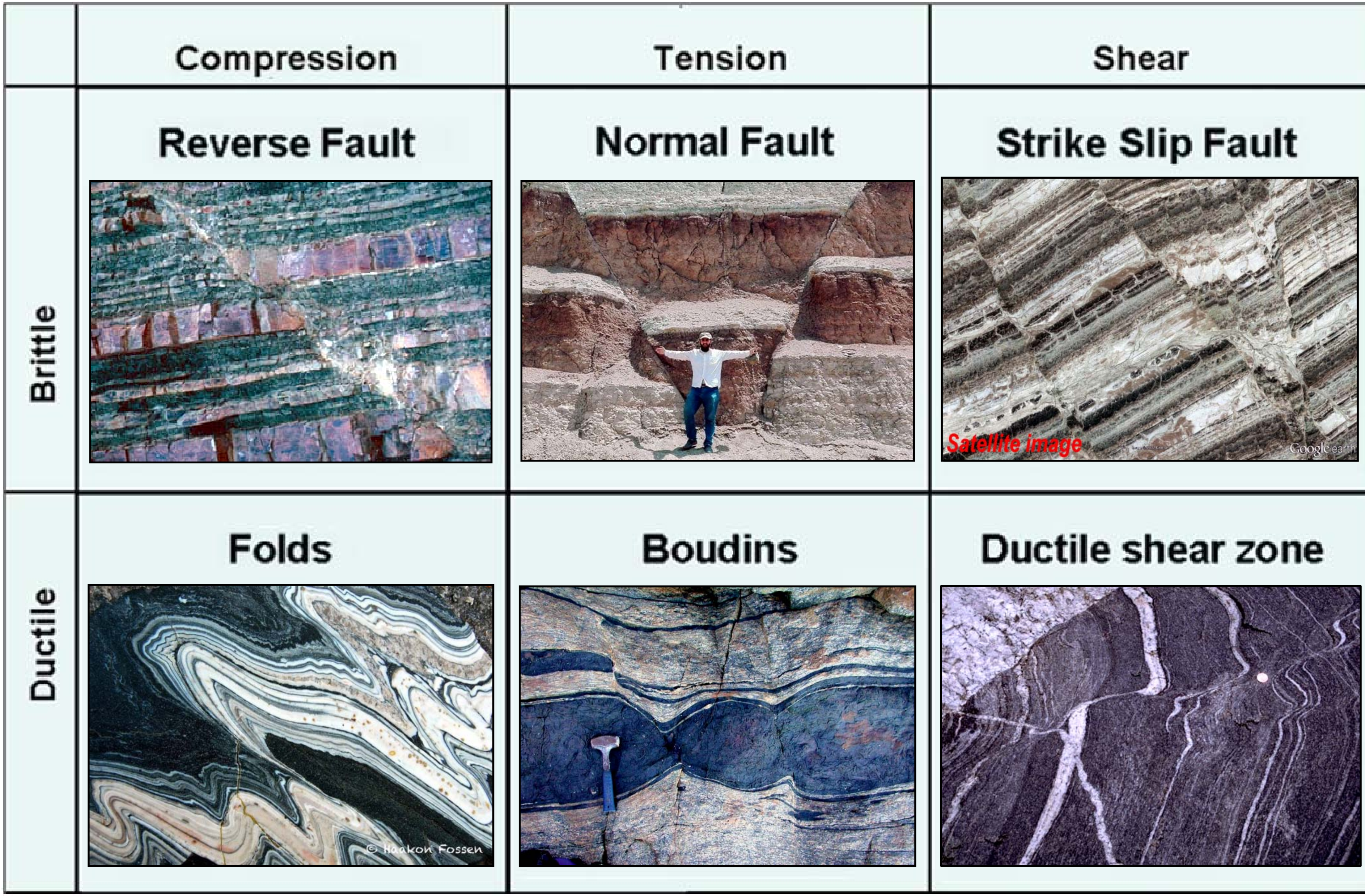
# Folds and Folding




**Types of structures that can be formed in brittle and ductile rocks under compression, tension and shear stresses**

**A fold is a bend in a layered rock caused by compressive stress (buckling) or passive draping of layers over a lower structure or around a resistant object . Anticlines are hydrocarbon reservoirs. Folds host ore deposits in hinge areas due to flow of material to those locations.**

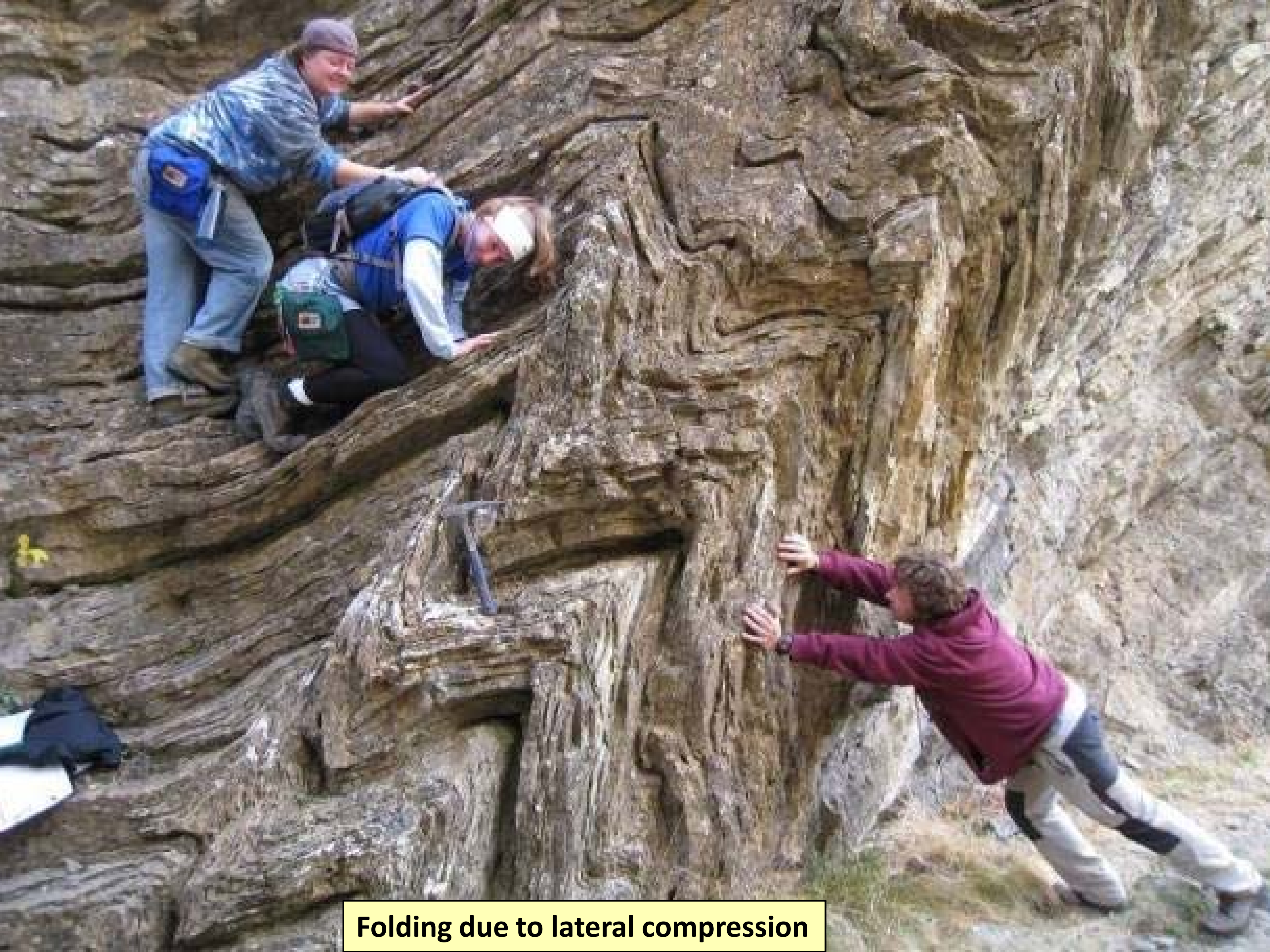
# ***Scales of Folds***

**Folds can present in all scales**

- ***microscopic*** **(require magnification)**
- ***mesoscopic*** **(specimen and outcrop size)**
- ***macroscopic*** **(larger scale)**

- ***microfolds:*** **folds in the microscopic scale.**
- ***minor folds :*** **specimen and outcrop scale.**
- ***major folds:*** **large folds, cannot be recognized by aided eye.**

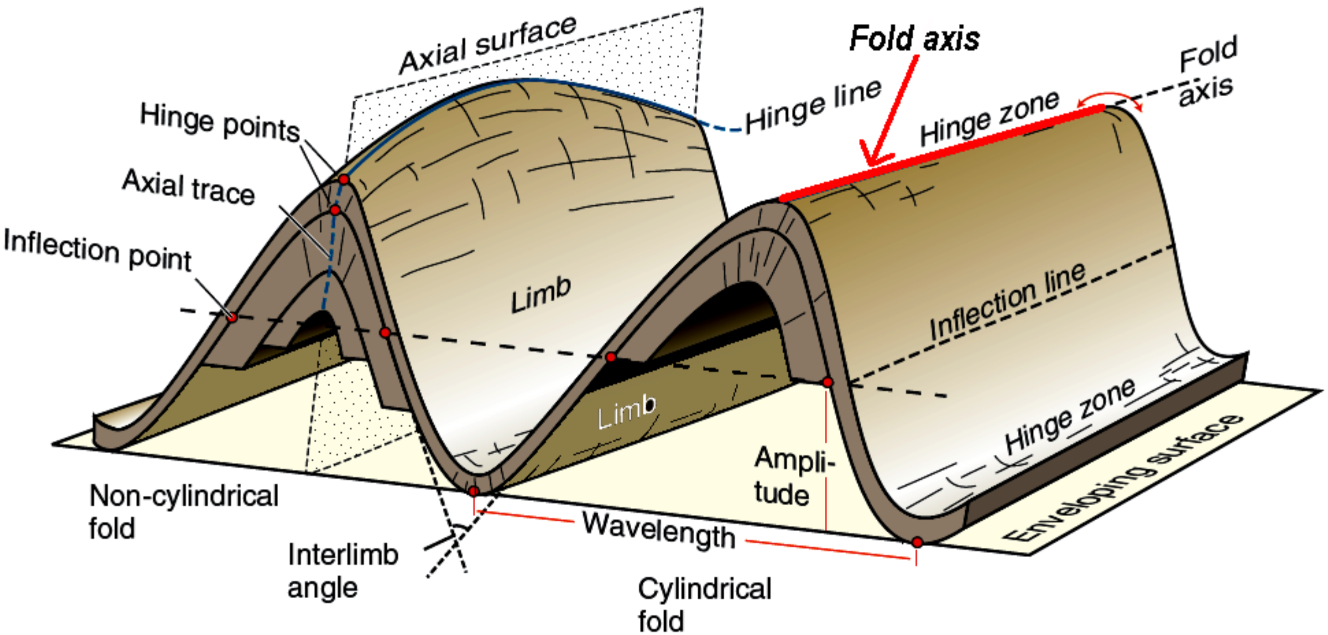
***Pumpelly's rule:* small-scale structures are generally mimic larger-scale structures *formed during the same phase of deformation.***

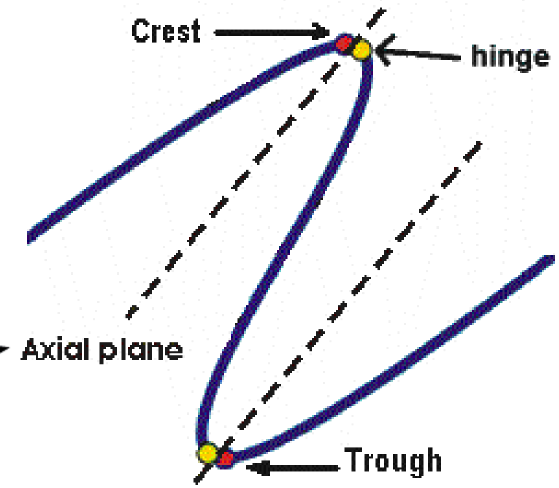


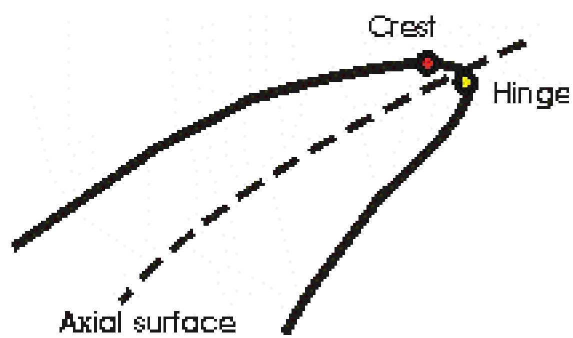
Folding due to lateral compression


**Landsat image of major folding, Hafafit area, Egypt**

# Fold terminology




**Hinge point:** is the point of maximum curvature on the folded surface.

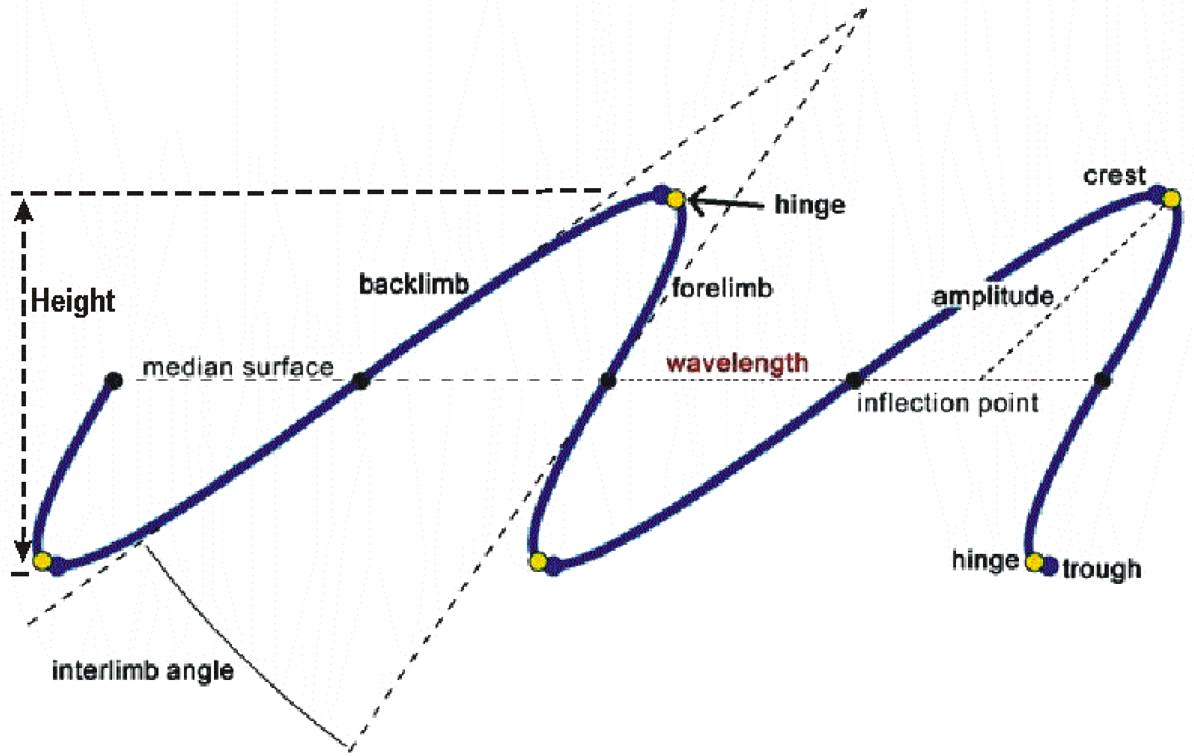
**Hinge line:** is the line of maximum curvature on the folded surface. It connects the hinge points on the surface.

**Crest and trough:** are the highest and lowest points in the folded surface.

**Fold axis :** In folds that have the geometry of a cylinder (cylindrical folds), the fold axis is the line when moved parallel to itself draws the folded surface. In other folds (non-cylindrical folds), the fold axis can be considered as the line connecting the crest points on the folded surface.

**Axial plane:** is the plane that divides the fold into two similar parts as possible. In some folds this plane is not a perfect plane, but a surface termed the **axial surface**.

**Axial trace:** is the projection of the axial plane on the map view or on the cross section.




**Wave length:** is the distance between two successive crests or troughs.

**Inflection point:** is the point at which the fold surface changes its direction of curvature.

**Median surface:** is the plane connecting the inflection lines on the folded surface.

**Interlimb angle:** is the angle between the two limbs of a fold. It is measured as the angle between the two tangential lines at the inflection points.

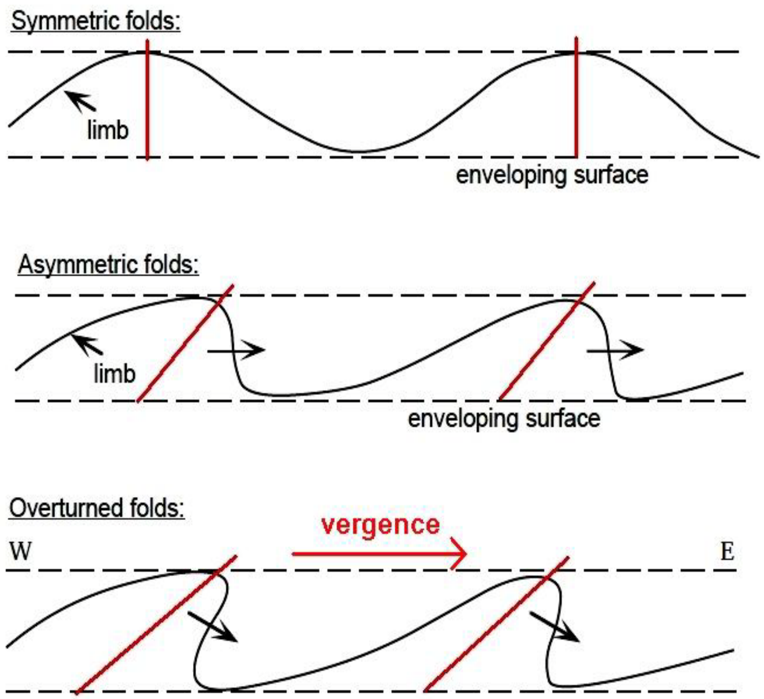
**Amplitude:** is the distance bisecting the angle between the two limbs between the hinge point and the median surface.

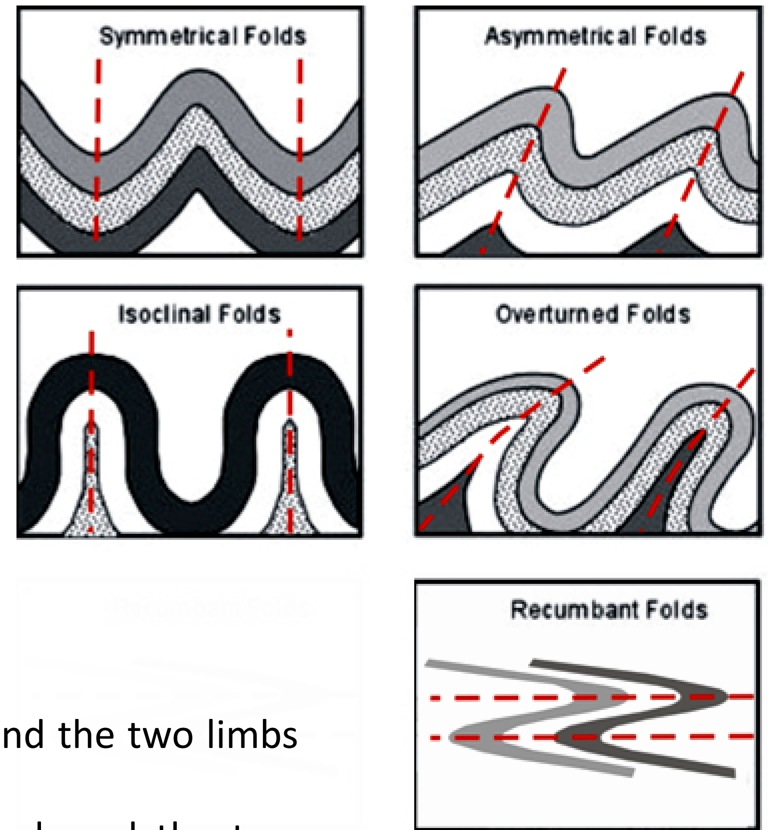
**Height:** is the vertical distance between the crest and trough in a folded surface.

**The orientation of a fold is defined by the orientation of the fold axis (its trend and plunge) and the orientation of the axial plane (its strike and dip).**

# Classification of folds

## I- based on the symmetry of limbs relative to the axial surface:




1- **Symmetric folds:** in which the axial plane is vertical, and the two limbs dip in opposite directions at equal angles.

2- **Asymmetric folds:** in which the axial plane is inclined, and the two limbs dip in opposite directions at different angles.

3- **Overturned folds:** in which the axial plane is inclined, and the two limbs dip in the same direction at different angles.

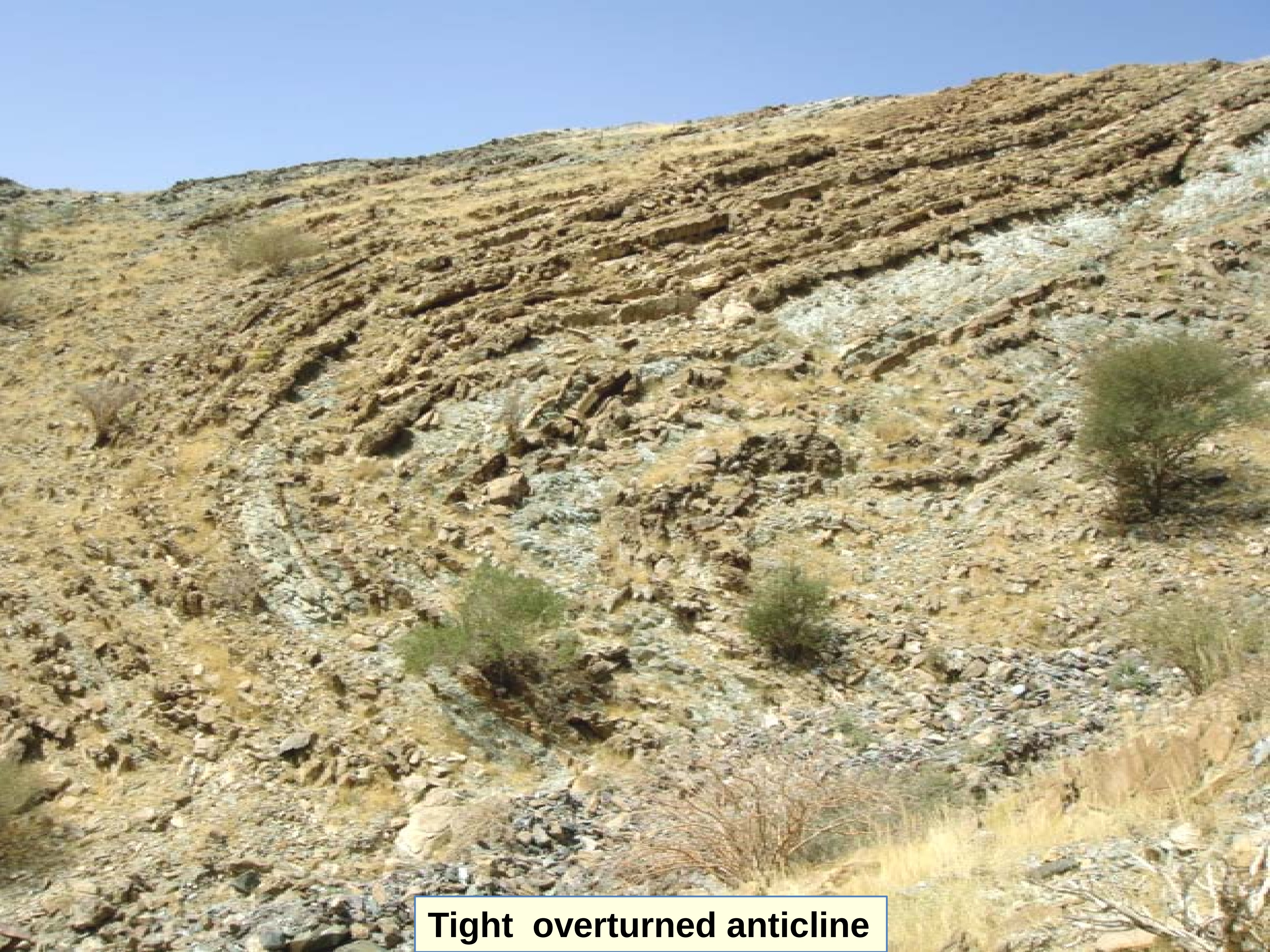
4- **Isoclinal folds :** in which the axial plane is inclined or vertical, and the two limbs dip in the same direction at equal angles.

5- **Recumbent folds:** in which the axial plane is horizontal.

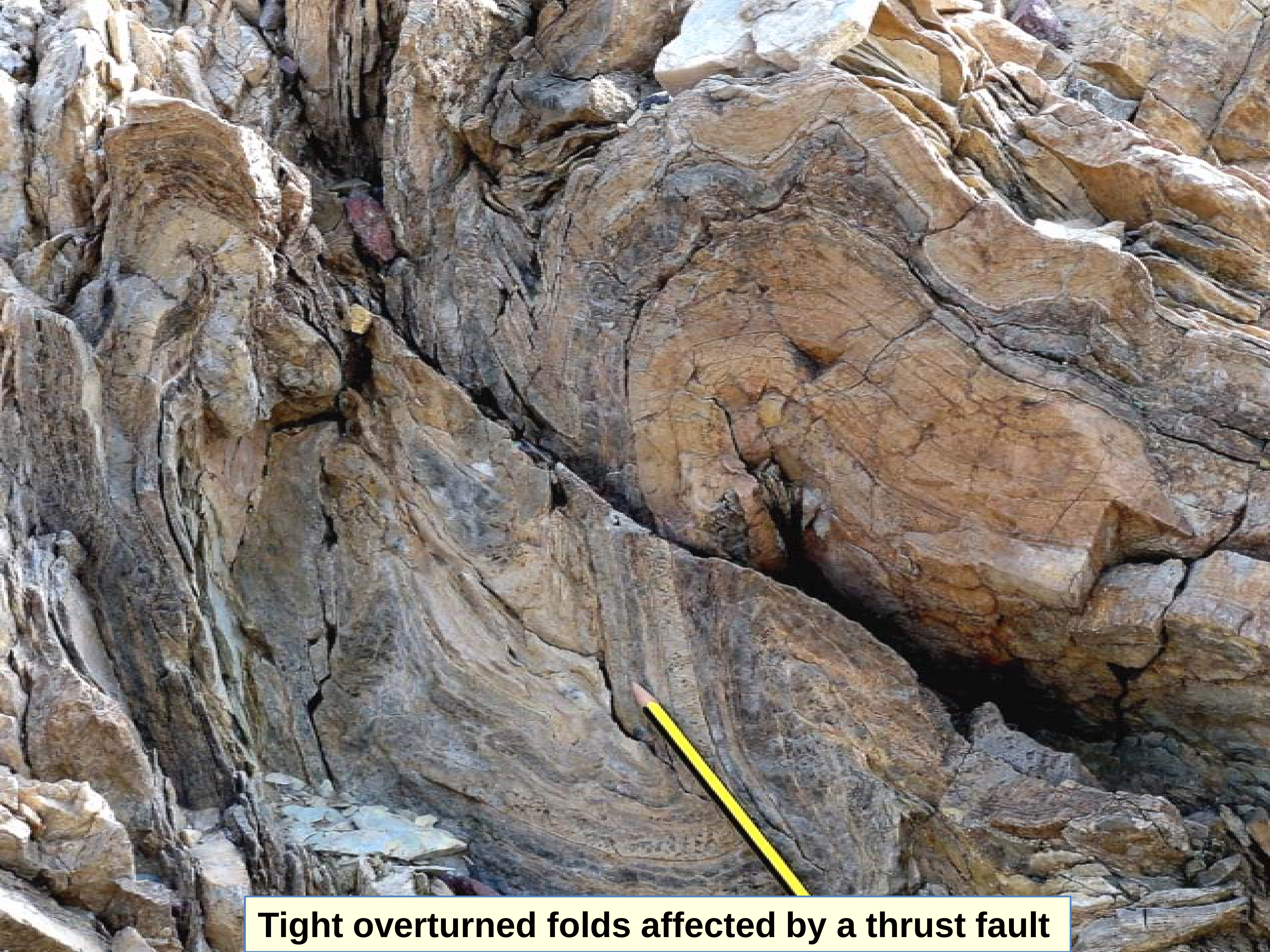
Fold vergence is the direction in which a fold is inclined or overturned, i.e. the direction of transport of the crests. In the previous figure, folds are verging to the east.

**Tight symmetric anticline**

**Tight overturned syncline**



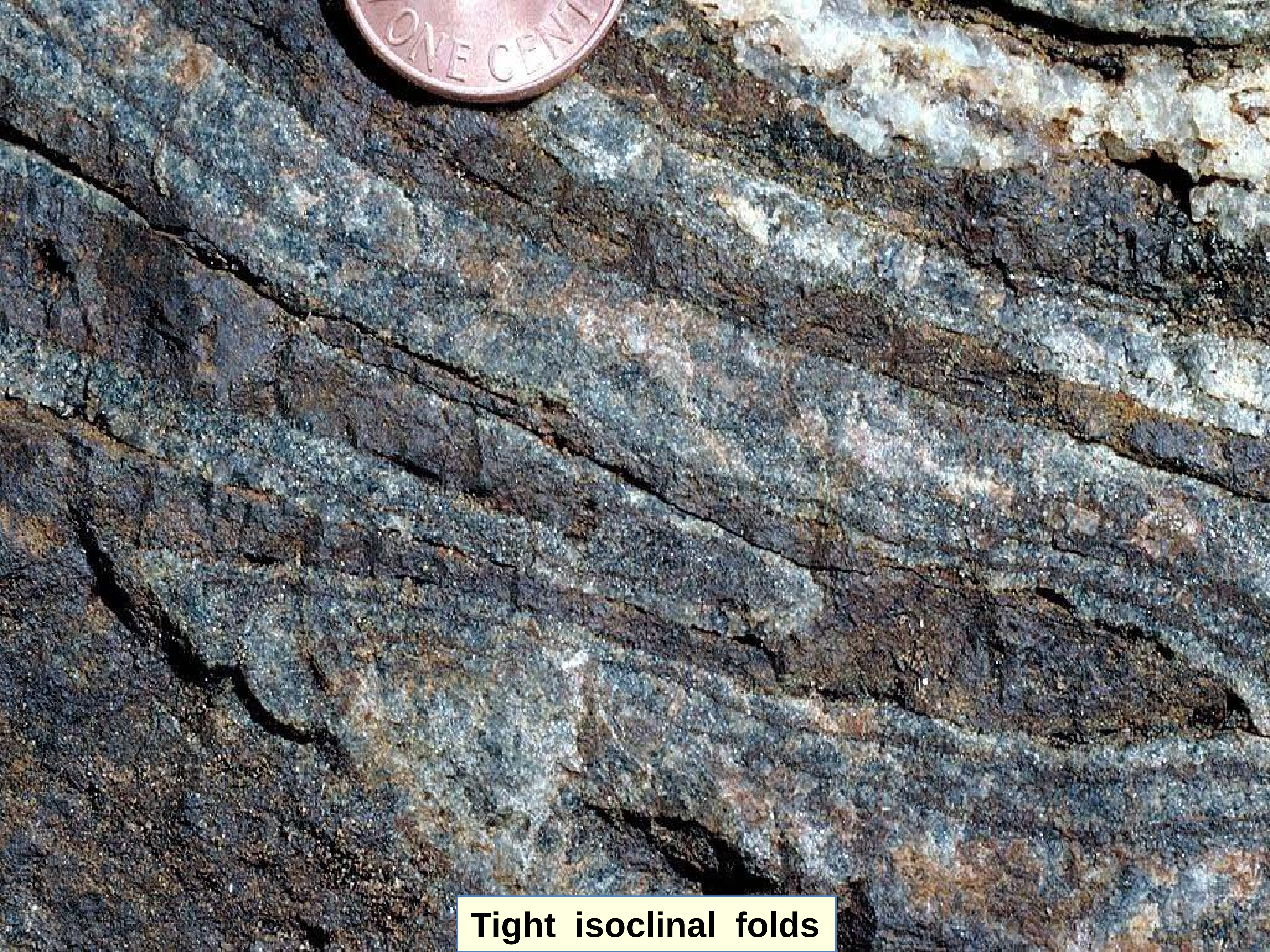
**Tight overturned anticline**



Tight overturned folds affected by a thrust fault

Tight isoclinal anticline

Tight isoclinal folds




**Tight isoclinal folds**

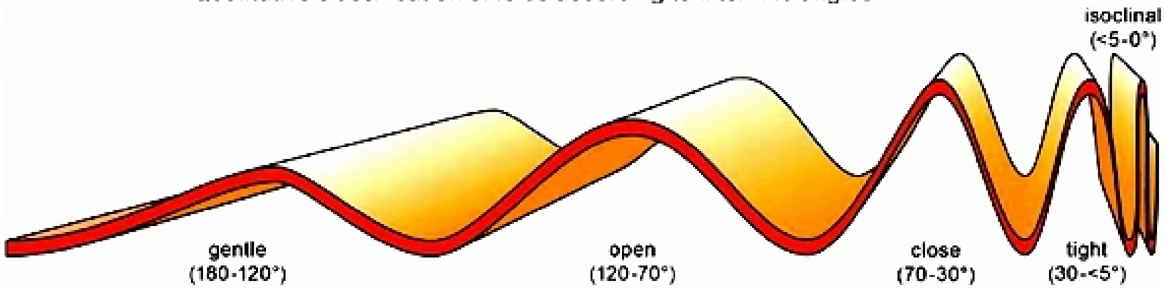

Recumbent Fold affected by a later normal fault in the lower limb

**Recumbent Folds**

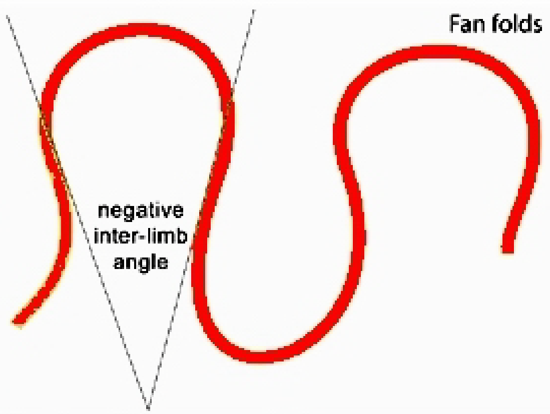
## II- Based on the value of the interlimb angle:

| inter-limb angle | tightness class |
|---|---|
| 180 to ca. 120° | Gentle |
| 120 -- 70° | Open |
| 70 -- 30° | Close |
| less than 30° | Tight |
| 0°, i.e. parallel limbs | Isoclinal |
| < 0° | Fan |

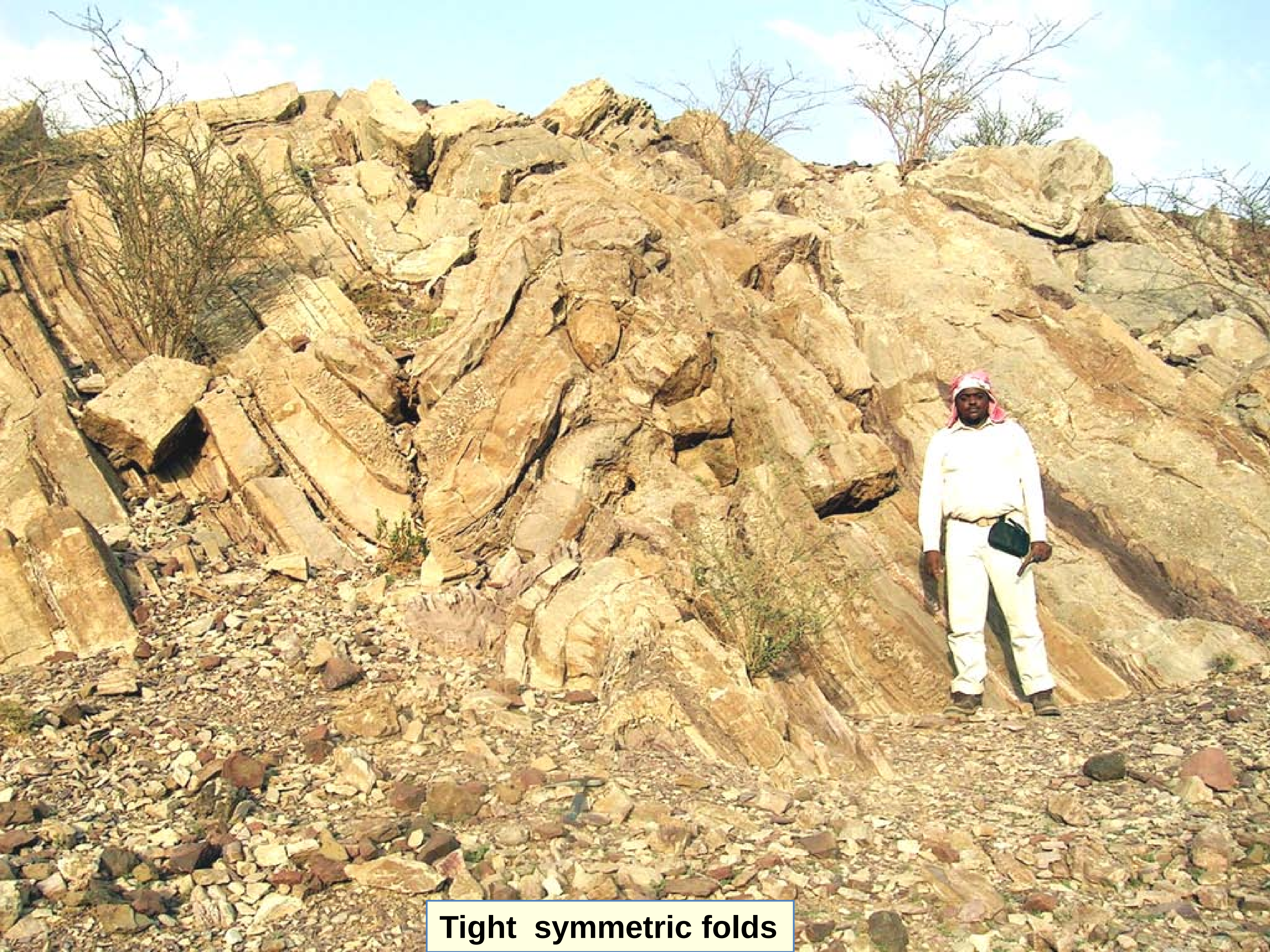
Qualitative classification of folds according to interlimb angles




**Fan folds** have negative interlimb angles.

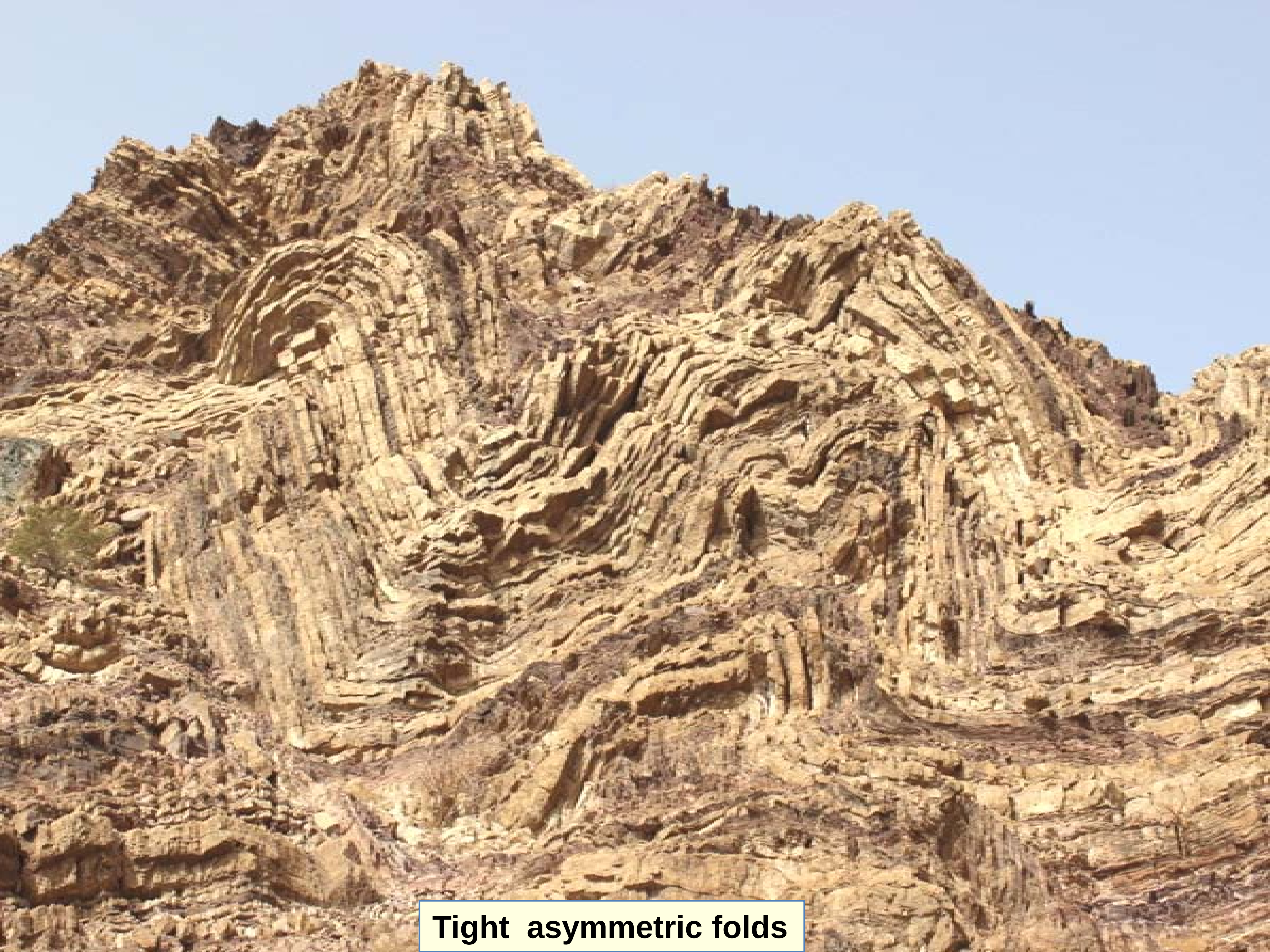


Open asymmetric anticline



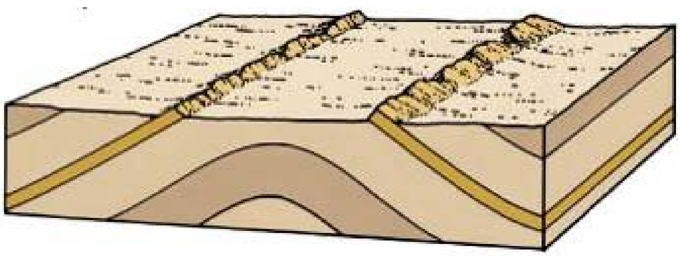
Tight symmetric folds

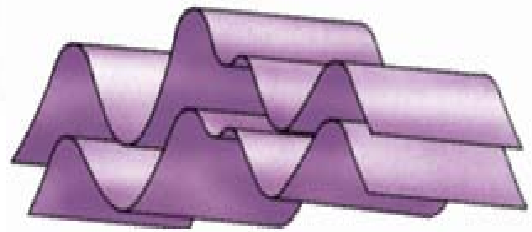
Tight asymmetric folds



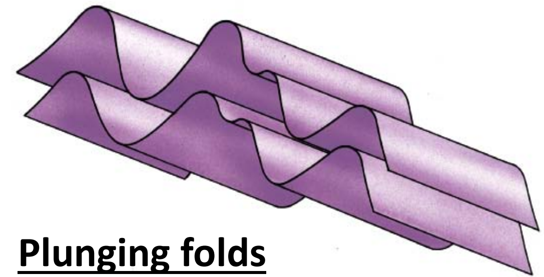
Tight asymmetric folds

## III- Based on the inclination of the fold axis:

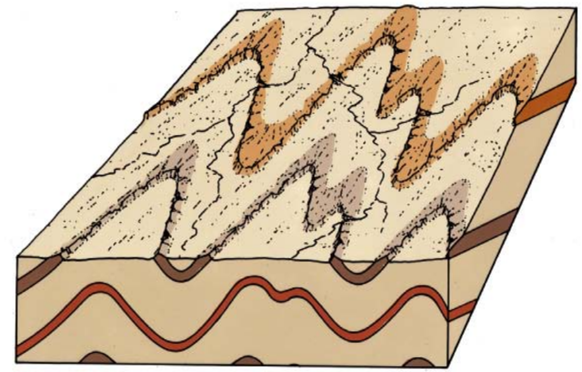




**Non-plunging anticline**



**Plunging folds**



**1- Non-plunging folds** have horizontal fold axes. The fold axis is defined by its trend from the north direction.

**2- Plunging folds** have inclined folding axes. The fold axis is defined by its trend from the north direction and its inclination (angle of plunge).

**The angle of plunge** of a line is the angle between that line and a horizontal line measured in a vertical plane.

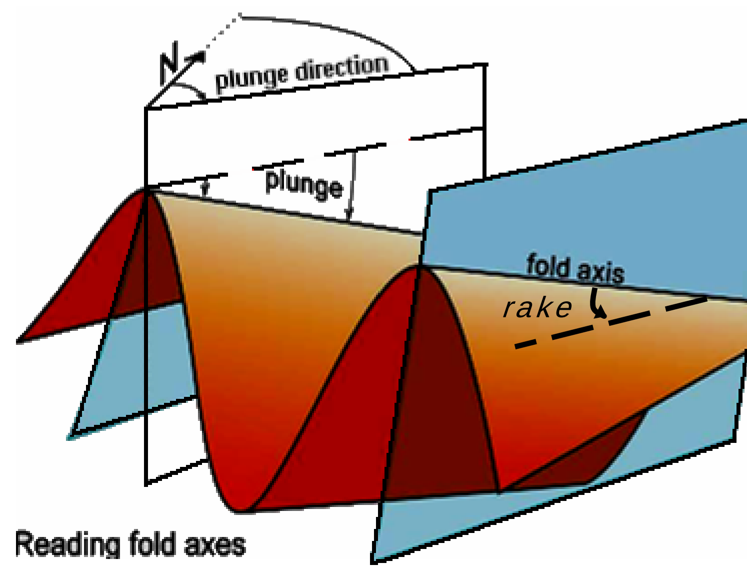
**The angle of pitch (rake)** of a line is the angle between that line and a horizontal line measured in a plane not vertical.

**The map view of folded beds is characterized by:**

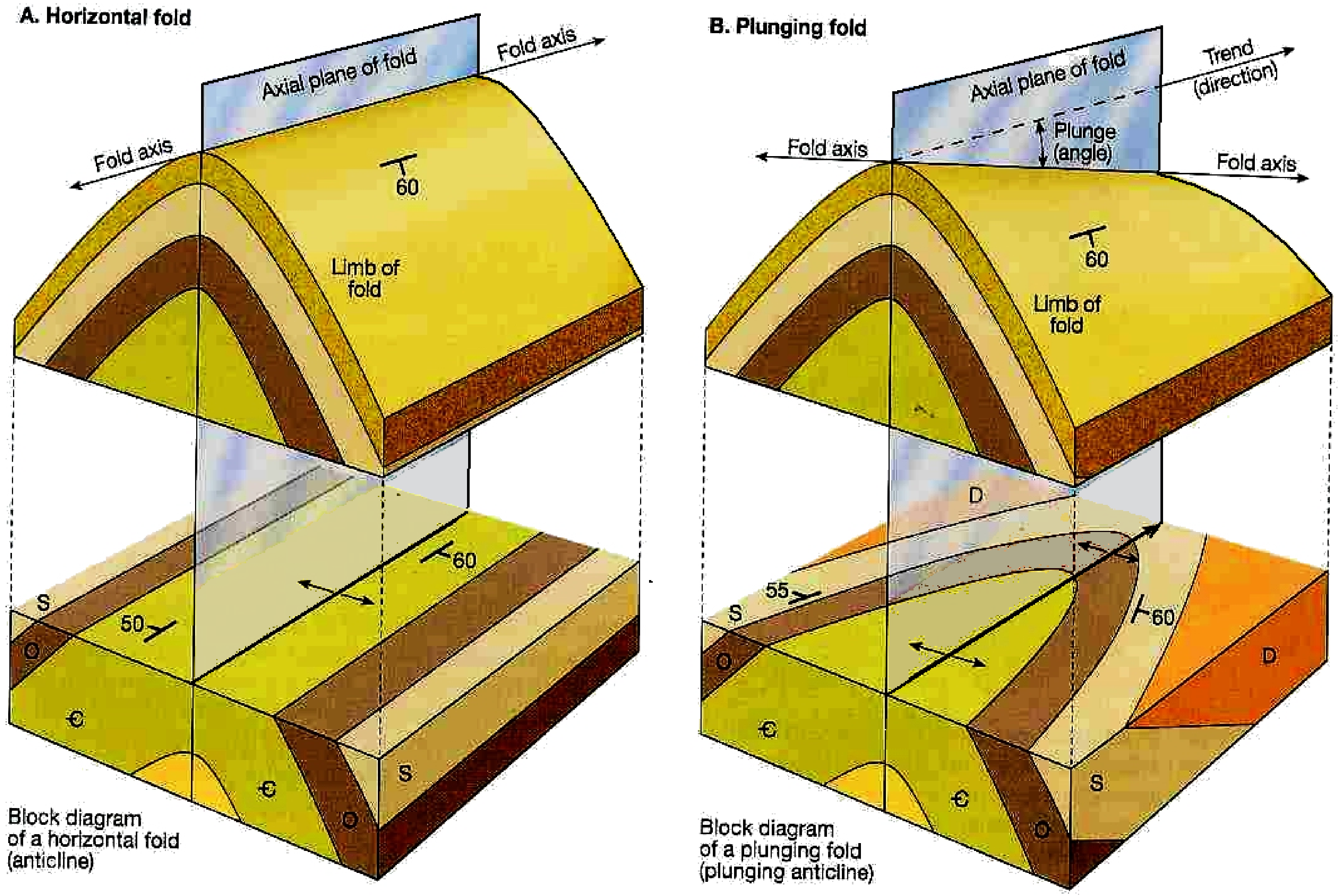
a- Repetition of beds around a common core.

b- Inversion of the direction of dip across a common core (except in case of overturned and isoclinal folds).

c- The presence of fold closures in plunging folds.



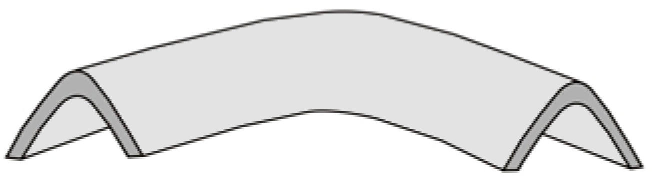

Reading fold axes



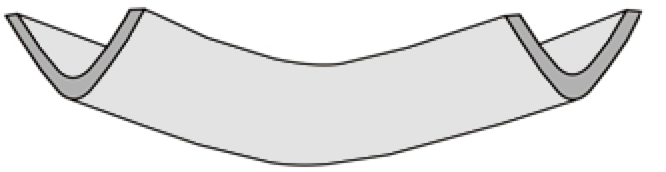

**Map view of non-plunging and plunging folds**

**3- Double Plunging folds:**

The fold axis is plunging in two opposite directions.



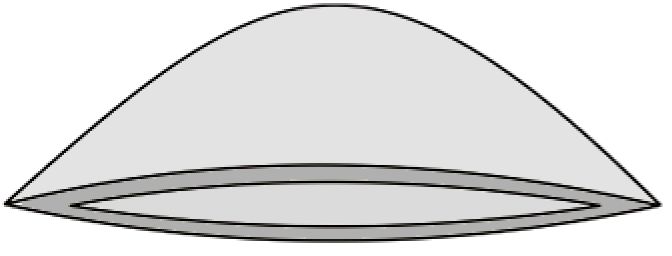
**Double plunging anticline**



**Double plunging syncline**

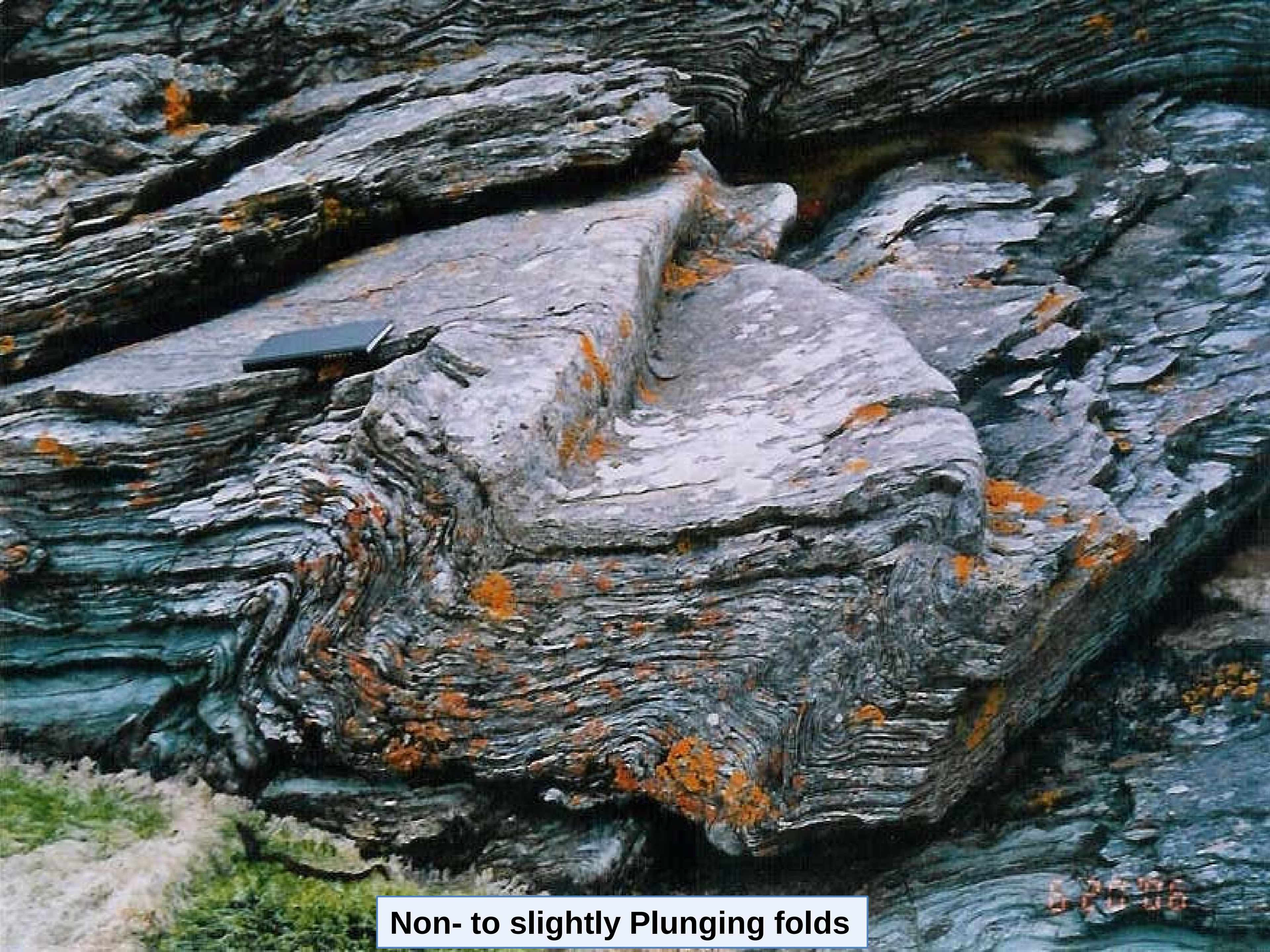
**4- Domes and basins:**

There is no definite direction for the fold axis. The fold axis can be considered plunging in all directions.



**Dome**

**Basin**



**Non- to slightly Plunging folds**

Plunging folds

Double plunging anticline

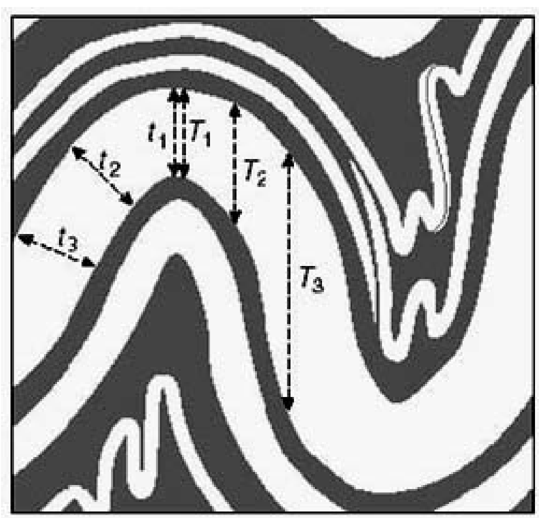
# IV- Based on the change in shape along the axial plane:

**1- Parallel folds**: characterized by:

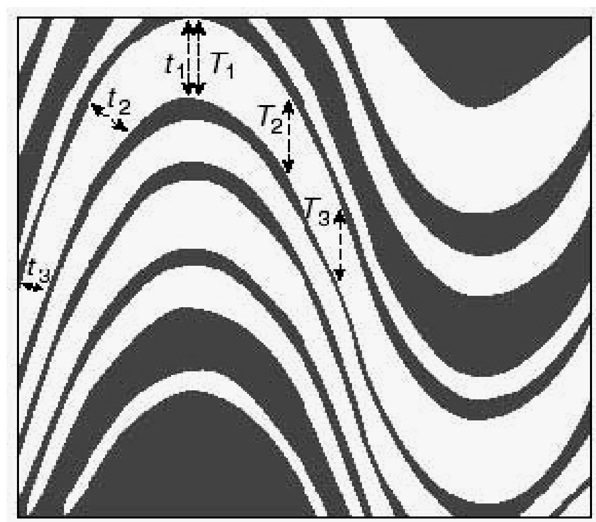
- Constant true thickness ($t_1$,$t_2$,$t_3$).
- Variable axial plane thickness ($T_1$,$T_2$, $T_3$).
  Maximum value at limbs.

**2- Similar folds:** characterized by:

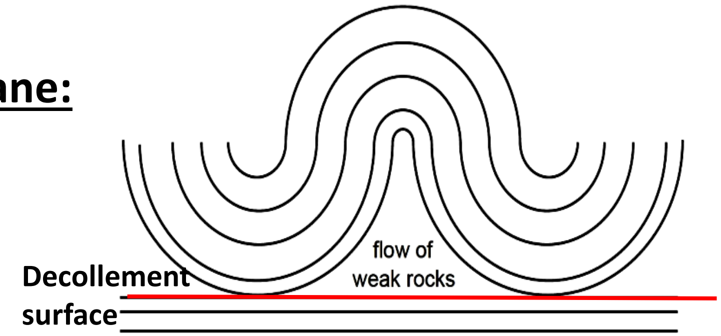
- Variable true thickness ($t_1$,$t_2$,$t_3$).
  Thick at crest and thin at limbs.
- Constant axial plane thickness ($T_1$,$T_2$, $T_3$).



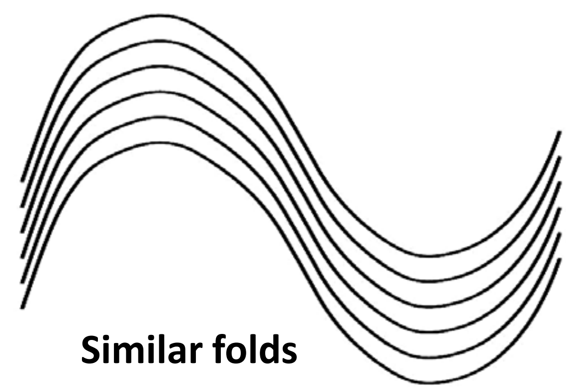

**Parallel folds**




**Similar folds**



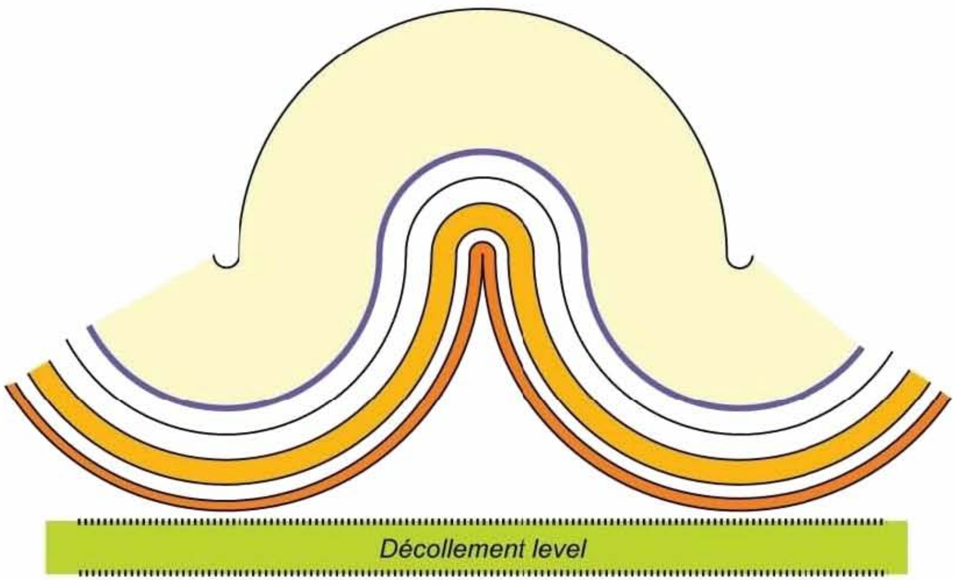

**Concentric folds:** all folded layers have the same center of curvature.
It needs the flow of material along a decollment surface at lower part of the fold to respond for space problem



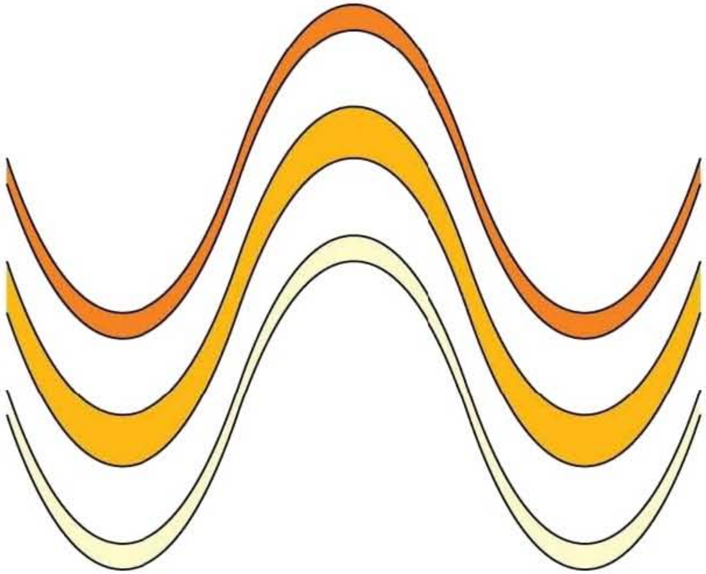
**Similar folds**

# Notice the effect of layer thickness on fold geometry

**ideal parallel**




**ideal similar**



**Parallel folds**

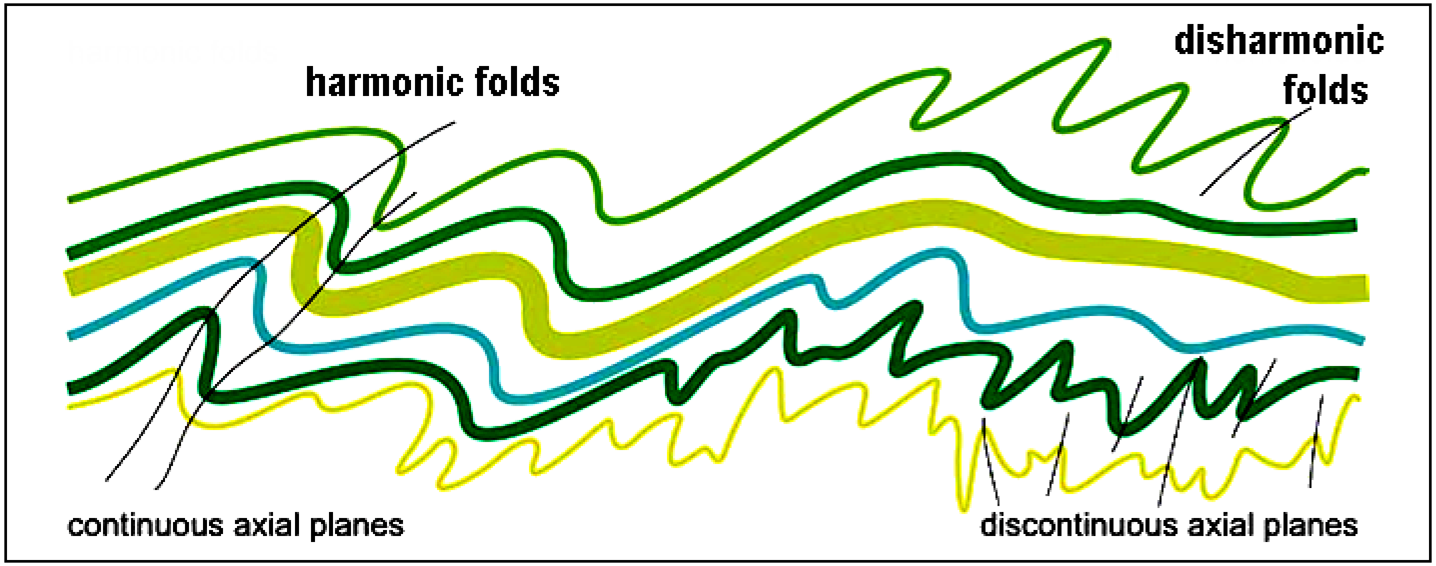
**Similar folds**

# Parallel folds

**Parallel folds**

**Similar folds**

## 3- Harmonic and disharmonic folds:

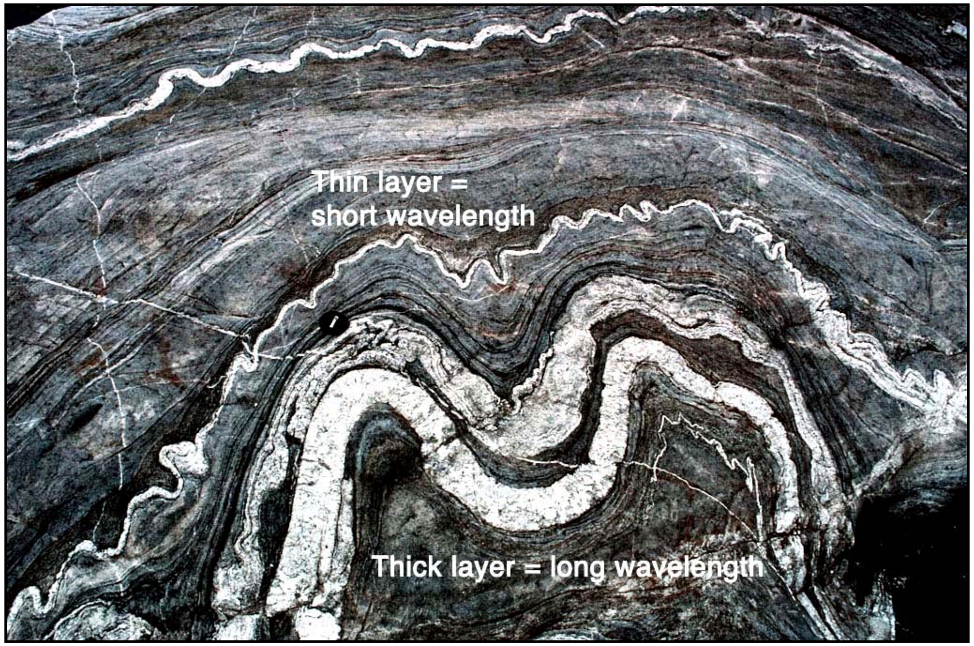



**Harmonic folds:** in which the axial planes of folds can be traced in successive layers.

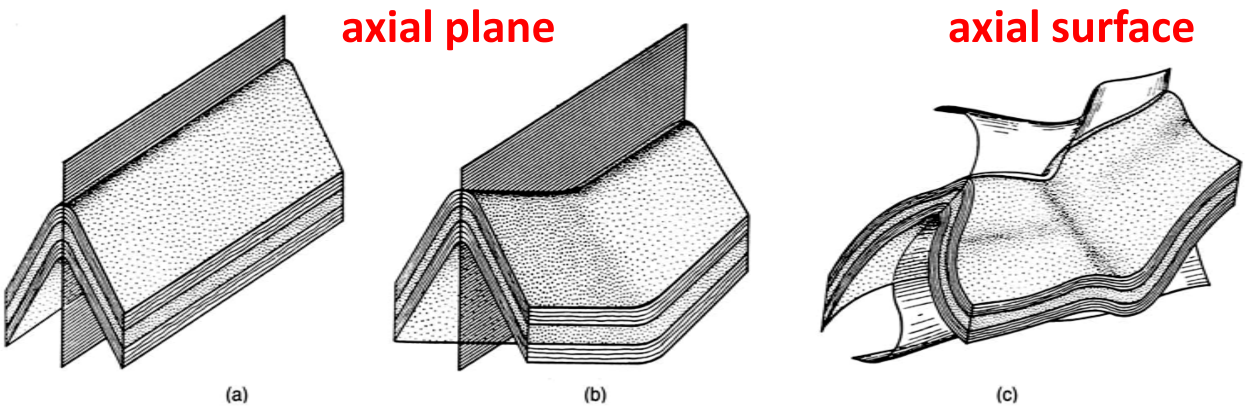
**disharmonic folds:** in which the axial planes are not continuous in successive layers.

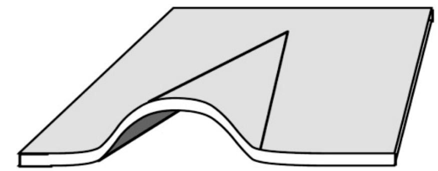
**Notice the effect of layer thickness on the wave length of folds. Thinner beds have smaller folds (smaller wave length).**

It is common to observe that geometrical characteristics change within the same fold from layer to layer.



## V- Based on the fold geometry:



**Conical**

**Developed at fold termination**

**Cylindrical** **Non-cylindrical**

1- **Cylindrical folds:** in which the geometry of the fold can be considered as a part of a cylinder. In this case the axial plane is a perfect plane, and the fold axis when moved parallel to itself will draw the folded surface. The fold axis has an almost constant orientation along the folded surface.

2- **Non-cylindrical folds:** in which the geometry of the fold does not follow the cylindrical geometry. The axial plane could be a perfect plane or a surface. The fold axis has a **variable orientation** along the folded surface.

3- **Conical folds:** the fold has the geometry of a cone. Most folds end at their terminals as conical folds.

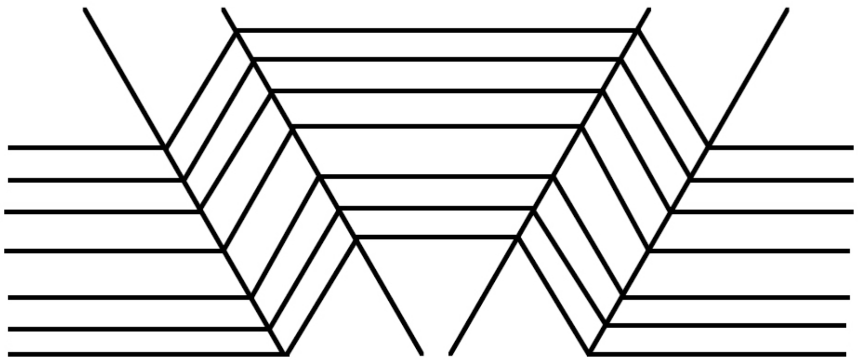

Cylindrical fold
Non-Cylindrical fold

## VI- Other fold types:

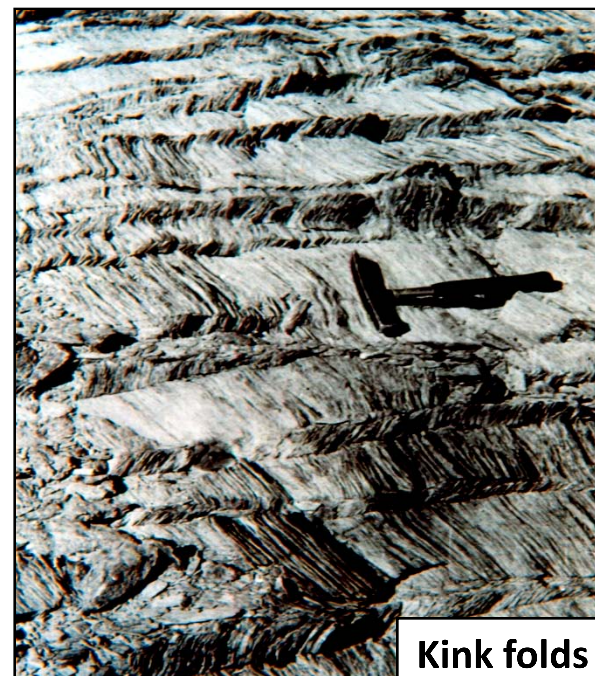
1- **Cheveron or angular folds:** are folds of sharp angular crests and troughs.

2- **Kinking or Kink folds:** Small (typical cm-scale) angular folds with straight hinges. kinks are only formed in metamorphic rocks as minor kinks of foliation.

3- **Box folds:** the fold has the shape of box. They represent conjugate kinks.



Chevern folds



Kink folds

Box folds

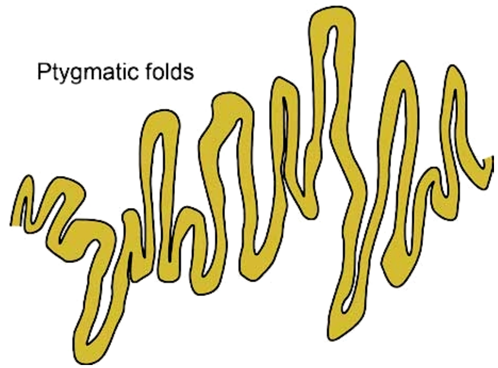
**Chevron folding**

**Chevron folding**


Box Folds


**kink Folds**

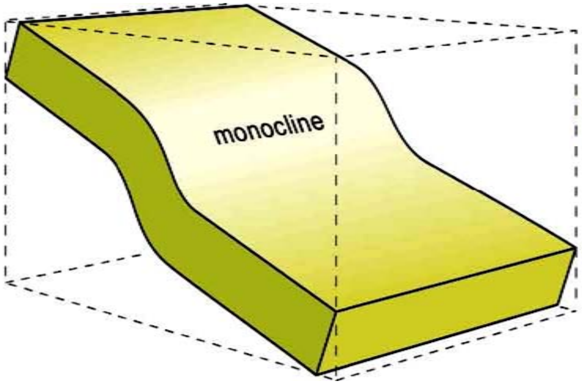
4- **<u>Ptygmatic folds</u>** are irregular lobate minor folds in thin bands (few millimeters thick) consisting of quartz and feldspars. In most cases, the surrounding rocks are not folded in the same style. In such case, these folds are primary in origin, formed during the injection of molten quartz and feldspar material; consequently, it should not be included in structural analysis.

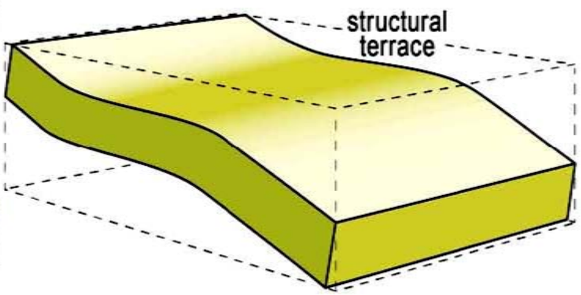


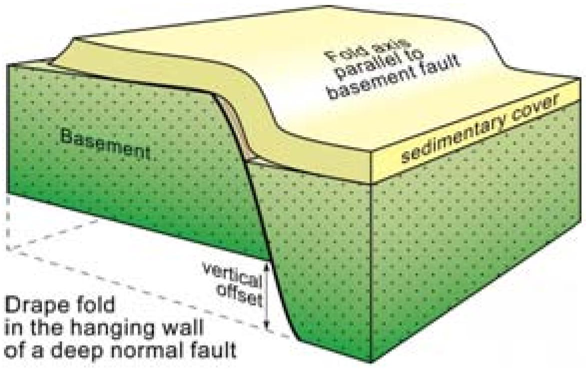

5- **<u>Monocline:</u>** is an abrupt change in the dip of horizontal beds. It s a step-like fold in rock strata consisting of a zone of steeper dip within a horizontal or gently-dipping sequence.

6- **<u>Structural terraces</u>:** represent beds inclined in one direction that become more or less flat or horizontal at one place.

**Both monoclines and structural terraces are formed due to the effect of subsurface faulting on the overlying ductile layers.**



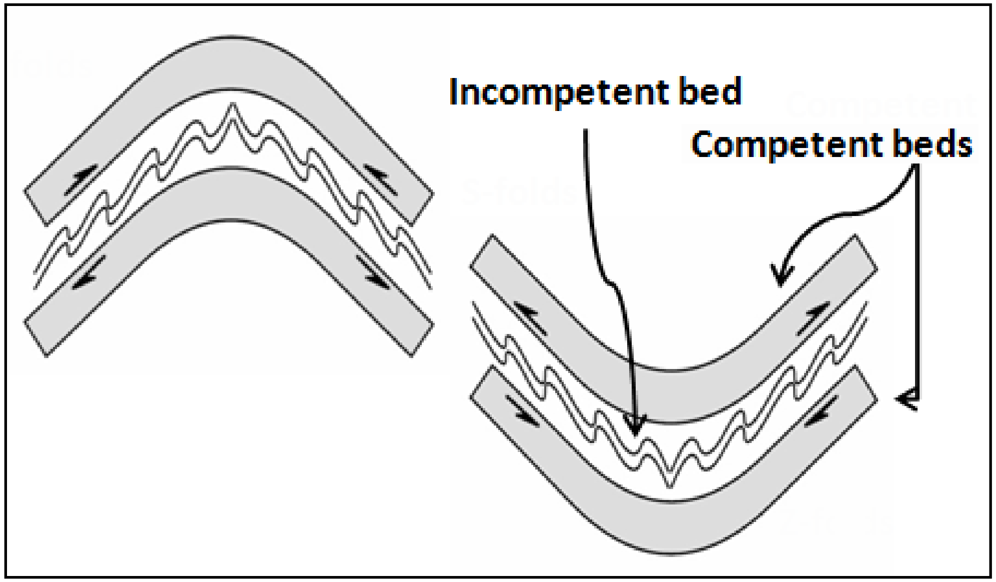



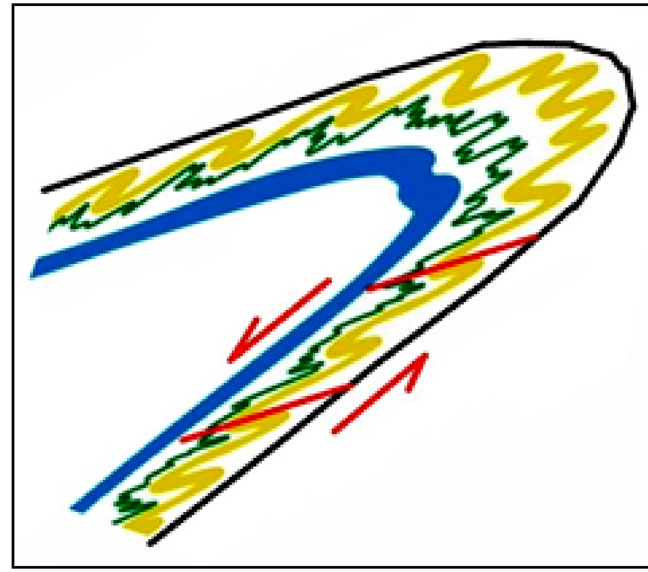



Ptygmatic Folds


Monocline

## 7- <u>Parasitic folds (Drag folds)</u>

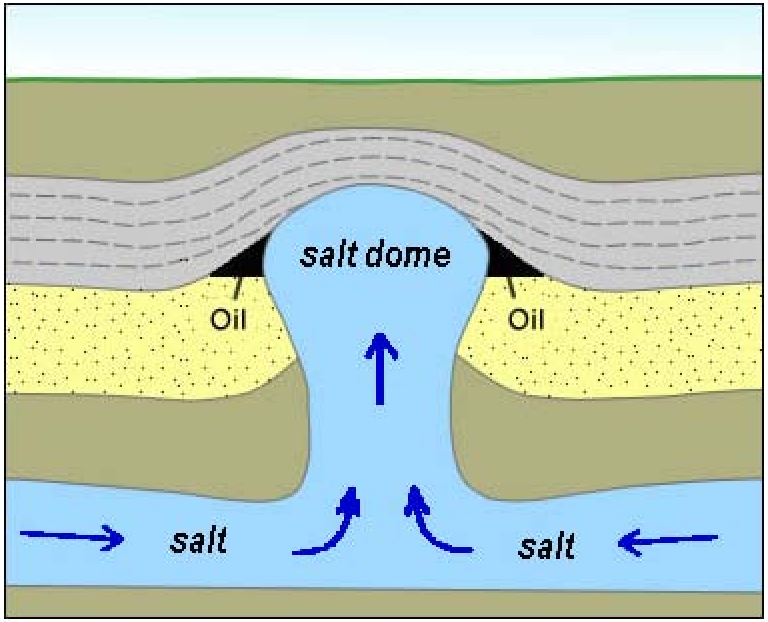


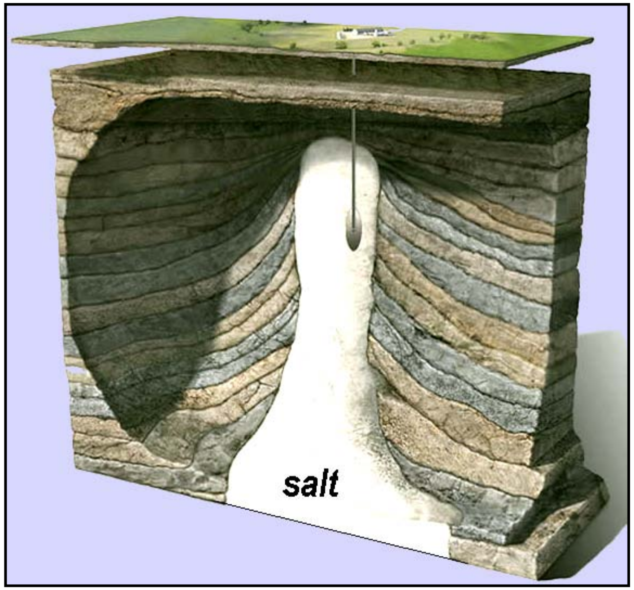



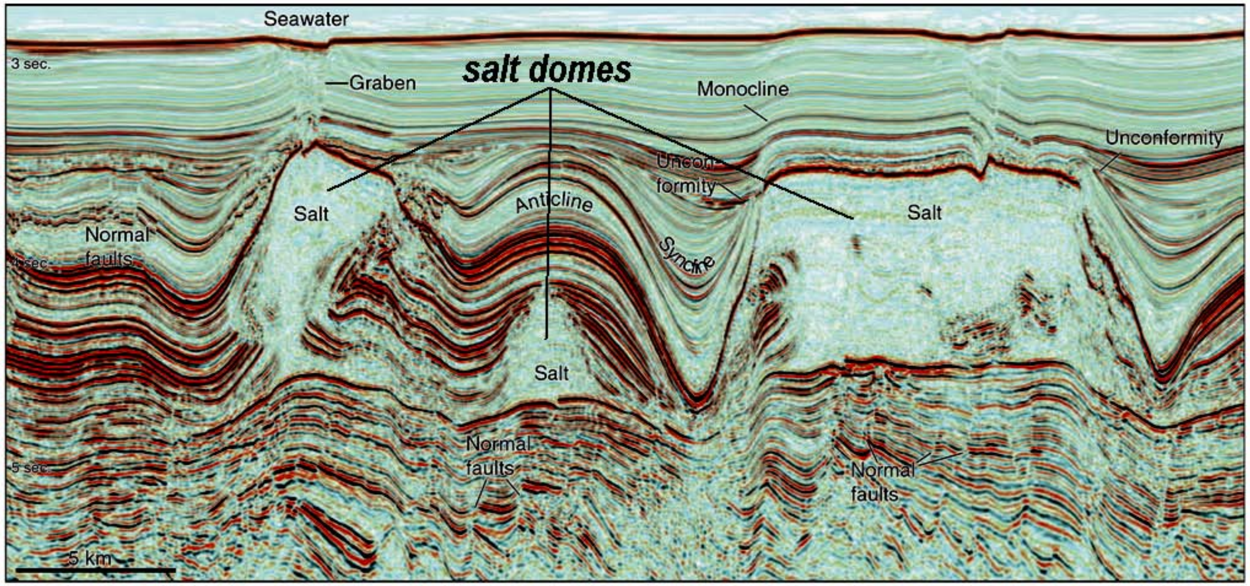
- **They are minor folds developed in an incompetent (ductile) layer surrounded by competent (hard) layers due to slip along the upper and lower surfaces during folding or any other reason such as slip of dipping beds over each other.**
- **The axes of drag folds have the same orientation as the major folds and can be used as a key to major folds.**
- **They indicate the direction of slip along the upper and lower surfaces.**
- **The direction of slip along the same surface is reversed across the hinge of the major fold.**
- **The direction of slip along the upper surface <u>points upward and towards the anticlinal axis</u>.**
- **Notice that in upright major folds the direction of slip along the upper surface is always pointing <u>upward</u>.**
- **<u>When slip along the upper surface points downward, this indicates that the beds are overturned and the major fold is an overturned fold.</u>**

**8- <u>Diapir folds (piercing folds):</u>**

- A diapir fold is a domal structure that is formed when a mass of ductile rock has flowed ductilely upward and pierced (penetrated) discordantly the overburden beds.
- Salt and shale are rocks that commonly tend to flow upward and form diapir folds.
- Diapir folds are formed due to the overburden load and the lower specific gravity of the piercing material than the surrounding rocks; accordingly the material tends to flow upward.
- **Salt dome** is a term used when the rock involved in diapirism is salt.
- **Salt domes** are very important structures because they are good traps for **oil accumulation**.

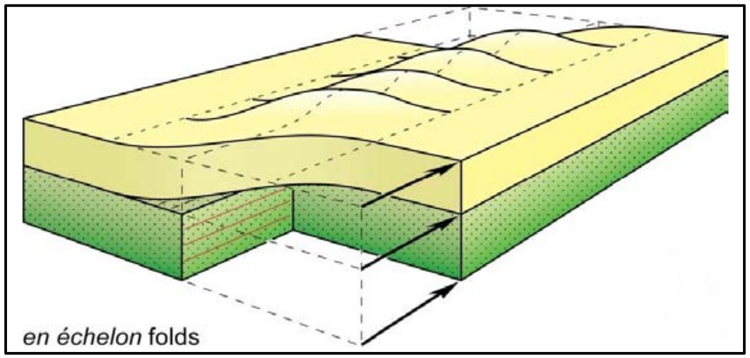


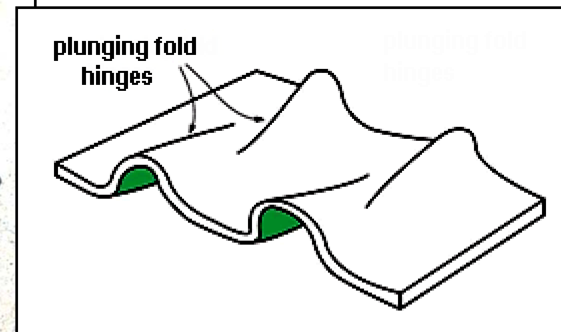



## Fold systems:
## 1- Enechelon folds

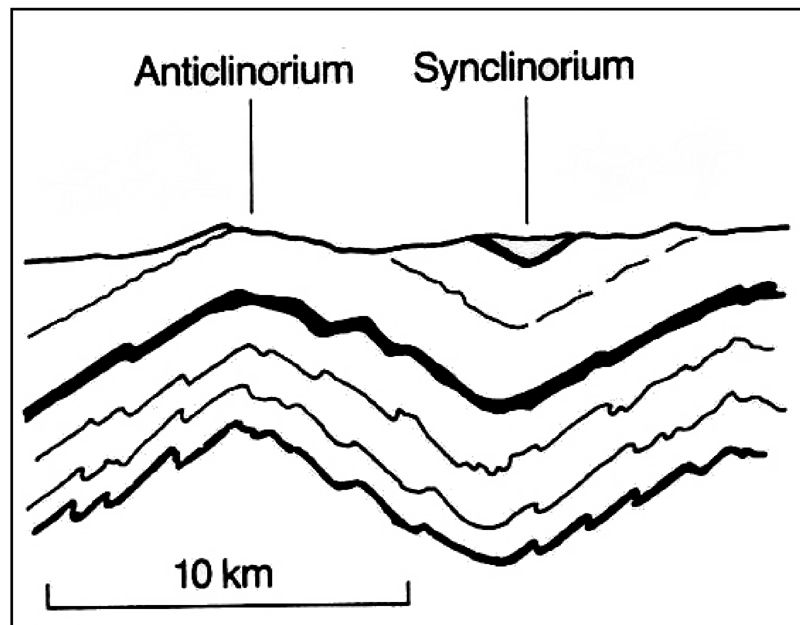
These folds occur at any scale. Each fold is plunging In opposite direction to the previous fold. They are formed in ductile layers by the effect of shear stresses (strike slip movement) affecting the basement below the ductile beds..



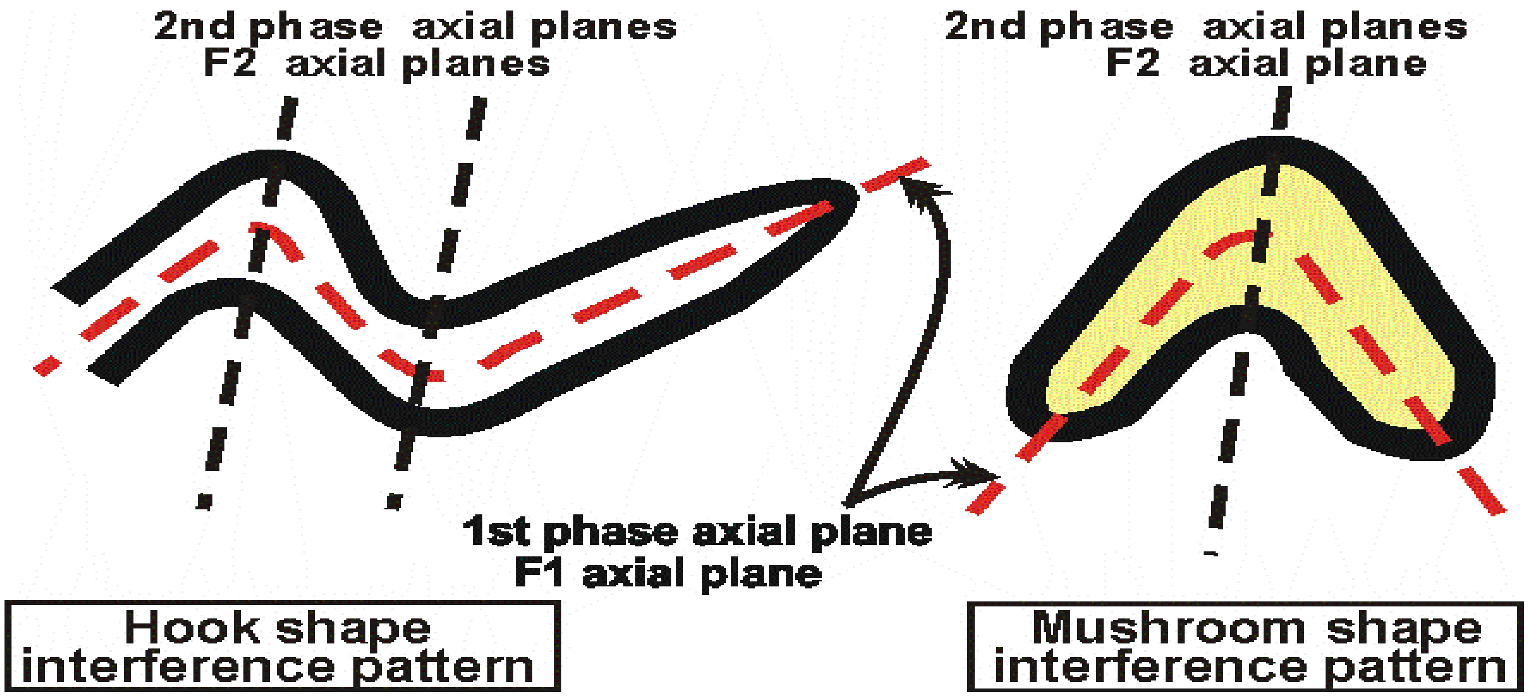

## 2- Anticlinorium and synclinorium:

These are major folds on the regional scale.; each of several kilometers across andconsists of many smaller folds in its limbs. Also the terms **"Anticlise" and "synclise"** are used in the same meaning.

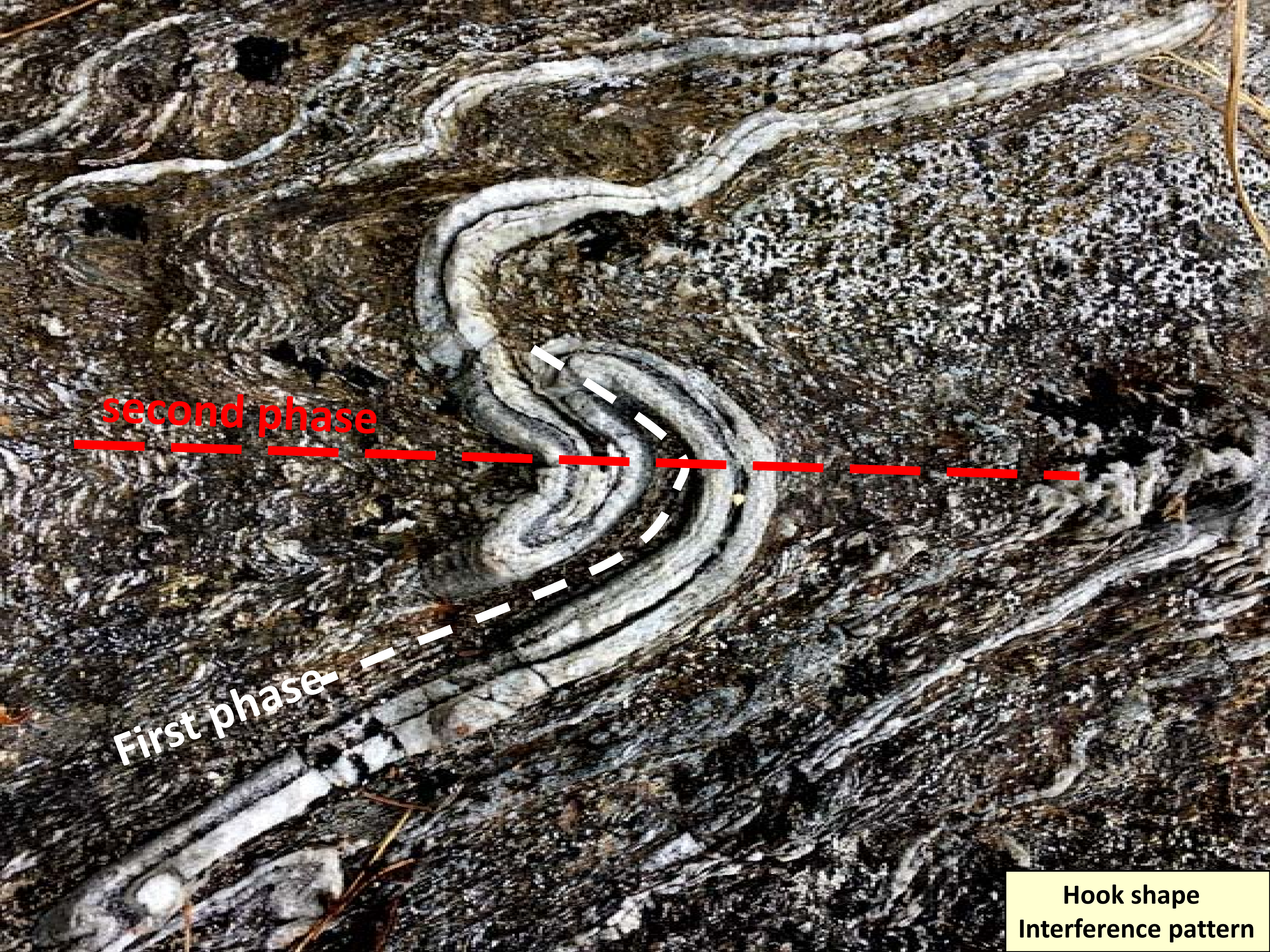


## Refolded folds (superposed folds):

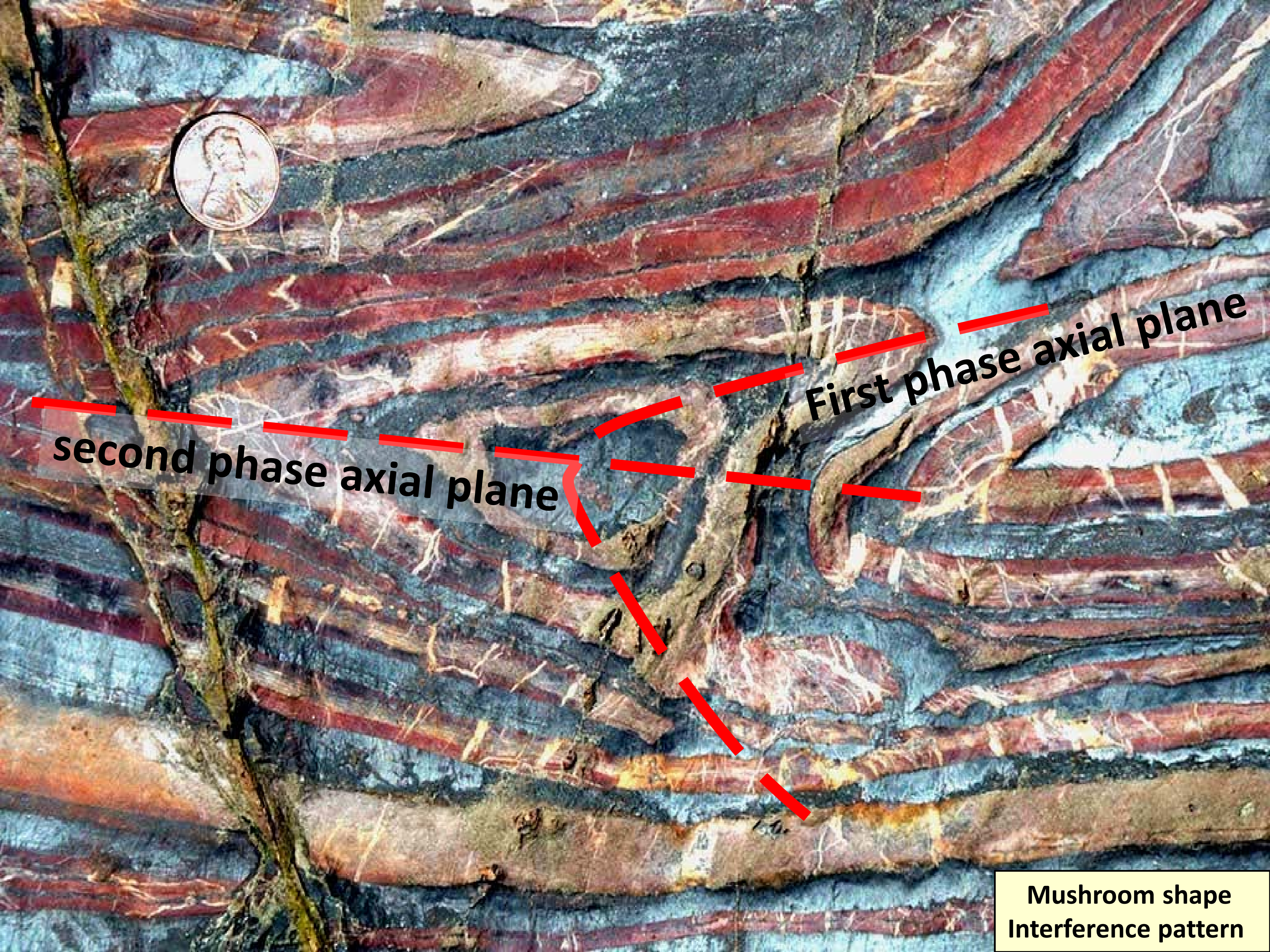
- These are folds formed by the effect of more than one phase of deformation.
- The resulted folds have shapes and geometry different from simple folds.
- The resulted shapes of folding are termed the **"Interference patterns",** as they are formed due to the interference of successive deformations.
- There are many different shapes of interference patterns. The resulted pattern is based on the relation between the orientation of the axes of folding in the successive phases. As examples are the "**hook**" and "**mushroom**" types.



Hook shape
Interference pattern


second phase
First phase
Hook shape
Interference pattern


Mushroom shape
Interference pattern


First phase axial plane
second phase axial plane
Mushroom shape
Interference pattern

## Causes of Folding

Folding of rocks may be caused by numerous factors or causes, which may be divided into two main types:

**1. Tectonic causes:** These are causes which are produced due to the forces operating within the Earth's crust, such as lateral compression caused by geotectonic processes

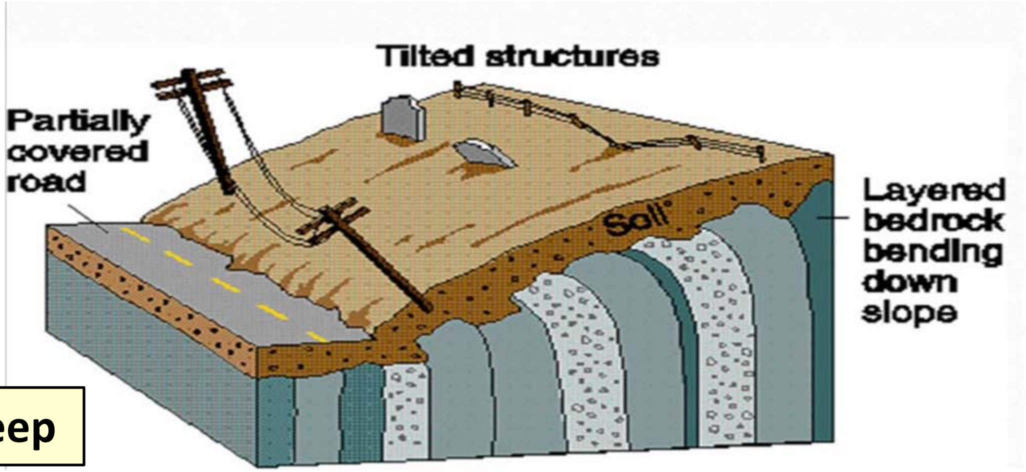
**2. None-Tectonic causes of folding:** These include all folding processes which are occurring over the ground surface, resulting, mainly due to the influence of gravitational force, such as

a) Land sliding: rapid sliding of rock material down slope.

b) Creeping (a gradual movement of rock and debris down a slope (a slow deformation of rocks and minerals in response to prolonged stress).

c) Differential compaction of sediments.

d) Subsidence into solution cavities.




Soil creep

Land sliding

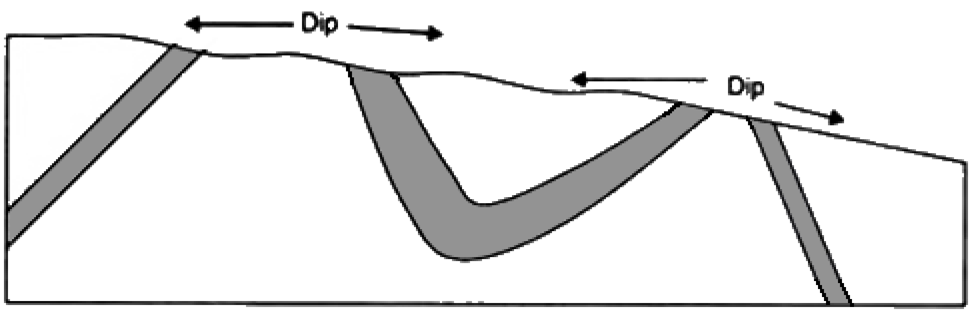
**Soil creep**

**Soil creep**

## Recognition of Folds in the Field:

**In recognition of folds the following factors are important:**

1. The **repetition** of outcrops of beds suggests the presence of a fold.
2. If folding is symmetric or asymmetric, the **reversal of dip** direction is enough to identify folds (as in the figure below). In anticlines the oldest bed will occupy the core of the fold, and in synclines the youngest bed will occur there.
3. In plunging fold as a rule give rise to curved outcrops the apex of which is called a '**closure**'.
4. In case of **overturned and isoclinal folds**, where all the limbs dip in the same direction, detailed observations about **overturned bedding** are necessary to identify folding. The features which aid in finding out the stratigraphic top of a bed are drag folds, rock cleavage (foliation), cross-bedding, graded bedding and symmetrical ripple marks.




*Repetition of outcrop notes the reversal of dip direction*

## Engineering Considerations of Folds

1. In major projects (e.g. dams, tunnels, railway stations, etc.), highly folded sites should be **avoided** because folds are easily fractured even due to a slight disturbance. The engineer may have to face much troubles sooner or later.
2. If the project is of a scattered nature like electric or telephonic poles the work can be carried out without much of a risk.
3. Folds are also important to a water supply engineer specially when he has to select a suitable site for digging wells for water supply purpose. It has been observed that if the excavation of a well is done through impervious (impermeable) strata it will not yield any amount of water. If another well is excavated through previous strata it will yield abundance of water. Fractured fold crests are good sites.
4. Synclinal folded rocks may yield hard and tough quality stones; whereas anticlinal folded rocks will yield weaker stones.
5. The anticlinal folds provide good traps for stored petroleum, and hence in oil exploration, folds must be taken in consideration.

N.B.:

Some of the figures and photos used in this lecture are used after previous literatures for the purpose of teaching for students.