their plane. They produced usually be seismic activity. Understanding faults is useful in design for long-term stability of dams, bridges, buildings and power plants. The study of fault helps understand mountain building. Faults may be hundreds of meters or a few centimeters in length.

What is a Fault?

• A fault is a break or fracture between two blocks of rocks in response to stress.
• Three types of stresses produce faults
1) Tension 2) Compression 3) Shear
• One block has moved relative to the other block. • The surface along which the blocks move is called a fault plane.

Parts of Faults: Fig. 1-44

A **fault line** is the surface trace of a fault, the line of intersection between the fault plane and the Earth's surface. Since faults do not usually consist of a single, clean fracture, geologists use the term **fault zone** when referring to the zone of complex deformation associated with the fault plane.

Fault scarp

The fault scarp is the feature on the surface of the earth that looks like a step caused by slip on the fault.

Fault trace

The fault trace is the intersection of a fault with the ground surface; also, the line commonly plotted on geologic maps to represent a fault.

Fault plane: Surface that the movement has taken place within the fault. On this surface the dip and strike of the fault is measured.

Hanging wall: The rock mass resting on the fault plane.
Footwall: The rock mass beneath the fault plane.

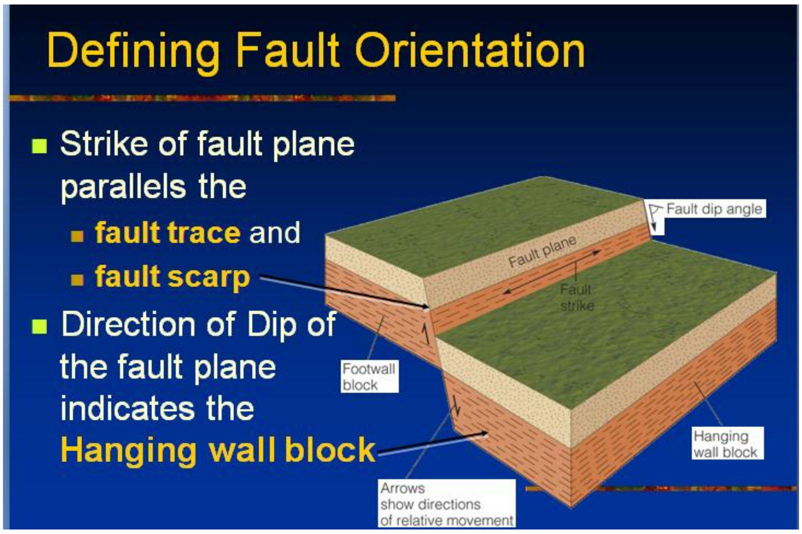


Fig. 1-44

Slip: Describes the movement parallel to the fault plane. **Dip slip**: Describes the up and down movement parallel to the dip direction of the fault. **Strike slip:** Applies where movement is parallel to strike of the fault plane. **Oblique slip:** Is a combination of strike slip and dip slip. **Net slip** (true displacement): Is the total amount of motion measured parallel to the direction of motion.
Heave: The horizontal component of dip separation measured perpendicular to strike of the fault. **Throw:** The vertical component measured in vertical plane containing the dip (Fig. 1-45).

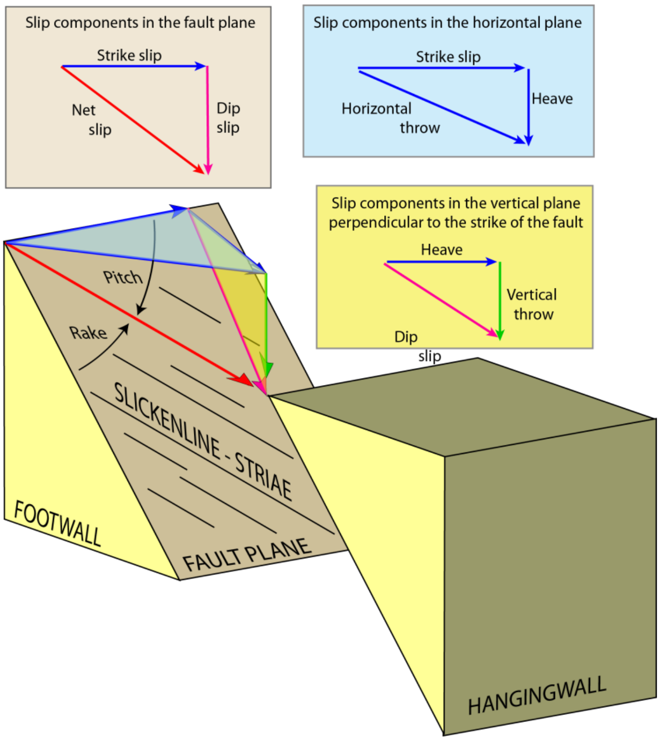


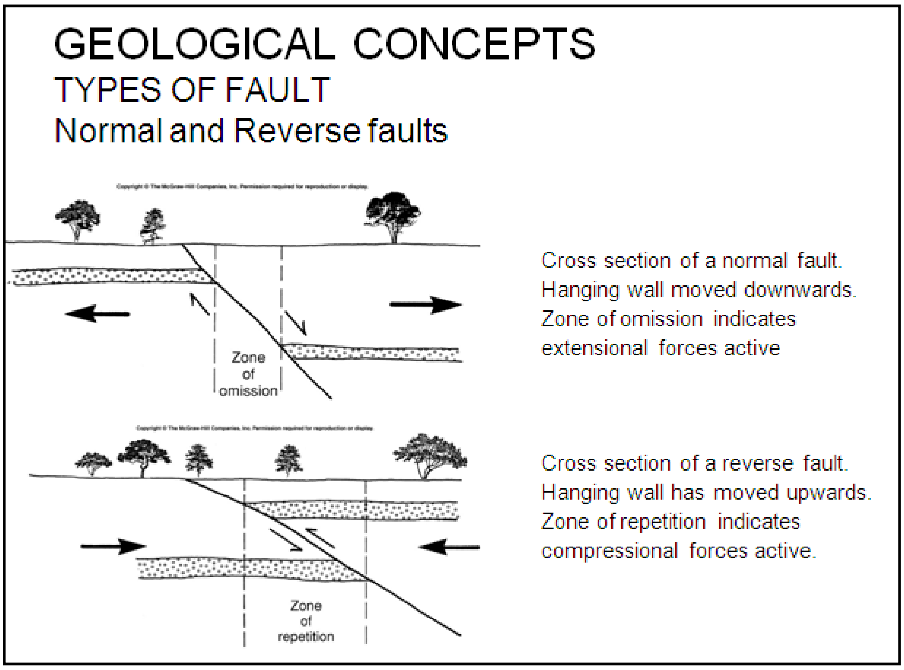
Fig. (1-45) Shows oblique slip fault accompanied by Sliken line-striae

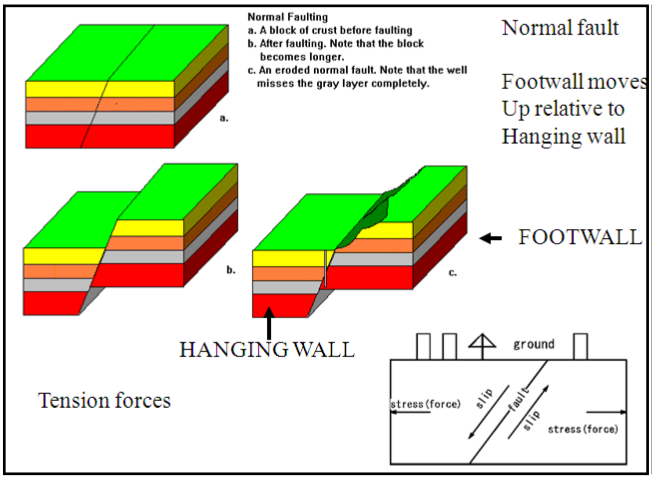
Features on the fault surface are:

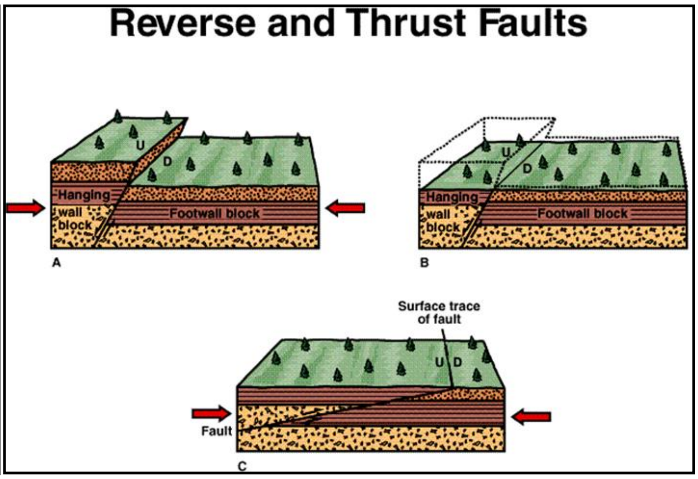
1) Grooves (parallel to the movement direction) 2) Growth of fibrous minerals (parallel to the movement direction) 3) Slickensides are the polished fault surfaces. 4) Small steps.
All are considered a kind of lineation. They indicate the movement relative trend NW, NE … etc.
Small steps may also be used to determine the movement direction and direction of movement of the opposing wall. Slicklines usually record only the last moment event on the fault.

Geologists categorize faults into three main groups based on the sense of slip:

- a fault where the relative movement (or slip) on the fault plane is approximately vertical is known as a dip-slip fault (Fig 1-46).
- where the slip is approximately horizontal, the fault is known as a transcurrent, wrench or strike-slip fault (Fig. 1-46).
- an oblique-slip fault has non-zero components of both strike and dip slip.







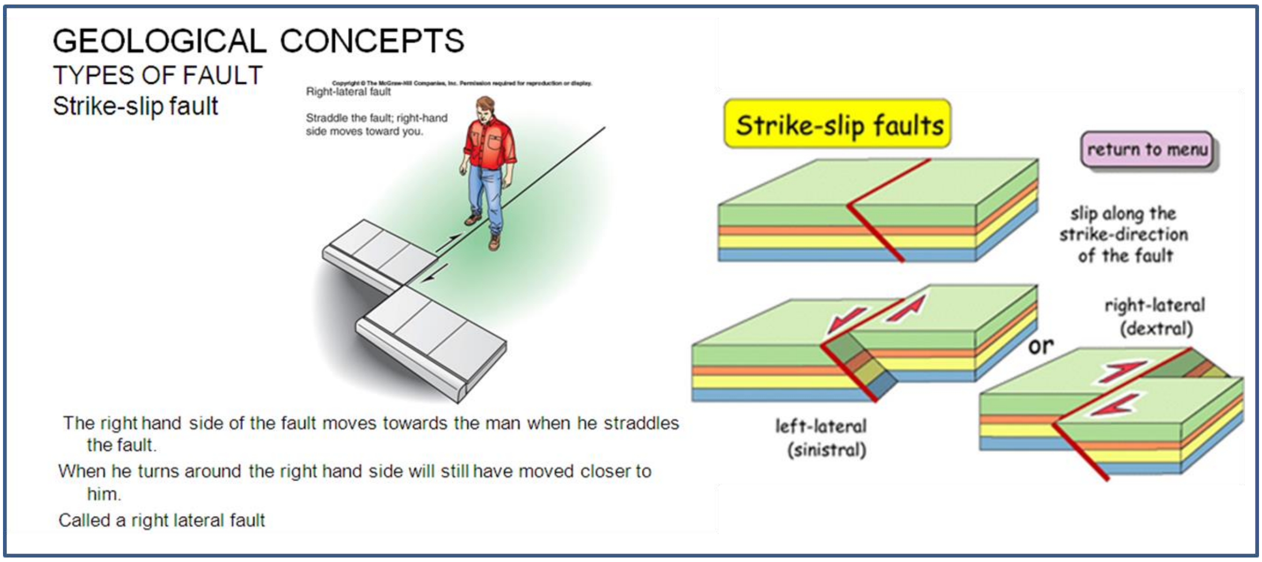


Fig. 1-46 Shows types of strike-slip faults.

The attitude of the fault is important because it is used to classify the fault as either dip-or strike slip. For example, if the displacement across the fault is parallel, then the fault is a **strike-slip fault** (Figure 1-46).

On the other hand, if the displacement is parallel to the dip and at right angles to the strike, then the fault is a **dip -slip** fault (Figure 1-46). However, sometimes the displacement is neither parallel to the strike nor to the dip, and, in such cases the fault is classified as an **oblique-slip fault** (Figure 1-46).

There are two types of strike-slip and two types of dip-slip fault. The two types of strike-slip fault are **right-lateral** (or **dextral**) and **left-lateral** (or **sinistral**) (Fig 1-46).

Strike-slip faults are vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed right lateral; if the block moves to the left, the motion is termed left lateral.

While the two types of dip-slip are normal and reverse (or thrust). In general, strike slip faults tend to have dips that are near vertical while dip-slip faults tend to dip about 60° for normal and 30° for reverse or thrust faults. For dip-slip faults, the block lying on top of the fault surface is referred to as the hanging wall while the one below is referred to as the footwall block.

The first step in classifying dip-slip faults is to identify the hanging and footwall blocks, completing this task, simply note that in normal faults the hanging wall moves down relative to the footwall while for reverse or thr ust faults the hanging wall moves up (Fig 1-46).

Oblique slip faults are classified on the basis of which of the two major components, strike- or dip-slip dominate (Figure 1.47). If the strike component dominates, then the fault would be classified as either an **oblique right-lateral** or an **oblique left-lateral** strike slip fault depending upon if the slip is dextral or sinistral respectively (Fig.1-47).

If on the other hand, the dip component dominates, then the fault would be classified as either an **oblique normal** or an **oblique reverse** fault depending upon if the hanging wall moved down or up relative to the footwall block respectively.

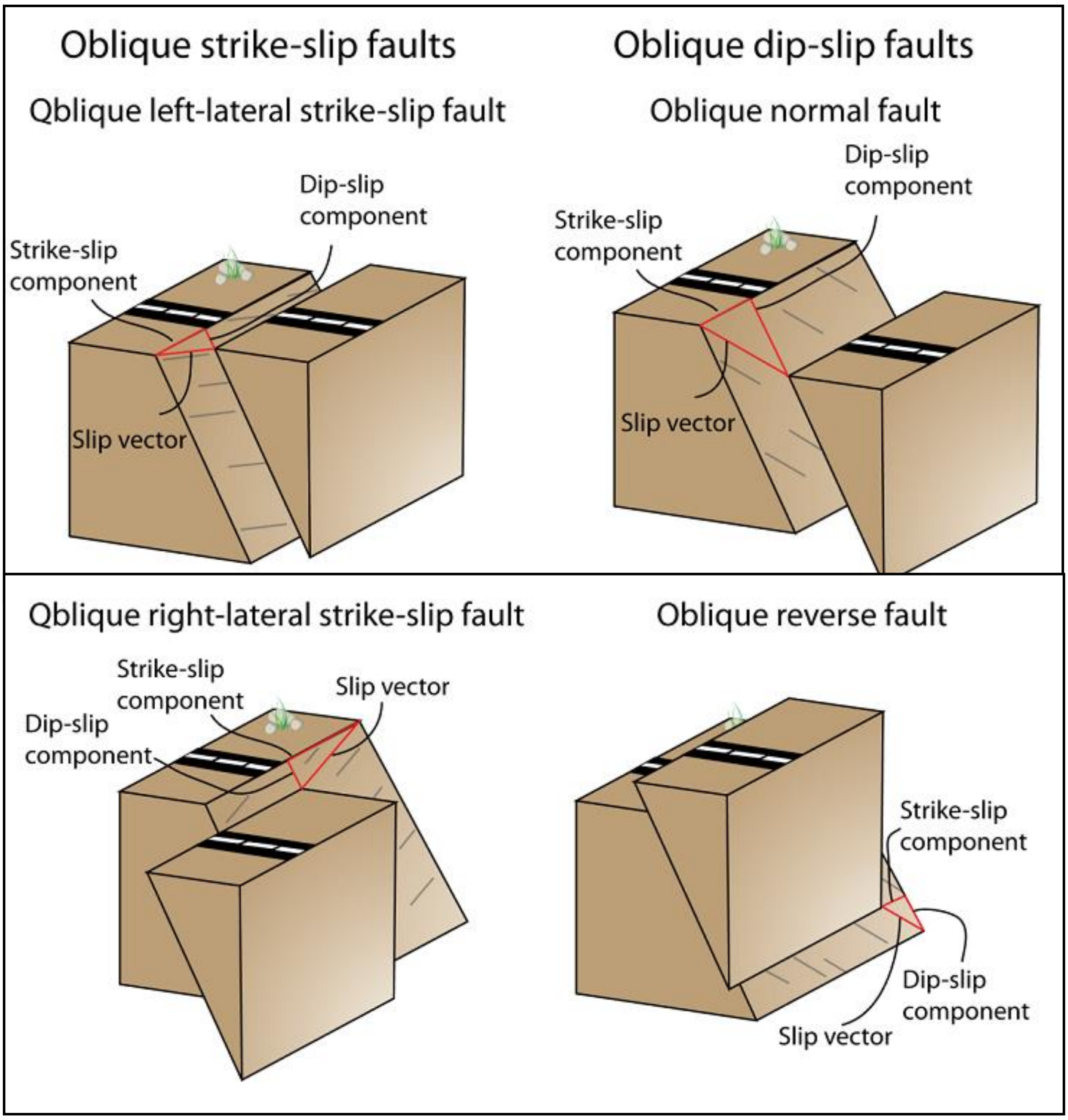
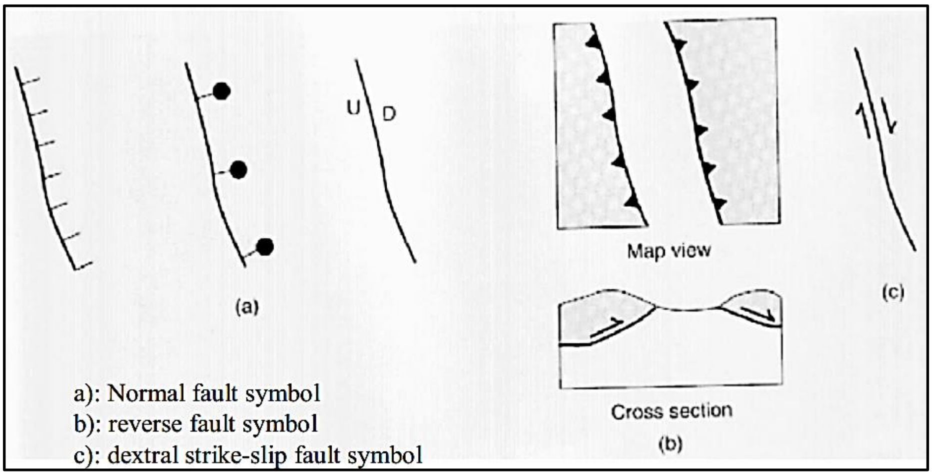


Fig. 1-47 Shows types of Oblique slip faults.

Symbol used in map concerning the faults:



Lecture: 9

Principal Stress Axes

The three principal stresses are conventionally labelled $\boldsymbol{\sigma_1}$, $\boldsymbol{\sigma_2}$ and $\boldsymbol{\sigma_3}$. $\boldsymbol{\sigma_1}$ is the maximum (most tensile) principal stress, $\boldsymbol{\sigma_3}$ is the minimum (most compressive) principal stress, and $\boldsymbol{\sigma_2}$ is the intermediate principal stress Fig.(1.48).

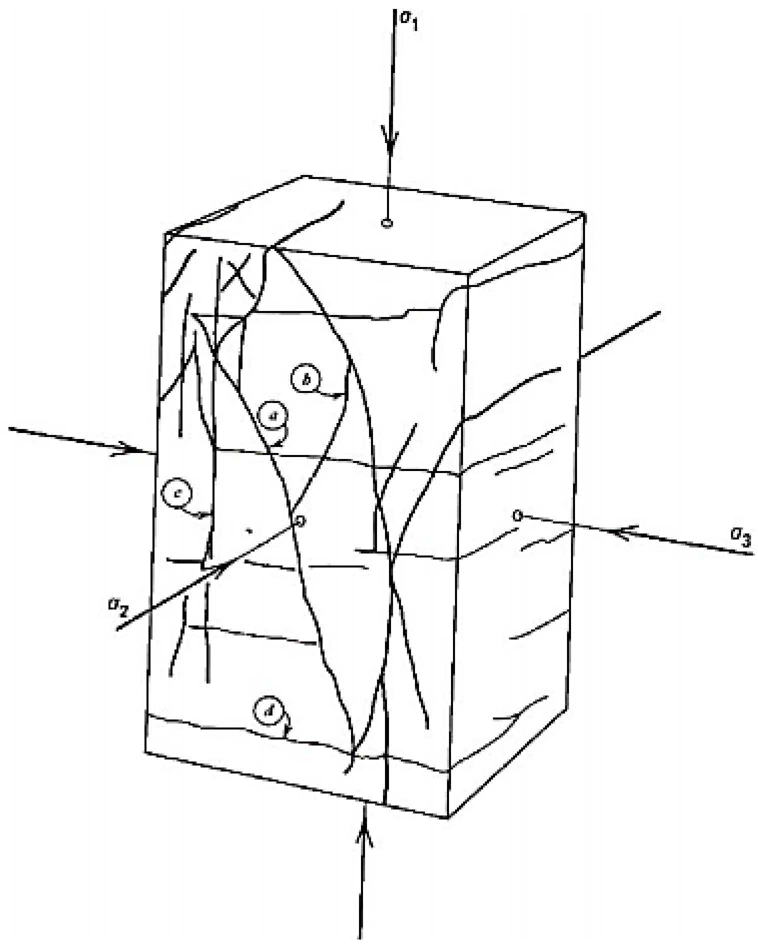


Fig.(1.48):Principal Stress Axes

We distinguish the principal stresses directions, i.e. the eigenvectors of the stress tensor, represented by the three unit vectors 1s ρ , 2s ρ and 3s ρ from the principal stress magnitudes, i.e. the corresponding eigenvalues $\sigma 1 \geq \sigma 2 \geq \sigma 3$, taken positive in compression.

Classification of Faults

Faults are most often classified by their stress state, as developed by E.M. Anderson in the early 1900's. [6] Anderson derived the belief that the magnitude of horizontal stresses (σ2 and σ3) relative to that of the vertical stress (σ1) can change, which gives rise to three main types of faults: thrust fault, normal fault and strike-slip fault (Figure 1.49). Principal stress directions are represented by the three unit vectors S1, S2 and S3, for their respective principal stresses σ1, σ2 and σ3. This also derives the three main tectonic regimes:

- S1 vertical: extensional tectonic regime
- S2 vertical: strike-slip regime
- S3 vertical: compressional regime

The basics of faulting and stress geometry assumes that the body of rock is homogeneous and isotropic, and that the shear surface of the fault follows Mohr-Coulomb shear failure criterion, that is, a fault occurs on the plane which intersects the failure envelope. Lineations on a slip surface indicate the movement direction, and are assumed to have the same direction and sense as the resolved shear stress on the fault plane. Striations represent the intersection of the fault surface with the S1-S3 plane. The intersection of conjugate faults defines the intermediate principal stress direction S2, and the acute angle between conjugate faults is bisected by the largest principal stress S1.

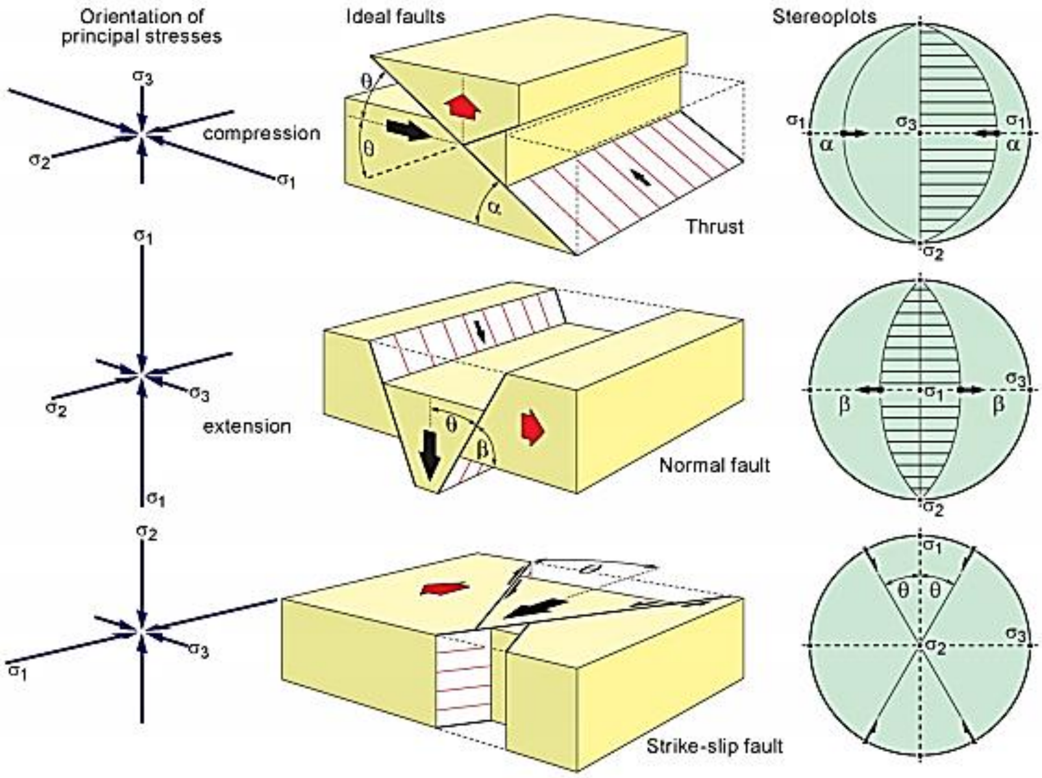


Fig.(1.49): Dynamic interpretation of faults: Anderson's "standard" relationship between stresses and ideal faults