STRUCTURAL GEOLOGY

KP Classes

Contents

Chapter 1: Structural Geology Basics

- Especially in the early stages of an investigation of the geology of an area, much attention is paid to determining and recording the location and orientation of various structural elements.
- Planes are the most common of these. They are also a useful starting point in the introduction to the geometrical methods of structural geology.

1.1: Definitions

Plane: a flat surface; it has the property that a line joining any two points lies wholly on its surface. Two intersecting lines define a plane.

Attitude: the general term for the orientation of a plane or line in space, usually related to geographical coordinates and the horizontal. Both trend and inclination are components of attitude.

Trend: the direction of a horizontal line specified by its bearing or azimuth.

Bearing: the horizontal angle measured east or west from true north or south.

Azimuth: the horizontal angle measured clockwise from true north.

Strike: the trend of a horizontal line on an inclined plane. It is marked by the line of intersection with a horizontal plane.

Structural bearing: the horizontal angle measured from the strike direction to the line of interest.

Inclination: the vertical angle, usually measured downward, from the horizontal to a sloping plane or line.

Cross section: representation of a geometry on a plane perpendicular to the earth's surface.

True dip: the inclination of the steepest line on a plane; it is measured perpendicular to the strike direction.

Apparent dip: the inclination of an oblique line on a plane; it is always less than true dip.

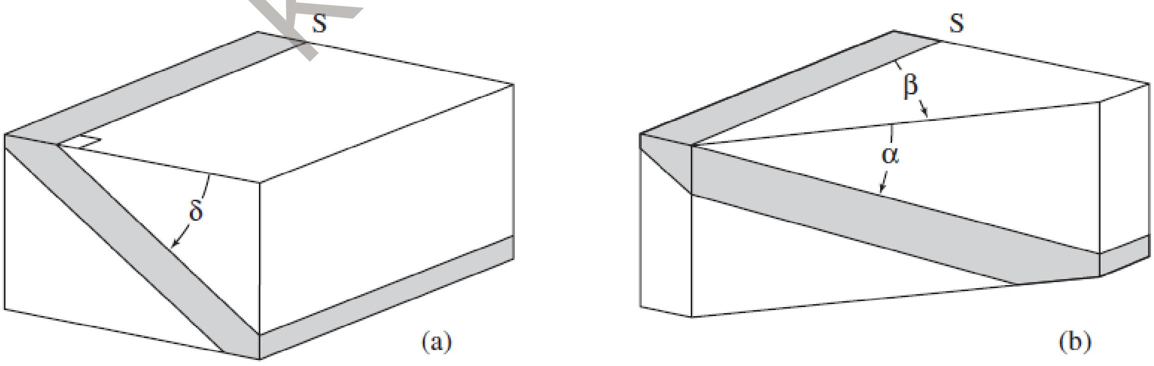


Figure: Strike *S*, true dip δ (delta), apparent dip α (alpha) and structural bearing β (beta).

Thickness: the perpendicular distance between the parallel planes bounding a tabular body, as displayed on any section perpendicular to these planes; also called the true or stratigraphic thickness.

Apparent thickness: the distance between the bounding planes measured in some other direction, for example, the perpendicular distance between the traces of the bounding planes on an oblique section, or in some other specified direction, as in a drill hole. It is always greater than true thickness.

Outcrop width: the strike-normal distance between the traces of the parallel bounding planes measured at the earth's surface. It may be measured horizontally or on an incline.

Depth: the vertical distance from a specified level (commonly the earth's surface) downward to a point, line or plane.

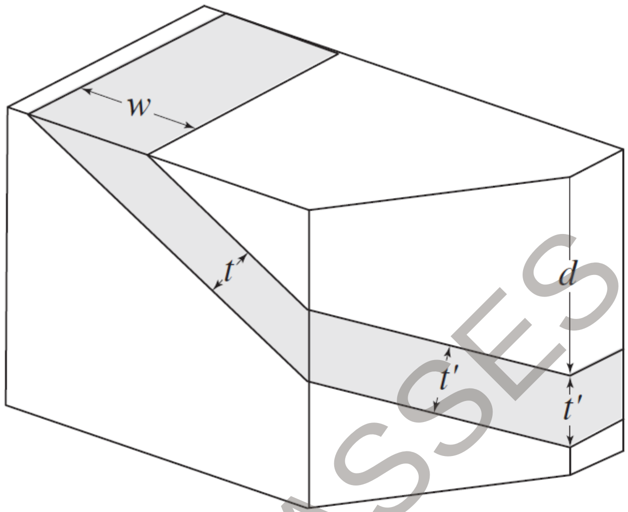


Figure: True thickness *t*, apparent thickness *t'*, outcrop *w* width *w* and depth *d*.

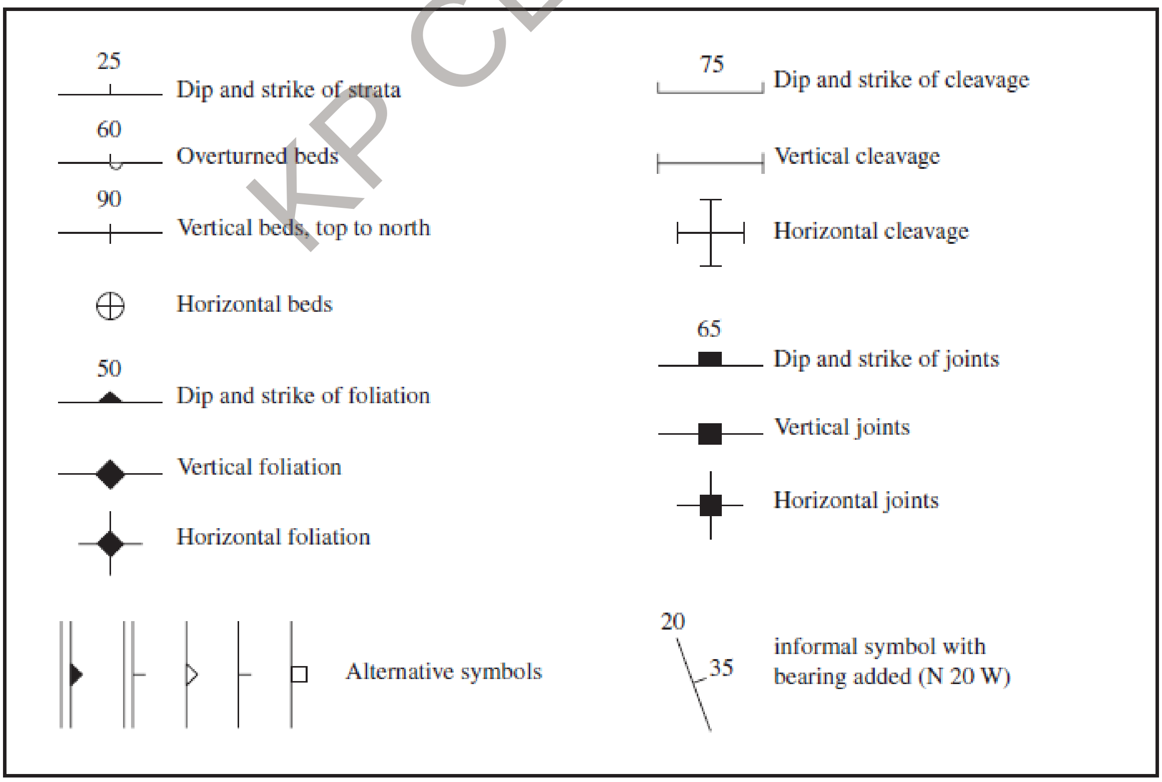


Figure: Map symbols for structural planes.

Line: the geometrical element generated by a moving point; it has only extension along the path of the point. Lines may be rectilinear (straight) or curvilinear (curved). Only straight lines are treated here.

Plunge: the vertical angle measured downward from the horizontal to a line (Fig. a).

Pitch: the angle between the strike direction and a line in a specified plane (Fig. b). Rake is synonymous.

Trend: the horizontal direction of the vertical plane containing the line, specified by its bearing or azimuth.

Rake: angle measured between a line and the strike of the plane that contains the line.

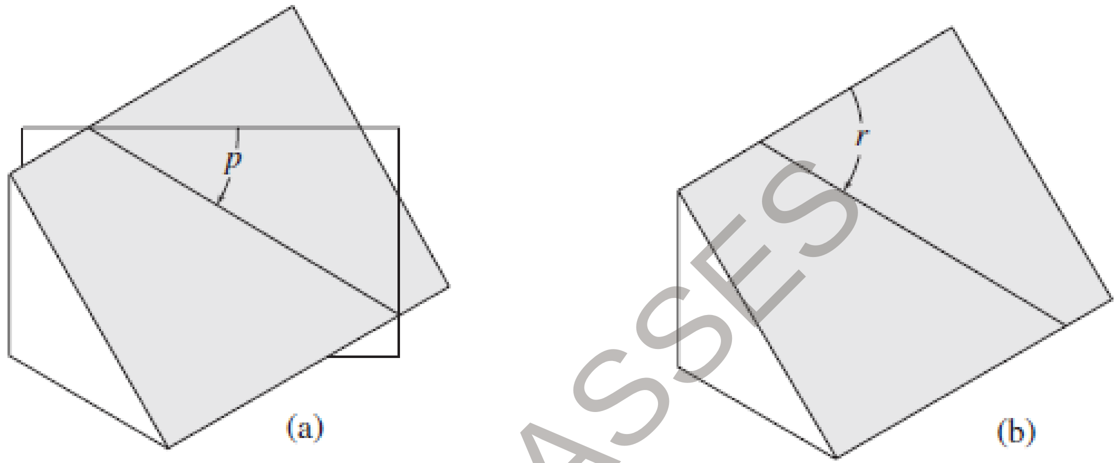


Figure: Inclination of a line: (a) plunge *p*; (b) pitch *r*.

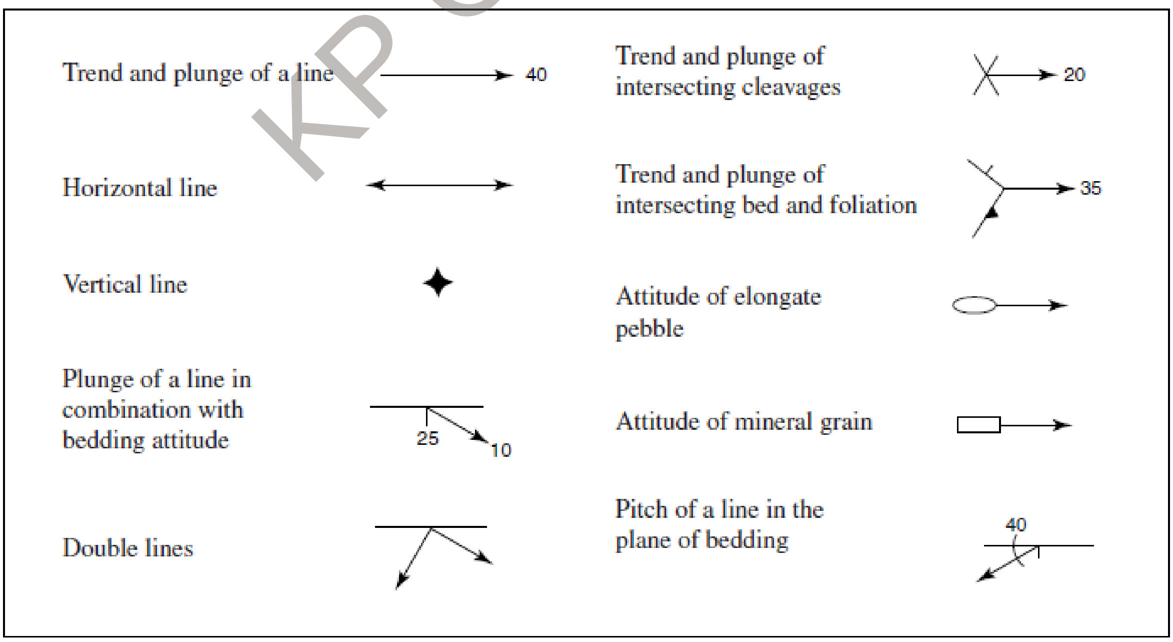
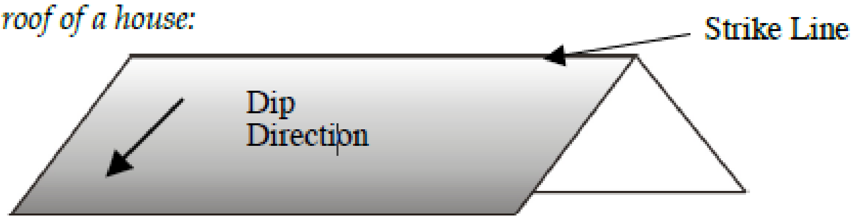


Figure: Map symbols for structural lines.

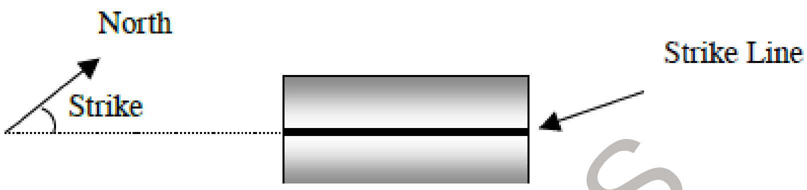
1.1.1: Strike & Dip

- Strike and dip describe the orientation of a plane in space.

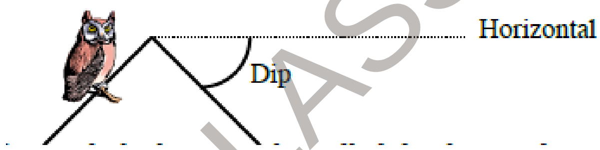
Example: the peaked roof of a house:



- Strike is the orientation of the intersection line of the plane in question (roof of a house) with the horizontal plane.
- If you were to look down on the house from directly above, it would look like this:



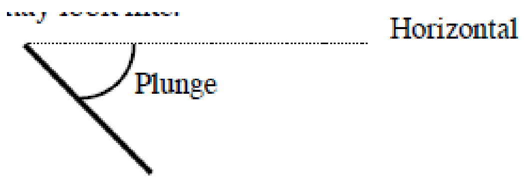
- The angle between the strike line and north is used to describe the strike. In this example the strike is, in essence, the direction the house is facing.
- If you look at the front of the house, it looks like this:



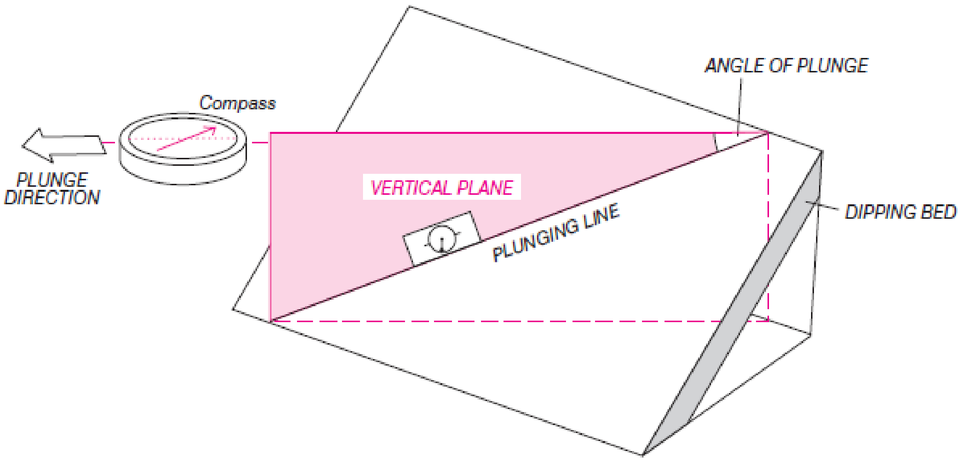
- The angle that the roof makes with the horizontal is called the dip. In this example the dip is, in essence, the steepness of the roof.

1.1.2: Trend & Plunge

- In structural geology, the orientations of linear features are also important. The orientation of lines in space can be described using two distinct angles referred to as the trend and plunge.
- To measure the trend and plunge of a linear feature, A horizontal line will look like a point. This line has a plunge of 0 degrees. But a line that is not horizontal will look like a line.
- To measure the trend of this line, you simply record the direction that you are facing when the linear feature is viewed dead on. From above, this will look like:

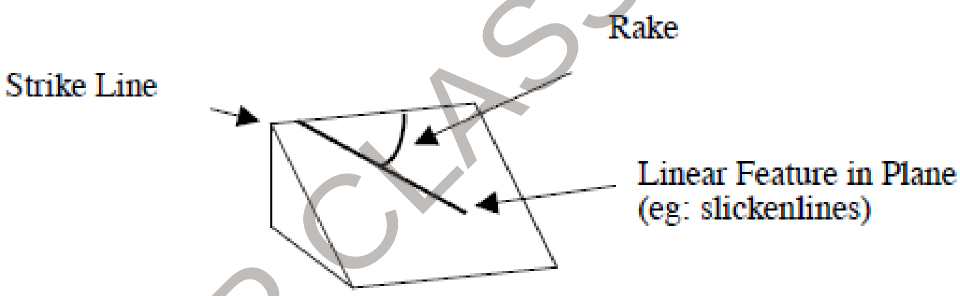


- To measure strike, you took the trend of a horizontal line that you called the strike line.
- To measure the dip, you envisioned a linear feature on the plane -- its dip direction line -- and you measured the plunge of that line.

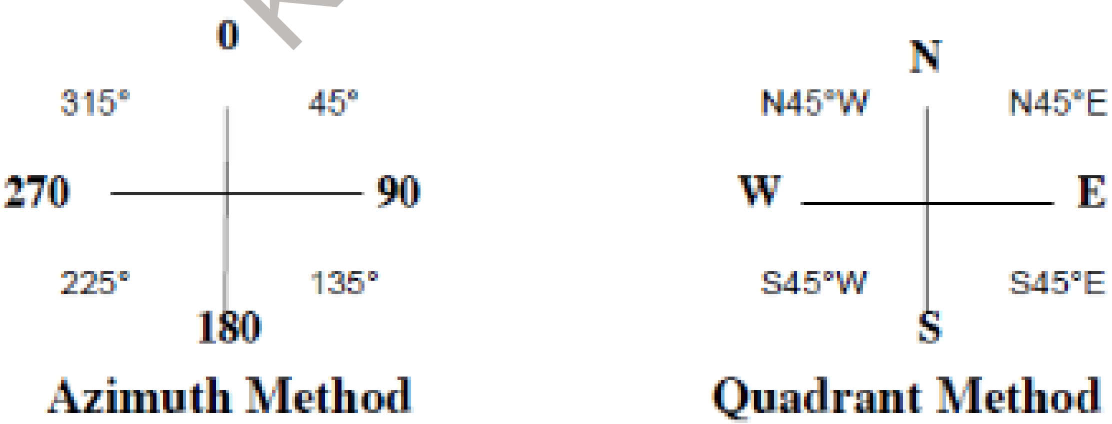


1.1.3: Rake

- Rake is a single angle measurement that, along with the strike and dip of a plane, will give the orientation of linear features that occur in a plane.
- You can measure rake by laying a protractor against the plane and measuring the angle between the strike line and the linear features.
- You can always use trend and plunge to describe the orientation of linear features but rake only describes linear features that exist in a plane.



1.1.4: Ways of Recording Strikes and Trends



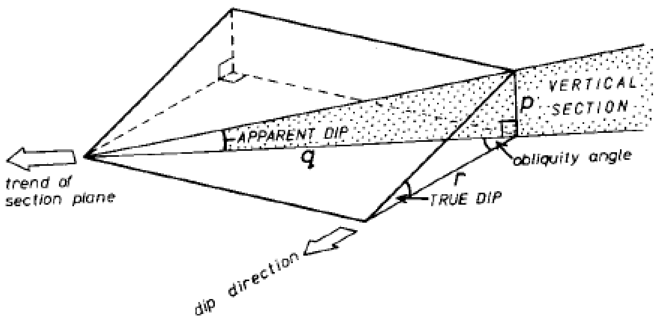
1.1.5: Right Hand (Rule) Convention

- Planes are non-directional; every plane can be properly described by two different strikes. Example:

- For the sake of brevity, we report only one of those numbers. The right-hand convention is one way to establish a consistent recording system.
- When looking along the strike direction that you report, the plane should dip off to your right.
- Point the fingers of your right hand down-dip of the plane you are measuring with your palm down.
- The direction your thumb is pointing is the orientation of the strike you should record.
- The photos below illustrate strike measurements (white dashed lines) on both a hanging wall (right) and a foot wall (left) exposure.

1.1.6: Apparent dip

- At many outcrops where dipping beds are exposed the bedding planes themselves are not visible as surfaces.
- Cliffs, quarries and cuttings may provide more or less vertical outcrop surfaces which make an arbitrary angle with the strike of the beds.
- When such vertical sections are not perpendicular to the strike, the beds will appear to dip at a gentler angle than the true dip. This is an apparent dip.
- The tangent of the angle of apparent dip = p/q,
  The tangent of the angle of true dip = p/r
  The cosine of the obliquity angle = r/q.
  Since it is true that:
  *p/r * r/q = p/q*
  it follows that:
  tan (apparent dip) = *tan* (true dip) * *cos* (obliquity angle)

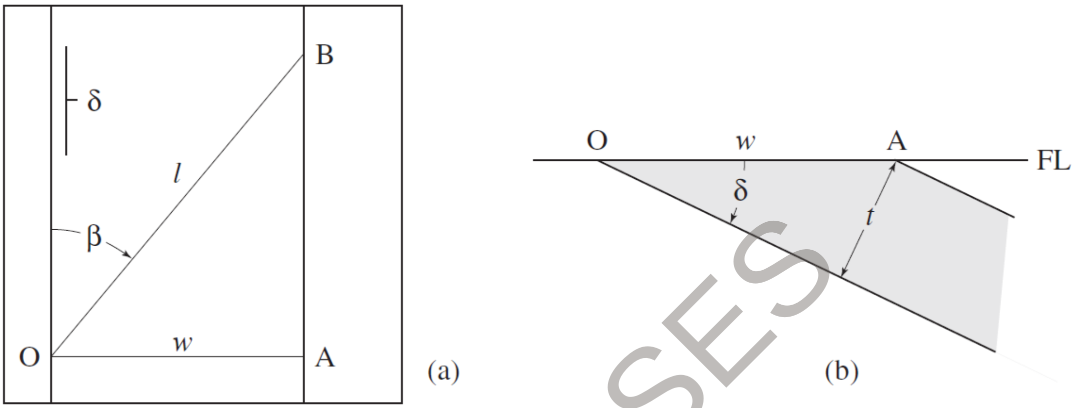


- It is a simple matter to derive an equation which expresses how the size of the angle of apparent dip depends on the true dip and the direction of the vertical plane on which the apparent dip is observed (the section plane).

- In figure the obliquity angle is the angle between the trend of the vertical section plane and the dip direction of the beds.

1.1.7: Measurement of True Thickness

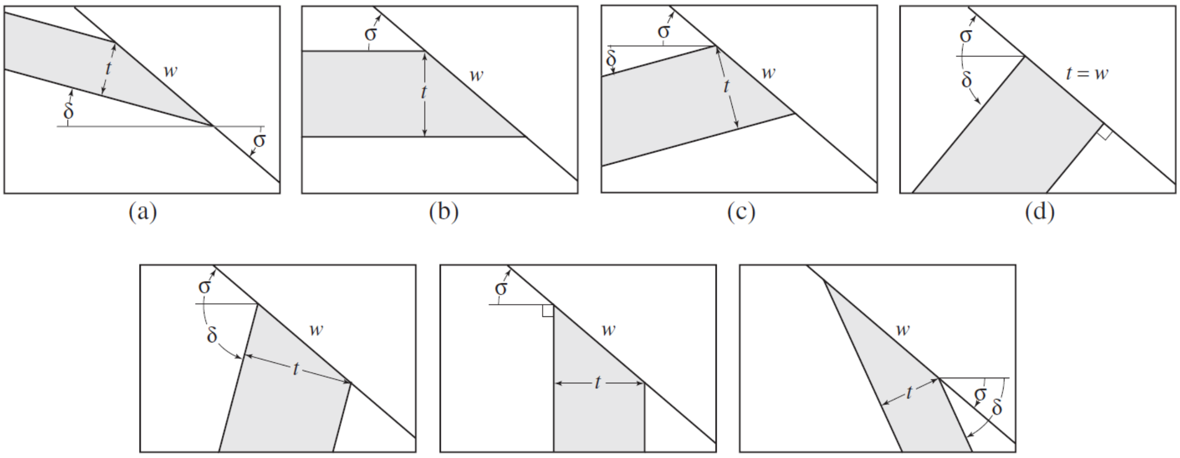
- All the solutions of true thickness require an edge view of the layer, that is, the image of the layer on a plane perpendicular to bedding.
- Of the many such planes one can always be readily found or constructed – it is the vertical plane parallel to the line of true dip.
- The simplest of the indirect approaches is to measure the width of the exposed layer perpendicular to the strike direction on a horizontal plane.



- Two measurements are required: the outcrop width w of the layer and the dip angle δ. Then the thickness t can be determined graphically in either of two ways.
  The thickness may also be calculated from

$$t = w \sin \delta$$

- In the more general case, thickness is determined from measurements made on sloping ground.
- We first consider the case where it is possible to measure the outcrop width directly. There are two alternatives.
  1. Thickness can be determined from the slope distance and slope and dip angles along the measured strike-normal traverse.
  2. It can also be found from the vertical and horizontal distances between the two ends of the traverse if the slope angle is known.



(a) (b) (c) (d)

(e) (f) (g)

- Slope and dip are in the same direction, $\delta < \sigma$ (Fig. a),

$$t = w \sin(\sigma - \delta)$$

- The bed is horizontal, $\delta = 0°$ (Fig. b),

$$t = w \sin \sigma$$

- Slope and dip are in the opposite directions, $(\delta + \sigma) < 90°$ (Fig. c),

$$t = w \sin(\delta + \sigma)$$

- Slope and dip are in the opposite directions, $(\delta + \sigma) = 90°$ (Fig. d),

$$t = w$$

- Slope and dip are in the opposite directions, $(\delta + \sigma) > 90°$ (Fig. e),

$$t = w \sin[180 - (\delta + \sigma)] = w \sin(\delta + \sigma)$$

- The bed is vertical, $\delta = 90°$ (Fig. f),

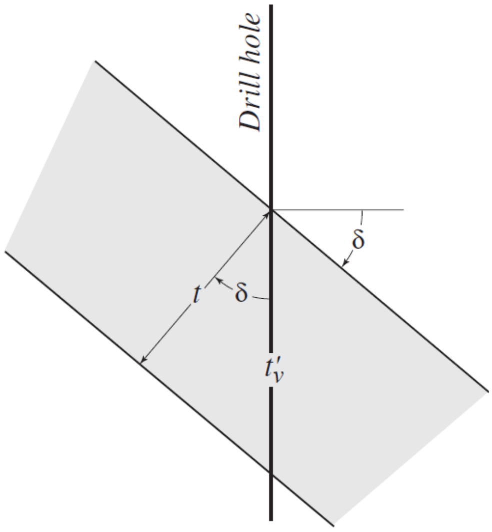
$$t = w \sin(90 - \sigma) = w \sin(90 + \sigma)$$

- Slope and dip are in the same direction, $\delta > \sigma$ (Fig. g),

$$t = w \sin(\delta - \sigma)$$

1.1.8: Thickness in drill holes

- In subsurface exploration by drilling it is important to determine the thickness of strata from measurements made in the drill holes or in recovered cores.



- If the hole is vertical then the determination of the thickness of a layer penetrated by the drill is particularly straightforward.

$$t = t_v \cos \delta$$

- where δ is the dip of the bed and t_v is the apparent thickness as measured in the vertical drill hole.
- Holes which are exactly vertical are difficult to drill, especially if the beds are steeply dipping.
- The measure of the angular departure of a drill hole from vertical is termed drift, measured by the drift angle ψ.
- There are two cases. If the drift is exactly in the down-dip direction (Fig. a),

$$t = t_m \cos (\delta + \psi)$$

- where t_m is the measured apparent thickness in the inclined hole. If the hole is exactly in the *up-dip* direction (Fig. b)

$$t = tm \cos (\delta - \psi)$$

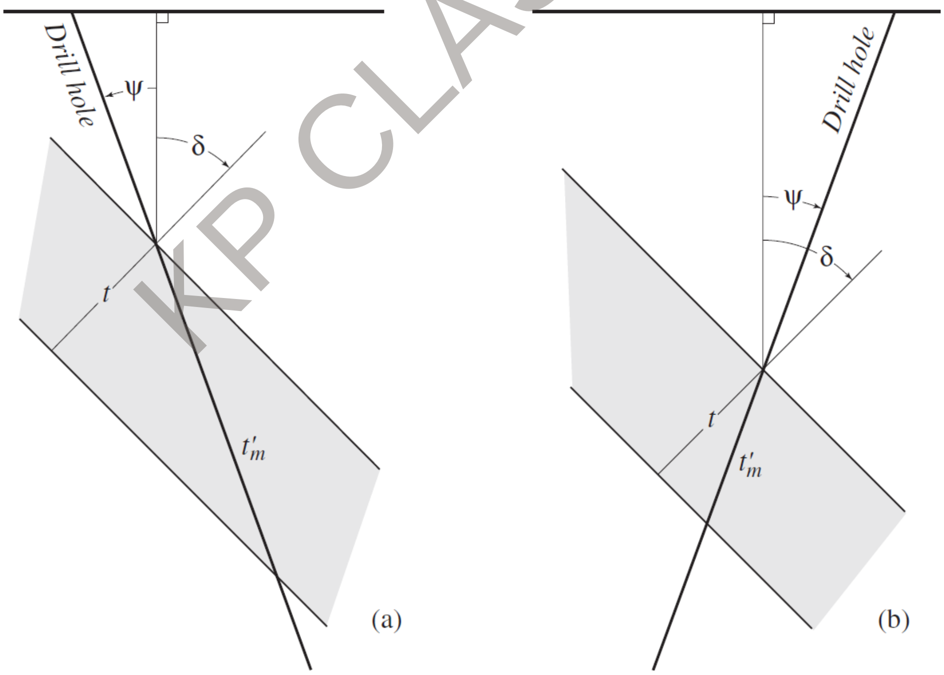


Figure: Thickness in inclined drill hole: (a) down-dip drift; (b) up-dip drift.

1.2: Contours

- A contour is a line that is, at every point, the same height above a reference level, sea level, and horizontal.

- A simple uniform slope would have contours at equally spaced intervals. The steeper the slope, the closer is the spacing of the contours.
- The contours on the steep side will be closer together than those on the less steeply sloping side. A hill, standing alone above the general level, will have concentric contours, seldom perfectly circular in nature.

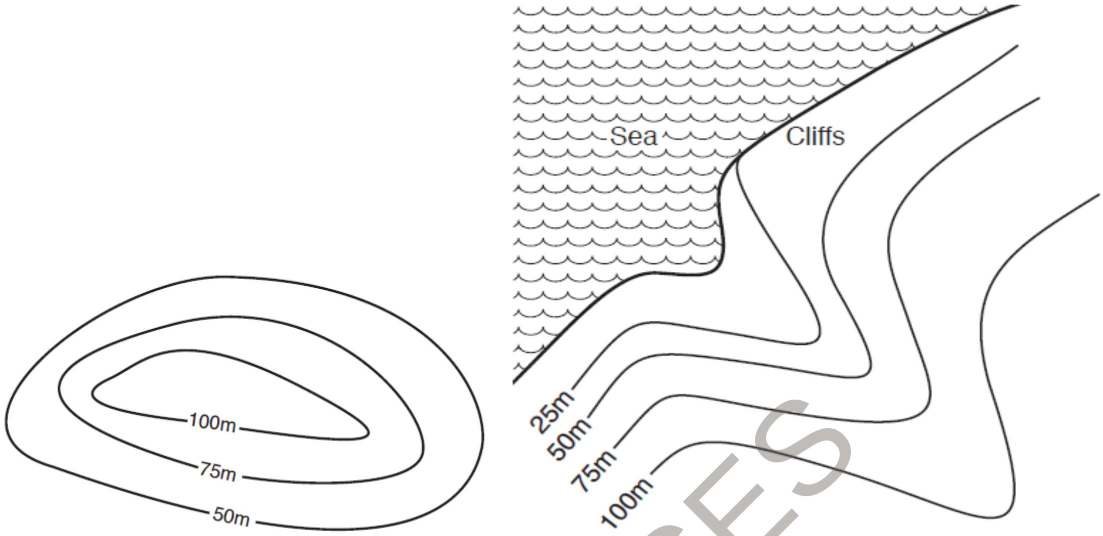


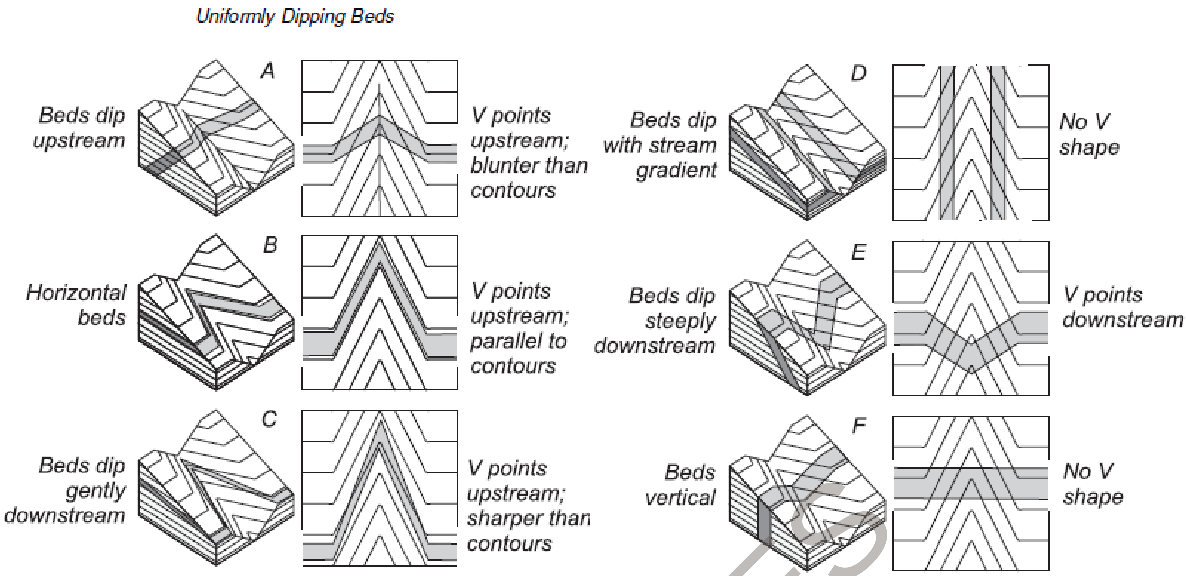
Figure: Left- An isolated hill, Right- A typical river valley

- A typical valley produced by erosion by a stream or river will be V-shaped in section and its contours will be V-shaped.
- Looking at a contour map we can envisage the complete topography of the area of the map.
- Tangent (angle of dip) = contour interval / spacing on map between contours

1.2.1: V-shaped outcrop patterns

- A dipping surface that crops out in a valley or on a ridge will give rise to a V-shaped outcrop (Figure below).
- The way the outcrop patterns vee depends on the dip of the geological surface relative to the topography.
- In the case of valleys, patterns vee upstream or downstream. The rule for determining the dip from the type of vee (the 'V rule') is easily remembered if one considers the intermediate case (Figure D) where the outcrop vees in neither direction.
- This is the situation where the dip is equal to the gradient of the valley bottom.
- As soon as we tilt the beds away from this critical position they will start to exhibit a V-shape.
- If we visualize the bed to be rotated slightly upstream it will start to vee upstream, at first veeing more sharply than the topographic contours defining the valley (Figure C).
- The bed can be tilted still further upstream until it becomes horizontal. Horizontal beds always yield outcrop patterns which parallel the topographic contours and hence, the beds still vee upstream (Figure B).
- If the bed is tilted further again upstream, the beds start to dip upstream and we retain a V-shaped outcrop but now the vee is 'blunter' than the vee exhibited by the topographic contours (Figure A).

- Downstream-pointing vees are produced when the beds dip downstream more steeply than the valley gradient (Figure E).
- Finally, vertical beds have straight outcrop courses and do not vee (Figure F).



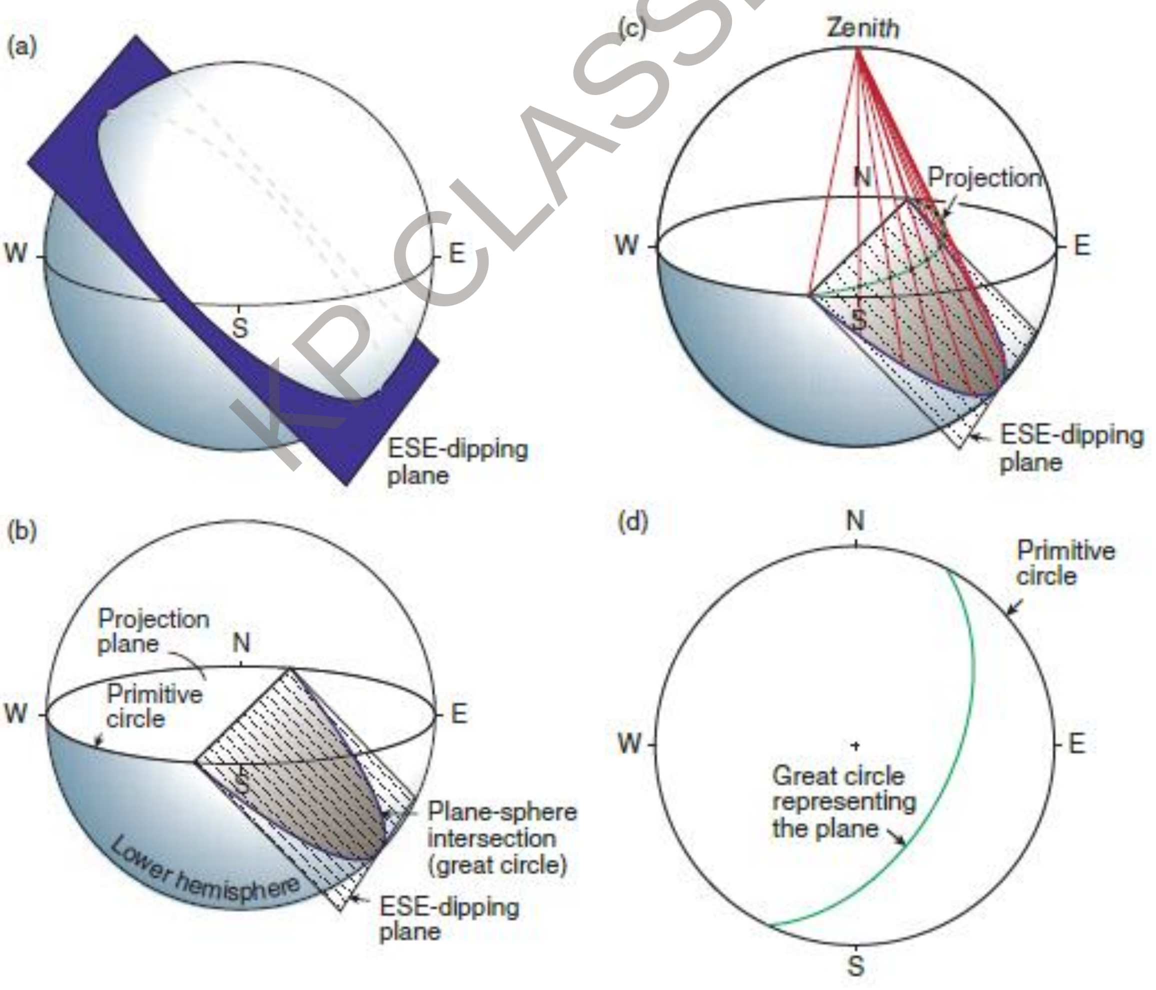
1.3: Stereographic projection

- Stereographic projection is about representing planar and linear features in a two-dimensional diagram.
- Two types:
  1. *Equal-area* (also referred to as a Schmidt net)
  2. *Equal-angle* (also referred to as a Wulff net)
- **Equal-angle stereonets** are used in crystallography because the plotted angular relationships are preserved, and can be measured directly from the stereonet plot.
- **Equal-area stereonets** are used in structural geology because they present no statistical bias when large numbers of data are plotted. On the equal-area net area is preserved so, for example, each 2° polygon on the net has the same area.
- In structural geology the stereonet is assumed to be a ***lower-hemisphere projection*** since all structural elements are defined to be inclined below the horizontal.
- This is unlike crystallographic projections where elements may plot on either the upper or lower hemisphere.
- The outer perimeter of the stereonet is termed the **primitive**. The primitive is always a perfect circle. Usually the diameter of the primitive is some convenient length (10 cm).
- The **north pole** of the stereonet is the upper point where all lines of longitude converge.

1.3.1: Projection of plane

- The orientation of a plane is represented by imagining the plane to pass through the centre of a sphere.
- The line of intersection between the plane and the sphere will then represent a circle, and this circle is formally known as a **great circle**.
- Except for the field of crystallography, where upper-hemisphere projection is used, geologists use the lower part of the hemisphere for stereographic projections.
- We would like to project the plane onto the horizontal plane that runs through the centre of the sphere.

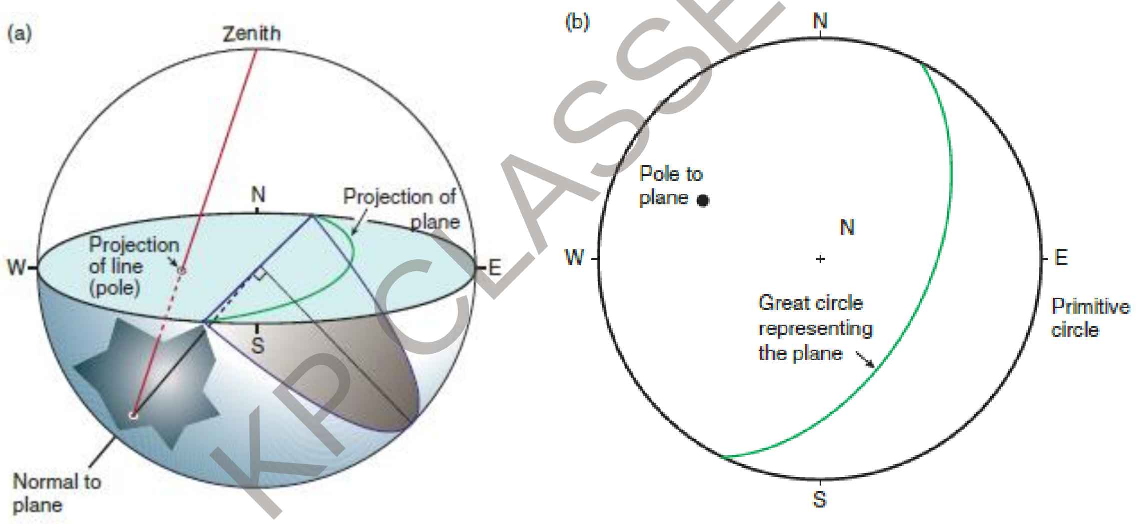
- Hence, this plane will be our projection plane, and it will intersect the sphere along a horizontal circle called the **primitive circle**.
- To perform the projection, we connect points on the lower half of our great circle to the topmost point of the sphere or the **zenith** (red lines in figure below).
- A circle shaped projection (part of a circle) then occurs on our horizontal projection plane, and this projection is a stereographic projection of the plane.
- If the plane is horizontal it will coincide with the primitive circle, and if vertical it will be represented by a straight line.
- Stereographic projections of planes are formally called cyclographic traces, but are almost always referred to as great circles because of their close connection with great circles as defined above.
- Once we understand how the stereographic projection of a plane is done it also becomes obvious how lines are projected, because a line is just a subset of a plane.
- Lines thus project as points, while planes project as great circles. A great circle (as any circle) can be considered to consist of points, each of which represents a line within the plane.
- Hence, a line contained in a plane, such as a slicken line or mineral lineation, will therefore appear as a point on the great circle corresponding to that plane.



Stereographic projection of an ESE- dipping plane

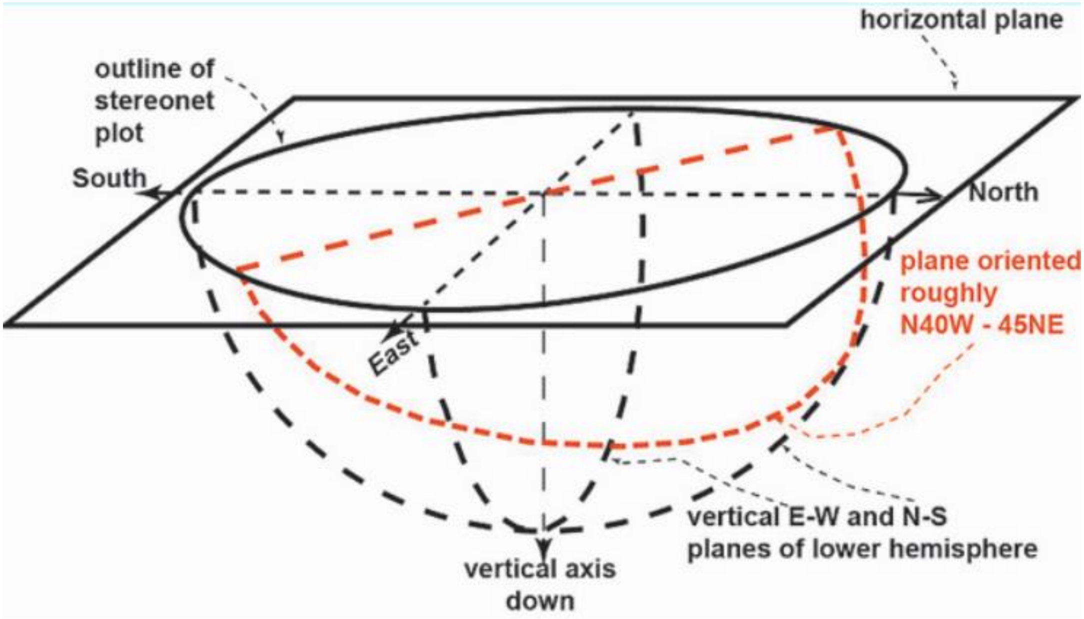
1.3.2: Projection of line

- We have also projected the line that is normal to a given plane, represented by the pole to the plane.
- The projection is found by orienting the line through the centre and connecting its intersection with the lower hemisphere with the zenith (red line in below figure).
- The intersection of this (red) line with the projection plane is the pole to the plane. Hence, planes can be represented in two ways, as great circle projections and as poles.
- Note that horizontal lines plot along the primitive circle (completely horizontal poles are represented by two opposite symbols) and vertical lines plot in the centre.
- For stereographic projections to be practical, we have to establish a grid of known **surfaces for reference**.
- We have already equipped the primitive circle with geographical directions (north, south, east and west), and we can compare the sphere with a globe with longitudes and latitudes.
- Longitudes and latitudes are the lines of intersection between great circles (the original meaning) and so-called small circles.
- If we now project the small and great circles onto the horizontal projection plane, typically for every 2- and 10-degree interval, we will get what is called a **stereographic net or stereonet**.

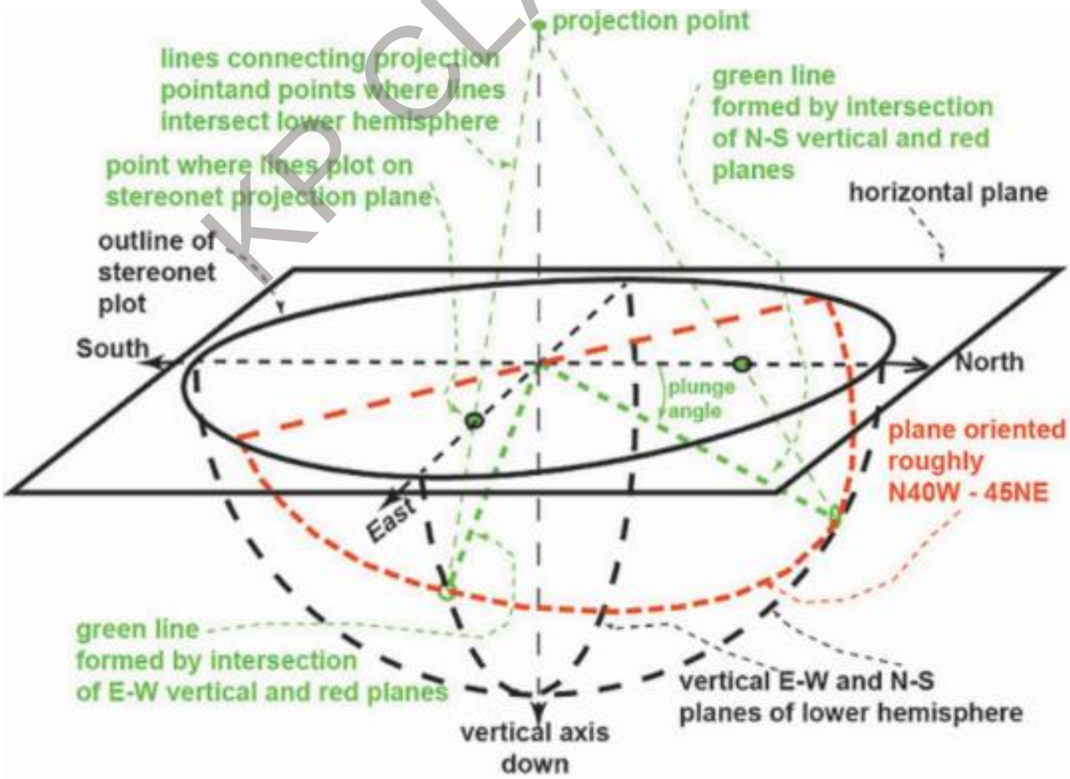


Stereographic projection of a line

- The longitudes are planes that intersect in a common line (the N–S line), and thus appear as great circles in the stereonet.
- The projections of the latitudes, which are not planes but cones coaxial with the N–S line, are usually referred to as **small circles** (also their projections onto the stereonet).
- The net that emerges from the particular projection described above is called the **Wulff net**.

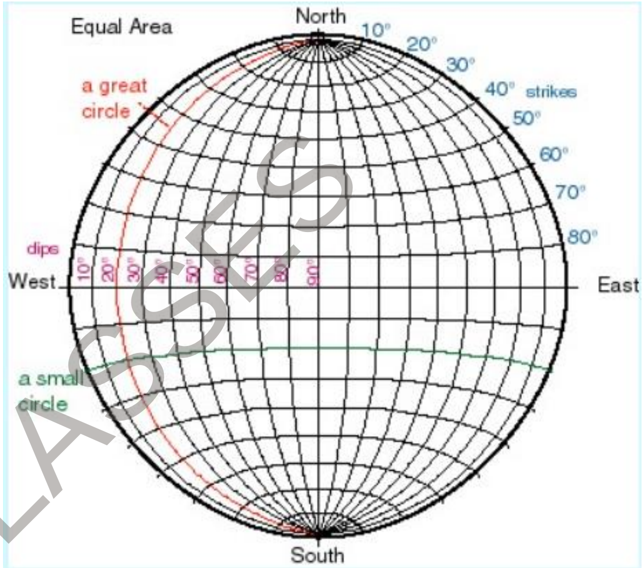


- A horizontal plane passes through a sphere, of which the lower hemisphere is shown, or considered (opposite to mineralogy where the upper hemisphere is considered).
- Where the lower hemisphere intersects the horizontal plane is the outward trace of the stereonet plot. Cardinal directions are shown.
- Planes and lines whose orientation is being plotted all pass through the centre. An example of such a plane is shown in red here.
- What is plotted on the stereonet is a projection of where a given line or plane intersects the lower hemisphere surface.

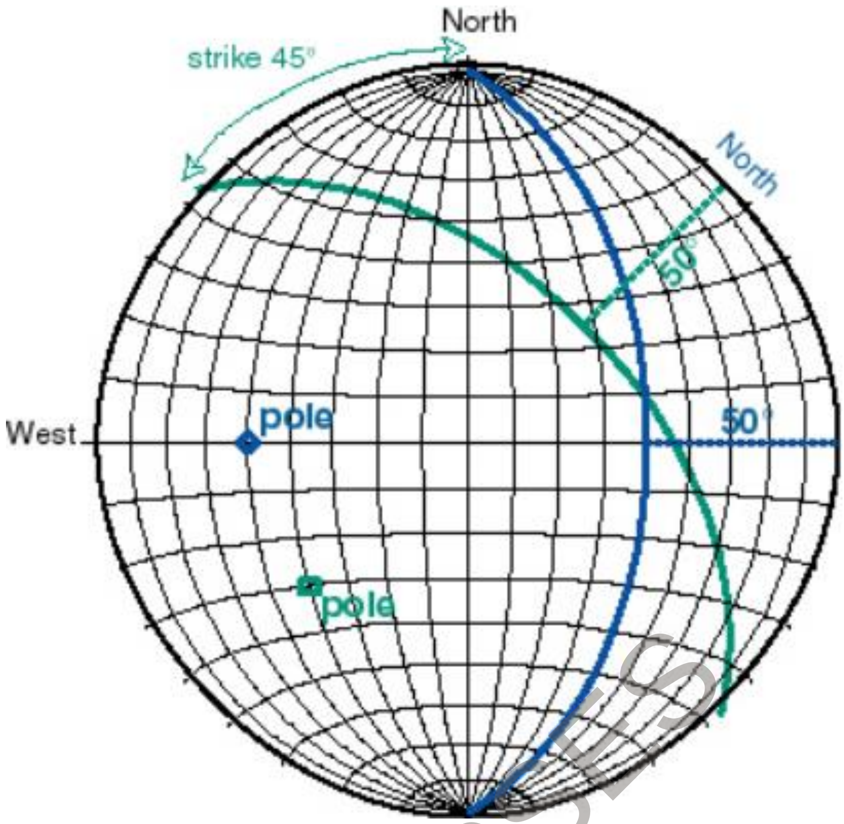


- We can now consider how two lines (the ones in green) plot. The one line is formed by the intersection of the N-S vertical plane and the red plane of interest, and the other by the E-W vertical plane and the red plane of interest.
- These could be thought of as the apparent dips of the red plane in a N-S and E-W vertical cross section respectively.
- There are different methods by which the points of intersection with the lower hemisphere are projected onto the stereonet.
- In this example a projection point exists one sphere radius directly above the centre. A line is drawn from that projection point to the lower hemisphere intersection point (light green dashed lines).
- Where that line passes through the stereonet project plane is where the line plots (the dark green dot). Note that a line plots as point - the point of intersection with the lower hemisphere.

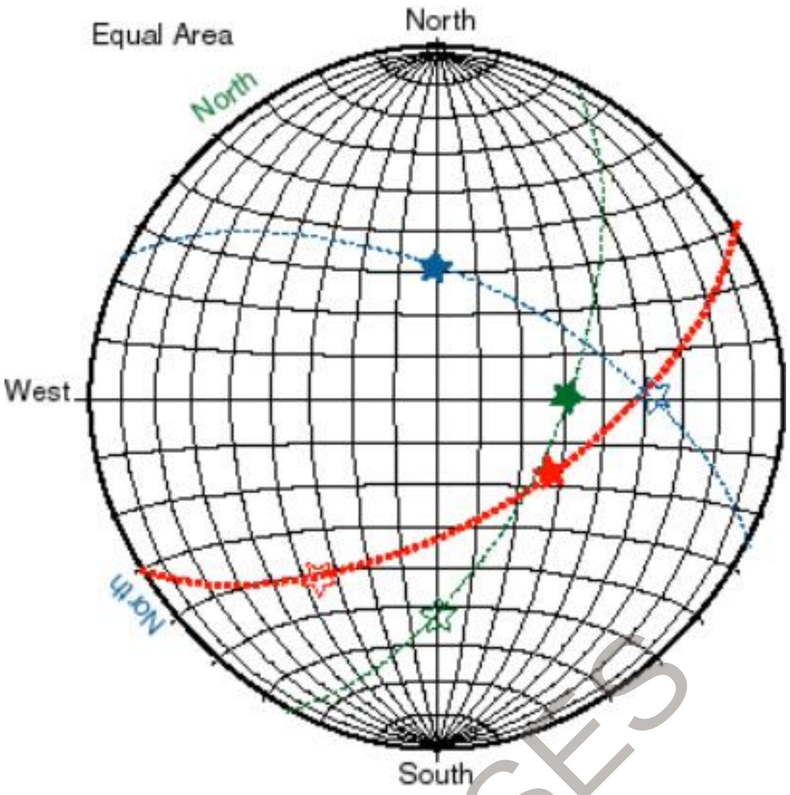
1.3.3: Projection of Plane and line in equal area net



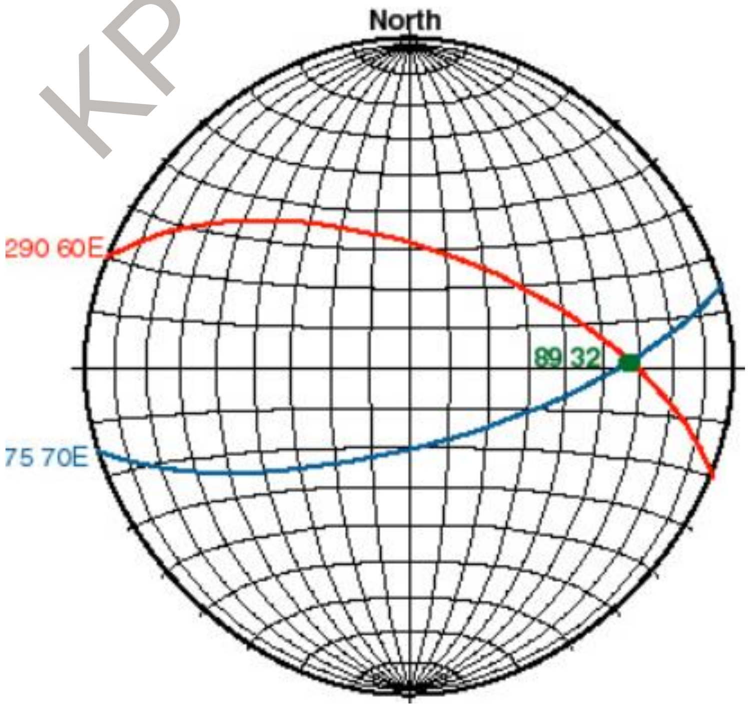
- The figure is an equal area stereonet projection showing great circles as arcuate lines connecting the North and South Points and small circles as arcuate lines in a latitudinal type position.
- The great circles represent north-south striking planes with dips in 10° increments.
- Those labelled with dip amounts on the left side, dip to the west.
- If the same plane was rotated about a vertical axis in the stereonet centre, they would then retain their dip, but have a different strike.
- The numbers in the upper right quadrant represent potential strike line positions from 10-80 degree, in 10degree increments (see below diagram).
- Small circles represent half of a conical surfaces with the apex at hemisphere centre. They are hemisphere surface paths from one line being rotated about another line (the pole of rotation), both passing through the hemisphere centre.
- More complex structural features can be represented by plots of multiple elements. Some examples are:
  - a fault plane, with the direction (line) of movement on it.
  - a cylindrical fold, often viewed as a great circle distribution of poles to the layering being folded.
  - a conical fold, often expressed as a small circle distribution of poles to the layering being folded.
  - an angular unconformity, expressed as the difference between the orientation of the bedding above and below.
  - a population of joints or any other structural feature, often expressed as a data cloud with dispersion around some average value.



- The above diagram shows the same plane in two positions. The blue plane position is where North has been rotated so that the great circles all have a strike of N45W (315°).
- In this case the North position is designated in blue. In this position it is easy to trace out the great circle with the appropriate dip, here 50 degrees to the NE.
- The green represents the plane's orientation when North is rotated back to its standard top-of-the-stereonet position.



- The open and filled red stars represent two lines (solid 124°, 58° and open 214°, 37°) and the dashed red great circle represents their common plane with a strike of 70-60SE.
- The green stars and great circle represent that line rotated 35 degrees counter clockwise so that the filled star is on the equatorial plane where you can count its plunge as about 58 degrees.
- The blue represents the position where you can count the plunge of the open star as about 37 degrees.



- In the above diagram two planes are plotted, one red, one blue. The strike and dips are given to the left.
- The green point represents their common line, i.e. the intersection between the two lines. The trend and plunge are given as 89°, 32°.
- Remember the convention is that the first number represents the trend direction and the second represents the plunge amount.

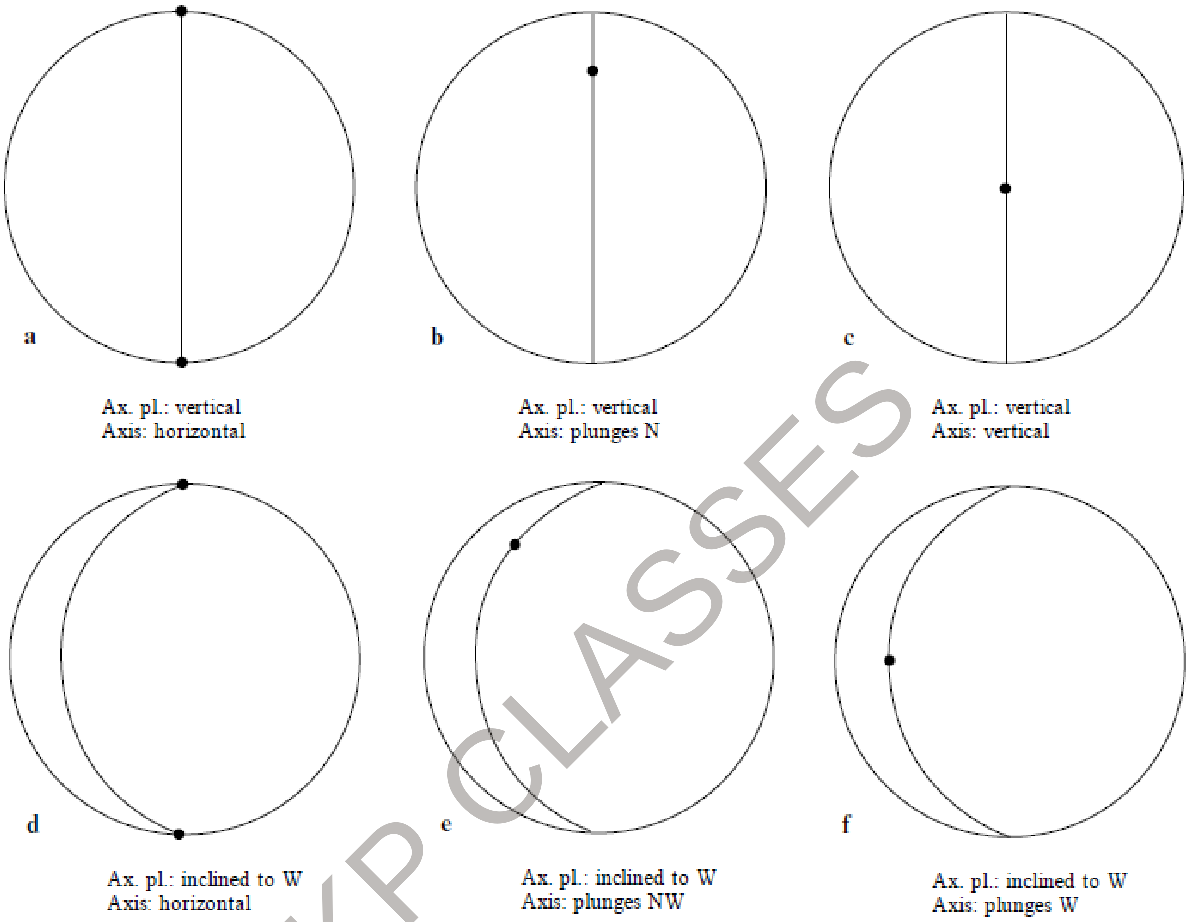
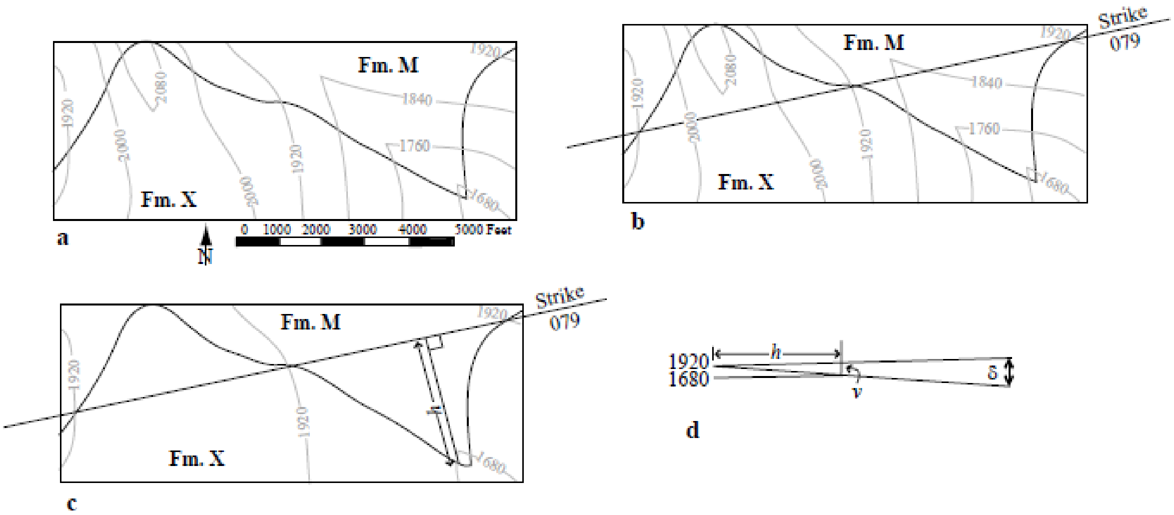


Figure: Simple equal-area diagrams showing orientation of the folds. Axis, axial plane.

1.4: Interpretation of geological map

- The map is an exceedingly important tool in geology. The graphical picture it gives of the location, configuration and orientation of the rock units of an area could be presented in no other way.
- The most important point to realize is that geological maps generally record both observations and interpretation.
- Geologic maps are drawn primarily from observations made on the earth's surface, often with reference to topographic maps, aerial photographs, or satellite images.
- The purposes of a geologic map are to show the surface distributions of rock units, the locations of the interfaces or contacts between adjacent rock units, the locations of faults, and the orientations of various planar and linear elements.
- Because the strike of a plane is a horizontal line, any line drawn between points of equal elevation on a plane defines the plane's strike.



- Figure a in the above figure is a geologic map with two rock units, Formation M and Formation X. The contact between these two rock units crosses several topographic contours.
- To find the strike of the contact, a straight line is drawn from the intersection of the contact with the 1920-ft contour on the west side of the map to the intersection of the contact with the 1920-ft contour on the east side of the map.
- The strike of this contact is thus determined to be 079°, as measured directly on the geologic map.
- To determine the exact dip, draw a line that is perpendicular to the strike line from another point of known elevation on the contact. In Fig. c, a line has been drawn from the strike line to a point where the contact crosses the 1680-ft contour.
- The length of this line (h) and the change in elevation (v) from the strike line to this point yield the dip d with the tangent equation (figure d).

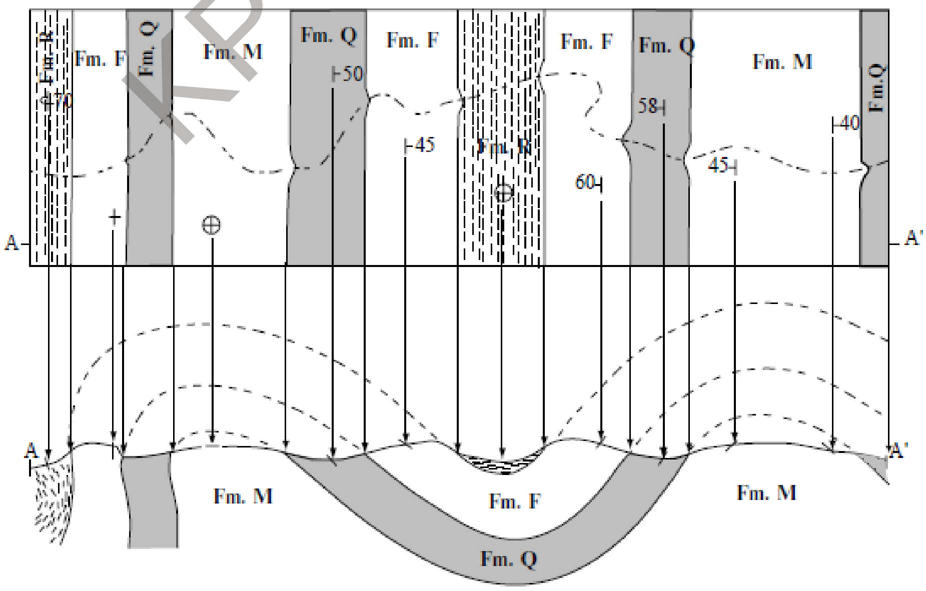
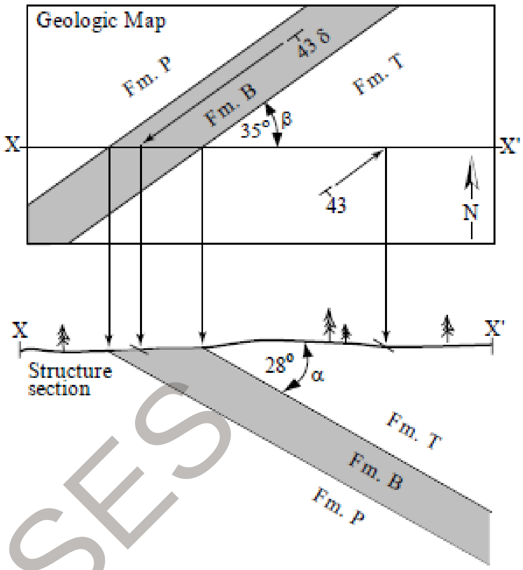
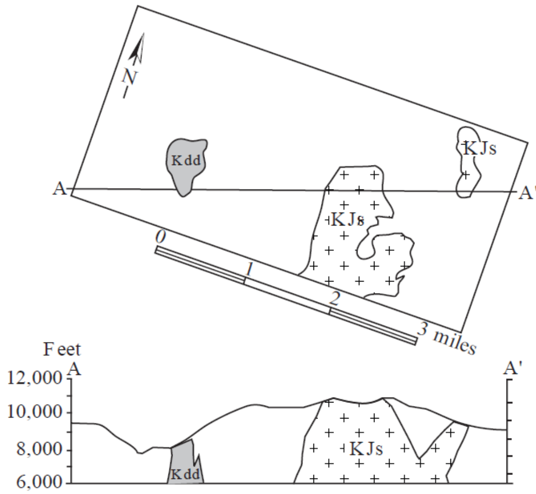


Figure: Basic technique for drawing a geologic structure section perpendicular to the strike of the bedding. Arrows show transfer of attitudes from map to section. Dashed lines represent beds that have been eroded away.

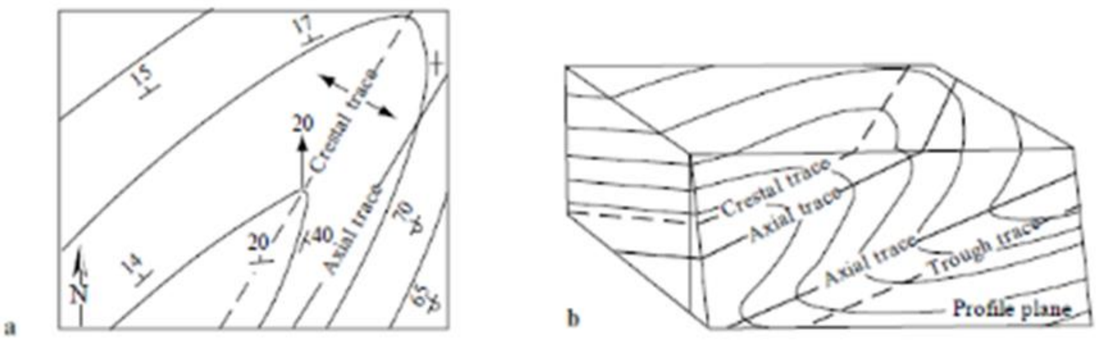
- Figure above shows a geologic map with all beds striking north–south. Section A–A’ is drawn east–west, perpendicular to the strike.
- Each bedding attitude and each contact is merely projected parallel to the fold axis to the topographic profile oriented parallel to the section line.
- On the topographic profile each measured dip is drawn with the aid of a protractor. Using these dip lines on the topographic profile as guides, contacts are drawn as smooth, parallel lines.



- Dashed lines are used to show eroded structures. Show as much depth below the earth’s surface as the data permit.
- When the section line intersects the strike of a plane at an angle other than 908, the dip of the plane as it appears in the structure section will be an apparent dip.
- Recall that the apparent dip is always less than the true dip.
- Figure given in the right side shows a geologic map in which the strike of Formation B has been projected along the strike to line X–X’ and then perpendicular to X–X’ to the topographic profile.
- The angle between the strike and the section line is 35°, the true dip is 43°, and the apparent dip is revealed by the alignment diagram to be 28°, which is the angle drawn on the structure section.



- Tabular intrusive bodies, such as dikes and sills, present no special problem. Irregular plutons, however, are problematic because in the absence of drill-hole or geophysical data it is impossible to know the shape of the body in the subsurface.
- Such plutons are usually drawn somewhat schematically in structure sections, displaying the presumed nature of the body without pretending to show its exact shape.



- Figure shows a set of folds in which the axial surface dips northwest, the axis plunges 20° north, and the crestal and trough traces are clearly not axial traces.
- The axial traces of such folds can only be reliably located in the profile plane.
- For any cylindrical fold, the dip of the bedding at the crestal or trough trace is the same as the trend and plunge of the fold axis.
- So, the crestal and trough traces are the easiest lines to draw on map outcrop patterns of folds.

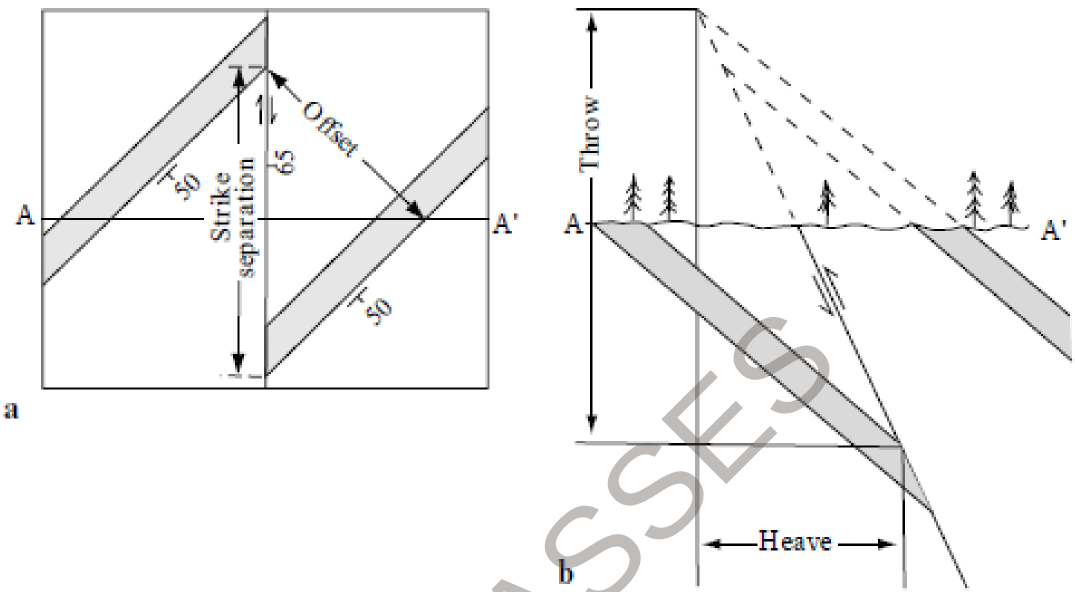


Figure: (a) Geologic map showing the difference between offset and strike separation. (b) Vertical structure section showing the heave and throw components of dip separation.

- Notice that the term separation is concerned with the apparent displacement of some reference horizon, and the terms right-lateral, left-lateral, normal, and reverse are used to describe the separation, whether or not the actual direction of movement is known.
- Similarly, arrows are often drawn along faults on geologic maps to indicate the sense of strike separation, even on faults with no history of strike-slip movement. More often than not, the actual slip path of a fault cannot be determined.
- When describing faults it is important to distinguish clearly between separation and slip.

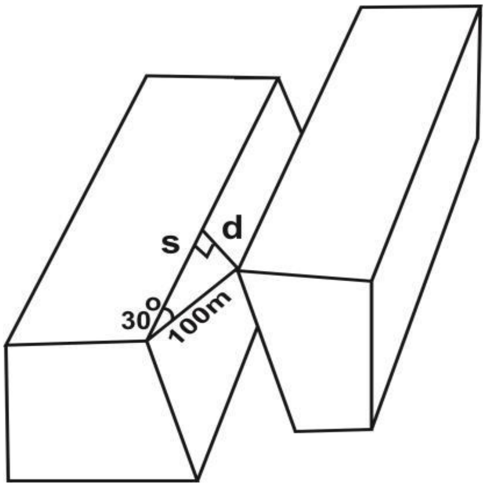
Practice Questions

Previous year Easy Questions

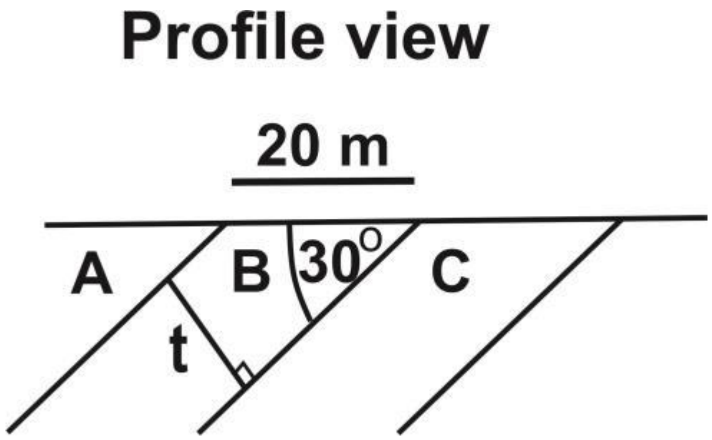
1. The angle that the line in a plane makes with horizontal line in that plane is called
   A. Dip (GATE 1997)
   B. Strike
   C. Plunge
   D. Rake
2. A magnetite bearing layered rock is exposed in an area. It has a very low dip and has near horizontal attitude. Its dip is measured accurately by (GATE 2004)
   A. Clinometer compass
   B. Brunton compass
   C. Photogrammetrically

D. Theodolite based elevation method

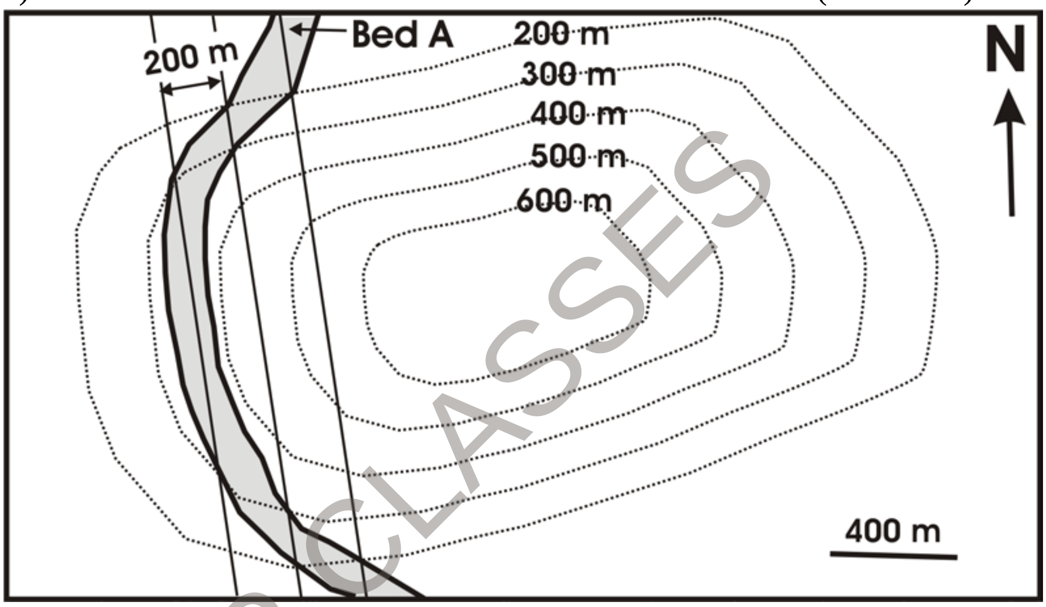
3. On a stereo plot the bedding plane plots as a straight line passing through the centre. The bed is (GATE 2005)
   A. Vertical
   B. Horizontal
   C. Steeply dipping
   D. Gently dipping
4. Outcrop pattern parallel to topographic contours signifies (GATE 2010)
   A. Horizontal beds
   B. Vertical beds
   C. Inclined beds
   D. Folded beds
5. Structure contours of a bedding plane at 100 m interval are spaced in such a manner that the horizontal equivalent is also 100m. The dip of the bedding plane is
   A. 30° (GATE 2014)
   B. 45°
   C. 60°
   D. 90°
6. The plunge of the normal to the axial planes of vertical and upright folds is
   A. 0° (GATE 2019)
   B. 45°
   C. 60°
   D. 90°
7. The strike (in degree notation) of a bed dipping 30° towards N45W is (JAM 2020)
   A. 045-225
   B. 025-205
   C. 020-200
   D. 030-210
8. In the block diagram, the net slip (=100 m) is resolved into strike slip (s) and dip slip (d) components. The value (in m, correct to two decimal places) of "s" is ____ (NAT) (JAM 2020)



9. The true thickness (t, in m) of bed B in the given diagram is _(NAT) (JAM 2020)



10. The true thickness of Bed A in the map given below is _____ m (answer in one decimal place). (JAM 2018)



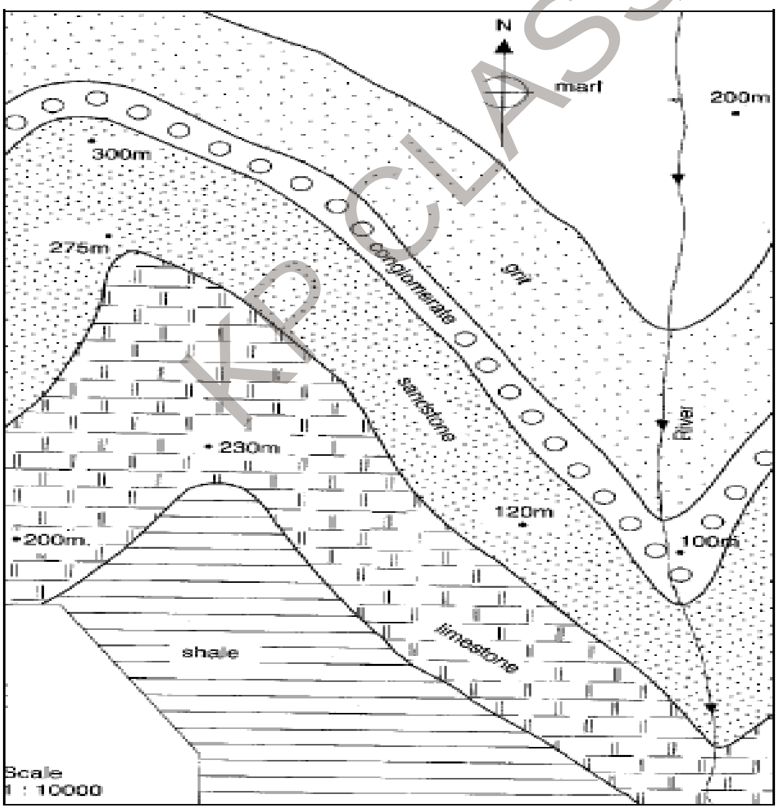
Previous year Difficult Questions

1. In an area dip of uniformly dipping beds and the topographic slope are in the same direction, but beds are gentler. By walking down, the slope, one encounters
   A. Gradually younger and younger beds (GATE 2001)
   B. Initially gradually older, then younger beds
   C. Initially gradually younger, then older beds
   D. Gradually older and older beds
2. A multinational company has drilled two exploratory vertical boreholes P and Q. borehole Q is located at an elevation of 350m at a map distance of 1000m due E from the borehole P at 0m. A N-S striking copper lode is encountered between 200m and 400m in borehole P and between 1550m and 1750 m in the borehole Q below the ground surface. Dip and thickness of the copper lode between the boreholes are (GATE 2003)
   A. Dip – 45°E, thickness – about 140m
   B. Dip – 45°W, thickness – about 140m
   C. Dip – 45°E, thickness – about 200m
   D. Dip – 45°W, thickness – about 200m
3. Statement for Linked Answer Questions 3 & 4:

A dipping limestone bed with a true width of 5 metres shows an apparent width of 10 metres on a horizontal surface. (GATE 2007)
Calculate the true dip of the limestone bed.

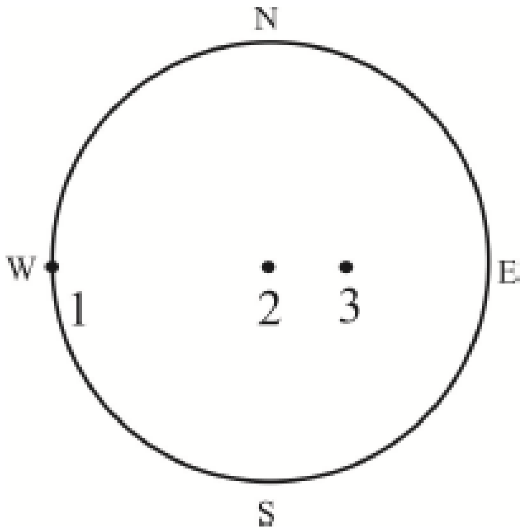
A. 70°
B. 50°
C. 30°
D. 10°

4. At what horizontal distance (metres) from the exposed upper surface of the bed should a vertical drill hole be made so as to intersect the top of the bed at a depth of 100 metres?
   A. 73.2 (GATE 2007)
   B. 173.2
   C. 273.2
   D. 373.2
5. A sandstone bed dipping 30° has an outcrop width of 20 m in a flat terrain. What is the true thickness (in m) of the bed? (GATE 2012)
   A. 5
   B. 10
   C. 20
   D. 30
6. Study the map below showing elevation of selected locations and outcrops of sedimentary beds (GATE 2012)



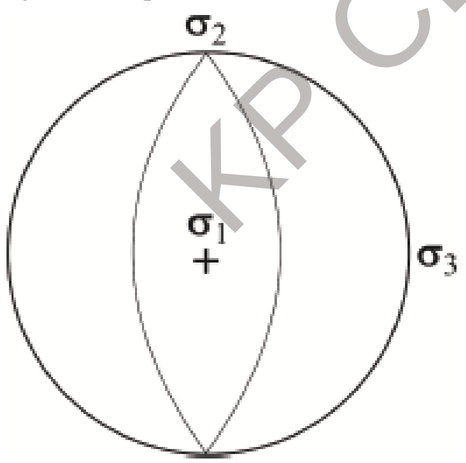
Which of the following statements is correct?
   A. The beds dip easterly
   B. The beds dip westerly
   C. The beds dip southerly
   D. The beds are folded

7. In the stereographic projection 1, 2 and 3 represent poles of three planes. Choose the correct combination of statement from the following. (GATE 2013)



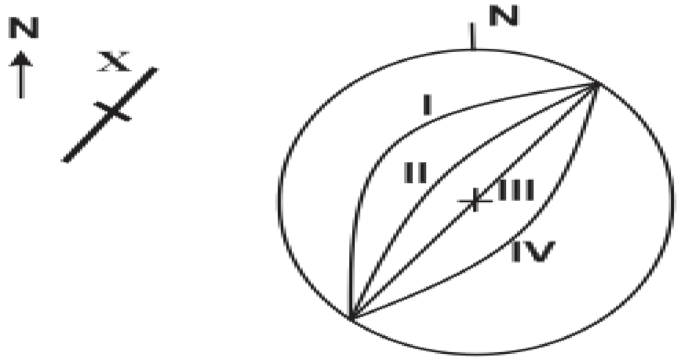
A. The plane corresponding to 1 is horizontal and the plane corresponding to 2 is inclined.
B. The plane corresponding to 1 is striking N-S and the plane corresponding to 2 is horizontal.
C. The plane corresponding to 2 is vertical and the plane corresponding to 3 is striking E-W.
D. The plane corresponding to 2 is striking E-W and the plane corresponding to 3 is inclined.

8. The stereographic projection below the principal stress axes and fault planes. The projection represents a (GATE 2013)



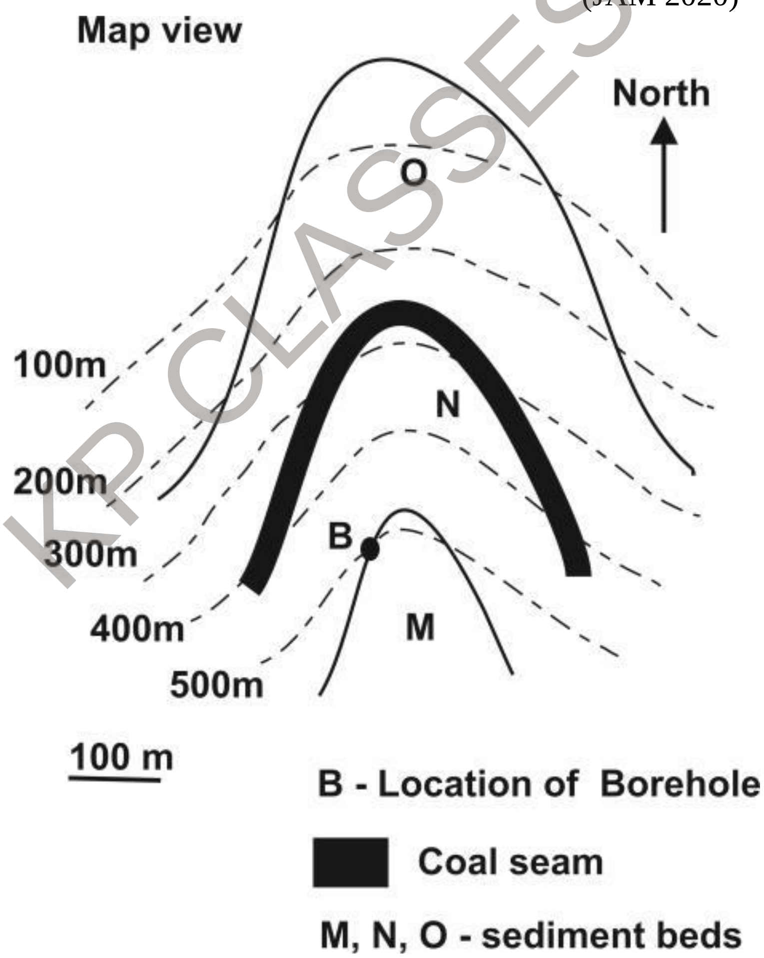
A. Normal fault
B. Reverse fault
C. Dextral fault
D. Sinistral fault

9. A bedding plane, pictorially represented at X, will be plotted in stereonet as (JAM 2020)

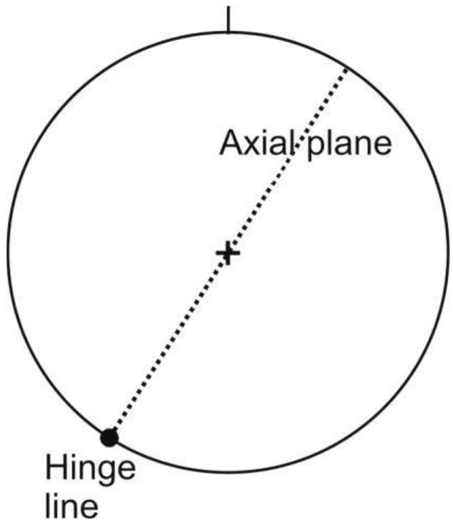


A. I
B. II
C. III
D. IV

10. A coal seam occurs in a stratigraphic sequence as shown in the figure. If a vertical borehole is drilled at location B, the coal seam will be intersected at a depth (in m) of ____
(JAM 2020)

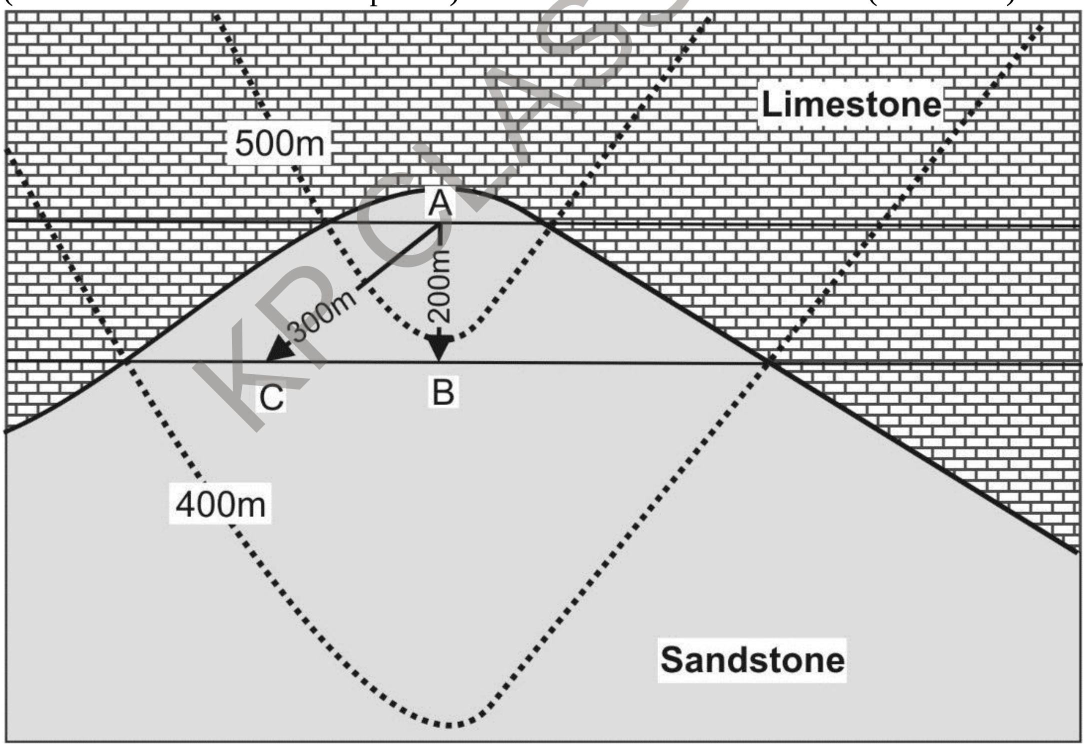


11. The figure shows stereographic projections of the axial plane and the hinge line of a fold. Which one of the following folds is represented in the figure? (JAM2019)

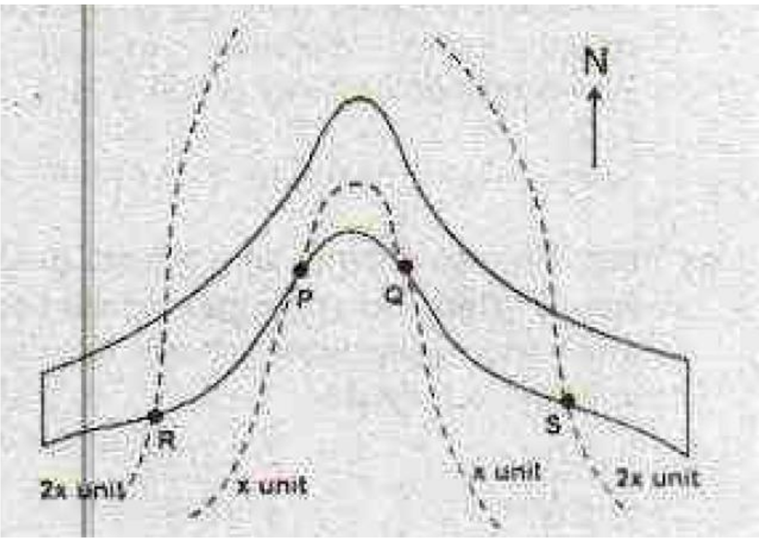


A. Upright plunging
B. Upright non-plunging
C. Reclined
D. Recumbent

12. The geological map shows the contact between sandstone and limestone. The two dotted curves are the contours of 400 m and 500 m, respectively. The difference between the dip angles of the contact surface along the AB and AC directions is __________ degree (rounded off to two decimal places). (JAM2019)

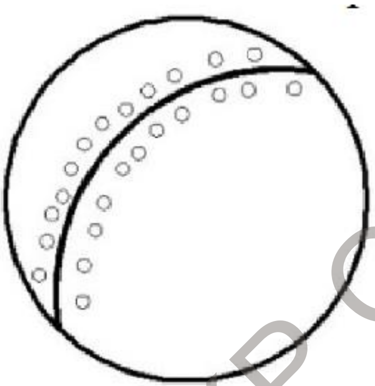


13. The outcrop pattern of a dipping bed (shaded) showing intersections with topographic contours (marked by dashed lines, and at altitudes x and 2x units above MSL) at P, Q, R and S is given in the diagram below. Assuming the horizontal distance between two strike lines at different altitudes, and in the direction of dip is 1.732x units, the dip amount and direction is calculated at (NET 2018)



A. 30°N
B. 60°S
C. 60°N
D. 30°S

14. The following figure shows the lower hemisphere, equal area plots of the poles to bedding surfaces. Which one of the following is the correct interpretation? (NET 2017)



A. The beds are folded cylindrically
B. The beds are folded non-cylindrically
C. The beds are folded isoclinally
D. The beds are not folded

Multiple Selected Questions

1. The attitude of a plane is represented by
   A. Dip
   B. Plunge
   C. Strike
   D. pitch
2. In which of the following case no V shape will form?
   A. Horizontal bed
   B. Vertical bed
   C. Bed dips with stream gradient
   D. All of the above
3. Find out the correct statement regarding stereographic projection.

A. Wulff's stereonet used for equal area projection
B. Pole of horizontal plane will lie in the primitive circle
C. Vertical plane will represent along the centre
D. Great circles are running from N-S

ANSWERS

Previous Year Easy Questions

1. D 2. D 3.A 4.A 5.B 6.A 7.A 8. 86-87 9. 10 10. 89.4

Previous Year difficult Questions

1. D 2. C 3.C 4.B 5.B 6.C 7.B 8.A 9.C 10. 100 11.B

12. 8.13 13.A 14.A

Multiple Select questions

1. AC 2. BC 3. CD

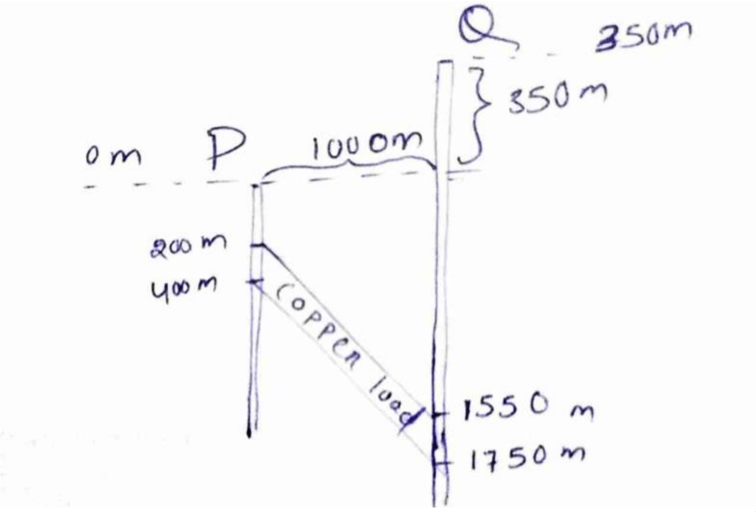
EXPLANATIONS

Previous Year Easy Questions

1. Rake is formally defined as the angle between a line and the strike line of the plane in which it is found, measured on the plane.
2. Magnetite being magnetic in nature deflects compass needle.
3. The bedding is vertical because in stereographic plot centre plots vertical where as periphery indicates horizontal bed.
4. Horizontal beds gives the outcrop pattern which is parallel to topographic contour while vertical beds cut the topographic contour vertically.
5. Structure contours are the curves that connects points of equal height above a datum level that are contained within a structure. For a dip of 45°, the structure contour intervals and the horizontal equivalent are equal.
6. For both vertical and upright folds, the axial planes are vertically oriented. Normal to them would be horizontal, plunge for which will be zero.
7. The strike direction will always lie perpendicular to dip direction.
8. Net slip = 100m
   Dip angle = 30°
   Strike slip = net slip * cos 30° = 86.60
9. Width of the outcrop = 20m
   Dipping angle = 30°
   True thickness = width * sin30° = 10m
10. Ground distance between two strike line =200m
    Vertical thickness = 100m
    Dip = $\tan^{-1}$ (100/200) = 26.56°
    True thickness = vertical thickness * cos (dip angle)
    = 100*cos (26.56) = 89.4m

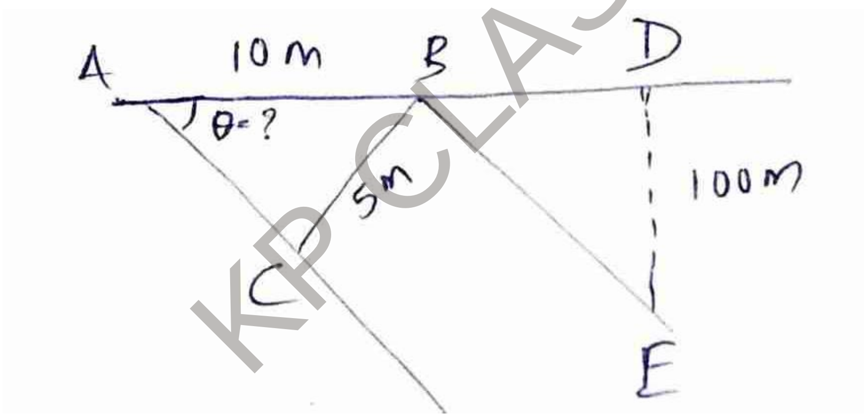
Previous Year difficult Questions

1. When topographic slope is greater than the bedding slope then, when we go in the dip direction will encounter older and older beds.
2. Distance between two boreholes = 1000m



In P borehole copper lode lies at depth of 200m
In Q borehole copper lode lies at depth of = 1550 – 350 = 1200m
The vertical dip of copper load is = 1200 – 200 = 1000m
Thickness of load is 400 – 200 = 200m
Dip = $\tan^{-1}(1000/1000)$ = 45°E

3. True width of limestone bed = 5m



In ABC triangle $\sin\theta = \frac{5}{10} = 0.5$
True dip = 30°

4. Let's the drill is made x distance away from B to met the required condition then in BDE triangle:

$\tan\theta = \frac{100}{x}$

$x = \frac{100}{\tan 30°}$

X= 173.2m

5. Width of the outcrop = 20m
Dip angle = 30°
True thickness = width * sin30° = 20* (1/2) = 10m
6. River flowing towards south hence, general dip direction of the beds is towards south.

7. Plane corresponding to pole 1 is vertical and striking N-S and the plane corresponding to pole 2 is horizontal.
8. Since maximum principal stress is perpendicular where as minimum and intermediate principal stresses are horizontal which will generate the extension resulting in normal faulting.
9. The bedding plane shown pictorially, is the symbol of a vertical plane. Hence, it will be plotted in the centre of the stereonet.
10. Point B where the bore hole will be drilled lies at a elevation of 500m
    Strike line passes across the coal seam which also goes through the point B is 400m strike line.
    Hence, the depth of coal seam will be = 500- 400 = 100m
11. The figure shows stereographic projection of the axial plane and the hinge line of a fold. Upright Nonplunging fold as shown in the diagram, the axial plane id vertical and hinge line is horizontal with 0° plunge. Any fold with vertical axial plane and Nonplunging hinge line is known as upright Nonplunging fold.
12. The contour interval between two strike line = 100m
    Ground distance in AB direction = 200
    Dip angle along AB = $\tan^{-1}(100/200) = 26.56°$
    Ground distance in AC direction = 300
    Dip angle along AC = $\tan^{-1}(100/300) = 18.43°$
    Difference = 26.56 - 18.43 = 8.13°
13. Horizontal topographic distance is = 1.732x units
    Vertical distance between two strike line = 2x-x = x unit
    Dip amount = $\tan^{-1}(x/ 1.732x) = 30°$
    For dip direction we will observe that the strike amount is gradually decreasing towards north hence, the bed is dipping towards north.
14. Cylindrical folds can be considered as being made up of an infinite number of parallel straight lines drawn on bedding plane. Here in the equal area plot it is showing straight hinge line and beds are folded cylindrically.

Multiple Select questions

1. Strike and dip refer to the orientation or attitude of a geologic plane and general direction of the dip is also included while pitch and plunge determined the attitude of a line.
2. In case of horizontal bed, the bed cuts according to the erosion of the valley. Hence, v shape will form there.
3. Wulff's stereonet used for equal angle projection and for equal area Schmidt's stereonet is used. Horizontal planes plotted along the primitive circle and vertical plane along the centre. Great circles are curved circles running from N-S.

Chapter 2: Stress, strain and deformation

Dynamic analysis is concerned with **force** and **stress** (force per unit area).

2.1: Force

- We frequently use the words force and stress in casual conversation. In science, however, these terms have very specific meanings. For example, the force of gravity keeps us on the Earth's surface and the force of impact destroys our car.
- Newton's first law of motion, also called the **Law of Inertia, says** that in the absence of a force a body moves either at constant velocity or is at rest.
- Change in velocity is called **acceleration [a]. Force [F],** according to **Newton's Second Law of Motion**, is mass multiplied by acceleration:

$$[F] : [ma] : [mlt^{-2}]$$

- The unit of force is **kg · m/s²**, called a **newton (N)** in SI units. Force, like velocity, is a vector quantity.
- Natural processes can be described with four basic forces: (1) the gravity force, (2) the electromagnetic force, (3) the nuclear or strong force, and (4) the weak force.
- Forces that result from action of a field at every point within the body are called **body forces**.
- The magnitude of body forces is proportional to the mass of the body. Forces that act on a specific surface area in a body are called **surface forces**.
- The magnitude of surface forces is proportional to the area of the surface. Forces that act on a body may change the velocity of (that is, accelerate) the body, and/or may result in a shape change of the body, meaning acceleration of one part of the body with respect to another part.

2.2: Stress

- Stress, represented by the symbol **σ (sigma)**, is defined as the **force per unit area**.

$$[A], \text{ or } \sigma = F/A.$$

- Stress that acts on a plane is a vector quantity, called **traction**, whereas stress acting on a body is described by a higher order entity, called a **stress tensor**.
- Stress is expressed in terms of the following fundamental quantities:

$$[\sigma] : [mlt^{-2} \cdot l^{-2}] \text{ or } [ml^{-1} \cdot t^{-2}]$$

- The corresponding unit of stress **is kg/m ·s² (or N/m²)**, which is called a **pascal (Pa)**.
- Geologists continue to use the unit bar, which is approximately 1 atmosphere1 bar $=10^5$ Pa ≈1 atmosphere, whereas, 1 kbar =1000 bar $=10^8$Pa =100 MPa.
- The first word in dealing with stress is caution! Beginners in geology, encouraged in some cases by poorly worded textbooks, are apt to jump to dynamic conclusions based on observations of geometry.
- Despite many decades of research in structural geology, it is unusual to be able to make any quantitative deductions about stress from outcrop observations!
- Part of the problem is that geological strain rates for ductile deformation are very slow, we cannot directly determine what kind of stress makes what kind of structure, unless we are prepared to run our experiments for 10,000 years or more! For brittle deformation,

experimental simulation of structures is easier, but experimental structural geology is still a challenging field.

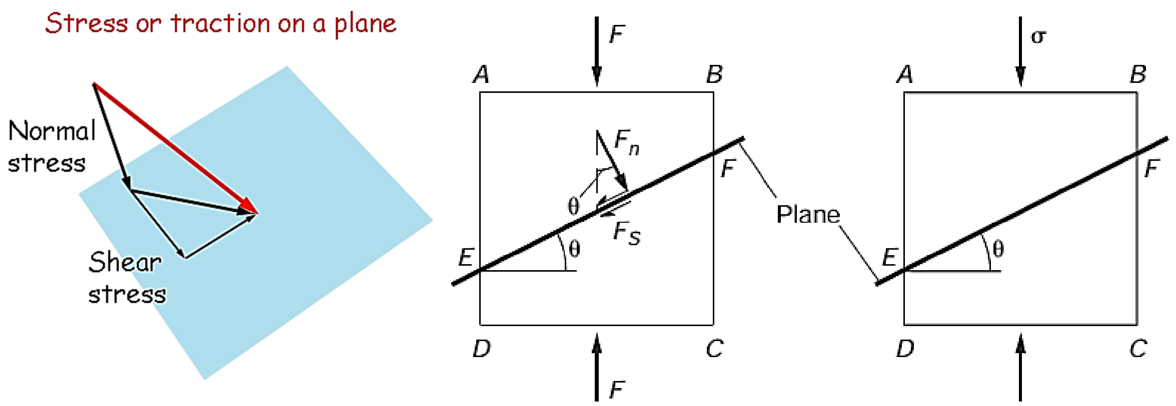
- That said, understanding of stress is critically important in areas of structural geology and engineering that deal with stress at the present day, such as earthquake studies, and the behavior of fluids (water, oil, gas) in the subsurface, so we do need to know how stress is measured, and the potential ways that structures are related to stress.
- **Note**: The word **stress** is used in two ways. It can describe the force concentration on a plane, also known as **traction**, (or, in the special case where the force is perpendicular to the plane, as **pressure).**
- However, it can also be used to describe the array of forces that act on all possible planes that pass through a point.
- This 3D state of stress cannot be described by a single vector - it is a **tensor** quantity. Some textbooks restrict the word **stress** to this tensor quantity, and use the word **traction** to for the vector that describes force concentration on a single plane.
- In these notes, the term 'stress' is used informally for both the tensor quantity and its vector manifestation. If there is any possibility of confusion, we will write 'stress on a plane' or 'stress tensor' to distinguish the two concepts.
- In formulas, the common convention is to use the Greek letter sigma σ for the stress vector.
- Tensors are usually represented by uppercase bold letters, but uppercase sigma (Σ) is used for too many other things! We will use an uppercase **T** if we need to represent the stress tensor algebraically.

2.3: Stress or traction on a 2D surface

- Stress acting on a plane is a vector quantity (sometimes called traction), meaning that it has both magnitude and direction.
- Stress on an arbitrarily oriented plane, however, is not necessarily perpendicular to that plane, but, like a vector, it can be resolved into components normal to the plane and parallel to the plane.

2.3.1: Normal stress and shear stress

- The vector component normal to the plane is called the normal stress, for which we use the symbol σ_n.
- The vector component along the plane is the shear stress and has the symbol σ_s (sometimes the symbol τ (tau) is used).



- The overall stress on the surface is equal to the vector sum of the normal and shear stress.
- Shear stress can itself be resolved into components parallel (for example) to the strike and the dip of the surface.
- In contrast to the resolution of forces, the resolution of stress into its components is not straightforward, because the area changes as a function of the orientation of the plane with respect to the stress vector.
- In right figure, stress σ has a magnitude F/AB and makes an angle θ with the top and bottom of our square.
- The forces perpendicular (Fn) and parallel (Fs) to the plane EF are:

$$F_n = F\cos\theta = \sigma\, AB\cos\theta = \sigma\, EF\cos^2\theta$$
$$(AB = EF\cos\theta)$$
$$F_s = F\sin\theta = \sigma\, AB\sin\theta =$$
$$\sigma\, EF\sin\theta\cos\theta = \sigma\, EF\, ½(\sin 2\theta)$$

and the corresponding stresses are:

$$\sigma_n = F_n/EF = \sigma\cos^2\theta$$
$$\sigma_s = F_s/EF = \sigma\, ½(\sin 2\theta)$$

- Both the shear force and the shear stress initially increase with increasing angle θ; at 45° the shear stress reaches a maximum and then decreases, while Fs continues to increase.

2.3.2: Sign convention

- Note that in geology we normally regard **compressive** normal stresses as **positive**, because compressive stresses are much more common in the Earth.
- This leads to some difficulties when we relate stress and strain, because we treat extensional strains as **positive**, and shortening as **negative**.

2.3.3: Units of stress

- The gigapascal 1 GPa = 10^9 Pa
- The CGS unit of stress is the **bar**, **1 bar =** 10^5 Pa
- Hence 1 kb = 10^8 Pa = 100 MPa
- Atmospheric pressure averages around 101325 Pa; hence 1 atm is close to 1 bar or 10^5 Pa
- The imperial unit is the pound-force per square inch, or psi. 1 psi = 6894 Pa
- To give a general idea of the range of crustal stresses, the mean stress (roughly equivalent to pressure) at the base of the continental crust is around 1 GPa, 10 kb, 10000 atm, or 14500 psi.

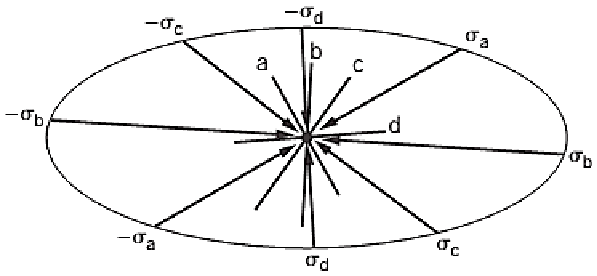
2.4: State of stress in 3D

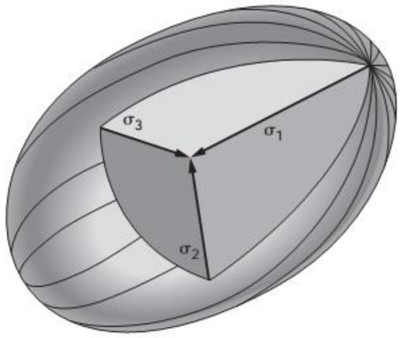
- To describe stress on a randomly oriented plane in space we need to consider the three-dimensional case.
- The unnecessary complications are limited by setting the condition that the body containing the plane is at rest.
- So, a force applied to the body is balanced by an opposing force of equal magnitude but opposite sign; this condition is known as Newton's **Third Law of Motion.**

2.4.1: Stress at a point

- Let shrink our three-dimensional body containing the plane of interest down to the size of a point for our analysis of the stress state of an object.

- A point defines the intersection of an infinite number of planes with different orientations. The stress state at a point, therefore, can describe the stresses acting on all planes in a body.

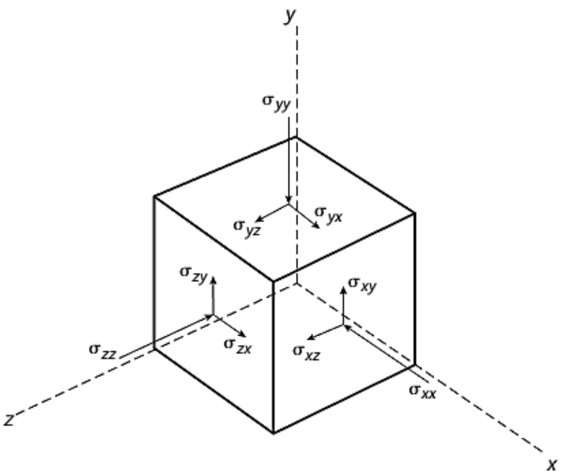




- In left figure the normal stresses (σ) acting on four planes (a–d) that intersect in a single point are drawn (we limit our illustrations to planes that are all perpendicular to the surface of the page).
- Because of Newton's Third Law of Motion, the stress on each plane must be balanced by one of opposite sign (σ = –σ).
- Because stress varies as a function of orientation, the magnitude of the normal stress on each plane (represented by the vector length) is different.
- If we draw an envelope around the endpoints of these stress vectors, we obtain an **ellipse** (ellipse is defined by at least three non-perpendicular axes).
- This means that the magnitude of the stress for all possible planes is represented by a point on this stress ellipse.
- In three dimensions, we obtain an envelope that is the three-dimensional equivalent of an ellipse, called an **ellipsoid** (right figure)
- This stress ellipsoid fully describes the stress state at a point and enables us to determine the stress for any given plane.
- Like all ellipsoids, the stress ellipsoid is defined by three mutually perpendicular axes, which are called the **principal stresses**.
- These principal stresses have two properties: (1) they are orthogonal to each other, and (2) they are perpendicular to three planes that do not contain shear stresses; these planes are called the **principal planes of stress**.

2.4.2: The components of stress

- The orientation and magnitude of the stress state of a body is defined in terms of its components projected in a Cartesian reference frame, which contains three mutually perpendicular coordinate axes, x, y, and z.
- Let's draw our point as an infinitely small cube whose ribs are perpendicular to each of the coordinate axes, x, y, and z.
- We resolve the stress acting on each face of a cube into three components (below fig).
- For a face normal to the x-axis the components are σ_{xx}, which is the component normal to that face, and σ_{xy} and σ_{xz}, which are the two components parallel to that face. These last two stresses are shear stress components.



Applying this same procedure for the faces normal to y and z, we obtain a total of nine stress components:

	In the direction of *x*:	*y*:	*z*:
stress on the face normal to *x*:	σ_{xx}	σ_{xy}	σ_{xz}
stress on the face normal to *y*:	σ_{yx}	σ_{yy}	σ_{yz}
stress on the face normal to *z*:	σ_{zx}	σ_{zy}	σ_{zz}

- In which σ_{xx}, σ_{yy}, and σ_{zz} **are normal stress components** and the **other six are shear stress components**.
- Because we specified that the body itself is at rest, three of the six shear stress components must be equivalent (σ_{xy} and σ_{yx}, σ_{yz} and σ_{zy}, and σ_{xz} and σ_{zx}).
- So, rather than nine components, we are left with six independent stress components to describe the stress acting on any arbitrary infinitesimal body.
- For any given state of stress there is at least one set of three mutually perpendicular planes on which the shear stresses are zero, these three faces are the **principal planes of stress**, and they intersect in three mutually perpendicular axes that are the **principal axes of stress**.
- The stresses acting along them are called the **principal stresses for a given point.**

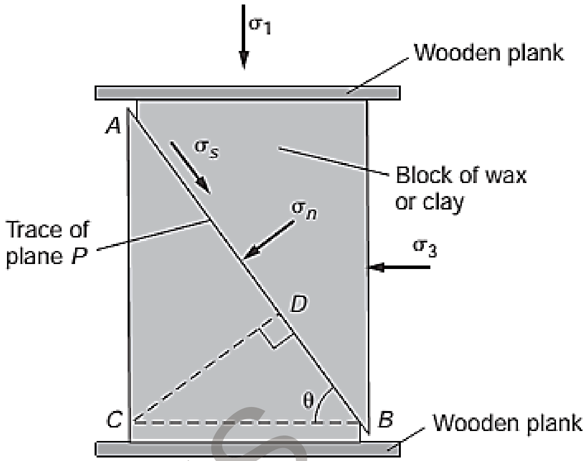
2.4.3: Stress states

- If the three principal stresses are equal in magnitude, we call the stress isotropic, if unequal then anisotropic.
- By convention, the maximum principal stress is given the symbol $\sigma 1$, the intermediate and minimum principal stresses acting along the other two axes are given the symbols $\sigma 2$ and $\sigma 3$.
- Thus, by (geologic) convention $\sigma 1 \geq \sigma 2 \geq \sigma 3$. By changing the relative values of the three principal stresses we define several common stress states:

General triaxial stress:	$\sigma_1 > \sigma_2 > \sigma_3 \neq 0$
Biaxial (plane) stress:	one axis = 0 (e.g., $\sigma_1 > 0 > \sigma_3$)
Uniaxial compression:	$\sigma_1 > 0$; $\sigma_2 = \sigma_3 = 0$
Uniaxial tension:	$\sigma_1 = \sigma_2 = 0$; $\sigma_3 < 0$
Hydrostatic stress (pressure):	$\sigma_1 = \sigma_2 = \sigma_3$

2.4.4: Deriving Some Stress Relationships

- Now that we can express the stress state of a body by its principal stresses. Let's carry an experiment where a block develops fracture due to compression.
- We want to determine what the normal and the shear stresses on the fracture plane are: The principal stresses acting on block are σ1(maximum stress), σ2 (intermediate stress), and σ3 (minimum stress).
- Because of atmospheric conditions, the values of σ2 and σ3 will be equal, and we may simplify our analysis by neglecting σ2 and considering only the σ1-σ3 plane (figure).
- The fracture plane makes an angle θ (theta) with σ_3. We can resolve AB along AC (parallel to σ_1) and along BC (parallel to σ_3).
- By trigonometry, we see that the area represented by AC= sin θ, and the area represented by BC= cos θ.



- Next, we consider the forces acting on each of the surface elements:

$$\text{force on side } BC = \sigma_1 \cdot \cos\theta$$
$$\text{force on side } AC = \sigma_3 \cdot \sin\theta$$

- The force on side AB consists of a normal force and a shear force and for equilibrium, the forces acting in the direction of AB must balance. Resolving along CD:

$$\text{force} \perp AB = \text{force} \perp BC \text{ resolved on } CD + \text{force} \perp AC \text{ resolved on } CD$$

or

$$1 \cdot \sigma_n = \sigma_1 \cos\theta \cdot \cos\theta + \sigma_3 \sin\theta \cdot \sin\theta$$
$$\sigma_n = \sigma_1 \cos^2\theta + \sigma_3 \sin^2\theta$$

- Applying trigonometric relationships:

$$\cos^2\theta = ½(1 + \cos 2\theta)$$
$$\sin^2\theta = ½(1 - \cos 2\theta)$$

- Simplifying, gives: $\sigma_n = ½(\sigma_1 + \sigma_3) + ½(\sigma_1 - \sigma_3)\cos 2\theta$
- and,

$$\text{force parallel } AB = \text{force} \perp BC \text{ resolved on } AB - \text{force} \perp AC \text{ resolved on } AB$$

or

$$1 \cdot \sigma_s = \sigma_1 \cos\theta \cdot \sin\theta - \sigma_3 \sin\theta \cdot \cos\theta$$

- The force perpendicular to AC resolved on AB acts in a direction opposite to the force perpendicular to BC resolved on AB, hence a negative sign is needed in equation, which further simplifies to: $\sigma_s = (\sigma_1 - \sigma_3)\sin\theta \cdot \cos\theta$
- Applying trigonometric relationships: $\sin\theta \cdot \cos\theta = ½ \sin 2\theta$
- Simplifying, gives: $\sigma_s = ½(\sigma_1 - \sigma_3)\sin 2\theta$

- From equations we can determine that the planes of **maximum normal stress** are at an angle θ of 0° with σ3, because cos 2θ reaches its maximum value (cos 0°=1).
- Secondly, planes of **maximum shear stress** lie at an angle θ of 45° with σ3 because sin 2θ reaches its maximum value (sin 90° =1).

2.4.5: Stress tensor

- The stress ellipsoid is a convenient way to visualize the state of stress, but it is cumbersome for calculations.
- It is difficult to determine the stresses acting on a randomly chosen plane in a three-dimensional body.
- The stress tensor mathematically describes the stress state in terms of three orthogonal stress axes.
- It turns out that we can completely specify the **state of stress** at a point within the earth can be thought of as acting on the surfaces of a tiny cube.
- While the cube is stationary, forces on opposite faces must be equal and opposite, so there are three surfaces, with nine stress components, to consider. The nine components can be represented by a matrix, the stress tensor.

$$\begin{pmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{pmatrix}$$

- Arguments involving moments can be used to show that $\sigma_{12} = \sigma_{21}$ etc. so, the matrix is symmetric and there are only six independent components.
- A vector is a first-rank tensor (3^1 =3 components) and a scalar is a zero-rank tensor (3^0 =1 component).
- For stress tensor this means, $3^2 = 9$ components. Geologic examples of zero-rank tensors are pressure, temperature, and time; whereas force, velocity, and acceleration are examples of first-rank tensors.

2.4.6: Principal stresses

- In general, there will be three special mutually perpendicular planes, which suffer no shear stress, only normal stress.
- The poles to these planes are the **stress axes**, and the stresses that act along them are called **principal stresses.** $\sigma_1 > \sigma_2 > \sigma_3$. The stress axes correspond to the **eigenvectors** of the stress tensor.
- If the stress axes 1, 2, and 3 happen to coincide with the coordinate axes 1, 2, and 3 then the stress tensor becomes very simple.

$$\begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix}$$

- If two of the principal stresses are zero, then the state of stress is described as **uniaxial**.
- If one of the principal stresses is zero, and two are non-zero, then the stress is **biaxial**.

- If all three principal stresses are non-zero (even if two or three are the same) then the stress state is **triaxial**.

2.5: Type of stress

2.5.1: Mean stress

- If we take the average of the magnitudes of the three principle stresses, we are finding the **mean stress** which is equivalent to the normal concept of pressure (e.g. in metamorphic petrology).
- Mean stress $\sigma_m = (\sigma_1 + \sigma_2 + \sigma_3)/3$
- The mean stress is often called the hydrostatic component of stress or the hydrostatic pressure, because a fluid is stressed equally in all directions.
- Because the magnitude of the hydrostatic stress is equal in all directions it is an isotropic stress component. Isotropic stress acts equally in all directions, it results in a volume change of the body.

2.5.2: Deviatoric stress

- The rest of the stress, which we get by subtracting the mean stress from the three diagonal components of the stress tensor, is called the **deviatoric** or **differential** stress. In other word difference between mean stress and total stress is the deviatoric stress (σ_{dev}).
- Deviatoric stress = $\begin{pmatrix} \sigma_{11} - \sigma_m & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} - \sigma_m & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} - \sigma_m \end{pmatrix}$
- An easy way to think about the mean and deviatoric stress components is to consider that
  - the mean stress acts to change volume
  - the deviatoric stress acts to change shape

2.5.3: Differential stress

- Another useful measure of the part of the stress that acts to change shape is just the difference between the maximum and minimum principal stresses. This concept comes from the concept of Mohr diagram.
- Differential stress $\sigma_d = (\sigma_1 - \sigma_3)$
- This measure is very useful in studies of fracture formation, and any situation where the value of the intermediate principal stress is less important than the two extremes.

2.5.4: Effective stress

- Sometimes part of the mean stress in a rock is supported by pore fluid pressure. This reduces the effect of normal stresses on the mineral grains, effectively reducing the mean stress, but leaves the shear stresses unaffected.
- The effective stress (or effective pressure) is defined as the mean stress minus the pore fluid pressure.

2.6: Stress regimes

2.6.1: Standard stress states

- Standard states of stress are those where stress is due entirely to gravity acting on the rocks of the lithosphere.

- The **hydrostatic** and **lithostatic** states of stress are the simplest, in which all three principal stresses are equal $\sigma_1 = \sigma_2 = \sigma_3$. Under these circumstances the stress ellipsoid is a sphere and the directions of the stress axes are undefined.
- **Hydrostatic** stress describes the situation in a water body at rest. Because water is virtually incompressible all surfaces 'feel' the same stress $\sigma_1 = \sigma_2 = \sigma_3 = \rho gz$ where ρ is the density of water, g is the acceleration due to gravity, and z is the depth. If the water in a porous rock unit is in continuous connection with the surface, the pressure in that fluid is likely to be approximately hydrostatic.
- **Lithostatic** stress is similar, but due to the density of overlying rock, not water. It's an appropriate description for parts of the crust that have remained stable under their own weight for long periods of geologic time; slow ductile deformation has allowed them to behave like a heavy fluid.
- The **Uniaxial-strain** state of stress is an adjusted state of stress that resembles the lithostatic state but takes into account the fact that rocks are compressible.
- Therefore, the effect of the weight of overlying rock is to cause **compaction.** Because of compaction vertical surfaces do not 'feel' as much stress as horizontal surfaces.
- In theory, the reduction in the horizontal stress is a function of Poisson's ratio ν, a measure of compressibility that we will meet shortly.

$$\sigma_x = \sigma_y = \frac{\nu}{1-\nu}\sigma_z = \frac{\nu}{1-\nu}\rho gz \,;$$

- In practice, the state of stress in most sedimentary basins undergoing compaction is somewhere between the uniaxial strain state and the lithostatic state.
- **Note:** the word "uniaxial" is used differently in stress and strain studies. Uniaxial strain describes a situation where two of the principal strains are equal; in uniaxial stress two of the principal stresses are zero.

2.6.2: Tectonic stress states

- In general, the stress axes σ_1, σ_2 and σ_3 do not coincide with the spatial axes, though *at the Earth's surface*, one of the stress axes always roughly coincides with the vertical axis "z".
- This is because the Earth's surface is approximately horizontal and is a surface of zero shear stress (neglecting the rather small shear stresses imposed by flowing water and air.)
- This principle was first put forward by Anderson, and a state of stress in which one principal stress is vertical is often described as **Andersonian**.
- There are three Andersonian regimes of stress, each characterized by a particular distribution of faults.
  - Gravity or normal-fault regime: σ_1 vertical
  - Wrench or strike-slip regime: σ_2 vertical
  - Thrust regime: σ_3 vertical
- Note that in each of these regimes the dominant faults are **conjugate faults** which lie on either side of σ_1 and intersect along σ_2.

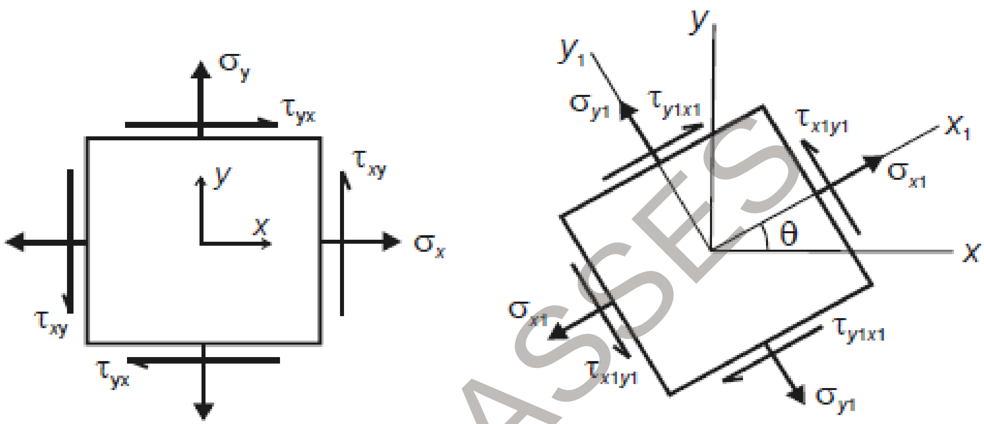
2.6.3: Calculating the stress on a surface

- Matrix multiplication- It's possible to calculate the stress on any surface (known as the **resolved stress** or traction) by geometrical constructions, but if the stress tensor is known, it is easier by matrix multiplication. For linear algebraists, if the state of stress is represented by the stress tensor **T**, and **x** is a vector representing the pole to a plane, then the stress vector **σ** on that plane is calculated by matrix multiplication

$$\boldsymbol{\sigma} = \mathbf{T}.\mathbf{x}$$

2.7: Mohr's circle for stress

- The transformation equations for plane stress can be represented in graphical form by a plot known as Mohr's Circle.
- This graphical representation is extremely useful because it enables you to visualize the relationships between the normal and shear stresses acting on various inclined planes at a point in a stressed body.
- Using Mohr's Circle you can also calculate principal stresses, maximum shear stresses and stresses on inclined planes.



$$\sigma_{x1} = \frac{\sigma_x + \sigma_y}{2} + \frac{\sigma_x - \sigma_y}{2}\cos 2\theta + \tau_{xy}\sin 2\theta$$

$$\tau_{x1y1} = -\frac{(\sigma_x - \sigma_y)}{2}\sin 2\theta + \tau_{xy}\cos 2\theta$$

- If we vary θ from 0° to 360°, we will get all possible values of σ_{x1} and τ_{x1y1} for a given stress state. It would be useful to represent σ_{x1} and τ_{x1y1} as functions of θ in graphical form.

2.7.1: Analysis of Stress and Strain

- When a structural element is subjected to several types of loads acting simultaneously, say bending and torsion, principal stresses occur.
- These stresses act on principal planes where the shear stresses are zero. In addition, many engineering problems, such as axial bars, beams in bending and circular members in torsion, are examples of a state of stress called **plane stress** ($\sigma z = \tau zx = \tau zy = 0$).
- Our procedure for determining principal stresses for a state of plane stress is as follows:
- Determine the point on the body in which the principal stresses are to be determined.
- Treating the load cases independently and calculated the stresses for the point chosen. When applicable combine the stresses to determine the state of stress at the point.
- Choose a set of x-y reference axes and draw a square element centred on the axes.

- Identify the stresses σ_x, σ_y, and $\tau_{xy} = \tau_{yx}$ and list them with the proper direction.
- Calculate the principal stresses, the maximum shear stress and the principal plane if required.

Principal Stresses (Shear Stress = 0):

$$\sigma_1 = \frac{\sigma_x + \sigma_y}{2} + \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}}$$

$$\sigma_2 = \frac{\sigma_x + \sigma_y}{2} - \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}}$$

Maximum Shear Stress:

$$\tau_{max} = \sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^{\ 2}}$$

$$\tau_{max} = \frac{\sigma_1 - \sigma_2}{2}$$

Principal Planes (*Planes on which Principal Stresses Act*):

$$2\theta_p = \tan^{-1}\frac{2\tau_{xy}}{\sigma_x - \sigma_y}$$

Plane of Maximum Shear Stress:

$$2\theta_s = \tan^{-1} - \frac{\sigma_x - \sigma_y}{2\tau_{xy}}$$

Average Stress (*Shear Stress is Maximum*):

$$\sigma_{avg} = \frac{\sigma_x + \sigma_y}{2}$$

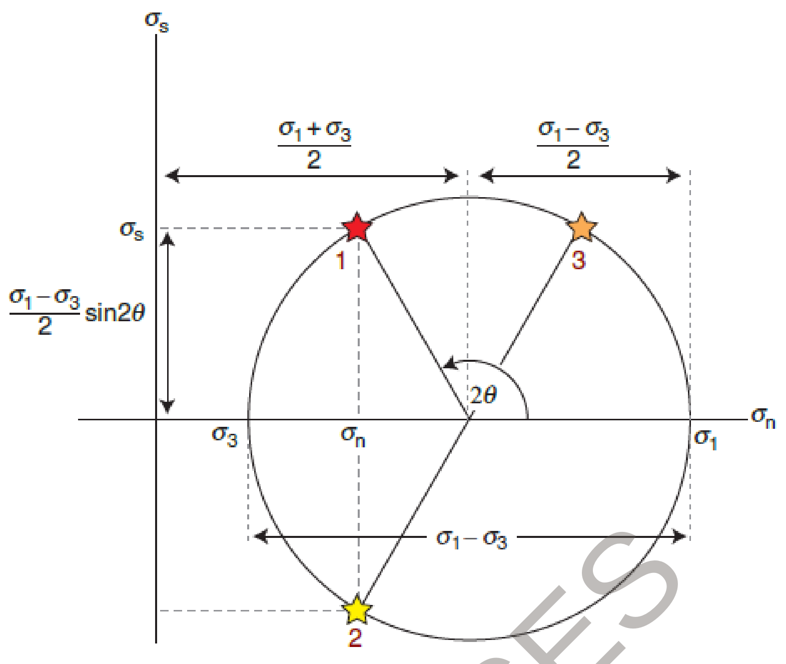
Important Observations:

- Principal stresses occur on mutually perpendicular planes.
- Shear stresses are zero on principal planes.
- Planes of maximum shear stress occur at 45° to the principal planes.
- The maximum shear stress is equal to one half the difference of the principal stresses.

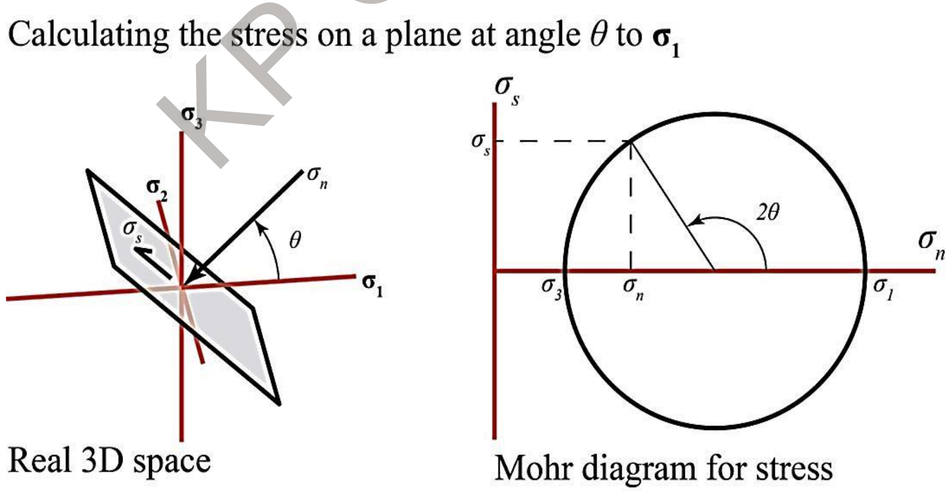
2.7.2: Construction of Mohr diagram

- To construct a Mohr diagram we draw two mutually perpendicular axes; σ_n is the abscissa (x-axis) and σ_s is the ordinate (y-axis).
- The maximum principal stress (σ_1) and the minimum principal stress (σ_3) act on plane P, which makes an angle θ with the σ_3 direction.

- In the Mohr construction we then plot σ_1 and σ_3 on the σ_n-axis because they are normal stresses.



- We then construct a circle through points σ_1 and σ_3, with the midpoint, at $1/2(\sigma_1+\sigma_3)$ as center, and a radius of $1/2(\sigma_1 - \sigma_3)$.
- Next, we draw a line from center to red star such that obtuse angle is equal to 2θ (we plot twice the angle θ, which is the angle between the plane and σ_3 ,we measure 2θ from the σ_1-side on the σn-axis).
- When this is done, the Mohr diagram is complete and we can read off the value of σ_n, along the σ_n-axis, and the value of σ_s, along the σs -axis for our plane.

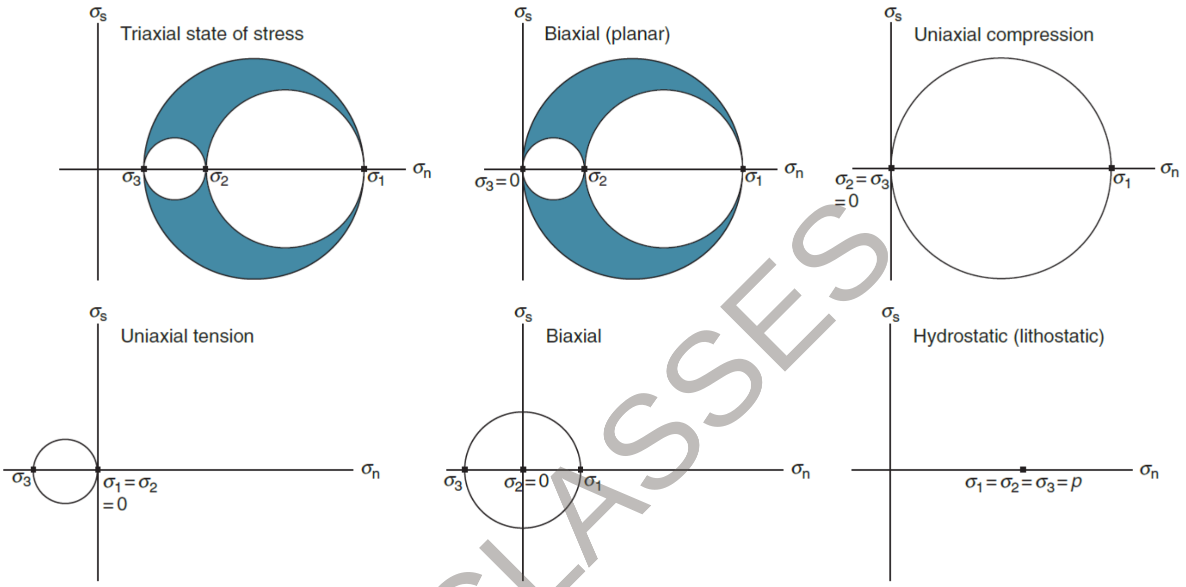


$$\sigma_n = \frac{\sigma 1+\sigma 3}{2} + \frac{\sigma 1-\sigma 3}{2}\cos 2\theta$$

$$\sigma_s = \frac{\sigma 1-\sigma 3}{2}\sin 2\theta$$

- As normal stress is plotted on the x-axis of a graph, and shear stress is plotted on the y-axis, therefore, all possible combinations of normal and shear stress fall inside a circle, that crosses the x axis at σ_1 and σ_3

- If we restrict attention to planes parallel to σ_2 then the combinations of normal and shear stress lie on the circle itself. The highest stresses always fall on these planes, so this is a useful diagram for predicting fractures.
- It's possible to use it to predict the orientation of the plane that first exceeds the failure strength of the rock.
- The conditions for brittle failure are represented by a failure envelope. When the differential stress becomes large enough, the Mohr circle intersects the failure envelope and fracture occurs.
- For other orientations of planes, a 3D Mohr diagram is needed; it consists of 3 Mohr circles, one each for planes parallel to σ1, σ2, σ3.



2.8: Measuring of neotectonic stress

- It is difficult to measure stress directly. Most methods of measuring stress actually measure the effect of stress on some material - the strain.
- Typically, we try to choose a material for which the relationship between stress and strain (the constitutive equation) is very well known.
- There are only a few methods for the direct measurement of stress in the Earth at present day. However, the present state of stress is important in petroleum production because it partially determines whether fractures are held open.
- In all these methods, we actually measure an elastic strain. We can use this to estimate stress because elastic strain and stress are typically linearly related.

2.8.1: Borehole breakouts

- Boreholes may respond to deviatoric stress by showing breakouts. Typically, in breakout a borehole becomes elliptical, and the orientation of the elliptical outline can be determined from oriented calliper logs.
- The long axis of the ellipse represents the minimum compressive stress acting on the borehole, whereas the short axis represents the direction of maximum compression.
- The orientation of the breakout is often taken to show the orientations of two of the principal stresses. However, this assumes
  - the borehole is vertical; and

• the stress is Andersonian

- Strictly speaking, breakouts indicate the maximum and minimum stresses in the plane perpendicular to the well, which are not necessarily the stress axes.

2.8.2: Overcoring

- In overcoring, a strain gauge is embedded in the bottom of a borehole.
- Then the hole is deepened with a bit that leaves the strain gauge sticking up from the bottom of the borehole, surrounded by an annular empty space, removing the stress from the surrounding rock.
- The change of shape of the core is recorded (typically a very small change) and the stress is calculated from the elastic properties of the rock (which can be measured if the core is recovered to the surface).

2.8.3: Leakoff testing

- In leakoff testing a portion of a borehole is sealed, and then fluid is pumped into the sealed portion.
- When the fluid pressure exceeds the minimum principal stress σ_3 the effective σ_3 becomes negative (tensile) allowing fractures to open.
- This method can measure the magnitude and potentially the orientation of σ3 if the induced fractures can be imaged.

2.8.4: Earthquake focal mechanisms

- Earthquake focal mechanisms define a fault plane and a nodal plane, and allow the definition of P (compression) and T (extension) axes that define the elastic strain released in the earthquake.
- The axes are placed so as to bisect the nodal planes. Assuming that stress is directly related to elastic strain, the P axis is equated with σ1 and the T axis with σ3, giving directions but not magnitudes for the principal stresses.

2.9: Measuring paleostress from faults

Principles

Information from faults

Faults give information about

- Overall strain
- The stress that caused faulting

Several methods have been developed to look at whole populations of faults. In general, these methods look at the orientations of faults, together with slicken lines on those fault surfaces.

Assumptions

- In analyzing fault populations, we need to assume that the slicken lines formed more-or-less in the orientation we find them now.
- Furthermore, we often have to assume that the strain axes associated with deformation by faults coincide with the stress axes. This is only reasonably true if
    - the rock is isotropic and

- the deformation is non-rotational.

Hence fault slip analysis only works in areas of low strain in reasonably homogeneous rocks where there have not been large rotations of blocks during deformation.

Conjugate faults

Geometry

- Many common configurations of faults are variations on the theme of **conjugate** faults: multiple faults in 2 families, with ~60° angle between them.
- We explain these dynamically as shear fractures resulting from critical stress for brittle failure (the Mohr-Coulomb failure model), which can also be replicated in experiments.
- Failure occurs first on planes oriented such that the plane normal (or pole) is at <45° (often about 30°) on either side of the minimum compressive stress σ_3; in other words, the fault planes are at ~30° to σ_1.

Joints or **veins** may also form if the fluid pressure was high at the time of fracturing. These are typically perpendicular to σ_3.

Criteria for conjugate faulting

In order to identify normal faults as conjugate we need to show:

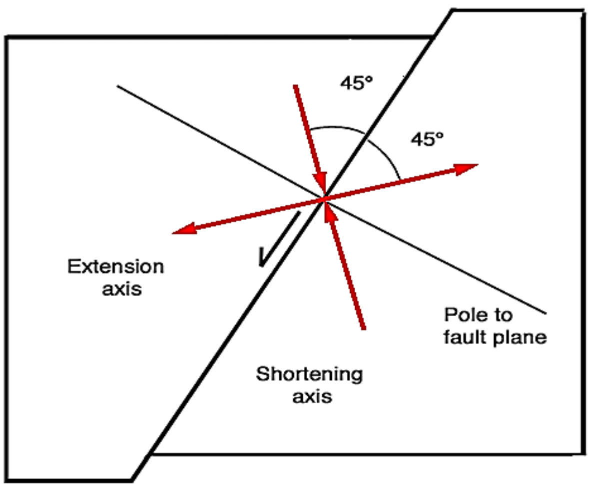
- orientation in two clusters at ~60°
- consistent slip (narrow wedge moved inward)
- both sets of faults active in same time interval

Conjugate faults indicate the orientations of the principal stresses, not their magnitudes

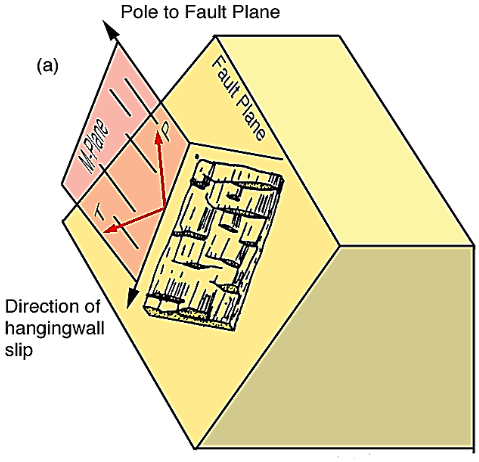
2.10: Orientation of mean P & T axes

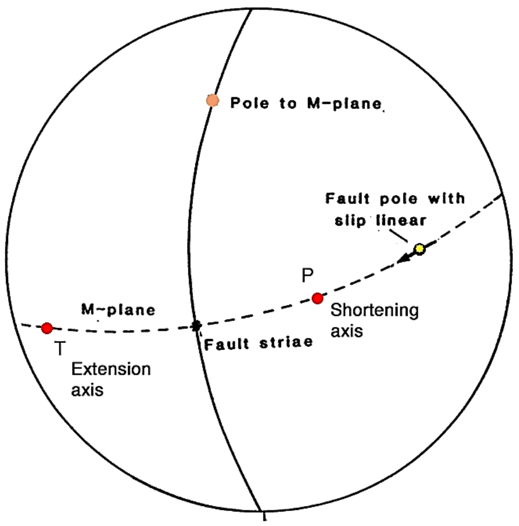
- Each fault in a volume of faulted rock contributes a small amount to the overall strain. If we 'average out' the strain due to a fault over a volume of the lithosphere, we can define strain axes S_1 and S_3. Both axes lie at 45° to the fault plane, and they are the same directions as the T and P axes identified in seismic studies of active faults.

Axes for a single fault, in 2D



Axes for a single fault in 3D





So the most obvious method of dealing with data from numerous faults is to plot the P and T axes from all the faults and find the mean of each, to give an estimate of the overall strain axes, often assumed to parallel the stress axes.

2.10.1: P&T dihedra

- Assumptions about P and T axes work best for new fractures in unfractured rock. If pre-existing fractures exist in a rock, they may undergo slip in response to states of stress that are not in the ideal directions. In this case the apparent P and T axes will be very scattered.
- The 'dihedra' method attempts to avoid this problem. We take each fault in turn. Suppose we have a normal fault with slicken lines in the direction and sense of the half arrow, then we can say in principle that the maximum compressive stress σ_1 must have been somewhere in the white dihedron.
- In other words, we can exclude the shaded dihedra. Conversely, the minimum compressive stress $\sigma 3$ must lie in the shaded dihedra.
- In 3D the dihedra look a bit like a focal mechanism from a recent fault.

Diagram of 2D dihedra

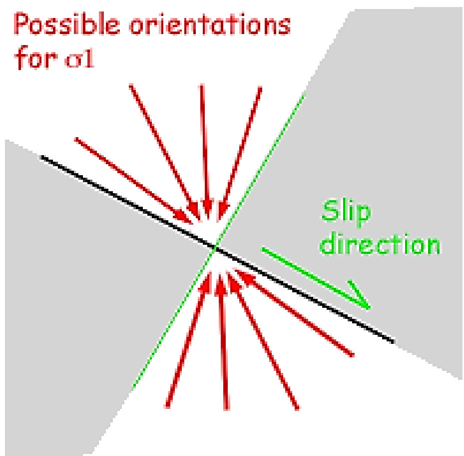
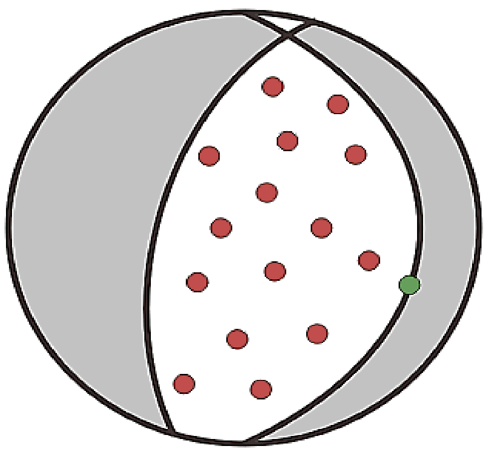


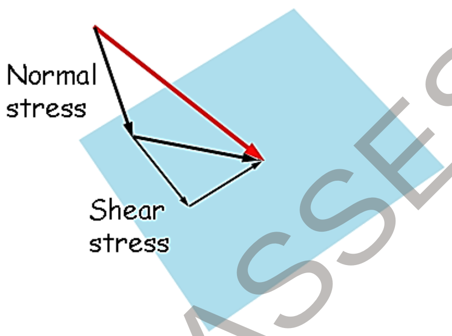
Diagram of 3D dihedra



- The above is for one fault. In the method of P and T dihedra, we look at all the faults.
- Each measurement from a fault plane is able to exclude exactly half the stereographic projection from consideration as a location for σ1, sometimes called the "P" axis.
- Typically, we use a computer program to take test points across the stereonet, and for each point we determine how many faults would be consistent with a P axis in that direction. Similarly, we contour for σ1 (or "T").
- Under favorable circumstances, with good, consistent data from faults that formed simultaneously with a range of fault orientations, we are able to locate the 'true' P and T axes within quite a small area of the stereographic projection.

2.10.2: Stress inversion

- In general, for a given state of stress in the earth, represented by stress tensor T, we can calculate the stress on any plane. There will be components of normal and shear stress.



- Ideally, if we can figure out the state of stress T, then the resolved shear stress should predict accurately the orientations of slicken lines on all the various fault surfaces.
- Stress inversion methods require more computer power than the previous methods. Typically, the computer takes an arbitrary trial state of stress T and predicts the resolved shear stress on all the observed fault surfaces.
- The difference between the predicted resolved shear stress and the slicken line orientation is calculated.
- This operation is repeated for a vast number of different states of stress T, and the state that minimizes the differences is chosen as the solution. In practice, there are numerous methods of stress inversion that differ in:
  - how the error is calculated
  - how the errors are summed
  - what methods are used to optimize the search; if trial values of T are chosen intelligently the errors can be minimized rapidly.

2.11: Response of materials to stress

For each material under a particular range of conditions, there is a relationship between stress and strain, or between stress and strain rate, which is called the **constitutive law**.

2.11.1: Elastic strain

- The simplest response is one in which finite strain is proportional to applied stress. In this case, if the stress decreases, the strain decreases too, so we say the strain is **recoverable,** or **elastic.**

- This type of strain is very important for understanding seismic waves and for geological engineering applications.
- However, natural elastic strains in rocks are small and are not preserved in ancient rocks.
- In elastic deformation, note that the **finite strain is related to stress** in a proportional way.

2.11.2: Young's modulus

- **Longitudinal Stress-strain relationship**
- **Hooke's Law:** In elastic deformation, the **finite strain is related to stress** in a proportional way.
- The stress-strain relationship in one dimension for an elastic material is
- Normal stress $\sigma_n = E.e$
- where E is **Young's modulus of elasticity** and e is the **extension** or fractional change in length**.**

2.11.3: Poisson's ratio

- **Length-width relationship**
- Most rocks when subjected to a compressive stress in one direction will tend to expand at right angles to this direction.
- This tendency is expressed by **Poisson's ratio** ν, the ratio of thickening to shortening when stressed in this way.
- Poisson's ratio $\nu = - e_x / e_z$
- Where e_z is the extension parallel to σ_1 and e_x is the extension perpendicular to σ_1.
- For a sample that retains constant volume, the Poisson's ratio will be 0.5. Most rocks show a negative change in volume when uniaxially stressed, and therefore show Poisson's ratio between 0.5 and 0.
- For an isotropic elastic material, it turns out that Young's modulus and Poisson's ratio are all that's necessary to describe the elastic properties. Though other moduli are sometimes used, they can be derived from these two quantities.

2.11.4: Brittle failure

Fracture propagation

- Most rocks near the Earth's surface, subjected to increasing differential stress, will eventually fail by brittle fracture.
- When failure occurs, the strength of the rock falls to zero across the plane of fracture. This is called loss of **cohesion**.
- Fractures actually propagate over a period of time (may be very fast), exploiting pre-existing microfractures. At any instant a fault is bounded by a **tip line**.

Fractures may propagate as

- Mode 1 - extensional fracture
- Mode 2 - shear fracture slip perpendicular to tip line
- Mode 3 - shear fracture slip parallel to tip line

Fracture condition

- The condition for failure can be represented on the Mohr diagram for stress by a **failure envelope.** Several different formulas for the failure envelope have been proposed.
- The simplest was suggested by Coulomb and is a straight-line relationship between shear-stress and normal stress acting on the plane that fractures.

- $\sigma_s = C + \sigma_n \tan \varphi$

- where φ is known as the **angle of internal friction**, and the constant C is the **cohesion**.
- The Mohr construction can be used to show that this predicts that shear fractures will form such that the fracture pole makes an angle with σ_1 given by:

$$\theta = 45° + \varphi/2$$

Pre-existing fractures

- Byerlee derived an empirical relationship for movement on **pre-existing fractures**
- Notice how under "**Byerlee's law**" the failure envelope does not extend into the tensile field on the left of the diagram.
- This means that the rock cannot sustain any tensile stress - it has no cohesion.

$\sigma_s = 0.85\sigma_n$ (for $\sigma_n < 200$ MPa)

$\sigma_s = 50$ MPa $+ 0.60\sigma_n$ (*for* $\sigma_n > 200$ MPa)

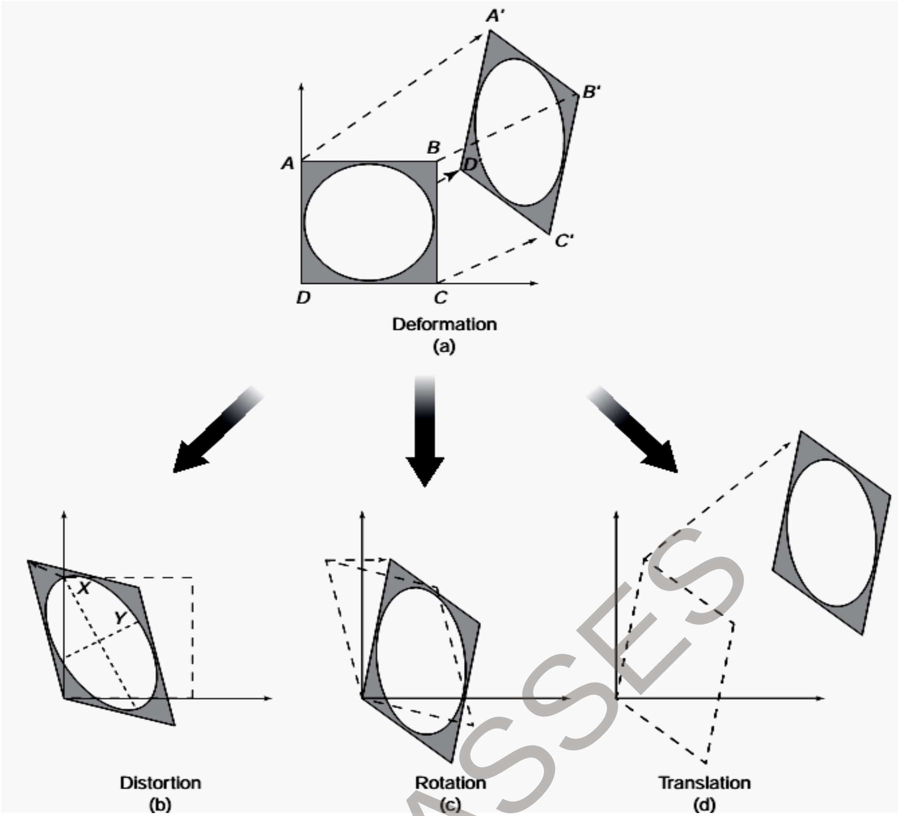
2.11.5: Faults vs. Cataclastic flow

- Many brittle fractures occur as discrete planes, but in some rock units the grains move independently or there are multiple anastomosing fractures, that create the appearance of continuous deformation.
- The resulting **deformation band** may appear ductile at outcrop scale but is brittle at microscopic scale.
- When independent grains move (e.g. in a poorly cemented sandstone), the deformation is called **granular flow.**
- When the moving particles are created by fracturing of pre-existing grains, the process is called **cataclastic flow.**
- These types of flow may have a significant effect on porosity. In loosely cemented rocks with high initial porosity, cataclastic and granular flow may act to reduce the porosity and permeability by creating a denser packing of particles.
- Faults of this type can act as barriers to the migration of fluids in the subsurface.
- On the other hand, in highly cemented non-porous rocks, cataclastic flow may lead to the creation of porosity, a phenomenon known as **dilatancy**.
- Such faults may act as conduits for fluids and may become mineralized as a result.

2.12: Deformation and Strain

- The study and quantification of these distortions, which occur in response to forces acting on bodies, is the subject of "Deformation and Strain".
- When forces affect the spatial geometry of a body, we enter the realm of deformation. Most simply stated: deformation of a body occurs in response to forces.
- The response of a body to forces may have many faces. In some cases, the body is merely displaced or rotated, in other cases, the body becomes distorted.
- Deformation and strain are closely related terms that are sometimes used as synonyms, but they are not the same.
- Deformation describes the collective displacements of points in a body; in other words, it describes the complete transformation from the initial to the final geometry of a body.
- This change can include a **translation**, a **rotation**, and a **distortion**. Strain describes the changes of points in a body relative to each other; so, it describes the distortion of a body.

- The displacement of points within the body, represented by the four corner points of the square, are indicated by vectors.



- Their sum gives the total displacement field. a change in the order of addition of these vector components affects the final result.
- Deformation, therefore, is not a vector entity, but a second-order tensor. When the rotation and distortion components are zero, we only have a translation.
- This translation is formally called rigid-body translation (RBT), because the body undergoes no shape change while it moves.
- When the translation and distortion components are zero, we have only rotation of the body.
- By analogy to translation, we call this component rigid-body rotation (RBR), or simply spin And, when translation and spin are both zero, the body undergoes distortion; this component is described by strain. So, strain is a component of deformation and therefore not a synonym.
- Deformation describes the complete displacement field of points in a body relative to an external reference frame, such as the edges of the paper.
- Strain, on the other hand, describes the displacement field of points relative to each other. This requires a reference frame within the body, an internal reference frame, like the edges of the square.
- One final element is, the hydrostatic component of the total stress, however, contributes to deformation by changing the area (or volume, in three dimensions) of an object.
- Area or volume change is called dilation and is positive or negative, as the volume increases or decreases.
- Because dilation results in changes of line lengths it is similar to strain, except that the relative lengths of the lines remain the same.

- Thus, it is useful to distinguish strain from volume change. In summary, deformation is described by:
  - Rigid body translation (or translation)
  - Rigid body rotation (or spin)
  - Strain
  - Volume change (or dilation)

2.12.1: Homogeneous strain and the strain ellipsoid

- Strain is homogeneous when any two portions of the body that were similar in form and orientation before are similar in form and orientation after strain.
- Homogeneous strain changes a square into a parallelogram and a circle into an ellipse; we define homogeneous strain by its geometric consequences:
  - ➢ Originally straight lines remain straight
  - ➢ Originally parallel lines remain parallel
  - ➢ Circles became ellipses; in three-dimension, sphere became ellipsoids.
- When one or more of these three restrictions does not apply, we call the strain heterogeneous.
- Homogeneity of deformation is a matter of scale. Consider a heterogeneous deformation feature like a fold, which can be approximated by three essentially homogeneous sections: the two limbs and the hinge.
- In a homogeneously strained, two-dimensional body there will be at least two material lines that do not rotate relative to each other, meaning that their angle remains the same before and after strain.
- In homogeneous strain, two orientations of material lines remain perpendicular before and after strain.
- These two material lines form the axes of an ellipse that is called the **strain ellipse**. Note that the lengths of these two material lines change from the initial to the final stage; otherwise we would not strain our initial circle.
- Analogously, in three dimensions we have three material lines that remain perpendicular after strain and they define the axes of an ellipsoid, the strain ellipsoid.
- The lines that are perpendicular before and after strain are called the **principal strain axes**.
- Their lengths define the strain magnitude and we will use the symbols X, Y, and Z to specify them, with the convention that $X \geq Y \geq Z$.
- In three-dimensional space, therefore, we use the three axes of the strain ellipsoid and three rotation angles.
- This means that the strain ellipsoid is defined by six independent components, which is reminiscent of the stress ellipsoid.

2.12.2: Strain path

- The measure of strain that compares the initial and final configuration is called the finite strain (*f*), when intermediate strain steps are determined they are called incremental strains (*i*).
- In fig 2 (2a &2b), Finite strains for the distortion of a square are the same, because the initial and final configurations are identical.
- The steps or strain increments, by which these final shapes were reached, however, are very different. Therefore, we may say that the strain paths of the two examples are different, but the finite strains are the same.

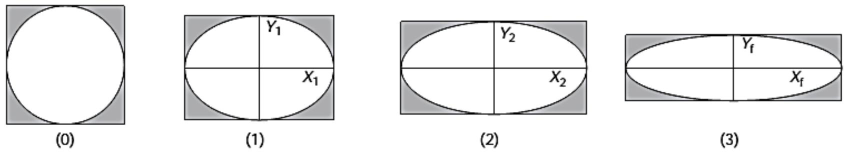


Fig.2a

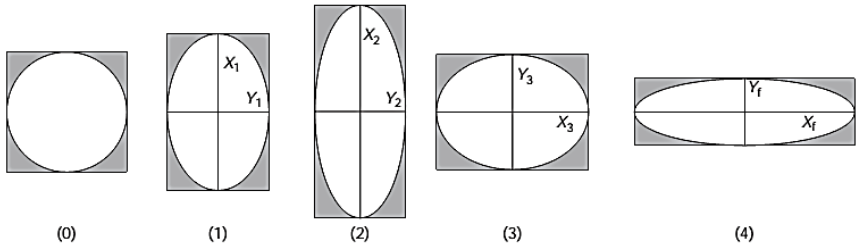
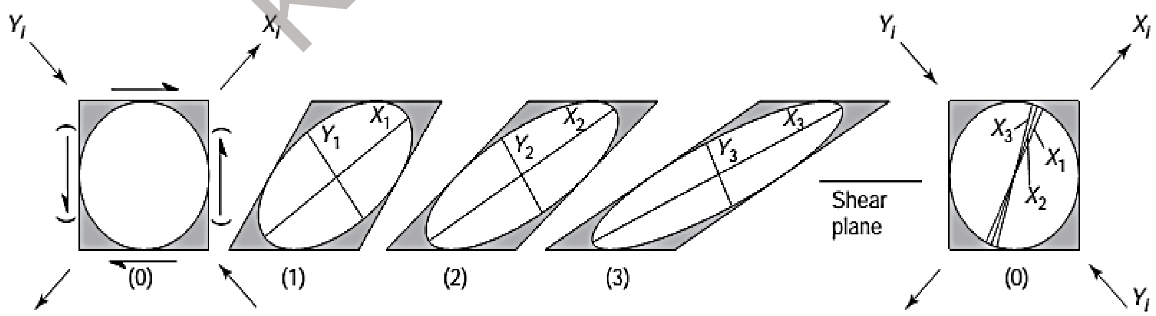


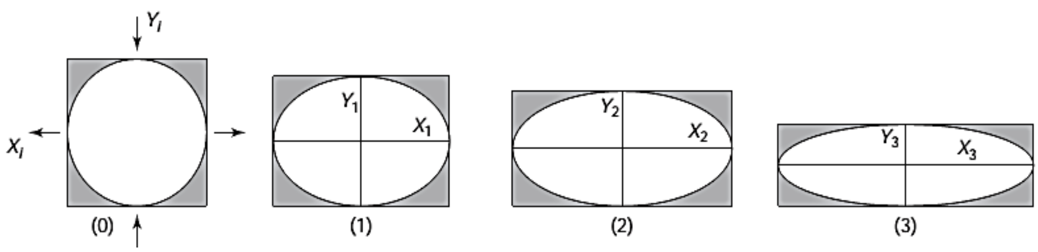
Fig. 2b

2.12.3: Coaxial and non-coaxial strain

- Earlier, we saw that strain involves the rotation of material lines where a material line is made up of a series of points in a body.
- There is no mechanical contrast between the material line and the body as a whole, so that material lines behave as passive markers.
- All material lines in the body, except those that remain perpendicular before and after a strain increment (principal strain axes) rotate relative to each other.
- In the general case for strain, the principal incremental strain axes are not necessarily the same throughout the strain history.
- In other words, the principal incremental strain axes rotate relative to the finite strain axes, a scenario that is called **non-coaxial strain** accumulation.
- The case in which the same material lines remain the principal strain axes at each increment is called **coaxial strain** accumulation.
- The component describing the rotation of material lines with respect to the principal strain axes is called the internal vorticity, which is a measure of the degree of non-coaxiality.

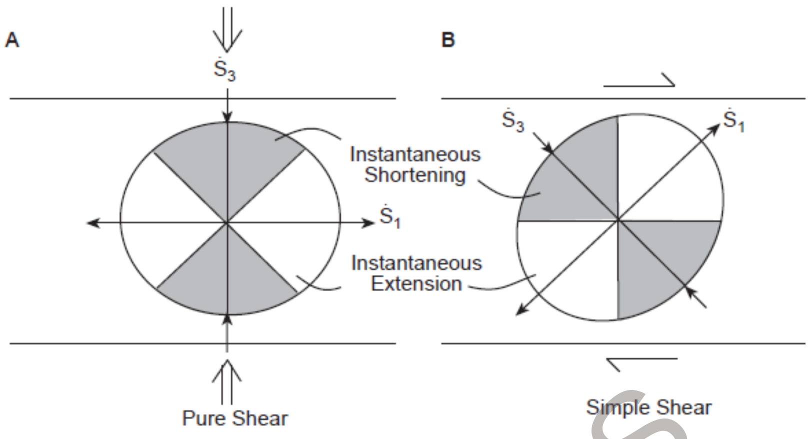


Non-coaxial strain



Coaxial strain

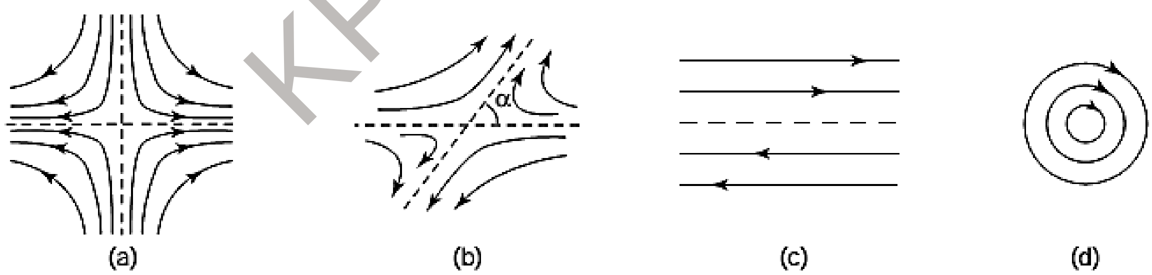
- If there is zero internal vorticity, the strain history is coaxial, which is sometimes called **pure shear**.
- The non-coaxial strain history describes the case in which the distance perpendicular to the shear plane remains constant; this is also known as **simple shear**.



- In reality, a combination of simple shear and pure shear occurs, which we call general shear.
- Internal vorticity is quantified by the **kinematic vorticity number**, W_k, which relates the angular velocity and the stretching rate of material lines.

$$W_k = \cos \alpha$$

- For pure shear $W_k=0$. For general shear $0 < W_k < 1$. For simple shear $W_k=1$.Rigid-body rotation or spin can also be described by the kinematic vorticity number (in this case, $W_k = \infty$) (remember that this rotational component of deformation is distinct from the internal vorticity of strain).



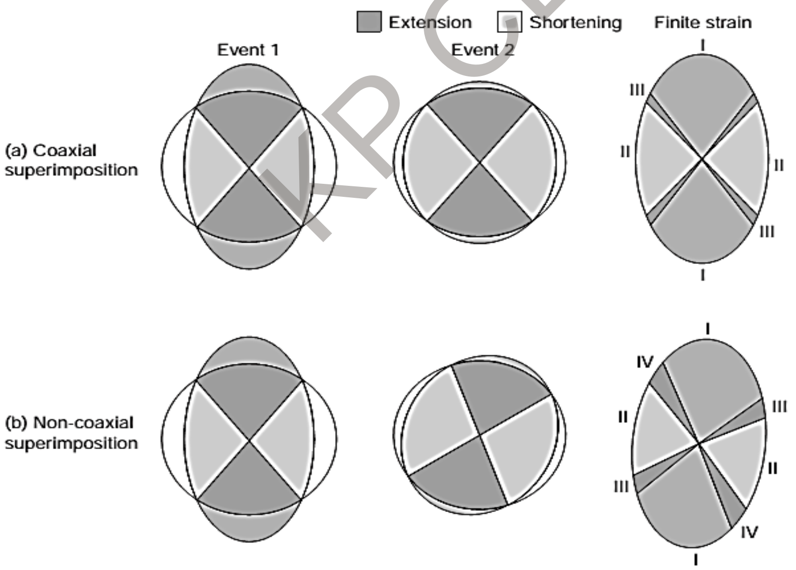
Particle paths or flow lines during progressive strain accumulation. These flow lines represent pure shear (a), general shear (b), simple shear (c), and rigid-body rotation (d). The cosine of the angle α is the kinematic vorticity number, W_k, for these strain histories; $W_k = 0$, $0 < W_k < 1$, $W_k = 1$, and $W_k = \infty$, respectively.

TYPES OF STRAIN

Coaxial strain	Strain in which the incremental strain axes remain parallel to the finite strain axes during progressive strain
Heterogeneous strain	Strain in which any two portions of a body similar in form and orientation before strain undergo relative change in form and orientation (also: *inhomogeneous strain*)
Homogeneous strain	Strain in which any two portions of a body similar in form and orientation before strain remain similar in form and orientation after strain
Incremental strain	Strain state of one step in a progressive strain history
Instantaneous strain	Incremental strain of vanishingly small magnitude (a mathematical descriptor); also called *infinitesimal incremental strain*
Finite strain	Strain that compares the initial and final strain configurations; sometimes called *total strain*
Non-coaxial strain	Strain in which the incremental strain axes rotate relative to the finite strain axes during progressive strain

2.12.4: Superimposed strain

- The strain path describes the superimposition of a series of strain increments. Considering only the two-dimensional case we recognize regions of extension and regions of shortening separated along two lines of zero length change in the strain ellipse.
- When we coaxially superimpose a second strain increment on the first ellipse, we obtain three regions: (I) a region of continued extension, (II) a region of continued shortening, and (III) a region of initial shortening that is now in extension.
- Superimposing an increment non-coaxially on the first strain state results in four regions: (I) a region of continued extension, (II) A region of continued shortening, (III) A region of initial shortening that is now in extension, and (IV) A region of extension that is now in shortening.



Superimposed strain. The strain ellipse contains regions in which lines are extended and regions where lines are shortened, which are separated by lines of zero finite elongation. (a) Coaxial superimposition of a strain event 2 produces regions in which lines continue to be extended (I), and regions where lines continue to be shortened (II), separated by regions where shortening during event 1 is followed by extension during event 2 (III). (b) Non-coaxial superimposition additionally produces a region where extension is followed by shortening during event 2 (IV). Practically this means that structures reflecting different strain states may be formed, especially in non-coaxial strain regimes such as shear zones.

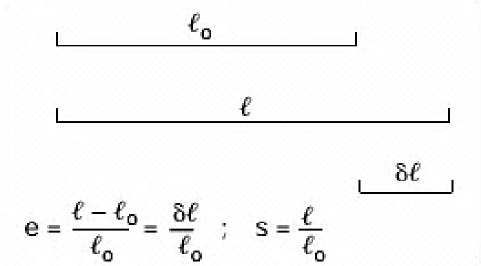
2.12.5: Strain quantities

- Having examined the necessary fundamentals of strain, we can now turn our attention to practical applications.
- In the next sections we will examine strain quantification using three measures: length change or longitudinal strain, volume change or volumetric strain, and angular change or angular strain.

Longitudinal Strain

- Longitudinal strain is defined as a change in length divided by the original length. Longitudinal strain is expressed by the elongation, e, which is defined as:

$$\mathbf{e} = (l - l_o)/l_o \quad \text{or} \quad \mathbf{e} = \delta l/l_o$$



- Where **l** is the final length, $\mathbf{l_o}$ is the original length, and **δl** is the length change. Because we divide values with the same units, longitudinal strain is a dimensionless quantity.
- This definition of elongation implies that negative values of '**e**' reflect shortening whereas positive values of '**e**' represent extension.
- We label the maximum, intermediate, and minimum elongations, $\mathbf{e_1}$**,** $\mathbf{e_2}$, and $\mathbf{e_3}$, respectively, with $\mathbf{e_1 \geq e_2 \geq e_3}$.

Volumetric Strain

- A relationship similar to that for length changes holds for three-dimensional change. For volumetric strain**,** Δ, the relationship is:

$$\Delta = (V - V_o)/V_o \quad \text{or} \quad \Delta = \delta V/V_o$$

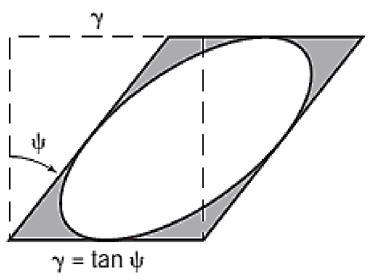
- Where **V** is the final volume, $\mathbf{V_o}$ is the original volume, and **δV** is the volume change. Volumetric strain is a ratio of values with the same units, so it also is a dimensionless quantity.
- Positive values for Δ represent volume gain, whereas negative values represent volume loss.

Angular Strain

- Angular strains are slightly more difficult to handle as they measure the change in angle between two lines that were initially perpendicular.
- The change in angle is called the angular shear, **ψ**, but more commonly we use the tangent of this angle, called the shear strain, **γ**.

$$\gamma = \tan \psi$$

- The shear strain is a dimensionless parameter.



Other Strain Quantities

- In calculations such as those associated with the Mohr circle for strain; we make use of a quantity called the **quadratic elongation**, λ, which is defined as

$$\lambda = (l/l_o)^2 = (1 + \mathbf{e})^2$$

- where **l** is the final length, **l_o** is the original length, and **e** is the elongation.
- The root of the quadratic elongation is called the **stretch**, **s,** which is a convenient strain parameter that directly relates to the dimensions of the strain ellipsoid.

$$\mathbf{s} = \lambda^{1/2} = l/l_o = 1 + \mathbf{e}$$

- Quadratic elongation, **λ**, and especially the stretch, **s,** describe the lengths of the principal axes (X, Y, and Z) of the strain ellipsoid:

$$X = s_1,\ Y = s_2,\ Z = s_3 \qquad \text{with } X \geq Y \geq Z, \text{ and}$$

$$X^2 = \lambda_1,\ Y^2 = \lambda_2,\ Z^2 = \lambda_3$$

- A circle with unit radius (r= 1) becomes distorted into an ellipse that is defined by the length of axes $\sqrt{\lambda_1}$ (i.e. = X) and $\sqrt{\lambda_2}$ (i.e.,=Y).
- As a consequence of this distortion, a line OP at an initial angle of ϕ with the X-axis becomes elongated (OP') with an angle ϕ' to the λ1/X-axis. **The relationship between ϕ and ϕ' is described by**:

$$\tan \varphi' = Y/X \cdot \tan \varphi = (\lambda_2/\lambda_1)^{1/2} \cdot \tan \varphi$$

$$\tan \varphi = X/Y \cdot \tan \varphi' = (\lambda_1/\lambda_2)^{1/2} \cdot \tan \varphi'$$

Natural strain in terms of the elongation, e, and the quadratic elongation, λ

- Elongation is defined as **$\delta l/l_o$**. This also holds for incremental strains, in which **l_o** represents the length at the beginning of each increment.
- For a vanishingly small increment (or infinitesimal strain), the elongation is defined as:

$$\mathbf{e}_i = \delta l/l_o$$

- The natural strain, ε (epsilon), is the summation of these increments:

$$\varepsilon = \sum_{l=l_o}^{l=l} \delta l/l_o = \int_{l_o}^{l} \delta l/l_o$$

- Integrating the above equation gives: $\varepsilon = \ln l/l_o = \ln \mathbf{s}$
- By using the formula for stretch, we will get:

$$\varepsilon = \ln (1 + \mathbf{e})$$
$$\varepsilon = \tfrac{1}{2} \ln \lambda$$

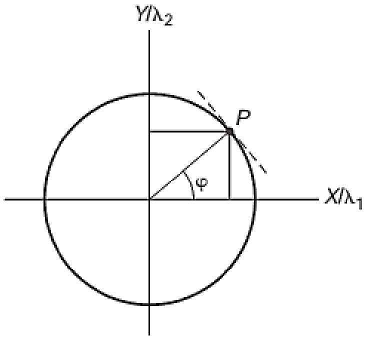
- This is the expression of **natural strain in terms of the elongation, e, and the quadratic elongation, λ.**

2.12.6: The Mohr circle for strain

- Strain state is described geometrically by an ellipsoid, so strain is a second-rank tensor.

- Mohr circle construction for strain can be used to represent the relationship between longitudinal and angular strain in a manner similar to that for σ_n and σ_s in the Mohr diagram for stress. Usually the quadratic elongation, λ, and the shear strain, γ, are used.
- Considering the following figure and applying some trigonometric relationships, we get:

$$\lambda = \lambda_1 \cos^2 \varphi + \lambda_3 \sin^2 \varphi$$
$$\lambda = \tfrac{1}{2}(\lambda_1 + \lambda_3) + \tfrac{1}{2}(\lambda_1 - \lambda_3) \cos 2\varphi$$
$$\gamma = [(\lambda_1/\lambda_3) - \lambda_3/\lambda_1 - 2)]^{1/2} \cos \varphi \sin \varphi$$
$$\gamma = -\tfrac{1}{2}(\lambda_1 - \lambda_3) \sin 2\varphi$$



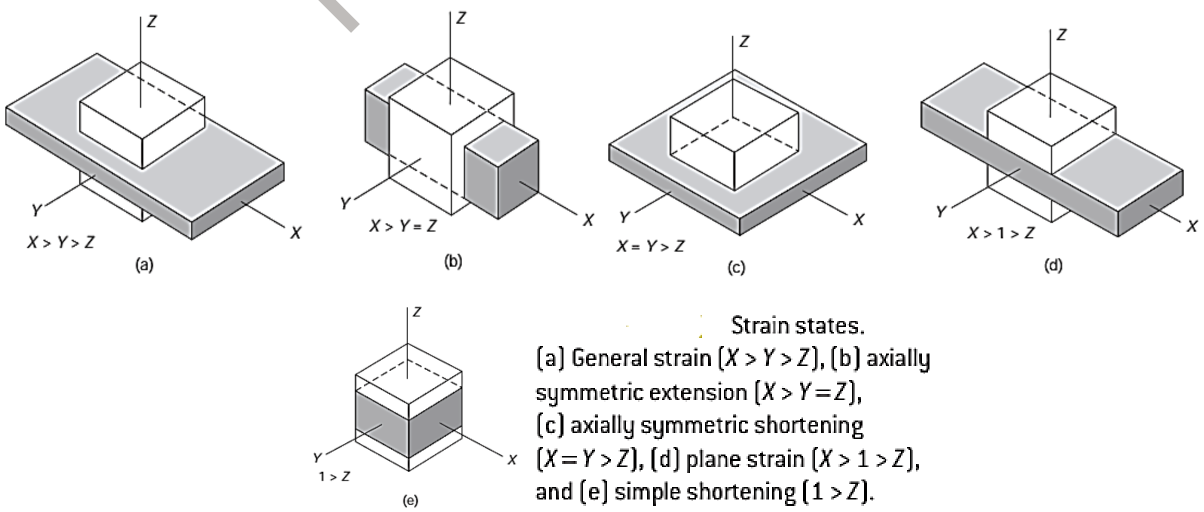
- But this expresses strain in terms of the undeformed state. It is more logical to express strain in terms of the deformed state.
- We therefore need to express the equations in terms of the angle ϕ' that we measure rather than the original angle ϕ, which is generally unknown.
- To this end we introduce the parameters $\lambda' = 1/\lambda$ and $\gamma' = \gamma/\lambda$ and use the equations for double angles. We then get:

$$\lambda' = \tfrac{1}{2}(\lambda_1' + \lambda_3') - \tfrac{1}{2}(\lambda_3' - \lambda_1') \cos 2\varphi'$$
$$\gamma' = \tfrac{1}{2}(\lambda_3' - \lambda_1') \sin 2\varphi'$$

- If you compare these equations with Equations of stress for the normal stress (σ_n) and the shear stress (σ_s)and follow their manipulation in Section - **Mohr Diagram for Stress**, we will find that above equations describe a circle with a radius ($\lambda_3' - \lambda_1'$), whose center is located at ($\lambda_1' + \lambda_3'$) in a reference frame with γ' on the vertical axis and λ' on the horizontal axis. This is the Mohr circle construction for strain.

2.12.7: Strain states

- Except for simple elongation, the strain states may represent constant volume conditions (that is, $\Delta = 0$), which means that $X \cdot Y \cdot Z = 1$. These strain states are illustrated in the following Figure:



Strain states.
(a) General strain ($X > Y > Z$), (b) axially symmetric extension ($X > Y = Z$), (c) axially symmetric shortening ($X = Y > Z$), (d) plane strain ($X > 1 > Z$), and (e) simple shortening ($1 > Z$).

TABLE :	STRAIN STATES
General strain[7] (triaxial strain)	A state in which all three strain axes have different lengths, as defined by the relationship $X > Y > Z$ (Figure a). This strain state does not imply anything about volume change.
Axially symmetric elongation	An axial strain that includes *axially symmetric extension*, where $X > Y = Z$ (Figure b), and *axially symmetric shortening*, where $X = Y > Z$ (Figure c). Axially symmetric extension results in a prolate strain ellipsoid, with extension occurring only in the X direction accompanied by equal amounts of shortening in the Y and Z directions ($Y/Z = 1$). This geometry is sometimes referred to as a cigar-shaped ellipsoid. Axially symmetric shortening requires equal amounts of extension ($X/Y = 1$) in the plane perpendicular to the shortening direction, Z. The strain ellipsoid assumes an oblate or hamburger shape.
Plane strain	A state where one of the strain axes (commonly Y) is of the same length before and after strain: $X > Y (= 1) > Z$ (Figure d). Thus plane strain is a special type of triaxial strain, but it can be conveniently described by a two-dimensional strain ellipse with axes X and Z, because no change occurs in the third dimension (Y). In many studies this particular strain state is assumed.
Simple elongation	A state where all material points move parallel to a straight line, defined by $X > Y = Z = 1$ or $X = Y (= 1) > Z$. In these two cases, a sphere becomes a prolate ellipsoid in extension and an oblate ellipsoid in shortening (Figure e), respectively. Because two strain axes remain of equal length before and after deformation, simple elongation must involve a change in volume ($\Delta \neq 0$), a volume decrease in the case of simple shortening and a volume increase in the case of simple extension.

2.12.8: Representation of strain (Flinn diagram)

- The inherently three-dimensional strain data can be conveniently represented in a two-dimensional plot, called a Flinn diagram, by using ratios of the principal strain axes.
- In the Flinn diagram for strain we plot the ratio of the maximum stretch over the intermediate stretch on the vertical (a) axis and the ratio of the intermediate stretch over the minimum stretch on the horizontal (b) axis:

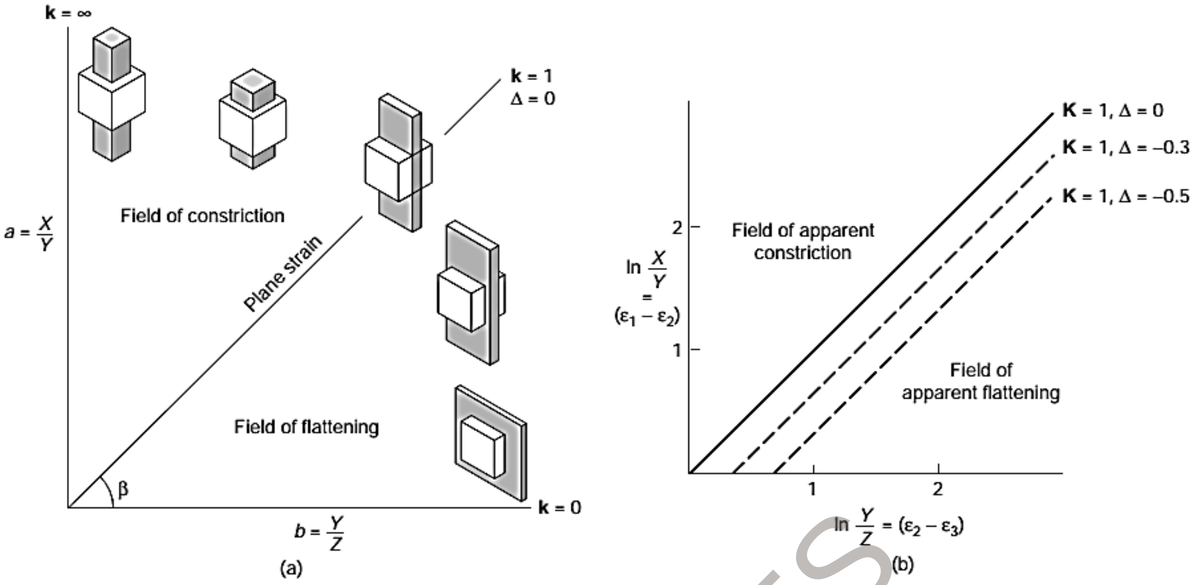
$$a = X/Y = (1 + e_1)/(1 + e_2)$$
$$b = Y/Z = (1 + e_2)/(1 + e_3)$$

- The shape of the strain ellipsoid is represented by the parameter**, k:**

$$\mathbf{k} = (a - 1)/(b - 1)$$

- The value of **k** describes the slope of a line that passes through the origin **(angle β)**
- A strain sphere lies at the origin of this plot (coordinates 1,1), representing a=b=1 or X=Y=Z=1.
- Ellipsoid shapes are increasingly oblate for values of **k** approaching 0 and increasingly prolate for values of **k** approaching ∞.
- If k=0, the strain is uniaxially oblate (a=X/Y=1), and if k=∞, the strain is uniaxially prolate (b=Y/Z=1).
- The value k=1 represents the special case for which **a** equals **b**, which is called plane strain (X≥Y=1 ≥Z).
- The line represented by k=1 state separates the field of constriction (∞>k>1) from the field of flattening (1 >k>0) in the Flinn diagram.
- **A useful modification of the Flinn diagram, called the Ramsay diagram,** uses the natural logarithm of the values a and b:

$$\ln a = \ln (X/Y) = \ln [(1 + e_1)/(1 + e_2)]$$
$$\ln b = \ln (Y/Z) = \ln [(1 + e_2)/(1 + e_3)]$$



- *Figure description: The Flinn diagram plots the strain ratios X/Y (a) In the Ramsay diagram (b) The logarithm of these ratios is used; in the case of the natural logarithm it plots $(\varepsilon 1 - \varepsilon 2)$ versus $(\varepsilon 2 - \varepsilon 3)$.*
- *The parameters k and K describe the shape of the strain ellipsoid. Note that volume change produces a parallel shift of the line k=1 or K=1.*
- Using $\ln \frac{X}{Y} = \ln X - \ln Y$, and $\varepsilon = \ln(1 + e)$
- The above equation can be derived as

$$\ln a = \varepsilon_1 - \varepsilon_2$$
$$\ln b = \varepsilon_2 - \varepsilon_3$$

- The parameter k of the Flinn diagram becomes K in the Ramsay diagram.

$$\mathbf{K} = \ln a/\ln b = (\varepsilon_1 - \varepsilon_2)/(\varepsilon_2 - \varepsilon_3)$$

- Both logarithmic plots with base e (natural logarithm, ln) and base 10 (log) are used in the Ramsay diagram.
- The Ramsay diagram is similar to the Flinn diagram in that the line K=1 separates the fields of constriction (∞> K>1) and flattening (1 >K>0) and the unit sphere lies at the origin (ln a = ln b=0).
- The origin in the Ramsay diagram has coordinates (0, 0). There are a few advantages to the Ramsay diagram**.**
- **First**, small strains that plot near the origin and large strains that plot away from the origin are more evenly distributed**.**
- **Second**, the Ramsay diagram allows a graphical evaluation of the incremental strain history, because equal increments of progressive strain (the strain path) plot along straight lines, whereas unequal increments follow curved trajectories.
- In the Flinn diagram both equal and unequal strain increments plot along curved trajectories.

2.13: Formula sheet (Stress and Strain)

Basic measures of stress

Stress Tensor

$$T = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}$$

Where σ_{xx} is normal stress on plane x
And σ_{xy} is shear stress on plane x parallel to axis y
T is symmetric (i.e. $\sigma_{xy} = \sigma_{yx}$)

Principal stresses

$\sigma_1 > \sigma_2 > \sigma_3$ are the normal stresses that operate parallel to the eigenvectors of **T** (The stress axes)

Mean stress

If the magnitudes of the principal stresses are $\sigma_1,\ \sigma_2, and\ \sigma_3$ then: $\sigma_m = {(\sigma_1 + \sigma_2 + \sigma_3)}/{3}$

Differential stress

$\sigma_d = \sigma_1 - \sigma_3$
Maximum shear stress = $\frac{\sigma_d}{2}$

Deviatoric stress

$$T_d = \begin{pmatrix} \sigma_{xx} - \sigma_m & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} - \sigma_m & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} - \sigma_m \end{pmatrix}$$

Stress on a plane

For a plane with unit normal vector x, $\sigma = T.x$
Resolved normal stress $\sigma_n = \sigma.x$
If σ is the magnitude of the stress on the plane, σ_n is the magnitude of the normal stress and σ_s is the magnitude of the shear stress, then: $\sigma^2 = \sigma_n^2 + \sigma_s^2$

Basic measures of strain

Strain in one dimension

Extension (sometimes elongation) e = $\frac{l - l_o}{l_o}$

Stretch S = $\frac{l}{l_o}$ = 1+e

Quadratic elongation $\lambda = \frac{l^2}{l_o^2} = (1+e)^2$

Natural strain $\varepsilon = \ln(S) = \ln(1+e) = \ln(\frac{l}{l_o})$

Where original length is l_o and new length is l.
Engineering shear strain $\gamma = \tan\Psi$
Tensor shear strain $e_s = 0.5 \tan\Psi$
Where angle of shear is Ψ

Strain in 2 dimensions

Principal strains are designated by subscripts 1 and 3, e.g. principal elongations are $e_1 > e_3$, principal stretches are $S_1 = X$, $S_3 = Z$

Strain ratio $R_s = \frac{S_1}{S_3}$

Dilation $1+\Delta = S_1 S_3$

Fundamental strain equations (Mohr circle)

For a line at an angle θ from the S_1axis, if $\lambda\grave{} = \frac{1}{\lambda}$ and $\gamma = \frac{\gamma}{\lambda}$ then

$\lambda\grave{} = \frac{\lambda_3' + \lambda_1'}{2} - \frac{\lambda_3' - \lambda_1'}{2}\cos(2\theta)$ and $\gamma = \frac{\lambda_3' - \lambda_1'}{2}\sin(2\theta)$

If λ\` is plotted against γ these are the equations of a circle centered at

$\lambda = \frac{\lambda_3' + \lambda_1'}{2}$ with radius $\frac{\lambda_3' - \lambda_1'}{2}$.

Shear zones

For a simple shear zone with angle of shear Ψ, shear strain γ, the extension axis S_1 is inclined to the shear zone boundary with angle θ given by: $\gamma = \tan\Psi = 2/\tan(2\theta)$

Reorientation of lines from strain ellipse

For a line with initial orientation α and orientation after deformation α′

$\frac{\tan\alpha - \theta}{\tan\alpha\prime - \theta\prime} = R_s$

Where R_s is the strain ratio, θ is initial clockwise angle of S_1 from x axis; θ′ is clockwise angle of S_1 from x axis after deformation.

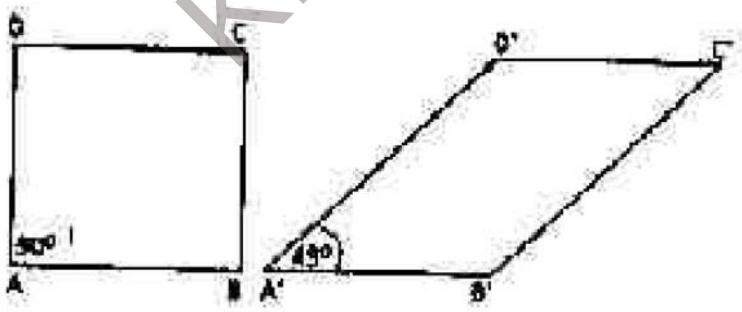
Practice Questions

Previous year Easy Questions

1. Which of the following quantities has no unit? (GATE 1997)
   A. Stress
   B. Hydrostatic pressure
   C. Strain
   D. Viscosity
2. The maximum value of poison's ratio for rocks is (GATE 1998)
   A. 0.25
   B. 0.50
   C. 1.00
   D. 2.00
3. In plastic body, the stress is proportional to (GATE 1999)
   A. Strain
   B. Strain rate
   C. Yield stress
   D. None of the above
4. Shearing stress on any two perpendicular planes in a body under stress is
   A. Unequal in magnitude but of same sign (GATE 2001)
   B. Unequal in magnitude but of opposite sign
   C. Equal in magnitude but of opposite sign
   D. Equal in magnitude and of same sign
5. The stress regime at the mid-oceanic ridges is tensional in character. This is supported by earthquakes due to (GATE 2003)
   A. Normal faulting
   B. Strike slip faulting
   C. High angle reverse faulting
   D. Opening of rift at the ridge crest
6. Which of the following cannot be used as a shear sense indicator? (GATE 2004)
   A. Mica fish
   B. V-pull apart
   C. Φ-type porphyroclasts

D. Quartz c-axis LPO (Lattice preferred orientation) pattern

7. The ratio of axial stress to corresponding axial strain for elastic material known as (GATE 2008)
   A. Bulk modulus
   B. Poisson's ratio
   C. Shear modulus
   D. Young's modulus
8. The maximum and the minimum principal stresses are denoted by σ1 and σ3, respectively. The differential stress can have an absolute value greater than σ1 when (GATE 2018)
   A. σ1 and σ3 are both compressive.
   B. σ1 is compressive and σ3 is tensile.
   C. σ1 and σ3 are equal.
   D. σ1 and σ3 are both tensile
9. which one of the following lists only kinematic parameters? (GATE 2019)
   A. force, translation, rotation
   B. translation, rotation, distortion
   C. stress, distortion, translation
   D. force, stress, strain
10. which of the following statement is correct? (NET 2019)
    A. folds are brittle structures but faults are ductile structures
    B. folds are ductile structures but faults are brittle structures
    C. both fold and faults are brittle structures
    D. both fold and faults are ductile structures
11. How many lines of "No finite longitudinal strain" are there in a strain ellipse? (NET2019)
    A. Two
    B. One
    C. Three
    D. None
12. The following schematic figures show deformation of a square ABCD into a parallelogram A'B'C'D'. (NET 2018)



    A. 0.5
    B. 1.0
    C. 1.5
    D. 2.0

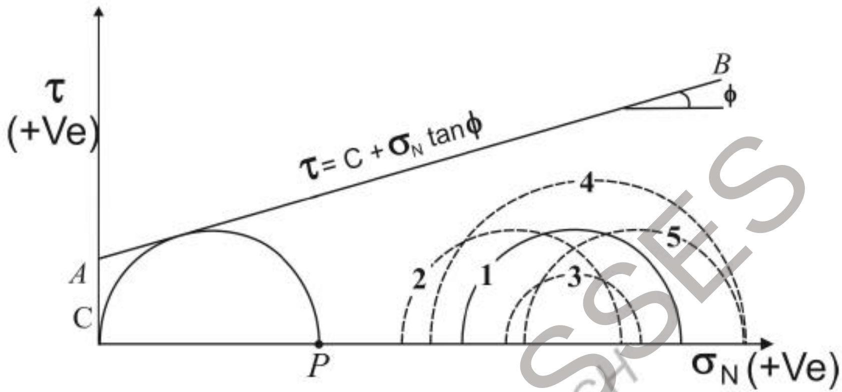
Previous year Difficult Questions

1. If the angle between a line and the principal axis (X) of the strain ellipse having aspect ratio of 3.0 is 30°, the angle is (NAT) (GATE 1999)

A. 45°
B. 75°
C. 35°
D. 60°

2. Which one of the following sets of structures is useful in deciphering the sense of shearing in a ductile shear zone? (GATE 2003)
   A. Veins arrays, syntaxial veins and boudins.
   B. Symmetrical folds, hinge lines of folds and axial plane foliation in folds.
   C. Crenulation foliation, spaced cleavage and axial plane foliation.
   D. Extensional crenulation foliation, S-C mylonitic foliation and mica-fish.

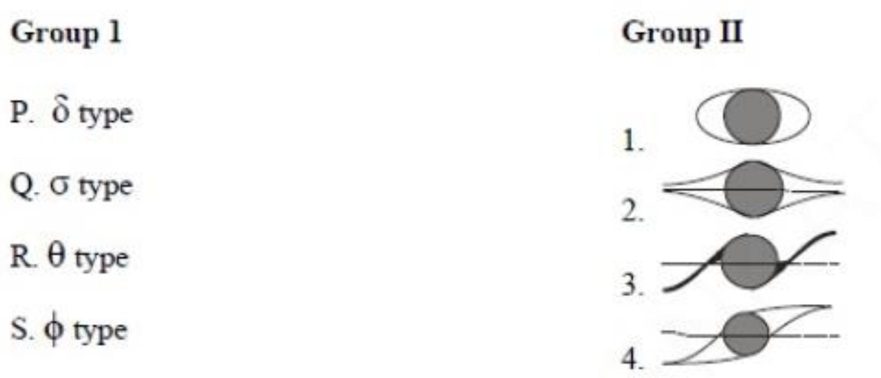
3. The Mohr- Coulomb failure envelope (A-B) of a porous limestone is given below. The point P represents (GATE 2013)



   A. Uniaxial tensile strength
   B. Uniaxial compressive strength
   C. Indirect tensile strength
   D. Shear strength

4. For a condition represented by the circle 1 in the above figure, if pore water pressure increases, the circle will change to (GATE 2013)
   A. Circle 2
   B. Circle 3
   C. Circle 4
   D. Circle 5

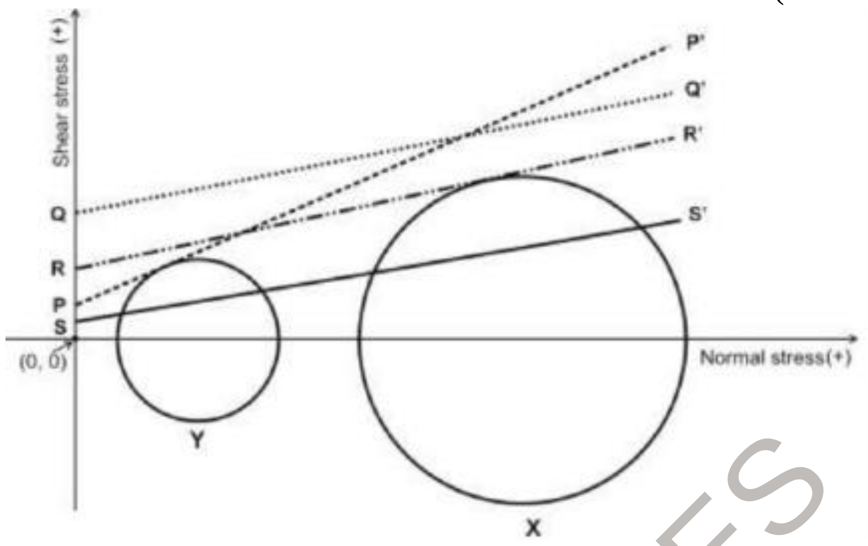
5. Match the type of mantled porphyroclasts in group I with the corresponding figure in Group II. (GATE 2015)



   A. P-1, Q-3, R-2, S-4
   B. P-3, Q-4, R-1, S-2

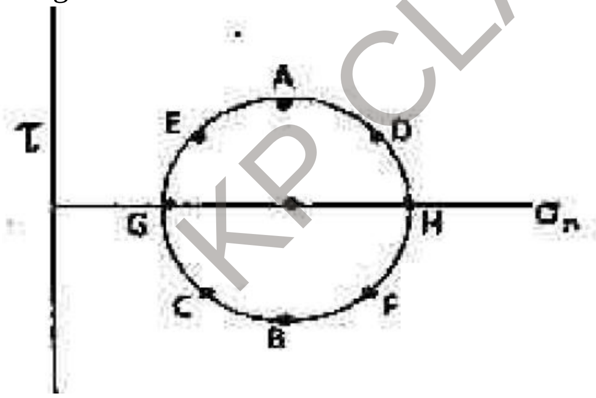
C. P-3, Q-1, R-2, S-4
D. P-2, Q-1, R-4, S-3

6. A rock follows Mohr-Coulomb failure criterion. Which one of the Mohr-Coulomb failure envelopes shown below allows failure of the rock under stress state Y, but not under stress state X? (GATE 2018)



A. PP'
B. QQ'
C. RR'
D. SS'

7. Which one of the following pairs of points represents principal planes of stress ellipse in the figure? (NET 2018)



A. A and B
B. C and D
C. E and F
D. G and H

8. If $\sigma_1 \geq \sigma_2 \geq \sigma_3$ are the principal stresses, then which one of the following represent a uniaxial state of stress? (NET 2018)

A. $\sigma_1 \geq \sigma_2 \geq \sigma_3 > 0$
B. $\sigma_1 \neq 0,\ \sigma_2 \neq 0,\ \sigma_3 = 0$
C. $\sigma_1 \neq 0,\ \sigma_2 = 0,\ \sigma_3 = 0$
D. $\sigma_1 - \sigma_2 - \sigma_3 \neq 0$

Multiple Selected Questions

3. A substance in which deformation continues after yield strength is called
   A. Brittle substance
   B. Ductile substance
   C. Plastic substance
   D. Clastic substance
4. Which among the following is true for pure shear?
   A. Kinematic vorticity number is 1
   B. Non-rotational
   C. Coaxial
   D. All of the above
5. Poisson's ratio is related to
   A. Shear stress
   B. Transverse strain
   C. Transverse stress
   D. Longitudinal strain

ANSWERS

Previous Year Easy Questions

1. C 2. B 3. D 4. D 5. A 6.B 7. D 8.B 9.B 10.B 11.A 12.B

Previous Year difficult Questions

1. D 2. D 3.B 4.A 5.B 6.A 7.D 8.C

Multiple Select questions

1. BC 2. BC 3. BD

EXPLANATIONS

Previous Year Easy Questions

1. Strain is the relative change in shape or size of an object due to externally applied forces. It has no unit.
2. Most of the rocks shows negative change in volume as they are uniaxially stressed, which shows poison's ratio lies between 0.50 to 0.
3. The body which does not have the property of opposing the external deforming force is called as plastic body. Within the limit of elasticity, stress in directly proportional to strain but after that they show nonlinear relationship.
4. Shearing stress on any two perpendicular planes in a body under stress is equal in magnitude and of same sign.
5. The extensional nature of the ridge tectonics is documented by fault plane solutions indicative of normal faulting as is seen for some selected earthquakes along the Mid Atlantic Ridge.
6. Mica fish, Φ-type porphyroclasts and Quartz c-axis LPO (Lattice preferred orientation) pattern are used as a shear sense indicator.
7. Young's modulus is also known as tensile modulus or elastic modulus, is a mechanical property of linear elastic solid materials. It defined as the ratio of axial stress to axial strain.
8. Differential stress, $\sigma d = \sigma 1 - \sigma 3 \Rightarrow \sigma 3 = \sigma 1 - \sigma d$

since σd > σ1, σ3 must be negative. Therefore, σ3 is tensile.

9. Stress is not a kinematic but a dynamic parameter. Translation, rotation and distortion are kinematic deformed parameters.
10. When rock deform in a ductile manner, instead of fracturing to form faults or joints, they may bend or fold and resulting structures are called as folds. Faults are the result of rocks behaving in a brittle fashion.
11. The lines of no finite longitudinal strain in the strain ellipse correspond to two planes of no finite longitudinal strain (no stretching, no rotation) in the strain ellipsoid.
12. Shear strain is the ratio of the change in deformation to its original length perpendicular to the axes of the member due to shear stress. Here along the AB there is no change is observed hence, shear strain along AB is 1.

Previous Year difficult Questions

1. Angle between a line and the principal axis

$$\theta = \tan^{-1}[\frac{1}{aspect\ ratio}]$$

$$\theta = \tan^{-1}\frac{1}{3} = 60°$$

2. Extensional crenulation foliation, S-C mylonitic foliation and mica-fish. All these structures are formed by shear forces and hence these structures also preserve the shear direction which were operated to them in the past. Hence, they are good shear sence indicator.
3. Uniaxial compressive strength is the strength of a material to withstand when compressive stress is applied from one direction.
4. Increase in pore water pressure decreases the normal strength of the rock. Hence, the circle 1 will change to circle 2.
5. These porphyroblasts are formed by the deformation and the symbols are named according to their shape.
6. Rock will fail when the Mohr circle touches the failure envelope.
   PP' – No failure under X, Failure under Y
   QQ' – No failure under Y, No failure under X
   RR' – Failure under X, No failure under Y
   SS' – Failure under X, Failure under Y. It will not be possible to generate stress states X and Y in this case as the rock will rupture at much lower differential stresses for the respective confining pressures.
7. Principal stresses are maximum and minimum value of normal stresses on a plane on which there is no shear stress. Point G and H in the figure are point of principal stress.
8. A uniaxial stress acts in one direction only. Hence, in case of uniaxial stress state only one of the principal stresses is nonzero.

Multiple Select questions

1. The yield point is the point on a stress – strain curve that indicates the limit of elastic behavior and the beginning of plastic behavior. Hence, after the yield strength the substance is either ductile or plastic.
2. Pure shear is a three-dimensional homogeneous flattening of a body. It is an example of irrotational strain in which the body is elongated coaxially with kinematic vorticity number 0.

3. Poisson's ratio is the ratio of transverse strain to longitudinal strain mainly due to longitudinal stress.

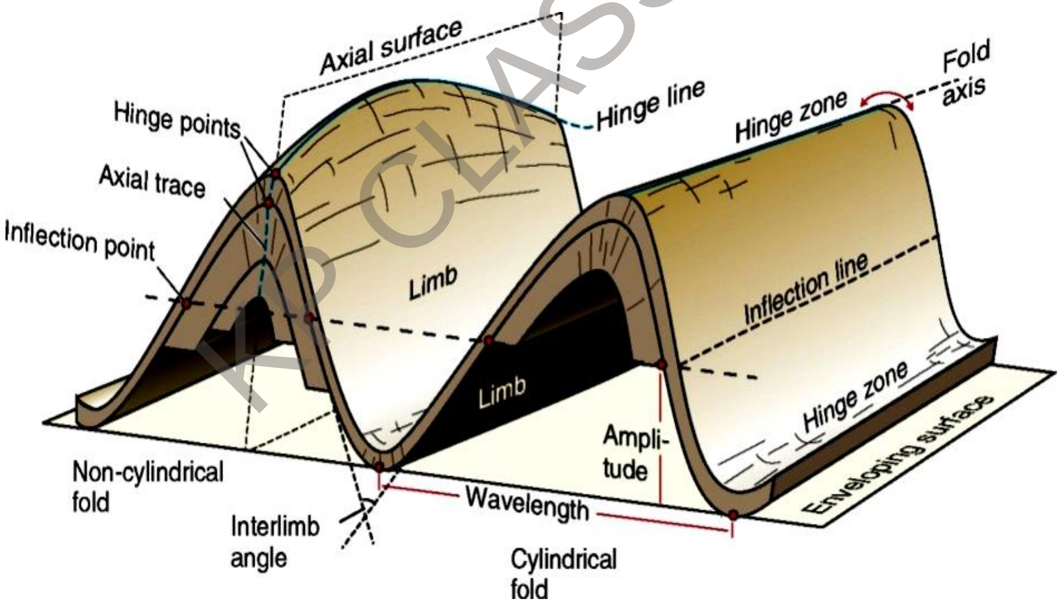
Chapter 3 – Folds and folding

- Folds are bends or flexures in the earth's crust, and can therefore be identified by a change in the amount and/or direction of dip of rock units.
- Most folds result from the *ductile deformation* of rocks when subjected to *compressional* or *shear stress*.
- In order to understand and classify folds, we must study their forms and shapes, and be able to describe them. The following definitions are therefore essential for the description of a fold:

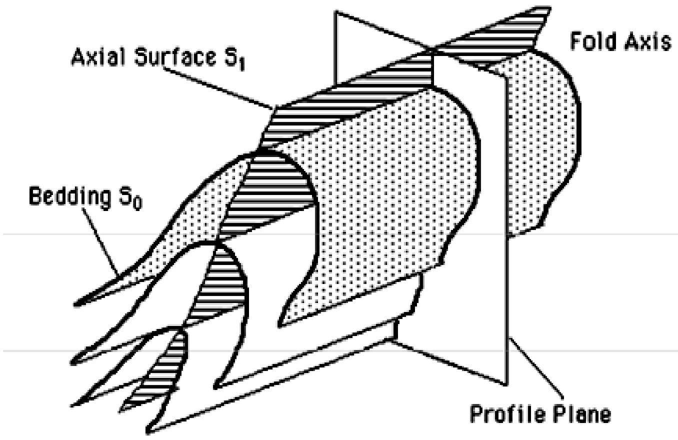
3.1: Terminologies

- **Fold Axis-** A line on the surface of a fold which when moved parallel to itself, generates the surface of the fold. Fold axis is a property of **cylindrical folds** only. **Non-cylindrical folds** do not have a fold axis.
- **Cylindrical fold**- Fold in which a straight hinge line parallels the fold axis; in other words, the folded surface wraps partway around a cylinder.
- **Non-cylindrical fold**- Fold with a curved hinge line.
- **Hinge**- The curved zone where the two limbs join. The hinge may be sharp and abrupt, but more commonly the curvature of the hinge is gradual, and a hinge zone is defined.
- A spectrum of hinge shapes exists, from the pointed hinges of **kink bands** and **chevron folds** (sharp and angular folds) to the well-rounded hinges of **concentric folds**.
- **Hinge line**: Is the line of maximum curvature on a folded surface. The hinge line almost always coincides with the **axis** of the fold (except in the case of a **non-cylindrical fold**).
- The hinge line is defined as the line lying in the plane that bisects a fold into two equal parts.
- **Limb**- Less curved portion of a fold.
- The **axial plane** is an imaginary plane dividing the fold into two equal parts known as **limbs**.
- It is therefore the plane which includes all hinge lines for different beds affected by the same fold. If this plane is irregular it is called **axial surface**.
- The **crest** of a fold can be considered the highest point on a folded surface. The **trough** is the lowest point on a folded surface. The **crests** and **troughs** may not necessarily coincide with the **hinge**.
- The **interlimb angle**: Is the angle between two limbs of the same fold. It is measured in a plane perpendicular to that of the fold axis.
- The **angle of plunge** of a fold is the angle between the fold axis and the horizontal plane, measured in a vertical plane.
- The **direction of plunge** of a fold is the direction in which the fold axis dips into the ground from the horizontal plane.
- **Inflection point-** The position in a limb where the sense of curvature changes. In other words, the point of zero curvature.
- **Inflection line** is the line joining the points of zero curvature on a folded surface.

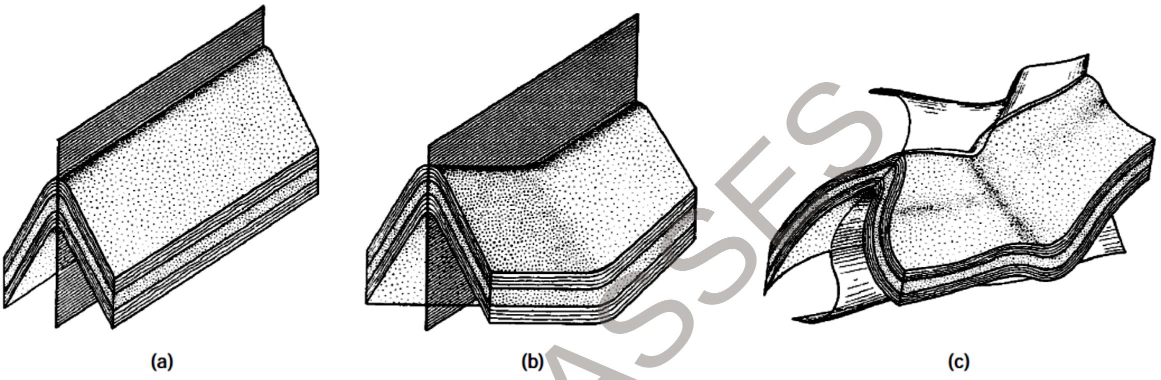
- **Inflection lines** subdivide the folded surface into two domains of opposing curvatures: **antiforms** (convex upwards; limbs dip away from each other) and **synforms** (concave upwards; limbs dip towards each other).
- The **median surface**: Is the surface that passes through points where the fold limb changes its curvature from concave to convex.
- The **amplitude** of a fold: is the vertical distance between the median surface and the fold hinge, both taken on the same surface of the same folded unit.
- The **wavelength** of a fold system is the distance between two consecutive **crests** or **troughs** taken on the same folded surface.
- **Cross section**- A vertical plane through a fold.
- **Profile plane**- The surface perpendicular to the **hinge line.**
- **Culmination**- High point of the **hinge line** in a **non-cylindrical** fold.
- **Depression**- Low point of the **hinge line** in a **non-cylindrical** fold.
- **Dome**- **Antiforms** with **hinge line** culmination.
- **Basin**- **Synforms** with **hinge line** depression.
- **Saddle**- **Antiforms** with **hinge line** depression.
- **Inverted saddle**- **Synforms** with **hinge line** culmination.
- An imaginary plane that is tangential to the hinge zones of a series of small folds in a layer is called the **enveloping surface**.
- **Polyclinal folds** belong to groups of folds with sub-parallel hinge lines but non-parallel axial surfaces.



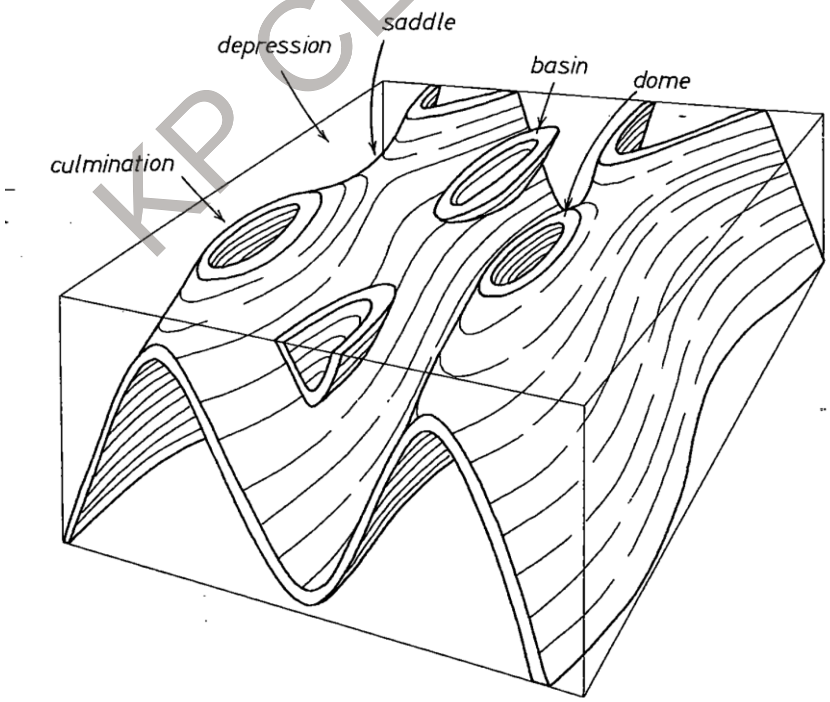
Geometric aspects of folds



Anatomy of folds



Cylindrical and Non-cylindrical folds



Parts of plunging fold

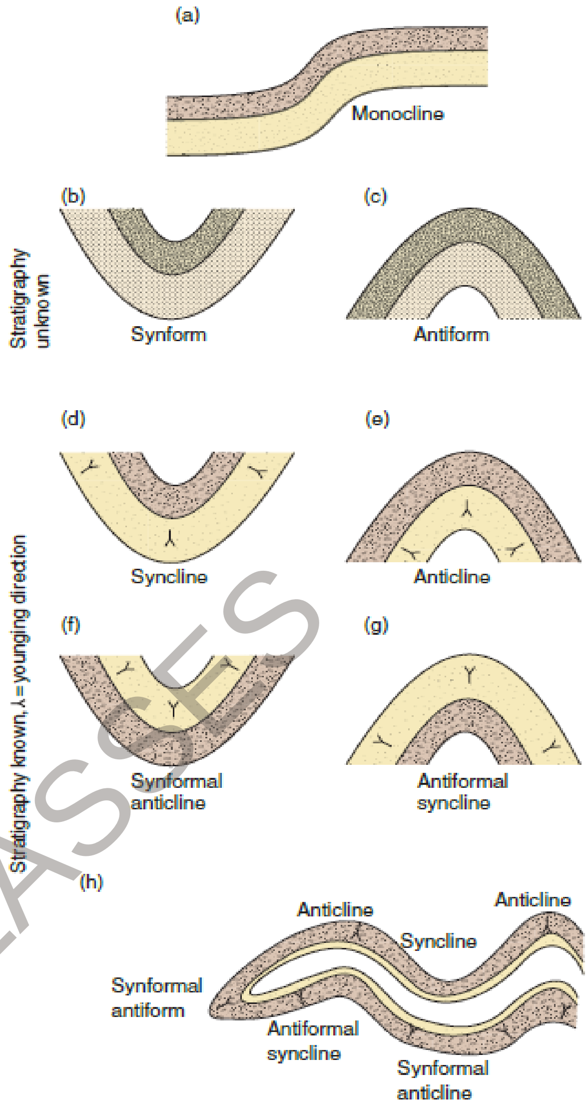
- Orogenic belts usually have regional anticlines and synclines. When the limbs of a major anticline are further folded into second-order and third-order anticlines (composite anticlines), it is called an **anticlinorium**.
- Similarly, when the limbs of a major syncline are further folded into second-order and third-order synclines (composite synclines), it is called a **synclinorium**.
- The second, third and higher order folds are also called parasitic folds because they develop on the main, regional fold structures. These folds are often called **parasitic** folds.
- Folds in which axial planes are continuous across successive folded layers that show approximately the same wavelength and amplitude are **harmonic**.
- Typically, similar folds that ideally maintain their shape throughout a section are harmonic.
- Folds in which the amplitude, wavelength and style change along discontinuous axial surfaces from one layer to another are **disharmonic**.
- Disharmonic folds develop because of differing rheology in the different layers. The incompetent beds are squeezed and adapt to the form imposed by the competent beds.
- Disharmonic folds are particularly common in areas of parallel folds because they die out with increasing depth along their axial plane, reaching over-tightening in the core.
- Consequently, their extent is limited to the center of curvature beyond which shortening should be accommodated by faulting or another type of folding.
- They may terminate downward at some surface, called **detachment** or **décollement,** along which they are separated (decoupled) from unfolded layers below. The Jura Mountains are typically cited for such relationships.

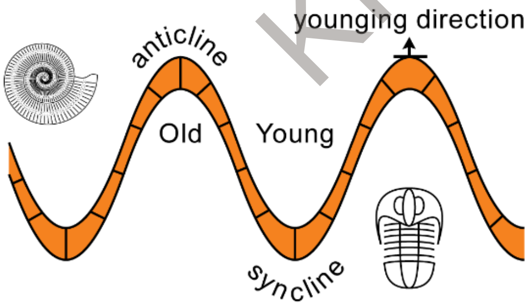
3.2: Classification of folds

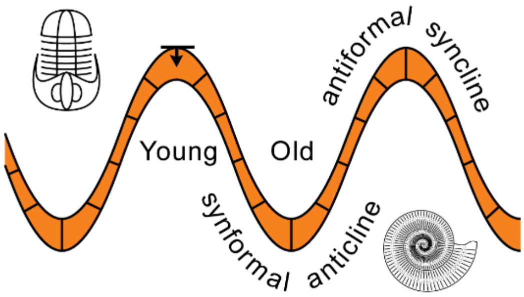
- Folds may be classified based on the direction of dip of their limbs, the inclination of their axial planes, the value of their interlimb angle, their plunge, and their general shape and effects on the thickness of the folded layers.
- In order to describe a fold correctly, one may have to use more that one of these classifications; e.g. recumbent anticline, open syncline, tight plunging anticline, ... etc. (see below).

3.2.1: On the basis of direction of dip of the limb

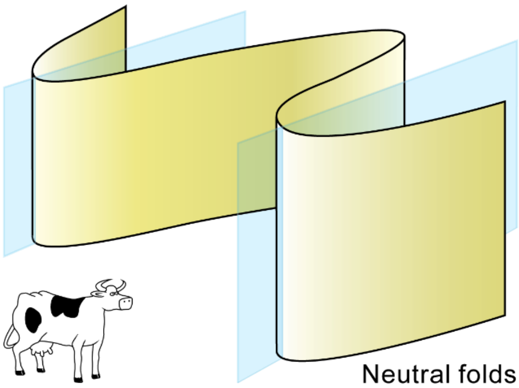
- When both limbs of a fold dip away from the fold axis, the fold is called an **antiform**.
- If both limbs dip towards the fold axis, the fold is known as a **synform**.
- If the relative ages of the folded units are known, such that the oldest units occur in the *core* then the fold is called "**anticline**".
- Similarly, if the youngest units occur in the core it is known as a **syncline.**
- **Antiformal anticlines, antiformal synclines, synformal anticlines and synformal synclines** are possible combinations of the dip of limbs and relative age of rocks occurring in the core of the fold.
- A **synformal anticline** is an anticline because the strata get younger away from its axial surface. At the same time, it has the shape of a synform, i.e. it is synformal.
- Similarly, an **antiformal syncline** is a syncline because of the stratigraphic younging direction, but it has the shape of an antiform.







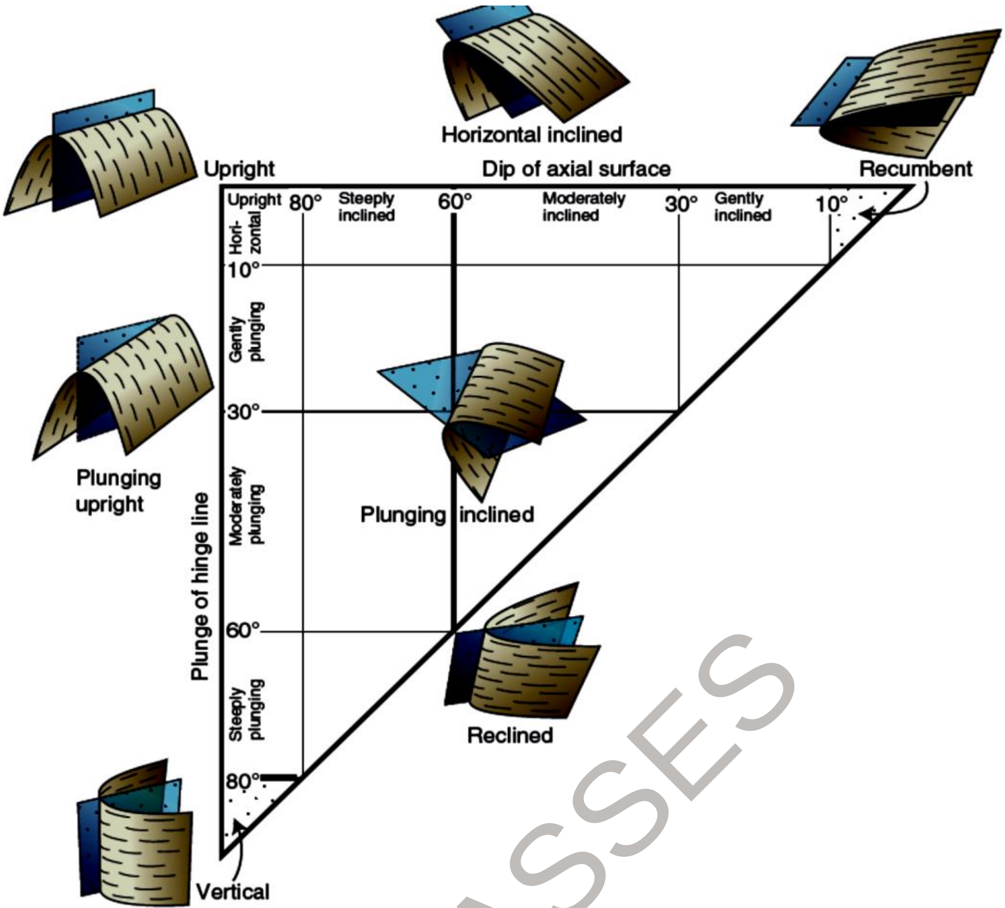
- Folds that are neither antiformal nor synformal, whose limbs converge sidewise, are **neutral folds**. They mostly comprise vertically plunging folds.



3.2.2: On the basis of orientation of hinge line and inclination of the axial plane

- Fold orientations are measured by the plunge and plunge direction of the hinge line and the dip and dip direction of the axial surface.
- For example, a fold with horizontal surface is called a **recumbent** fold.
- A **symmetrical** (or upright) fold is one in which the axial plane bisects the fold (and is vertical).
- If the axial plane is inclined at an angle < 45° (measured from the vertical plane), the fold is said to be **inclined**.
- If the angle of inclination of the axial plane is > 45° (from the vertical plane), then both limbs of the fold will dip in the same direction, and the fold is known as **inverted** or **overturned**.
- If the plunge angle of the hinge line is equal to the dip angle of the axial surface the fold is called a **reclined** fold.

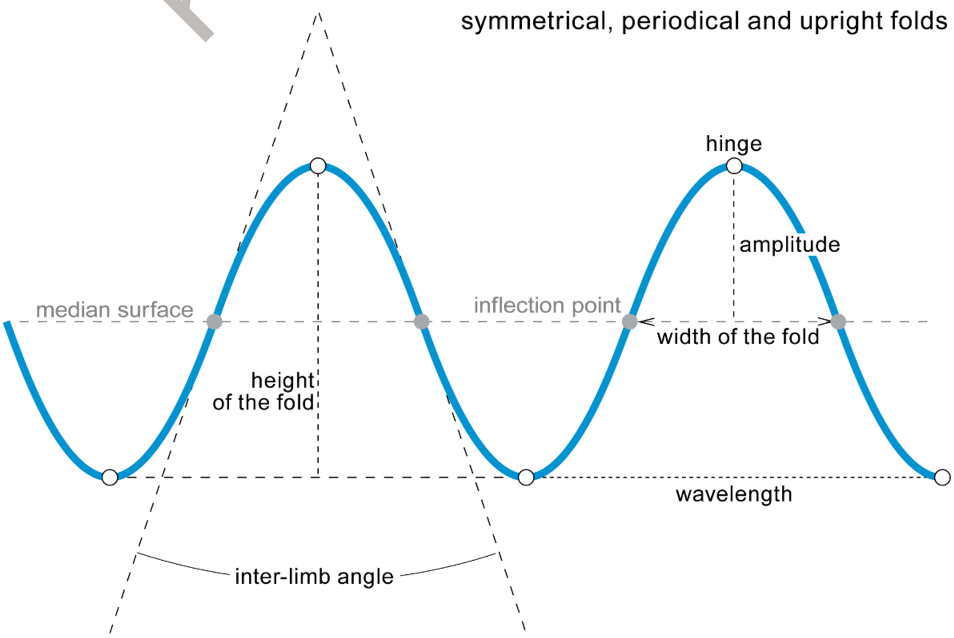
Plunge of Hinge Line	Dip of Axial Surface
Horizontal: 0°–10°	Recumbent: 0°–10°
Shallow: 10°–30°	Inclined: 10°–70°
Intermediate: 30°–60°	Upright: 70°–90°
Steep: 60°–80°	
Vertical: 80°–90°	

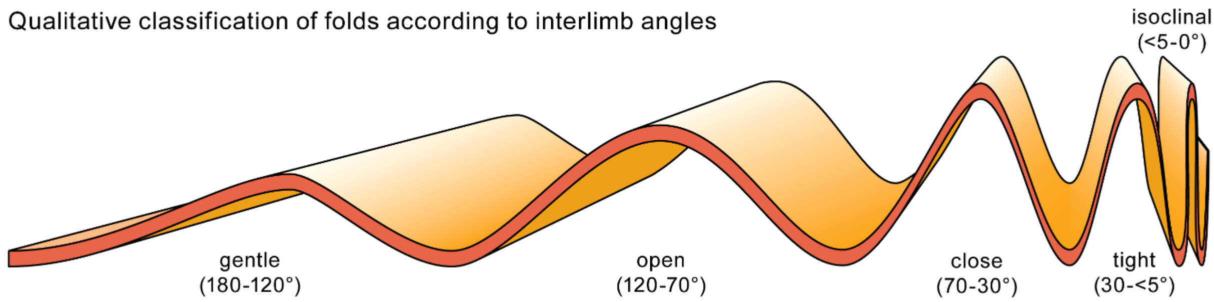


Classification of folds based on the orientation of the hinge line and the axial surface.

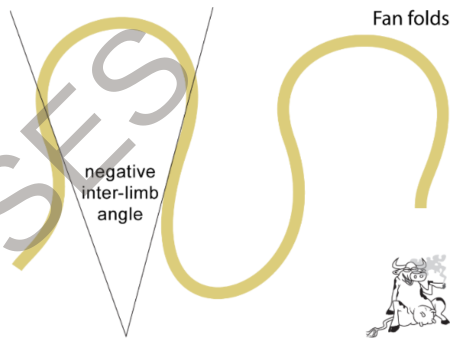
3.2.3: On the basis of the value of the interlimb angle

- In profile, the smaller angle made by the limbs of a fold is the **inter-limb angle,** a measure of the **tightness of the fold**.
- It is the angle subtended by the tangents at two adjacent inflection points, which may reflect the intensity of compression.





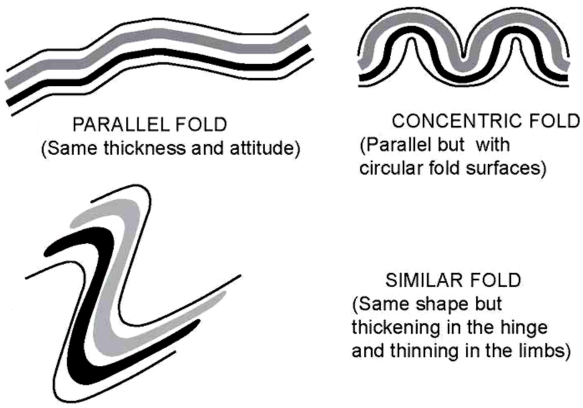
Inter limb angle	Tightness class
180° to 120°	Gentle
120° - 70°	Open
70°-30°	Close
Less than 30°	Tight
0°, i.e. parallel limbs	Isoclinal
< 0°	Fan

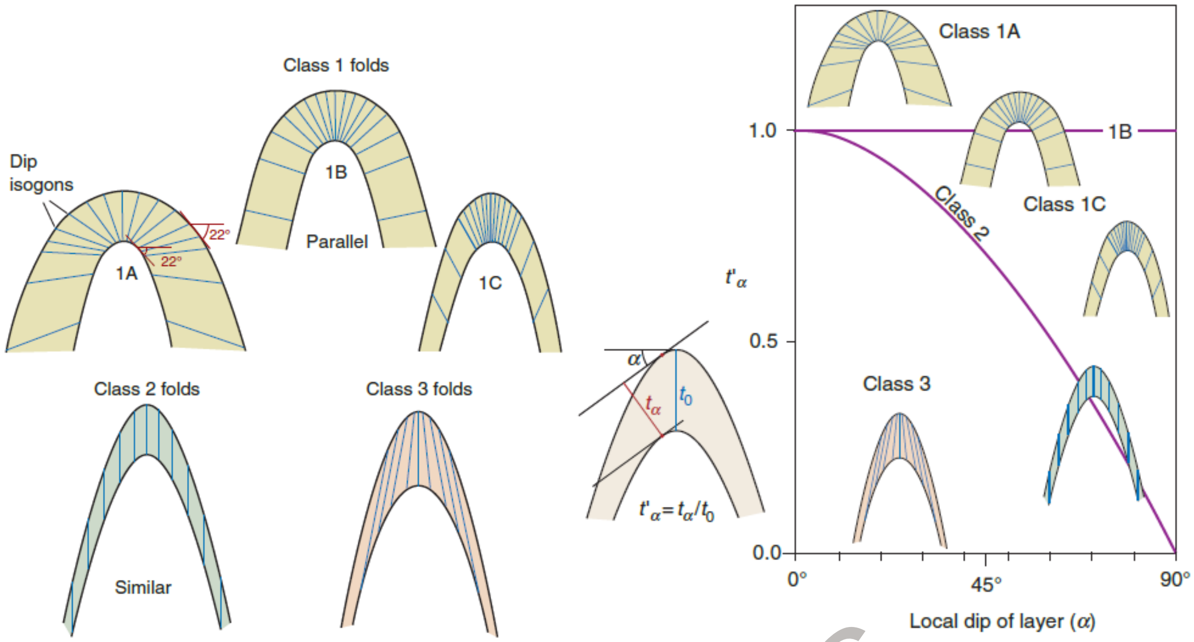


- A **cusp** is a fold where both hinge and inflection points are the same point; in other words, the fold has no inflection point.
- Its **tightness** is defined by a cusp-angle between the tangents to the folded surface at the cusp.
- **Fan folds** have negative interlimb angles.

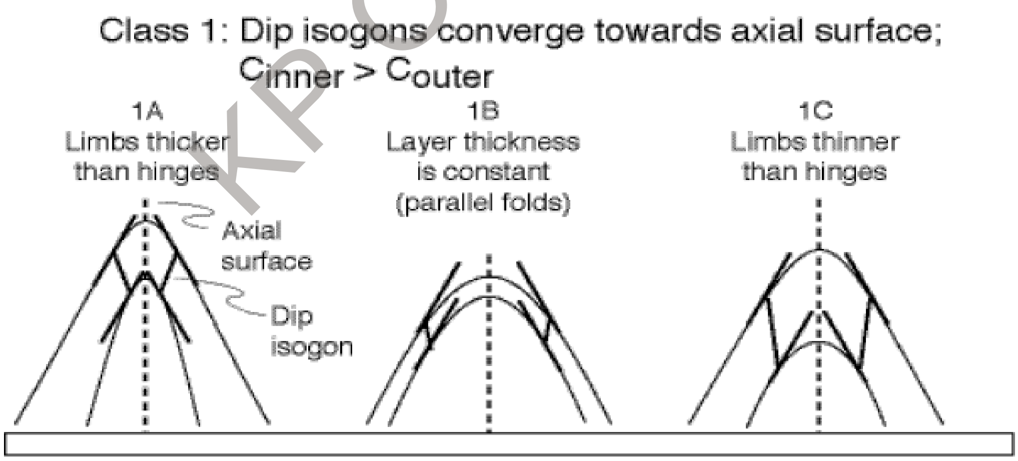
3.2.4: On the basis of dip isogon (Ramsay's Classification)

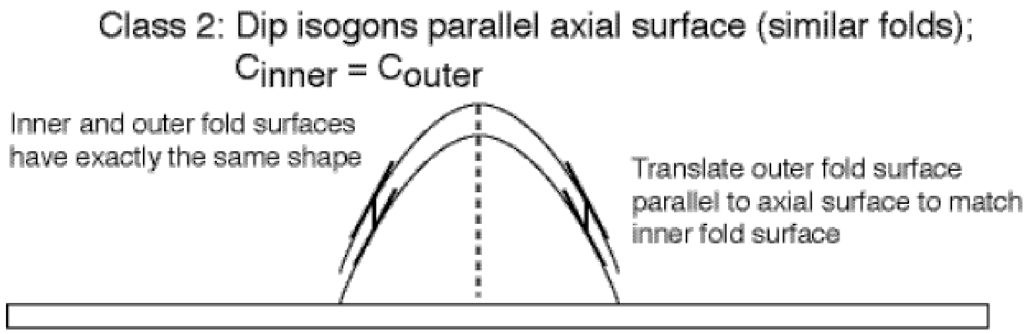
- Ramsay's classification of folds is based on the dip isogon. A dip isogon is the line joining points of equal dip.
- Two common types of folds are the Similar and Parallel folds.
- In **similar folds** the bedding shape remains the same from bed to bed whereas in parallel folds the bedding thickness remains unaltered from bed to bed.
- Class 1: Dip isogons converge toward the inner arc, which is tighter than the outer arc.
- Class 2 (**similar folds**, also called **shear folds**): Dip isogons parallel the axial trace. The shapes of the inner and outer arcs are identical.
- Class 3: Dip isogons diverge toward the inner arc, which is more open than the outer arc.

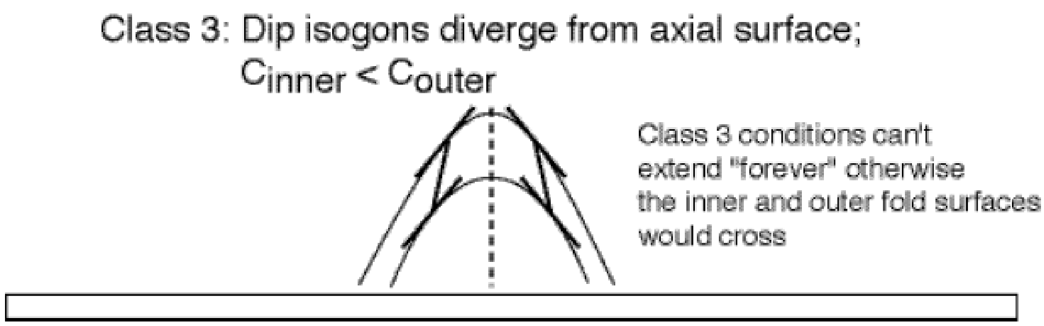




- Class 1 folds are further subdivided into classes 1A, 1Band 1C. 1A folds are characterized by thinned hinge zones, while 1B folds, also called **parallel folds**.
- If circle shaped hinge zone, **concentric folds**, have constant layer thickness.
- In parallel folds the shape of the beds must change from layer to layer in order the maintain constant bed thickness throughout.
- Class 1C folds have slightly thinned limbs. Class 2and, particularly, Class 3 folds have even thinner limbs and more thickened hinges.
- Among these classes, Class 1B(**parallel**) and 2 (**similar**) geometries stand out because they are easy to construct and easy to identify in the field.

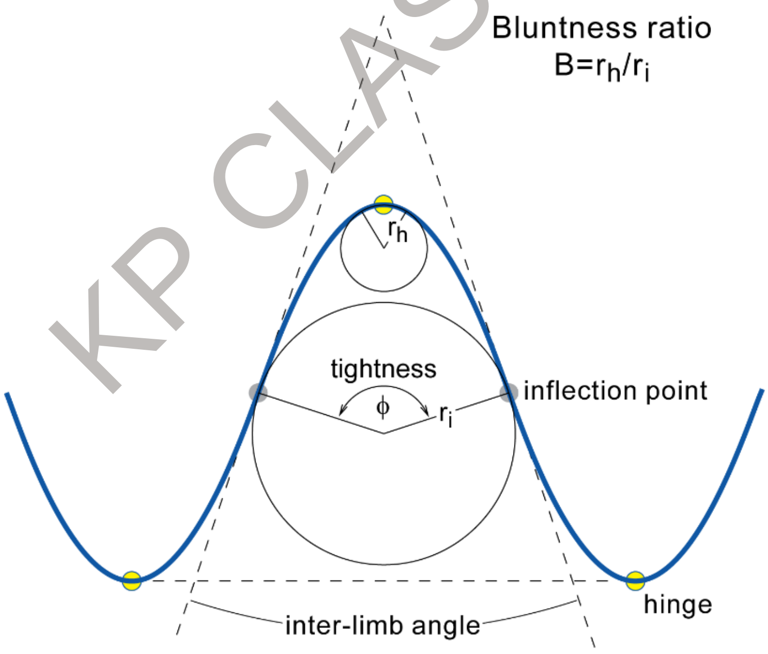






3.2.5: On the basis of fold closure

- The **fold closure** indicates the direction in which the limbs converge. For example, a fold closes westward.
- The shape of the fold closure depends on how the curvature of the folded surface changes around the hinge; it may be very sharp and the limbs relatively straight, or the curvature more regular around the fold.
- Fold closures are thus broadly described as **rounded** or **angular**. **Arrowhead folds** or **flame folds** have sharp hinges with distinctly, often sigmoidally curved limbs.
- The **bluntness ratio** is a quantitative measure of how round or angular the hinge is. It is defined as $B = r_h / r_i$
- Where r_h is the radius of curvature at the hinge and r_i the radius of the circle tangent to the limbs at the two inflection points. The angle between the two r_i is sometimes used to define the **tightness** of the fold.

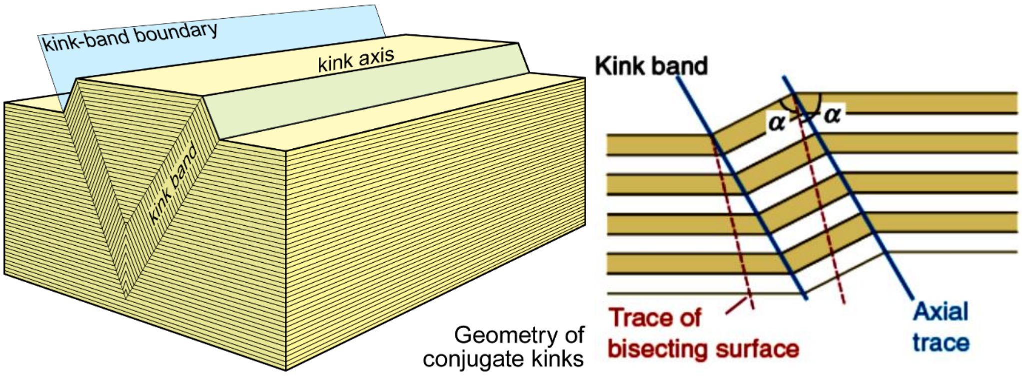


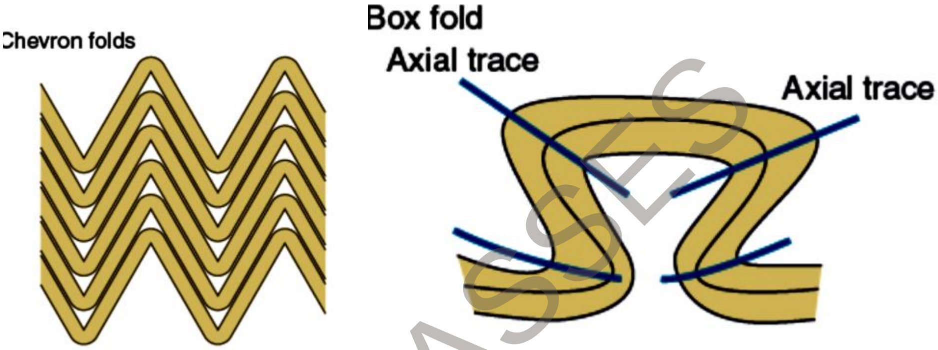
3.2.6: On the basis of axial trace

Kink folds

- **Kinks** are folds with straight, planar limbs (there is no inflection point) and angular hinges (the hinge zone is reduced to a point).
- They form in strongly anisotropic rocks in which the well-developed anisotropy is either thin, laminated beds or foliation planes.

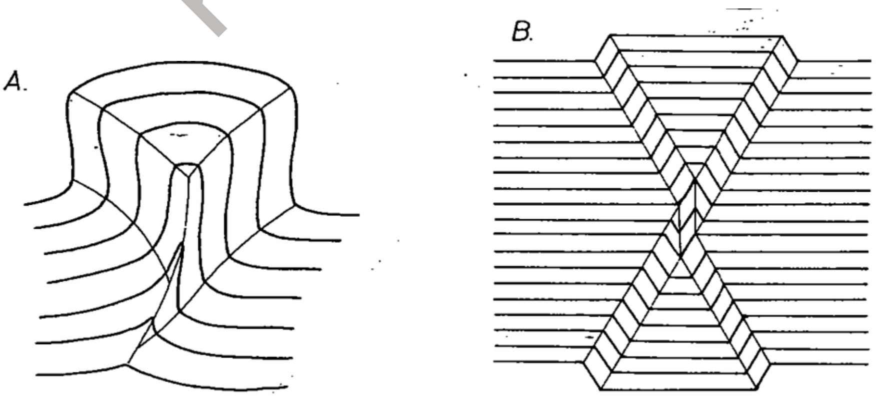
- Where kinks are markedly asymmetrical, the long narrow zone defined by the tabular, short limb is referred to as a **kink band** and the axial plane traces are referred to as **kink band boundaries**.
- **Chevron folds** are the larger-scale equivalent of kink folds.





Box fold

- It have two sets of axial surfaces developed, which is the case with so-called box folds, which are also called **conjugate folds** from the characteristic conjugate sets of axial surfaces.
- In order for a box fold to form, a layer must be detached from the underlying and overlying layers. They are therefore common in areas with weak basal layers.

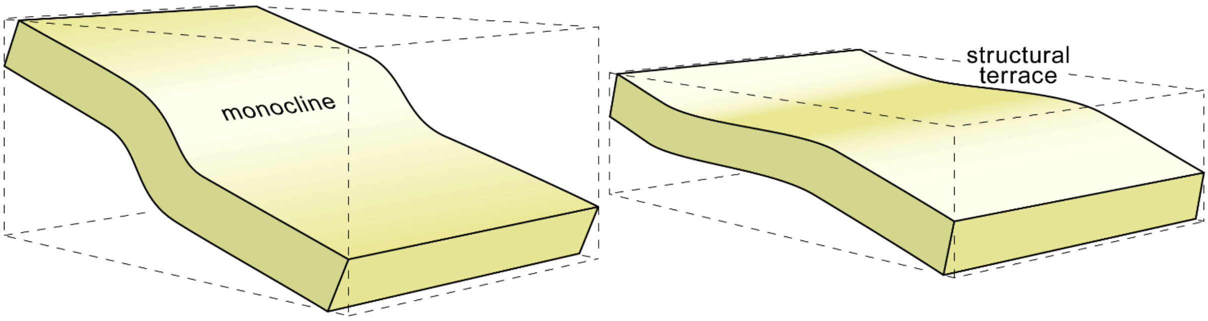


Conjugate folds of box fold type (A) and kink fold type (B)

Homocline – Monocline

- A succession of beds with uniform parallel attitudes over a large area forms a **homocline**.

- An antiform and an adjacent synform delimit a single limb. Such a flexure pair involving a local increase in the regional dip (i.e. only one tilted, step-like limb in an otherwise sub-horizontal or gently dipping sequence) constitutes a **monocline**.
- Conversely, a local decrease in the regional dip is a **structural terrace**.
- Monoclines and structural terraces are typically large-scale structures along margins of broad basins or uplift platforms in cratons.



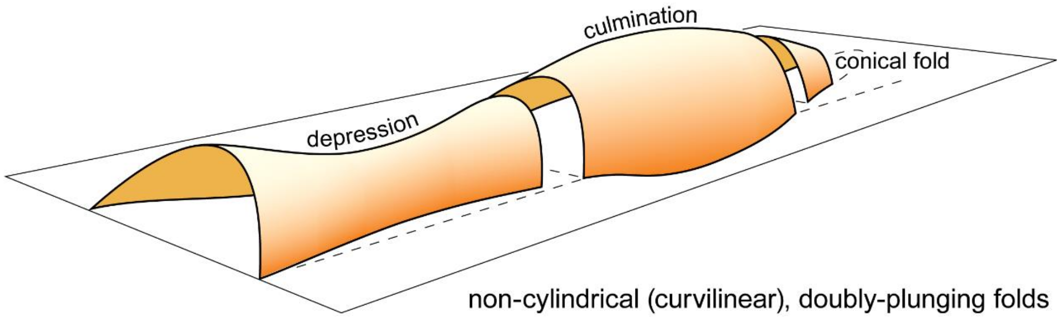
3.2.7: On the basis of cylindricity

Cylindrical folds

- Folds are often drawn as **cylindrical** structures, meaning that the fold axis is a straight line which, when moved parallel to itself, generates any single fold of the same generation.
- The axis of cylindricity is parallel to the fold axis. In three dimensions, a cylindrical fold appears as a straight line in a section parallel to its axis, whereas in any other section the trace of the folded surface has a wavy shape.

Doubly plunging folds

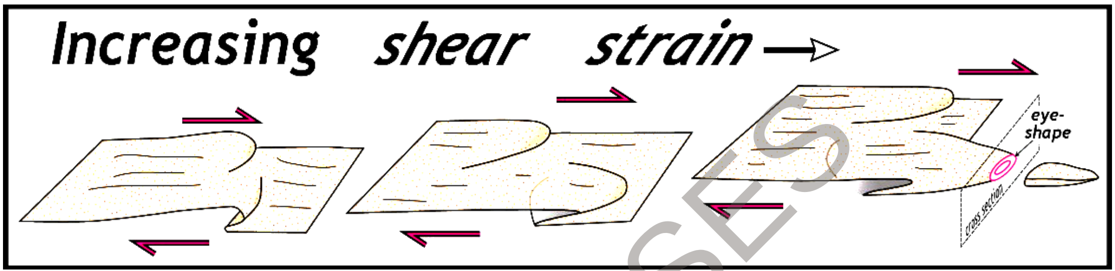
- However, hinge lines are rarely straight. **Non-cylindrical** folds deviate from the ideal cylindrical geometry.
- Hinges of non-cylindrical folds are curved within a plane (**curvilinear**) and, therefore, change in trend and plunge.
- A **conical fold** describes a non-cylindrically folded surface that has the approximate geometry of a cone.
- The plunge of the hinge line reverses along a **doubly plunging** fold. If the hinge line plunges away from a high point (the axis is convex upward), the high point is a **culmination**; if it plunges toward a low point (the axis is concave upward) the low point is a **depression.**
- Nearly circular culminations and depressions are **domes** and **basins**, respectively.



non-cylindrical (curvilinear), doubly-plunging folds

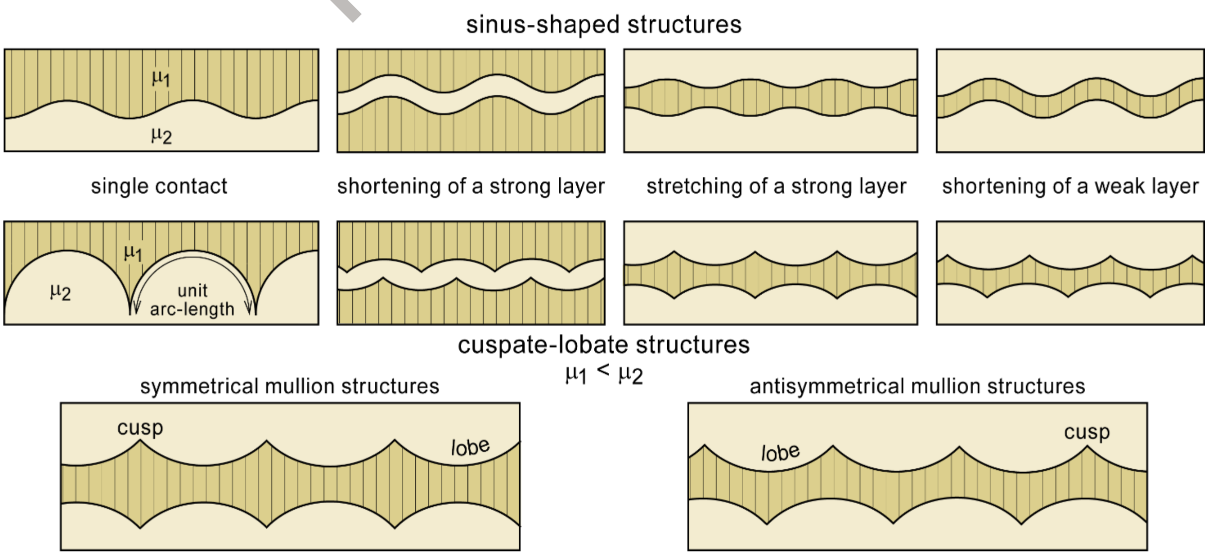
Sheath folds

- A **sheath fold** has a strongly curved hinge line sweeping around through an arc of more than 90° up to the hairpin bend.
- Sheath folds contain a long (stretching) axis along the length of the tube or tongue shape, whilst cross sections normal to this axis display closed geometries.
- Such elliptical sections or nested rings define **eye-folds**.
- These "tubular" folds generally reflect heterogeneous simple shear or flow superimposed on very simple buckles or perturbation of the simple shear flow such, for example, a foliation bulge around a rigid clast.
- Gentle bends of the initial buckle hinges are accentuated during subsequent shearing and evolve into tight isoclinal and non-cylindrical folds.
- During fold amplification, the fold axes may behave passively and rotate towards the shear direction until they become sub-parallel to the shear direction at high strain.
- Sheath folds are often characteristic of strongly deformed parts of shear zones



3.2.8: On the basis of buckling of an interface

- Buckle folding may also affect the planar interface between materials of contrasting viscosity.
- When this occurs, the folds have a characteristic form; those closing in one direction have a broad rounded shape (**lobate folds**) and hinges closing in the opposite direction have a narrow or **cuspate** shape.
- The **cusps** always point towards the material with the higher viscosity.
- Thus, in outcrops dominated by cuspate-lobate forms, it is possible to know at a glance, which layer was relatively stiffer than adjacent beds at the time of folding. This is a common cause of **mullion** structures.



Evolution of initially sinusoidal structures to cuspate-lobate forms

3.3: Fold system and folded multilayers

- A fold may bend a single surface, or affect one layer bounded by two surfaces or deform a stack of layers with several interfaces.
- The two sides of a folded layer are also distinguished with respect to the fold core as the **outer arc** and **inner arc**, respectively.
- A **fold system** is a group of folds, often of variable shape, size and orientation, yet spatially and genetically related.

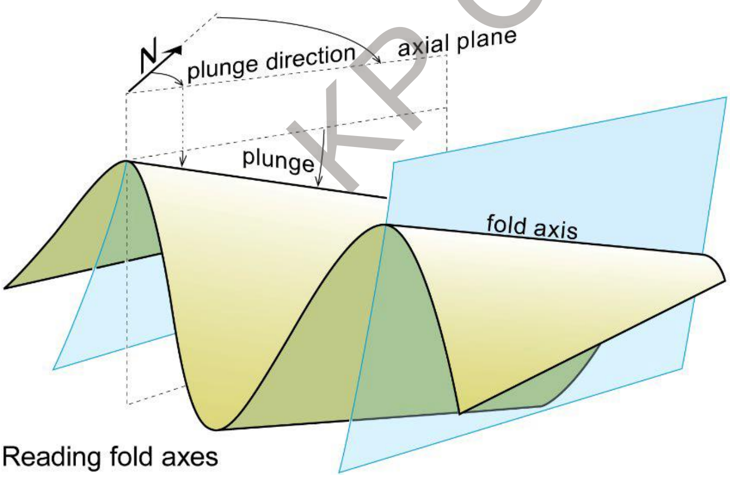
3.3.1: Orientation of folds

- A fold, in general, affects several superposed layers. The imaginary surface connecting the hinge lines on successive layer surfaces of the same fold is the **axial plane**.
- This plane is often curved and occasionally equidistant from each limb; in that case, it bisects the interlimb angle.
- The orientation of folds is completely given by the fold axis treated as a line and the attitude of the axial plane (**strike** and **dip**), together.

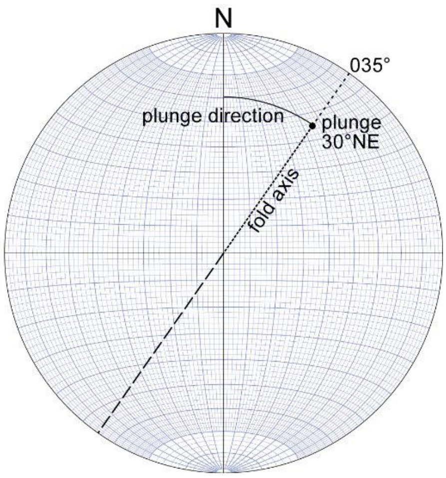
Fold axis orientation

The orientation of a fold axis is expressed by its **plunge** and its **plunge azimuth**:

- The **plunge** is the inclination measured from the horizontal in the imaginary vertical plane containing the hinge line.
- The direction of plunge (the trend) is the strike (azimuth, the bearing relative to North) of the imaginary vertical plane that contains the hinge line and the direction in which the downward inclination occurs.
- A general rule is that both the trend and plunge of minor order folds can be used for extrapolation in fieldwork.
- They also indicate the trend and plunge of first-order folds of the same generation.



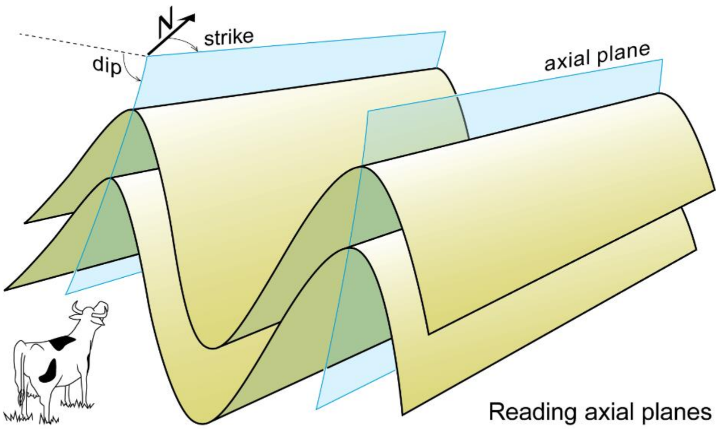
Reading fold axes



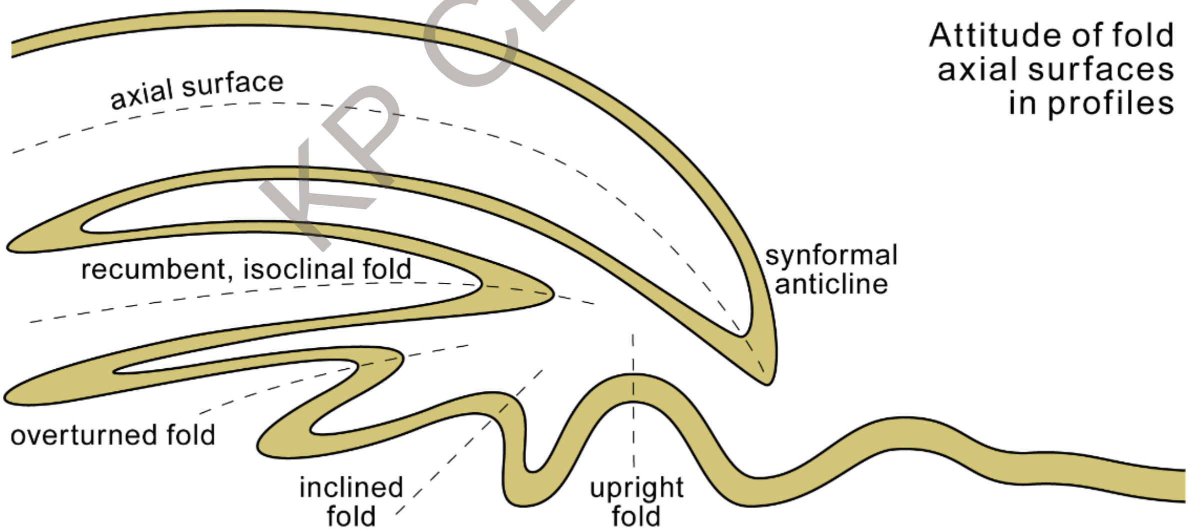
Axial plane orientation

- The axial planes cut the hinge zone of a folded surface along the fold axis.
- The orientation of the axial plane is expressed as a dip and strike or, in a more compact form, as a dip and **direction of dip**.
- As for any surface, the strike is the trend of the horizontal line contained in the surface; the angle dip is the angle between the surface and the horizontal plane.

- The direction of the dip of a surface is the trend of the line perpendicular to the strike of the surface looking down the dip.



- A semi-quantitative classification is valid for folds with sub-horizontal axes. **Upright** folds have approximately vertical axial surfaces.
- Folds with dipping axial planes are **inclined** (80° < **steeply** < 60° < **moderately** < 30° < **gently** < 10°) if the steeper limb has an upward-younging to vertical stratigraphy.
- The fold is an **overfold** if both limbs dip in the same direction as the axial plane and the steep limb has an up-side-down stratigraphy.
- Folds with sub-horizontal axial planes are **recumbent**. Fold nappes are large recumbent folds with inverted limb over several kilometres.
- **Plunging folds** have axial planes rotated by more than 90°.
- **Polyclinal folds** belong to groups of folds with sub-parallel hinge lines but non-parallel axial surfaces.



3.3.2: Layer thickness

- Changes in layer thicknesses reflect the material properties of the fold. There are two end-member geometries: parallel and similar folds.
- Approximations to these two morphologies exist in rocks, but the majority of natural folds lies somewhere between the two.
- Furthermore, some layers may approximate one of the ideal morphologies while other layers do not.

Parallel folds

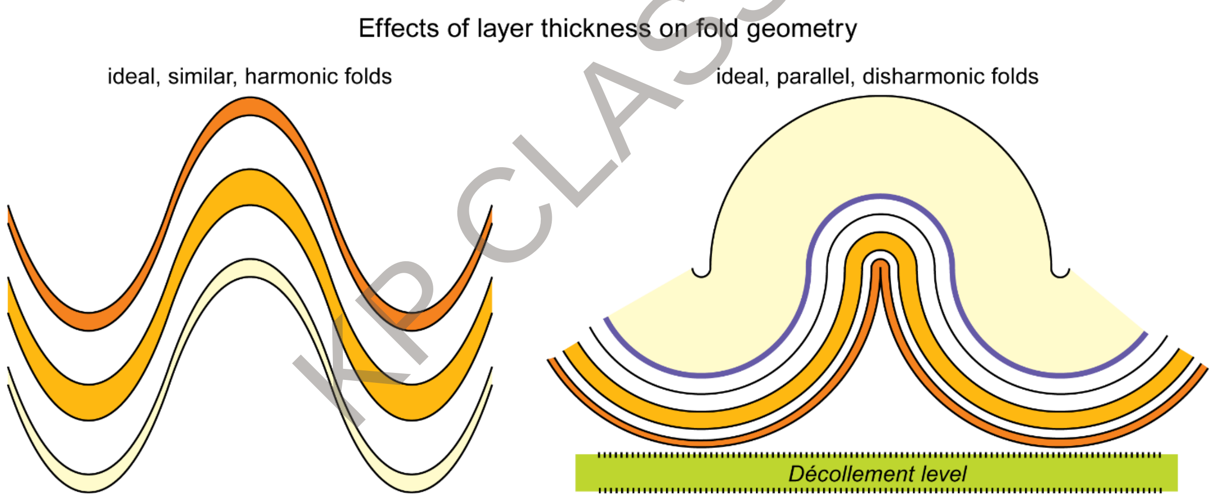
- A fold is **parallel** if the layer thickness, measured normal to the bed, is constant all around the fold. In other words, the layer boundaries are parallel curves.
- There are two types of parallel folds:

  - Rounded forms have smoothly curved limbs and broad hinges.

  - Angular forms have straight limbs and narrow hinge zones.

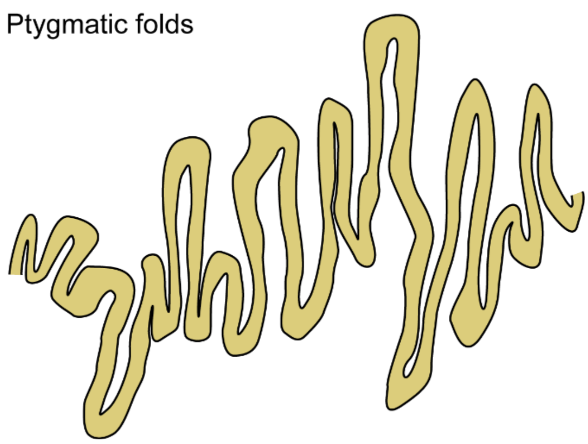
Rounded, parallel folds

- In profiles of **concentric folds**, the folded surfaces define circular arcs with a common centre.
- This geometry generates a space problem. Rounded antiforms reduce downward to a point (**cusp**).
- Similarly, deep and wide synforms wedge out upward. This geometrical limitation requires that parallel folds die out at depth.
- Incompetent beds below the antiformal cusps are squeezed in the antiforms. The lower boundary of the incompetent levels remains essentially unfolded.
- The incompetent layer between the undisturbed, flat footwall and the independently folded hanging wall is a “décollement” horizon. The Jura Mountains are classically cited for such relationships.



Ptygmatic folds

- **Ptygmatic** folds (buckle in ancient Greek) involve an irregularly folded, isolated “layer”, typically a quartzo-feldspathic vein in a much more ductile schistose or gneissic matrix.
- They occur in high-grade rocks, mostly migmatites, as trains of rounded and near parallel, commonly concentric folds in which the amplitude is large (>10) and the wavelength small with



respect to the almost constant layer/vein thickness (meander-like pattern).

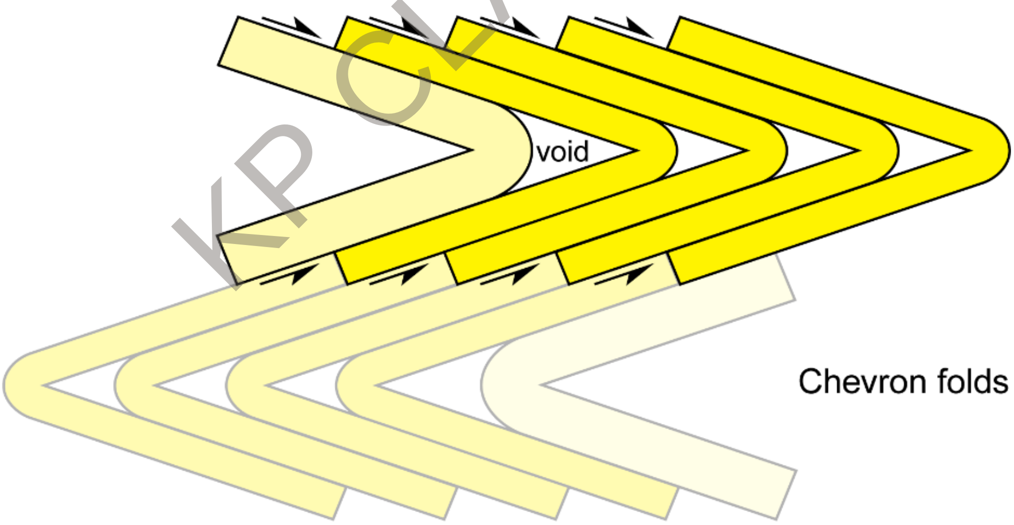
- They have a lobate, tortuous to squiggled appearance (for example, limbs fold back on themselves and the interlimb angle is negative) and tend to be polyclinal; however, the folded layer or vein contains no axial plane foliation.

Convolute folds

- **Convolute** folds have markedly curviplanar axial surfaces and are generally disharmonic (adjacent layers do not have the same wavelength and amplitude).
- Like ptygmatic folds, they look like complexly contorted but regular structures without axial plane cleavage. They are characteristic of slumped soft sediments.

Chevron folds

- **Chevron folds** are symmetric or slightly asymmetric folds with straight limbs, sharp angular hinges, and often-acute interlimb angles.
- These folds most likely form by flexural slip of multi layered rocks during layer-parallel shortening.
- They are common in multilayers of alternating competent and incompetent layers and combine both similar (in incompetent layers), and parallel (in competent layers) fold geometries. Asymmetrical chevron folds are also termed **zigzag folds**.
- The space problem in the hinge zone is resolved by ductile flow of the incompetent (dark) layers or collapse of competent layers in the hinge zone.
- Strained parts of competent layers are marked in red, showing that layer thickness is maintained on the limbs.
- **Kinks** are chevron folds in densely layered, anisotropic rocks (often schists).



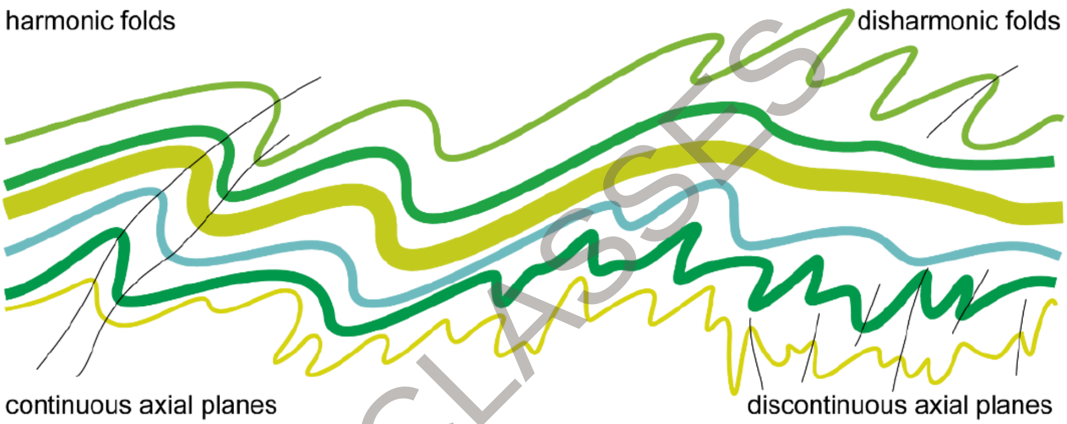
Similar folds

- Folds in which the layer thickness, measured parallel to the axial surface, is constant are **similar**.
- Similar folds tend to have persistent profiles, that is, all adjacent layers repeat the folded outline including wavelength, symmetry and general shape of a given layer: the strata are bent into similar curves.
- As a geometrical consequence, beds do not retain their original thickness throughout and the limbs are thinner than the hinges.

- Such folds do not die out upward or downward but maintain the same curvature in the hinges. This is the case for kink folds, in particular.
- In areas of intense folding, isolated, tight fold closures sandwiched between apparently unfolded foliation or layering surfaces are common; they die out upward and downward in otherwise unfolded rock; such structures are referred to as **intrafolial folds** or, if dismembered, as **rootless intrafolial folds**.

3.3.3: Axial plane continuity

- Folds in which axial planes are continuous across successive folded layers with approximately the same wavelength and amplitude are **harmonic**.
- Typically, similar folds that ideally maintain their shape throughout a section are harmonic.
- Folds in which the amplitude, wavelength and style change along discontinuous axial surfaces from one layer to another are **disharmonic**.
- Disharmonic folds develop because of differing rheology of the different layers. The incompetent beds are squeezed and adapt to the form imposed by competent beds.



- Disharmonic folds are particularly common in areas of parallel folds, which die out with increasing depth along their axial plane, reaching over-tightening in the core.
- Consequently, their extent is limited to the centre of curvature beyond which shortening should be accommodated by faulting or another type of folding.
- They may terminate downward at some surface, called **detachment** or **décollement,** along which they are separated (decoupled) from unfolded rock units below.

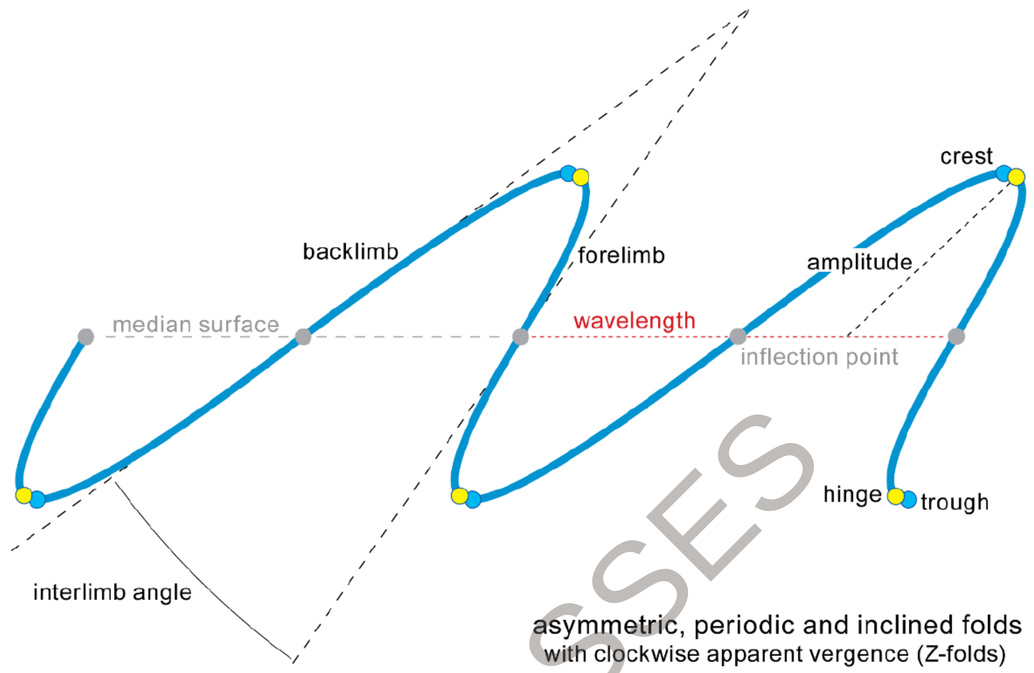
3.3.4: Symmetry

- Folds are **symmetrical** if the axial plane bisects the interlimb angle and divides the fold into two identical halves.
- In symmetrical folds with a vertical axial plane, the hinge line passes through the crest and trough of antiforms and synforms, respectively.
- If the axial plane is not a plane of symmetry, the limbs have unequal lengths and one limb dips more steeply than the other: the folds are **asymmetric**.
- Their leaning direction suggests a relative sense of movement, termed the **apparent vergence**.

3.3.5: Forelimb - Back limb

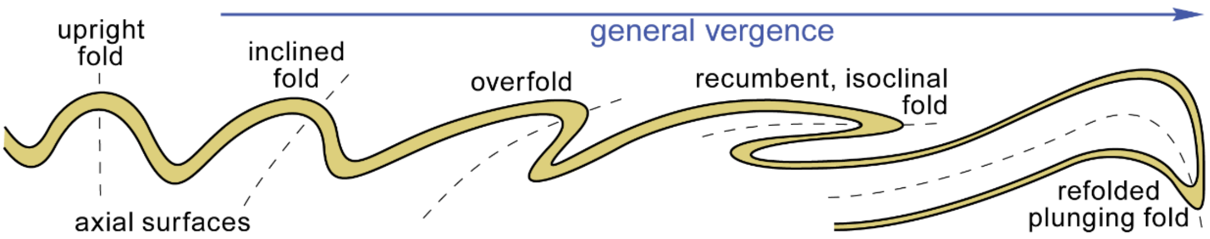
- An asymmetric or overturned antiform has a steep and short **forelimb** and a gentler, longer **back limb**.

- The forelimb is stratigraphically inverted in overfold anticlines. This forelimb is **reversed** or **inverted** or **overturned**, whilst the back limb is **normal**.
- Note that the overturned limb dips steeper, and the normal limb shallower than the axial plane.
- Note also that inverted bedding goes younger in the opposite direction to which it dips.



3.3.6: Facing and vergence

- The **vergence** is the direction of the apparent movement of the upper, long limb with respect to the shorter limb of an asymmetric fold**.**
- In that sense, vergence is simply the sense of asymmetry. The **true vergence** or **facing** is the younging direction along the axial plane in a direction perpendicular to the fold axis.
- Uniformly verging asymmetric folds are characteristic of thrust belts.
- Vergence is useful in working out the regional direction of transport and helps to fix an observation location on large folds.
- Antiformal synclines and synformal anticlines are **downward-facing folds** since the stratigraphy is inverted in passing along the axial plane; conversely, anticlines and synclines are **upward-facing folds**.
- Downward facing folds are normally formed during the refolding of the stratigraphically inverted limb of a recumbent fold.



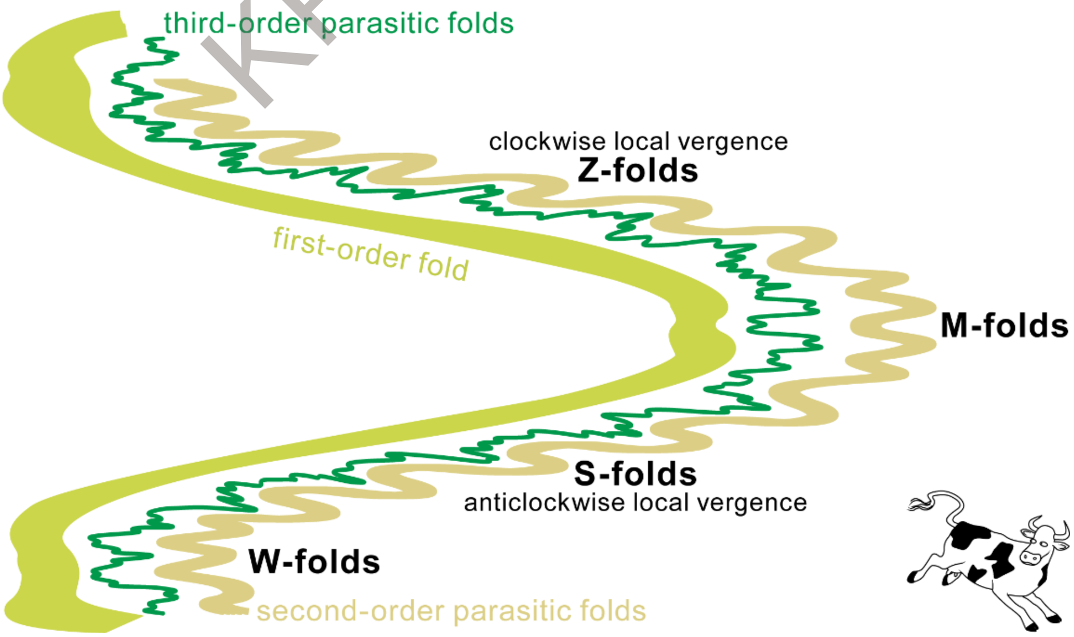
3.3.7: Fold trains

- A **fold train** is a series of folds along a particular layer or series of layers.

- Several folds may develop next to each other within a soft layer between virtually unfolded competent layers.
- When such layer-bounded fold trains display a systematic vergence, the sense of fold asymmetry affords a bulk relative sense of layer-parallel shear.
- These folds are termed **drag folds,** the implication being that the shear component of the velocity gradient across the layers has dragged the soft layer into a suite of folds characteristically non-cylindrical, asymmetric and disharmonic (i.e. the soft layer becomes detached from the adjacent layers). In the same way, drag folds may also develop within a thrust zone.
- Gravitational forces acting on plastically deforming layers can produce **cascades** of folds.

3.3.8: Parasitic folds

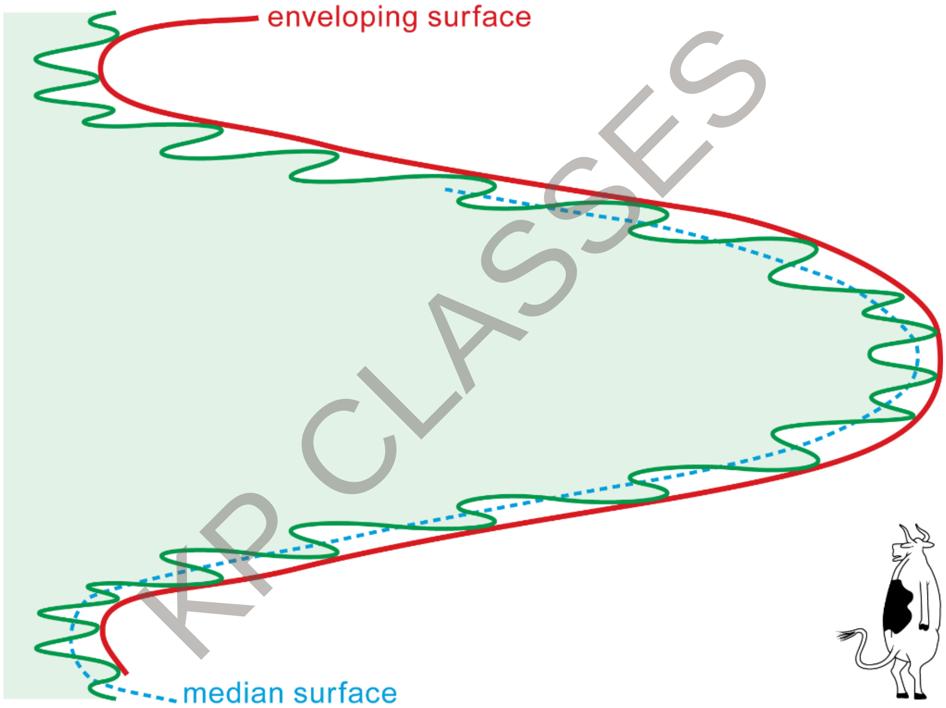
- Hinge zones and limbs of large folds often display folds of smaller wavelength and amplitude: larger and smaller folds are together **polyharmonic**.
- The small folds are named **parasitic** or **subsidiary folds** with respect to the larger ones.
- The largest folds are termed **first-order folds**, the next largest are called **second-order folds** and so forth.
- The axes of parasitic folds are habitually closely parallel to the axis of the major fold with which they are associated.
- They are said to be **congruous**, by contrast with **incongruous** parasitic folds whose axes deviate appreciably from the attitude of the major fold axis.
- First-order folds may be symmetrical whereas the congruous, second-order folds are asymmetrical.
- The sense of asymmetry, referred to as **local apparent vergence,** is consistently towards the hinges of higher-order antiforms.
- It changes systematically across the axial surfaces of the first-order folds, so that, looking down the axial direction, all parasitic folds in a limb have a **clockwise** apparent vergence and are described as **Z folds**, whereas those in the other limb have **anticlockwise** apparent vergence and are **S folds**.



- Symmetrical **M folds** generally occur in the hinge zone (**W** may be used for synforms as opposed to antiforms).
- The axial plane of the first order fold links and runs across second-order M folds and separates limbs with S and Z second-order folds.
- In the field, the asymmetry is used to locate hinges of the next larger order folds if they were both generated together.
- Note that flexural slip and/or flow provides a coherent explanation of why Z and S second-order folds form on the limbs of a first-order fold.
- Parasitic folds would initiate as symmetric buckle folds sheared hinge wards during the flexural flow of incompetent layers.

3.3.9: Enveloping and median surfaces

- The average orientation of a folded surface affected by a fold train is measured from the **enveloping surface**, which is constructed either as tangential to most or all of the hinge zones in the folded surface.



- The enveloping surface defines the limits of folds, thus relates the geometry of small- to large-scale folds in areas where there are so many small-scale folds that they obscure the general orientation of bedding (e.g. in a tightly folded limb).
- Which folds the enveloping surface touches depends on the scale at which the structure is being considered.
- The **median surface** joins the successive inflection lines of a folded layer and separates antiforms from synforms.
- The median and enveloping surfaces are generally almost parallel and, therefore, yield the same information.
- Axial planes of symmetrical folds are perpendicular to the enveloping and median surfaces.

3.3.10: Wavelength, arc length, amplitude and aspect ratio

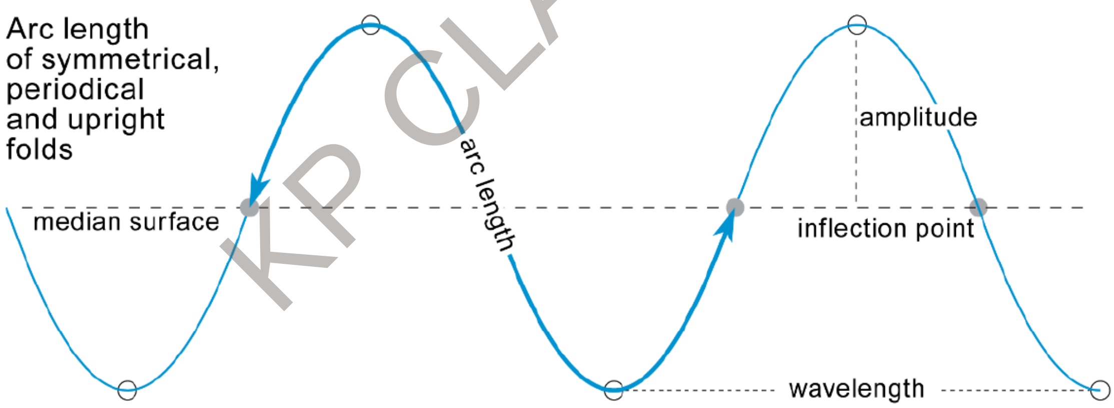
- Amplitude and wavelength define the **size** of a single fold and refer to the mathematical terminology used to describe a sinusoidal curve.

Wavelength

- The distance parallel to the median surface between two successive anticlinal (or synclinal) hinges seen in profile is the **wavelength**. The median surface length between the inflection points on equivalent (say left) limbs of two neighbouring folds is also the wavelength.
- The distance parallel to the median surface between two successive anticlinal (or synclinal) hinges seen in profile is the **wavelength**.
- The median surface length between the inflection points on equivalent (say left) limbs of two neighbouring folds is also the wavelength.
- The **arc length** is the distance along the folded plane between two points separated by one wavelength.

Amplitude

- The **amplitude** is measured by taking half the distance along the axial plane from one anticlinal hinge to the surface enveloping the two adjoining synclinal hinges (or vice versa), namely, the distance along the axial plane from the median surface to the hinge. A train of folds may fold a surface periodically or non-periodically.
- The term **pericline** is applied to large-scale antiforms or synforms whose amplitude decreases regularly to zero in both directions so that the fold has precise limits in space. Domes and basins are periclinal structures.



Aspect ratio

- The **aspect ratio** of a fold is the ratio of the amplitude to half the wavelength.
- Where folding is disharmonic, both wavelength and amplitude of folds vary between successive layers.

3.4: Fault-related folds

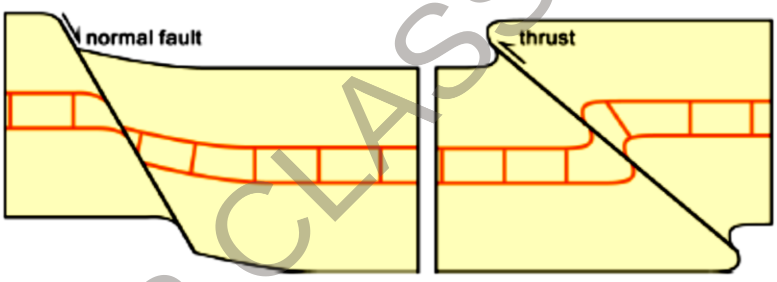
- There commonly are folds geometrically associated with faults. They are in general controlled by the fault geometry.

3.4.1: Drag folds

- Bedding is frequently bent in fault zones. These local flexures are known as **drag folds** and **fault drags**.

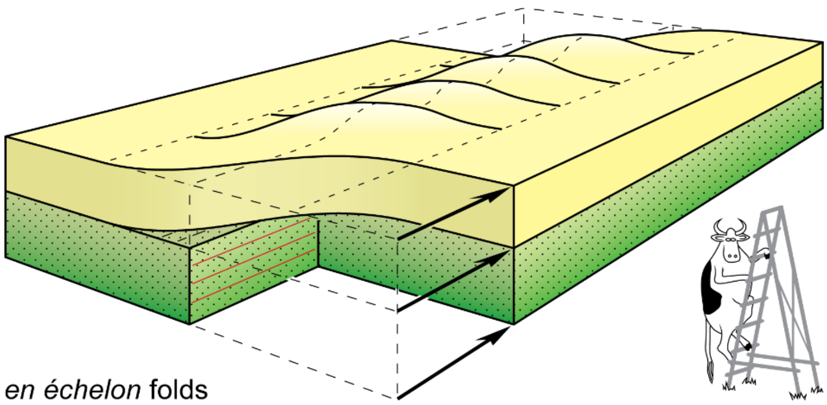
- They usually are convex toward the direction of the fault movement and are thus attributed to some frictional resistance to slip along the fault plane.
- This interpretation suggests that faulting is initiated first and that folding occurs adjacent to the fault as one block is dragged along the other (normal drag).
- However, folding might precede faulting, drag folds representing bending of rock before it breaks.
- The use of drag folds, intuitively inferring that the direction of folding is toward the direction of fault movement, can be misleading because convexity opposite to the sense of displacement, termed **reverse drag**, is common.
- For example, roll-over flexures on listric normal faults are hanging wall folds concave towards the slip direction.
- Reverse drag is hardly distinguished from normal drag when they appear separately.
- In addition, the orientation of drag folds is often not controlled by the movement direction but rather the intersection between bedding and the fault plane, and the drag may vary from reverse to normal from the centre to the termination of faults.
- Therefore, drags should be used with extreme care to ascertain the sense of slip along faults.
- Trains of drag folds are common in incompetent layers between two competent layers of in the proximity of thrust faults.

Drag folds against fault planes



3.4.2: En échelon folds

- In some non-cylindrically folded surfaces, doubly plunging and relatively short, nearly upright folds in parallel series have alternating antiform and synform axes oblique to the fold string.
- Such folds are stepped and consistently overlapping; they define an *en échelon* array.



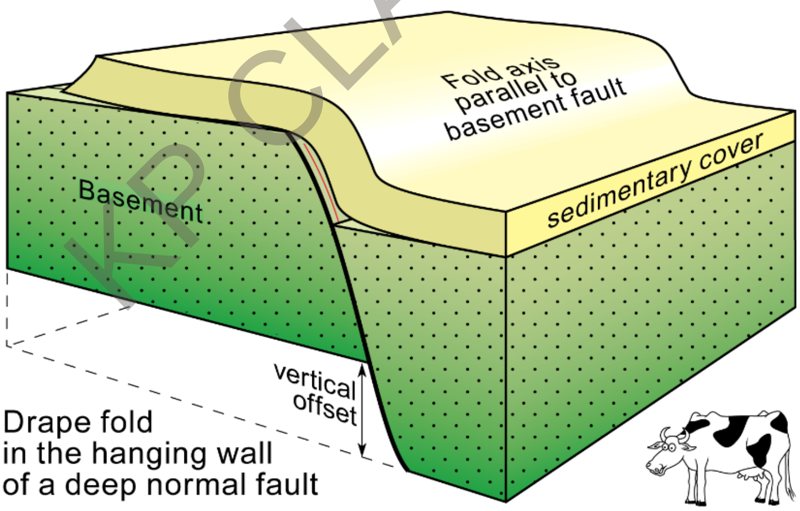
en échelon folds

- Note, however, that this term describes the geometry of the folded surface and is independent of the relationship of the structure to the horizontal and vertical.

- Taking the steep axial planes as roughly orthogonal to the shortening direction, their distribution permits to decipher the potential fault they are related to.
- Such folds are common above strike-slip faults that have not broken the cover but offset the basement blocks.
- The *en échelon* fold-pattern reveals the relative sense of movement along the basement fault.

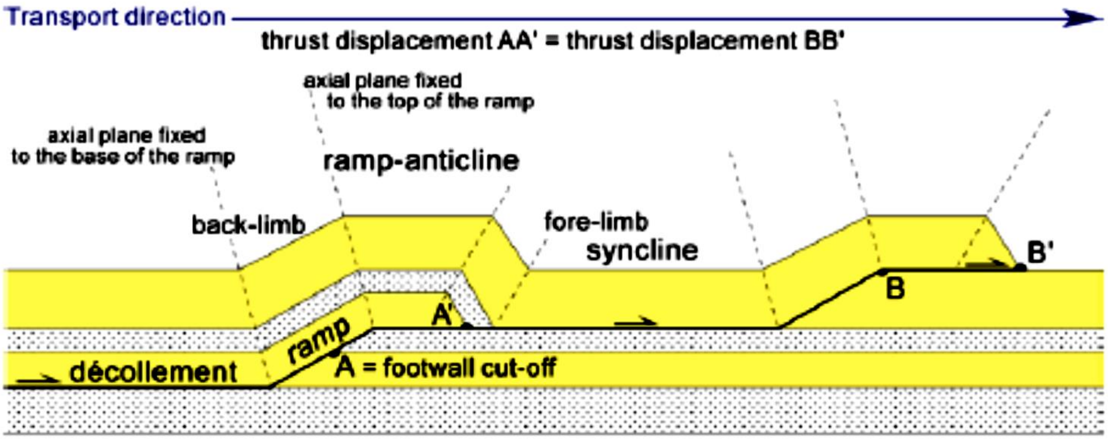
3.4.3: Drape folds - Forced folds

- Cover rocks can be more or less passively bent to conform to the topography of the buried basement / cover interface.
- An important shape-controlling factor is whether the cover remains welded to or is detached from the basement.
- **Drape folds** are generally open curvatures in a sedimentary layer that conforms passively to the configuration of underlying structures and geological bodies.
- An important shape-controlling factor is whether the cover remains welded to or is detached from the basement. A fold formed by differential compaction is an example.
- **Forced folds** are generally fault-related, long and linear flexures that relative movements of basement blocks generate in cover rocks.
- Their overall shape and trend are dominated by the shape and trend of the underlying forcing fault blocks.
- They are typically monoclines with long, gently-dipping back limbs and short, steeply-dipping forelimbs, the latter overlying the fault surface.
- They are equally common in compression and extension regimes. The type and amount of fault movement control the fold profile geometry.



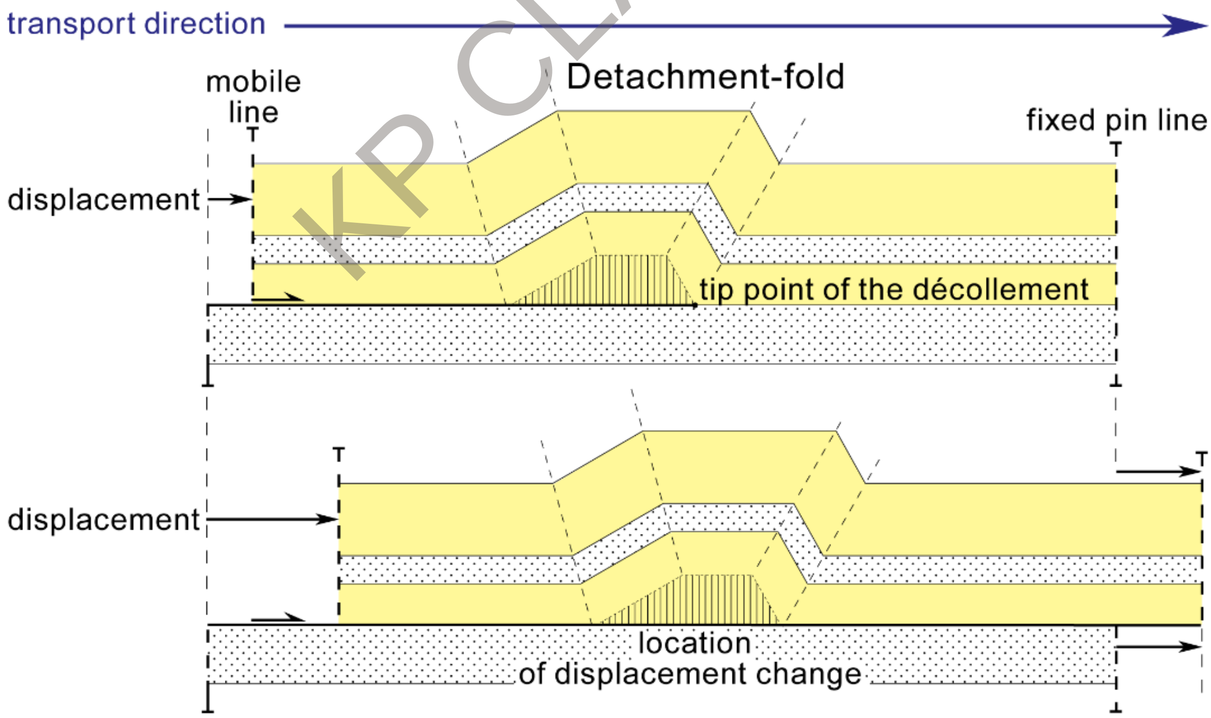
3.4.4: Thrust-related folds

- Thrust movement generates geometrically necessary folds in the allochthonous hanging-wall as it moves over topographic irregularities of the deep thrust faults. Kink-like, box folds result.



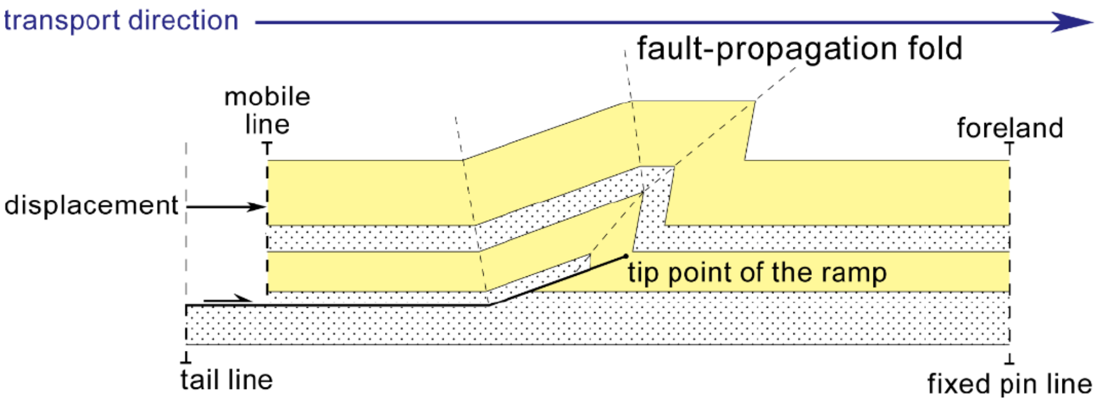
Passive folding of the hanging-wall of a flat-and-ramp thrust system

- Two types of ramp-related folds are common in thrust belts.
- **Fault bend folds** form and grow above a footwall ramp where a displacement plane steps from a lower flat to a higher one.
- As slip occurs, strata of the hanging wall slide over the fault bend. Passive syncline-anticline pairs at the base and top of the ramps accommodate in the hanging wall the shape of the footwall ramps.
- Specific geometries are maintained throughout the development of the folds.
  - (i) The anticline-syncline pair directly reflects the geometry of the fault bends.
  - (ii) The ramp anticline terminates downward into the upper-flat.
  - (iii) The forelimb is shorter and steeper than the backlimb.
  - (iv) The backlimb is parallel to the footwall ramp.

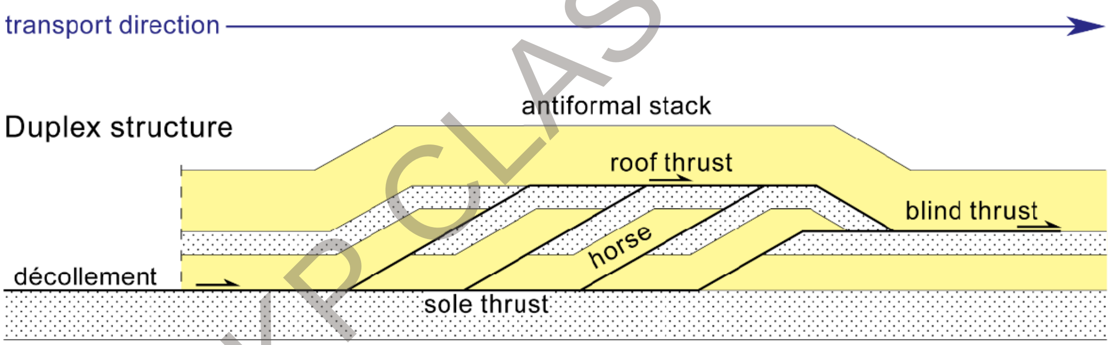


- In a **fault-propagation fold,** the ramp does not continue to an upper flat. Strata cut by the base of the ramp are shortened by thrusting.

- Fault slip decreases to zero in the up-section direction and the fault dies out into the axial surface of a syncline.
- Strata above and in advance of the upper tip line of the propagating thrust are shortened entirely by folding.

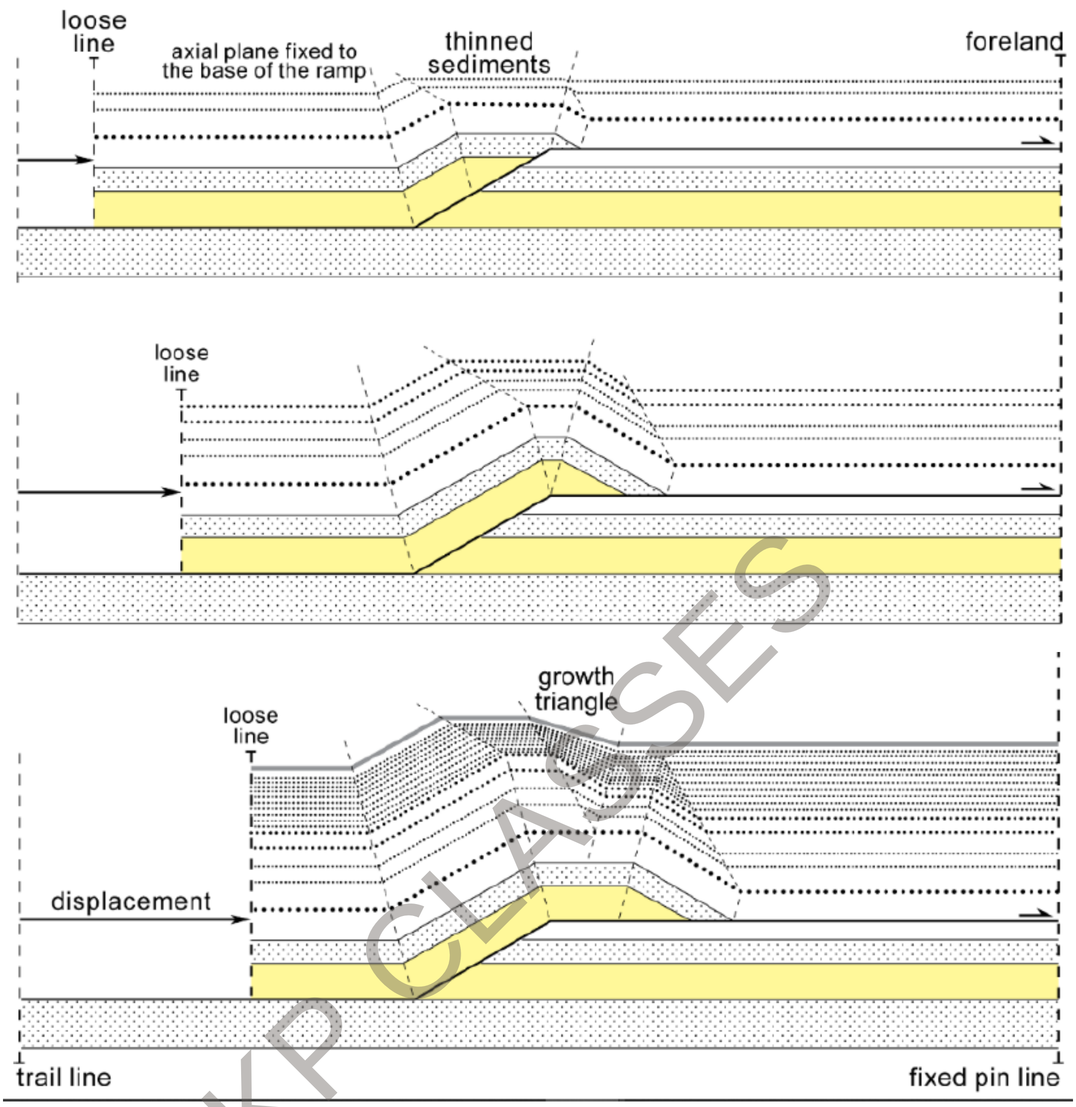


- Typically:
  - (i) Such folds are asymmetric in the direction of thrust movement,
  - (ii) They tighten with increasing displacement, and
  - (iii) Both limbs lengthen while the fault tip propagates upwards.
- Antiformal structures commonly grow over a ramp or a duplex zone to build **antiformal stacks.**



- **Growth folds** develop in sedimentary strata deposited at the same time as folding. Antiformal structures commonly grow over a ramp or a duplex zone to build **antiformal stacks.**
- The common association of folds and thrusts at a regional scale defines a **fold and thrust belt.**
- The fold shape is determined by the shape of an advancing ramp that does not tie into an upper flat.
- The **ramp** fault is replaced upward by an asymmetric fold, which is overturned in the direction of transport.
- There is a systematic and predictable geometric relation between a fold and the thrust that generated it, and we can therefore use fold geometry to infer fault position and geometry at depth.

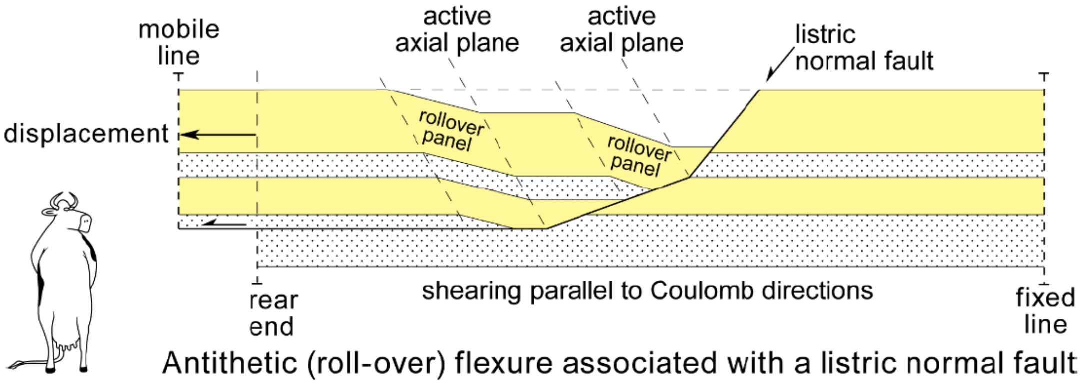
Change of layer thickness
on a synsedimentary, growth fault-ramp anticline



3.4.5: Normal fault-related folds

- As in thrust systems, shape and topographic irregularities of extensional faults generate folds.
- **Rollover anticlines** are gentle convex bending of upper-block beds toward the main listric fault.
- They form half-antiforms geometrically necessary to accommodate the concavity of the causal fault.
- As the hanging wall slips along the deep, gently dipping to flat-lying parts of the fault, an “empty” space opens between the displaced hanging wall and the shallower, steeper parts of the fault.
- Beds initially horizontal in the hanging wall must tilt and become gently convex upwards to fill up this space.
- **Growth folds** associated with normal faults are common. The geometry and size of these folds change as slip accumulates on the normal fault.
- These changes affect the distribution of concomitant sediments, generally producing wedge-shaped layers thinning towards the fault.

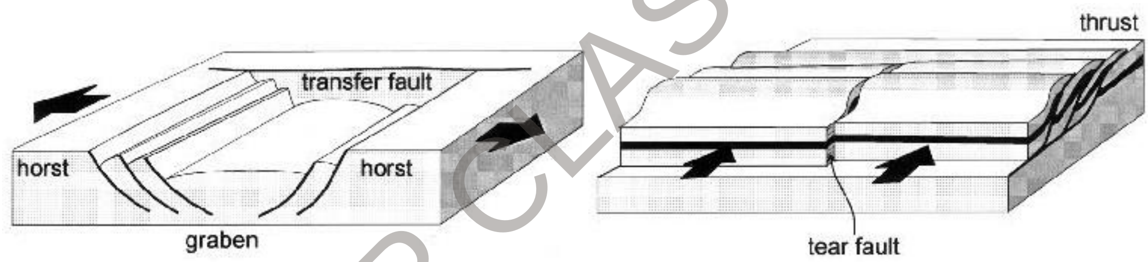
- The folded beds become gently concave upwards. Unconformities develop towards the fold crest and the fault; these same unconformities pass into correlative conformities in the adjacent basin.



Antithetic (roll-over) flexure associated with a listric normal fault

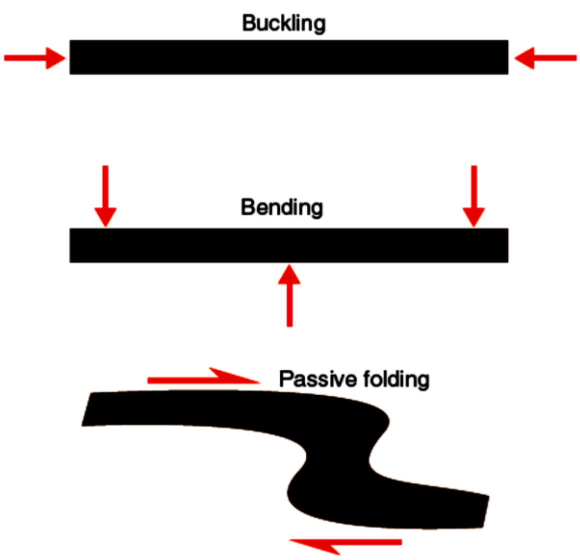
3.4.6: Tear faults

- A tear fault, also known as a transform fault, occurs when two tectonic plates slide in a lateral motion past each other.
- In areas like the Jura, strike-slip faults seem to tear the folds across. Such faults are attributed to differential advance of adjoining segments of the folds, with folds in one block being more closed and tighter than in the other.
- Tear-faults as such are transfer faults that originated during folding.



3.5: Mechanisms of folding

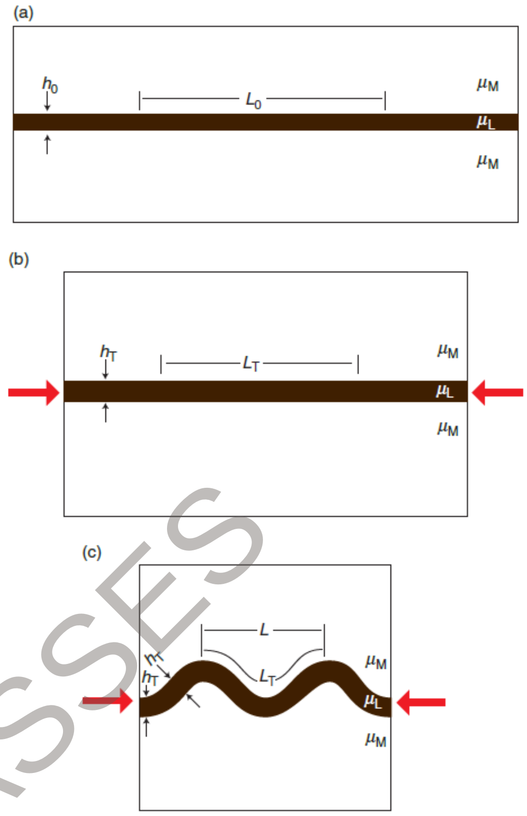
- The most important distinction between the ways fold form probably lies in whether the layering responds **actively** or **passively** to the imposed strain field.
- We will start out by considering **active folding (buckling)**, where the competence or viscosity contrast between the folding layer and its host rock is important.
- We will then look at **passive folding**, where layers are simply passive markers with no rheological influence, and then consider **bending,** where forces are applied across the layering.



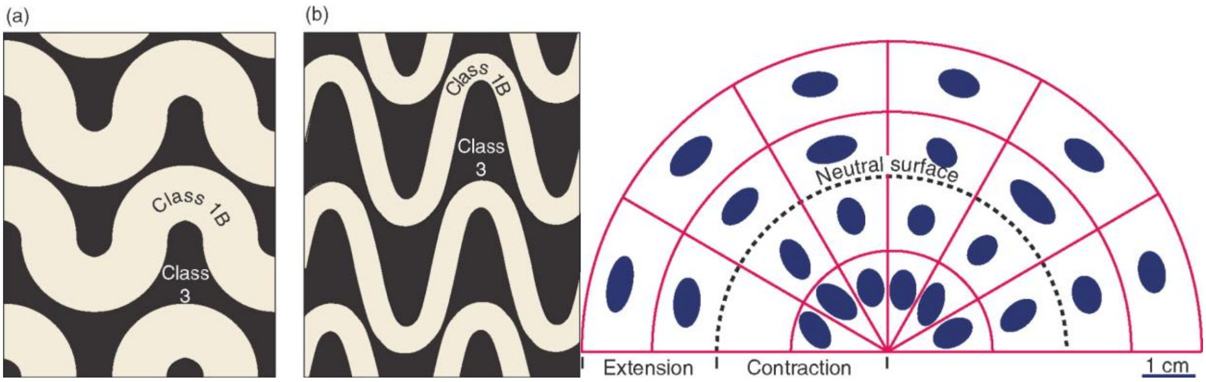
3.5.1: Active folding or buckling (Class 1B folds)

- **Active folding** or **buckling** is a fold process that can initiate when a layer is shortened parallel to the layering, as shown schematically in Figure. Such folds appear to have formed in response to layer-parallel shortening.

- A contrast in viscosity is required for buckling to occur, with the folding layer being more competent than the host rock (matrix).
- The result of **buckling** is rounded folds, typically **parallel** and with more or less sinusoidal shape.
- **Buckling** occurs when a competent layer in a less competent matrix is shortened parallel to the length of the layer.
- **Buckling** or active folding implies that there is layer parallel shortening and a viscosity contrast involved, and also irregularities on which folds can nucleate.



- Lo = length of the original layer
  ho = thickness of the original layer
  L_T = length of layer after initial shortening h_T = thickness of original layer after initial shortening
  μ_L = viscosity of layer
  μ_M = viscosity of matrix
  L = wavelength of fold
- The fold wavelength-thickness ratio (L/h) is constant if the material is mechanically homogeneous and deformed under same physical conditions.
- If the layer thickness varies then the wavelength is changed. The effect of folding disappears rapidly (~ 1 wavelength) away from the folded layer.
- Folds in the competent layer approximate Class 1B folds. If two or more competent layers, than the incompetent layers in between are folded into Class 1A and Class 3B folds.
- Cusps point to the more competent layers. The outer part of the competent layer is stretched while the inner part is shortened.

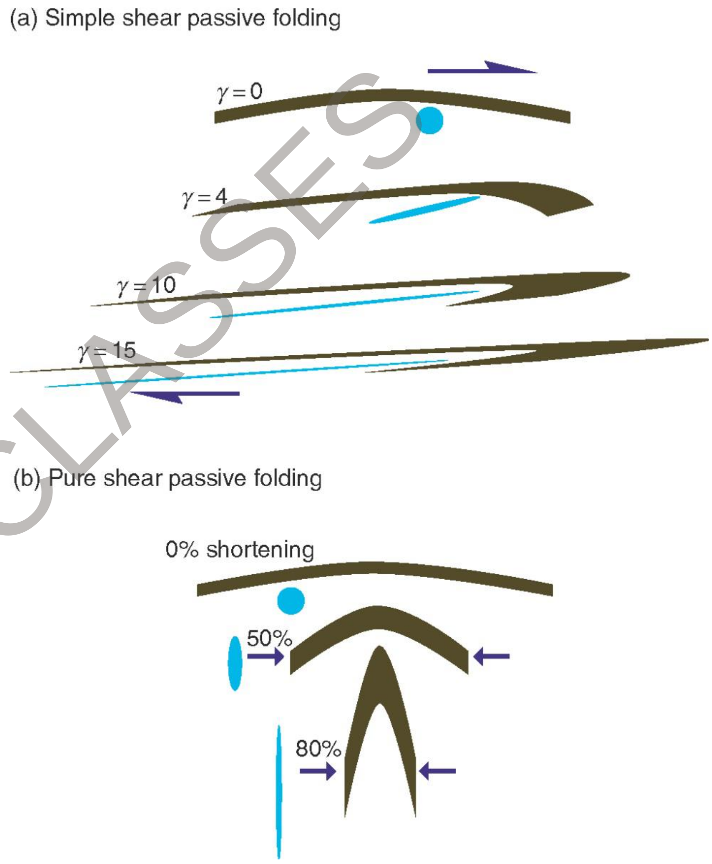


- Mathematical description of buckle folds:
  Disregarding layer shortening - $L_d/h = 2\pi(\mu_L/6\mu_M)^{1/3}$
  Including layer shortening – $L_{dT}/h_T = 2\pi(\mu_L/6\mu_M\,(T + 1)T^2)^{1/3}$
  where –

L_d = dominant wavelength
h = layer thickness
L_{dT} = dominant wavelength taking into account thickening
h_T = layer thickness after shortening
T = strain ratio X/Z = $(1 + e_1)/(1 + e_3)$

3.5.2: Passive folding (Class 2 folds)

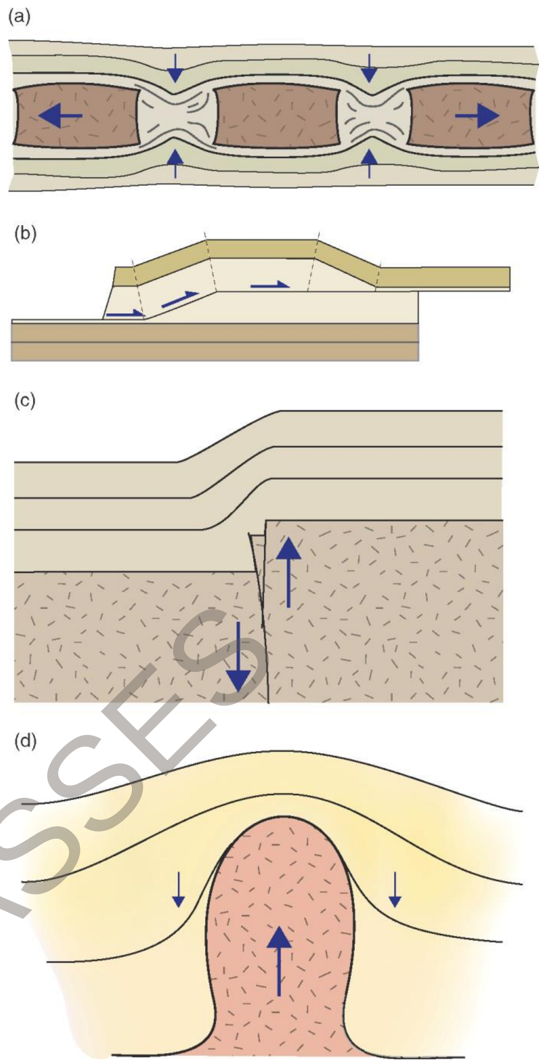
- **Passive folding** is typical for rocks where **passive flow** occurs, i.e. where the layering exerts no mechanical influence on the folding.
- In these cases, the layering only serves as a visual expression of strain with no mechanical or competence contrast to neighboring layers. Such layers are called passive layers.
- Perfectly passive folds produced by simple shear are **Class 2 (similar) folds**, and **passive folds** that are associated with simple shear, or at least a significant component of simple shear, are called **shear folds**.
- **Passive folds** generated by simple shearing are perfectly **similar folds**. **Passive folds** of perfect Class 2 geometry can easily be generated by differentially shearing a card deck.
- **Passive folding** produces **harmonic folds** where the layering plays no mechanical role and therefore no influence on the fold shape.
- Examples of **passive folding** are found where passive layers enter shear zones or otherwise are affected by heterogeneous strain.
- **Drag folds** along faults are examples typical for the brittle regime, although many layered sequences contain beds of quite different mechanical properties so that slip occurs between layers.



- **Passive folds** are frequently found in mylonite zones, particularly in monomineralic rocks such as quartzite, marble and salt.

3.5.3: Bending

- Bending occurs when forces act across layers at a high angle, unlike buckle folds where the main force acts parallel to a layer.
- This is also the case for passive folding, and the two are closely related.



- However, bending is generally thought of as something that is more directly forced upon the layers by geometries and kinematics of the bounding rock units.
- Differential compaction, where a sedimentary sequence compacts more in one area than in another due to different degrees of compaction of the underlying layers, is also a type of bending.
- This is common across the crests of major fault blocks in post rift-sequences in sedimentary basins, but can also occur along salt diapirs and shallow intrusions.
- Folds formed by differential compaction are gentle. Forceful intrusion of magma or salt can also bend roof layers.
- Again, the strain accumulation mechanism may vary, with flexural slip being a common constituent.
- In the plastic regime, bending is less common because of the high ductility of all or most parts of the deforming rocks. However, bending is frequently associated with rigid boudins.
- Examples of bending:
  - Between boudins
  - Above thrust ramps
  - Above reactivated faults
  - Above shallow intrusions or salt diapirs

3.5.4: Flexural slip and flexural flow (Class 1B)

- Flexural slip implies slip along layer interfaces or very thin layers during folding It is one of three kinematic models of folding (the others being flexural flow and orthogonal flexure) that maintains bed thickness and thus produces Class 1B or parallel folds.
- Simple flexural slip experiments can be performed simply by folding double sandwiches with jelly.
- The sandwich maintains its thickness even though slip occurs between the pieces of bread, until the fold becomes too tight.
- It is a prerequisite for flexural slip that the deforming medium is layered or has a strong mechanical anisotropy.
- In nature, the anisotropy could be mica-rich thin layers in a quartzite or mylonite, or thin shale layers between thicker sandstone or limestone beds in sedimentary rocks.
- Flexural slip can occur in the middle crust where plastic deformation mechanisms would be involved, but is perhaps more common where sedimentary strata are folded in the upper crustal brittle regime.
- In the latter case, bedding surfaces act like faults, and slicken lines will sometimes develop on slipping surfaces.

- In cases where strain is more evenly distributed in the limbs in the form of shear strain, as is more commonly the case in the plastic regime, flexural slip turns into the closely related mechanism called flexural shear or flexural flow.

3.5.5: Orthogonal flexure (also Class 1B)

- Orthogonal flexure, also called tangential longitudinal strain, is a deformation type with its own specific conditions:
- All lines originally orthogonal to the layering remain so throughout the deformation history.
- The result is stretching of the outer part and shortening of the inner part of the folded layer.
- The long axis of the strain ellipse is therefore orthogonal to bedding n the inner part of the layer and parallel to bedding in the outer part.
- Orthogonal flexure produces parallel folds with a neutral surface. Pure orthogonal flexure is only possible for open folds.
- When folds get tighter, the conditions for orthogonal flexure become harder and harder to maintain, and flexural slip or flow will gradually take over.
- Evidence for orthogonal flexure is typically found in stiff, competent layers that resist ductile deformation.
- Some have simplified the definition of orthogonal flexure to a mechanism resulting in outer-arc contraction and inner-arc extension.

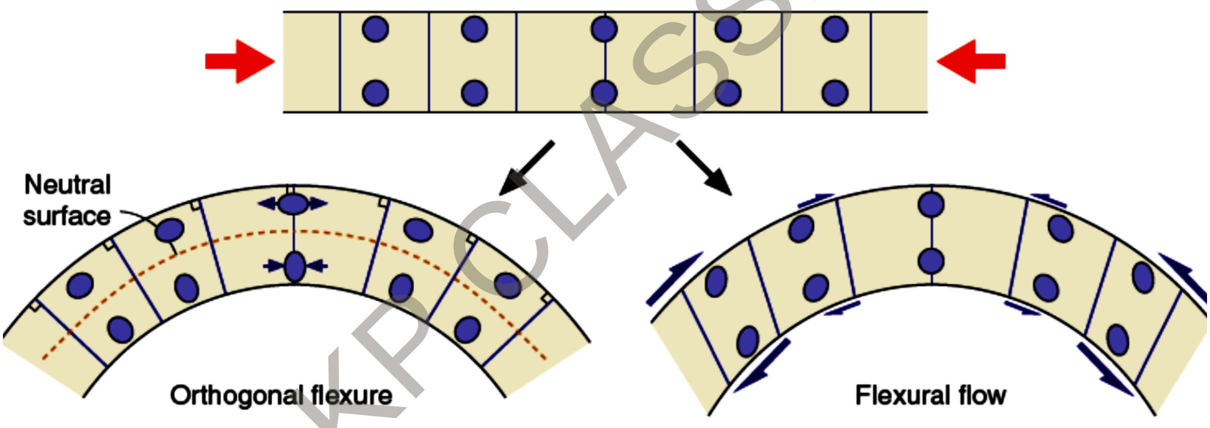


Figure: Layer-parallel shortening resulting in orthogonal flexure and flexural flow. Note what happens to the originally orthogonal lines. Strain ellipses are indicated.

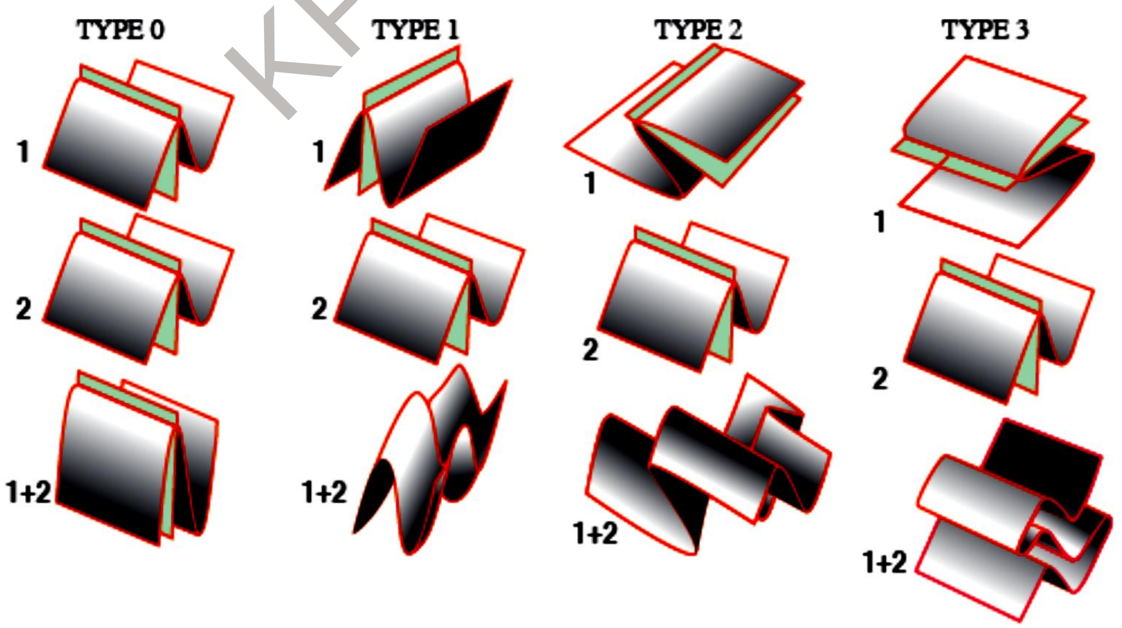
3.6: Superposed folding

- Structural geologists use the term **fold generation** to refer to groups of folds that formed at approximately the same time interval and under similar kinematic conditions.
- Commonly we find several fold generations in an area, which are labeled by the letter *F* (for *F*old) and a number reflecting the relative order of their formation: *F*1 folds form first, followed by *F*2 folds, *F*3 folds, and so on.
- Several fold generations may in turn form during an **orogenic phase**, which is noted by the letter *D* (for *D*eformation).
- In any mountain belt several phases may be present, which are labeled *D*1, *D*2, and so on, each containing one or more generations of folds.

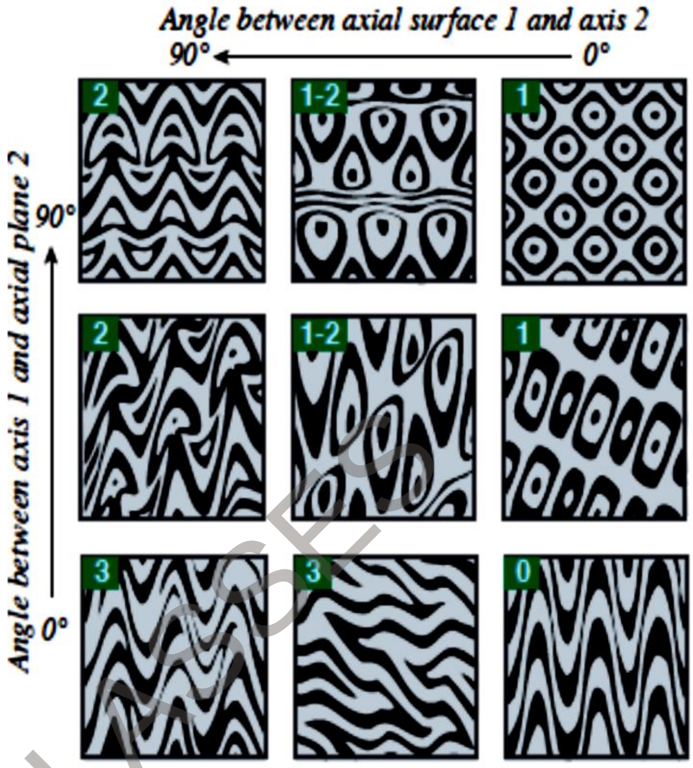
- From the onset it is important to realize that neither a deformation phase nor each of the individual fold generations have to be present everywhere along the orogen, nor do they occur everywhere at the same time.
- On a regional scale *deformation is irregularly distributed and commonly diachronous.* You can imagine that fold generations and deformation phase can rapidly become pretty complex.
- So we'll stick to two fold generations to examine the principles of superposed folding, which allows us to unravel the sequence (that is, relative timing) of folding.
- Generation is a relative time concept and only implies "older than" or "younger than"; you are the younger generation in the eyes of your parents.
- There are methods to determine the absolute ages of folds, such as dating of minerals that formed during folding, but we will not get into them here.
- The relative time principle of **superposed folding** is simple: folds of a later generation are superimposed on folds of an earlier generation.
- The determination of this temporal sequence, however, is not straightforward and requires careful spatial analysis.
- Superposed folding is a widespread phenomenon that is not restricted to high-grade metamorphic areas.
- Even in regions below the **greenschist facies** (temperatures below ~300°C), superposed folding is found.

3.6.1: Fold Interference Patterns

- In areas affected by two or more deformation phases we may find that folds may be superimposed on each other.
- In such cases of fold interference, we may find simple or complex patterns of folding that depend on the orientations of the two-fold sets.
- John Ramsay distinguished between three main patterns. **Type 1** is the classical dome-and basin structure, **Type 2** is the so-called boomerang type, and **Type 3** has been described as the hook-shaped type.

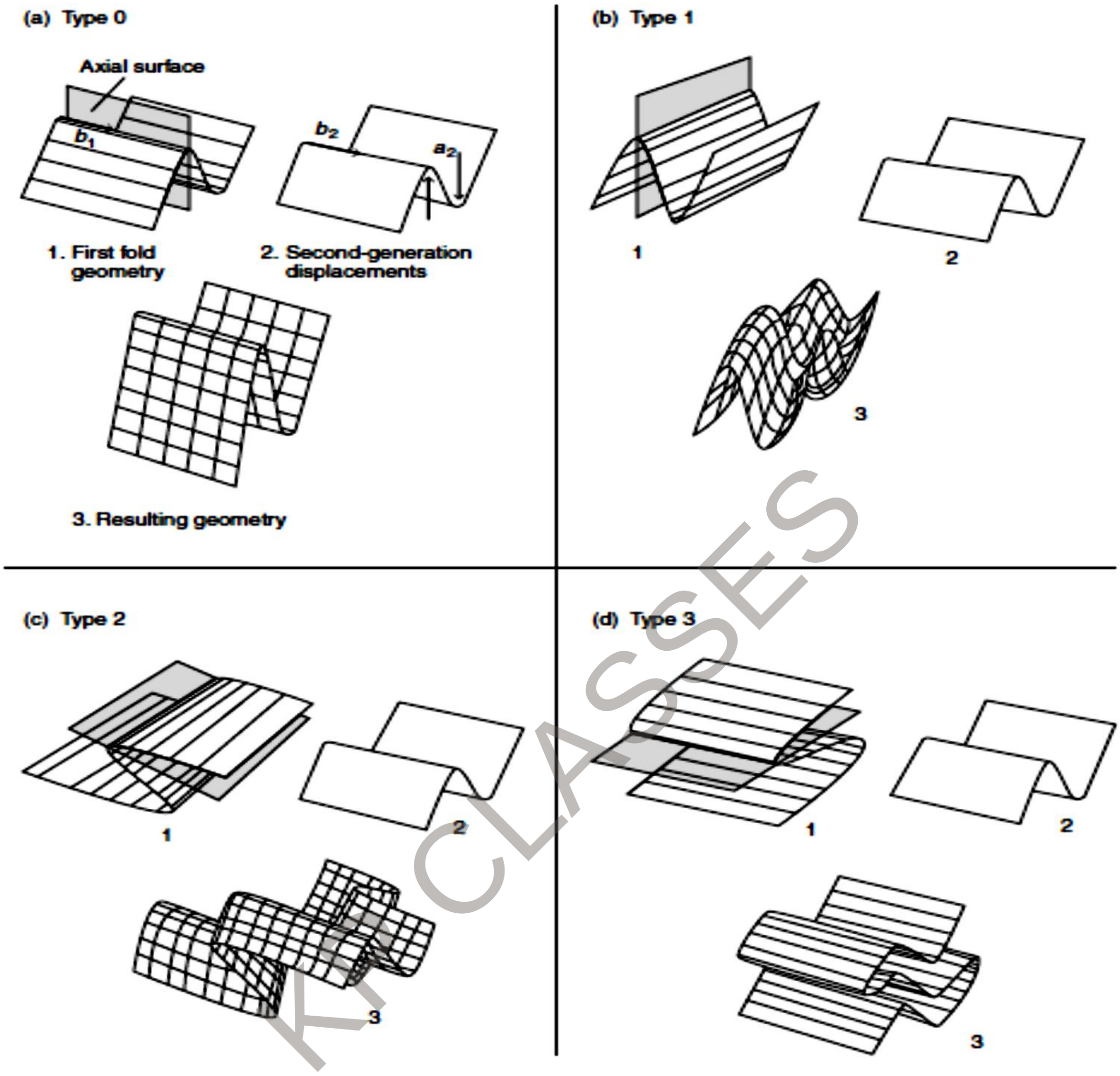


- Interference patterns typically arise from the overprinting of a second phase of deformation on an earlier set of deformation structures, but can also be the result of non-steady-state flow, where the orientation of the ISA locally or regionally changed during the course of the deformation.
- There is also a **Type 0** pattern defined by two identical, but temporally separate fold systems.
- The result of **Type 0** interference is simply a tighter fold structure. **Type 1** patterns can also be the result of a single phase of heterogeneous non-coaxial deformation, or by amplification of preexisting irregularities.
- These extremely non-cylindrical folds are often called sheath-folds.
- In general, it is useful to be able to recognize the geometric relations between different fold phases by use of the patterns depicted in the following Figure.



- We now turn to some important properties of the various fold interference types. **Type0** is a special condition, because the hinge lines and the axial surfaces of both fold generations are parallel.
- As a consequence, *F*1 is merely tightened by the superimposition of *F*2. You realize that, practically, Type 0 cannot be recognized in the field as an interference type by geometry alone (that's why we use the number 0).
- **Type 1** is also called a "dome-and-basin" structure and resembles an egg carton. Both the axial surfaces and the hinge lines of the two generations are perpendicular, producing this characteristic geometry (Figure a).
- **Type 2** is perhaps the most difficult geometry to visualize, but folding a piece of paper helps enormously.
- In outcrop, we often see a section through this geometry that resembles a "mushroom" pattern (Figure b).
- Note that this outcrop pattern is only generated in the horizontal surface that intersects Type 2; if we take another cut, say vertical, the outcrop pattern is quite different.
- Finally, **Type 3** (Figure c) is sometimes referred to as the "refolded fold" pattern, which is a misnomer because all four types are refolded folds.
- We just present the name so that you have heard it, and because very few people are otherwise able to remember the corresponding numbers of the types.
- We recommend that you use the descriptive terms "dome-and-basin," "mushroom," and "refolded-fold," however flawed, instead of the abstract Type 1, Type 2, and Type 3, respectively.

- Interference patterns are a function of the spatial relationship between hinge lines and axial surfaces of the fold generations, as well as the sectional surface in which we view the resulting patterns.

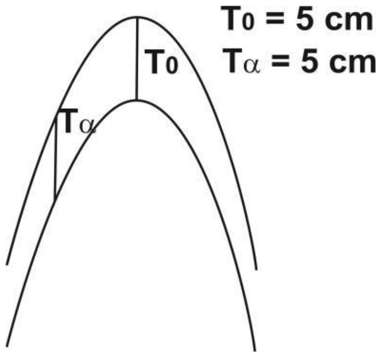


- Thus, the analysis of fold superposition is a three-dimensional problem.
- The four types that are shown in Figures above are only end-member configurations in an infinite array of possibilities.
- The presence of multiple fold generations has major implications for the interpretation of the deformation history.
- First, it implies that the kinematic conditions have changed to produce a fold generation with different orientation than before (except Type 0); so the deformation regime must somehow have changed.
- Secondly, folds of the first generation will have variable orientations depending on where they are measured in the fold superposition pattern.
- Orientation, therefore, is *not* a characteristic of fold generations in multiply deformed areas and should be used carefully as a mapping tool.

Practice Questions

Previous year Easy Questions

1. If the two limbs of a fold are parallel in outcrop on flat topography it must be
   A. Upright (GATE 1997)
   B. Recumbent
   C. Non-plunging
   D. Similar
2. Folds formed by layer parallel deformation are called (GATE 1998)
   A. Buckle fold
   B. Bending fold
   C. Parallel fold
   D. Similar fold
3. According to the classification of dip isogons a flattened parallel fold belongs to
   A. IA (GATE 1998)
   B. IB
   C. IC
   D. 2
4. In a fold if the curvature of the inner arc is lower than that of the outer arc, then the dip isogons (GATE 2002)
   A. Converge towards the inner arc
   B. Diverge towards the inner arc
   C. Remain parallel
   D. May converge or diverge
5. A horizontal bed is folded in a manner that the axial plane of the fold is vertical and strike N-S. if it is a non-plunging fold, the amount of dip of the bed in the hinge zone
   A. 0° (GATE 2003)
   B. 30°-50°
   C. 50°-70°
   D. 90°
6. An open fold may appear to be isoclinal when viewed in a section (GATE 2007)
   A. at a low angle to the fold axis
   B. perpendicular to the fold axis
   C. at 45° to the fold axis
   D. parallel to the axial plane
7. A 'gentle' fold with an interlimb angle equal to 160° appears tight (apparent interlimb angle equal to 20°) in horizontal section. According to the plunge of the fold axis, it can also be classified as (GATE 2018)
   A. horizontal fold.
   B. gently plunging fold.
   C. steeply plunging fold.
   D. vertical fold.
8. Identify the fold in the given figure, where T0 and Tα represent the axial plane thicknesses at the hinge and limb, respectively. (JAM 2020)

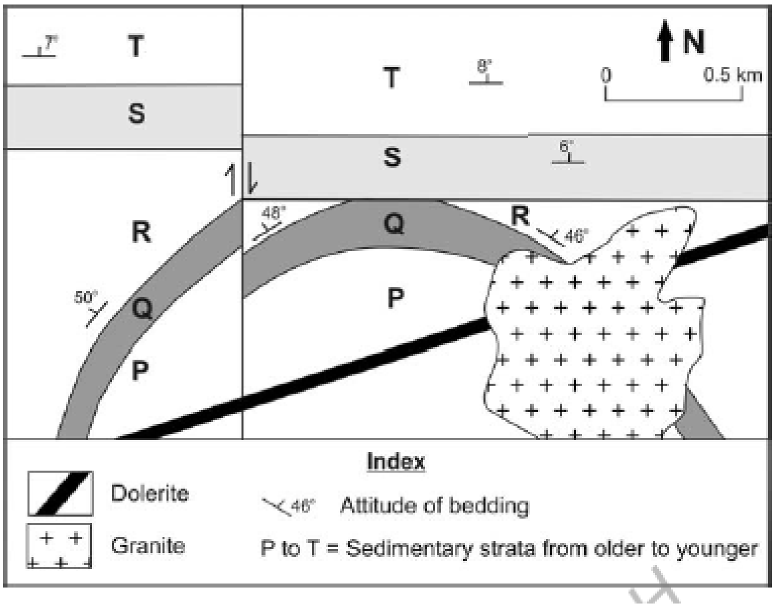


A. Parallel fold
B. Similar fold
C. Supratenuous fold
D. Flattened parallel fold

9. On a geological map of a flat area, the plunge direction of an antiformal anticline is
   (A) towards the fold closure (JAM2019)
   (B) away from the fold closure
   (C) towards the dip direction of the left limb
   (D) towards the dip direction of the right limb
10. Which of the following is the correct angle between the hinge line and the strike line of the axial plane in a reclined fold? (NET 2019)
    A. 0°
    B. 90°
    C. 30°
    D. 45°
11. The following sequence of rocks is observed while taking a traverse across the strike direction in an area: A-B-C-D-C-B-A
    What is the most likely interpretation? (NET 2018)
    A. The rocks are folded
    B. The rocks are faulted
    C. Presence of an unconformable sequence
    D. The rocks are jointed

Previous year Difficult Questions

1. Two interfering folds having axial planes, axes and flow direction at right angle to each other will result in (GATE 1999)
   A. Type 1 interference pattern
   B. Type 2 interference pattern
   C. Type 3 interference pattern
   D. None of the above
2. A set of cylindrical upright folds is superposed by another set of non-coaxial folds. The axis of the superposed folds at any spot is determined by (GATE 2001)
   A. Fold dihedral angle of the first set of folds
   B. Fold dihedral angle of the superposed folds
   C. Intersection of axial planes of the two sets of folds
   D. Intersection of the limbs of the first fold and the axial plane of the later folds
3. The figure below is the schematic geological map of a flat terrane (GATE 2011)

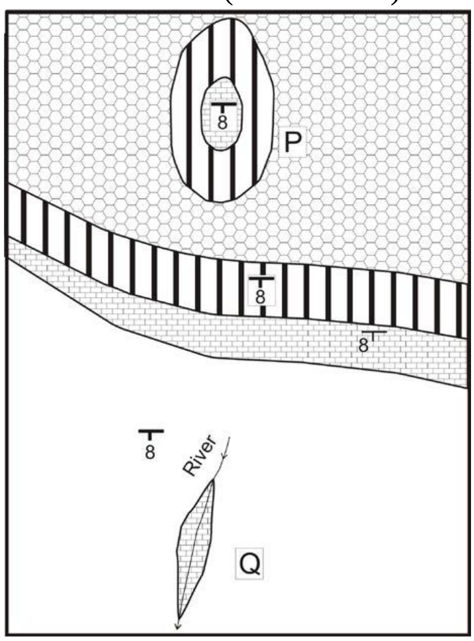


The strata P, Q and R have been folded into a

A. north-plunging anticlinal antiform
B. south-plunging anticlinal antiform
C. north-plunging synclinal antiform
D. south-plunging synclinal antiform

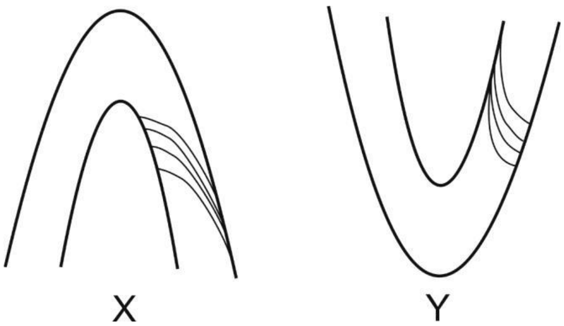
4. The granite pluton intruded in the above map (GATE 2011)
   A. before folding and faulting
   B. before faulting but after folding
   C. after development of unconformity but before faulting
   D. after development of unconformity and faulting

5. The geological map given below shows beds in a normal stratigraphic order. Which one of the following statements is true in respect of features near locations P and Q? (GATE 2014)



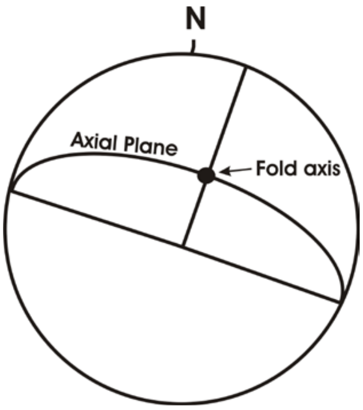
   A. P is an anticline and Q is a syncline
   B. Q is an anticline and P is a syncline
   C. P is an outlier and Q is an inlier
   D. Q is an outlier and P is an inlier

6. Figures X and Y show profile sections of folds traced by two cross-bedded sandstone beds. Which one of the following is the correct interpretation? (JAM2019)



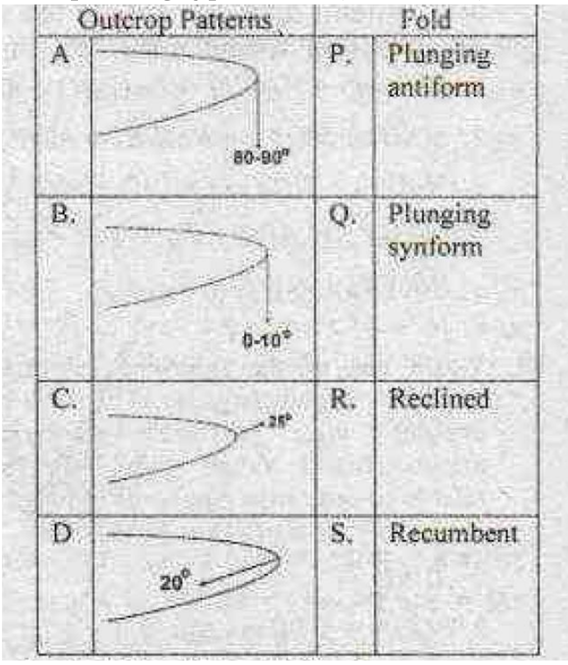
(A) X- Antiformal anticline; Y- Antiformal syncline
(B) X- Antiformal anticline; Y- Synformal syncline
(C) X- Overturned antiform; Y- Overturned synform
(D) X-Antiformal syncline; Y- Synformal anticline

7. The orientations of the fold axis and axial plane in the given figure indicate (JAM 2018)



(A) reclined fold
(B) vertical fold
(C) recumbent fold
(D) horizontal fold

8. Match the outcrop patterns of folds with corresponding types. (NET 2018)



Outcrop Patterns		Fold	
A	80-90°	P.	Plunging antiform
B.	0-10°	Q.	Plunging synform
C.	25°	R.	Reclined
D	20°	S.	Recumbent

A. A-P, B-Q, C-R, D-S
B. A-R, B-S, C-P, D-Q
C. A-R, B-S, C-Q, D-P
D. A-S, B-R, C-P, D-Q

9. Which one of the following structures is an example of ductile deformation? (NET 2017)

A. Faults
B. Fractures
C. Joints
D. Buckle folds

Multiple Select Questions

1. An anticline is
   A. An upward arched fold
   B. Youngest rock exposed along the hinge line
   C. Oldest rock exposed along the hinge line
   D. An downward arched fold
2. Which among the following fold has vertical axial plane?
   A. Inclined fold
   B. Upright fold
   C. Reclined fold
   D. Vertical fold
3. Which of the following mechanism is responsible for the formation of boudinage?
   A. Tensional force
   B. Compressional force
   C. Necking
   D. Bulging
4. True statement regarding the characteristics of synformal anticline.
   A. Convex upward structure
   B. Older rock lies at the core
   C. Rock is youngest along the hinge line
   D. Younger rock lies at the core

ANSWERS

Previous Year Easy Questions

1.C 2.A 3.B 4.B 5. A 6. A 7.B 8.B 9.A 10.B 11.A

Previous Year difficult Questions

1.B 2 D 3.A 4.D 5.C 6.D 7.A 8.B 9.D

Multiple Select questions

1. AB 2. BD 3. AC 4. BC

EXPLANATIONS

Previous Year Easy Questions

1. Non-plunging fold has a horizontal or near horizontal hinge line. Hence, in the outcrop two limbs show parallel orientation.
2. Buckle folds are formed when layers are compressed along their length. The deforming force is applied parallel to the rock layers.

3. Parallel folds are the folds in which the orthogonal thickness of layers remains constant throughout, so that adjacent, bounding, fold surfaces are parallel. Hence, it belongs to class IB of Ramsey classification.
4. If the curvature of the inner arc is lower than that of the outer arc, then the dip isogons are diverge from the axial plane and towards the inner arc also as it lies in class3 fold.
5. From the description it is depicted as the fold is non-plunging vertical fold, hence the dip of the bed at hinge zone is 0°.
6. At a low angle to the fold axis open fold has interlimb angle 100-120°.
7. Since the apparent interlimb angle (20 degrees) is very less compared to the true interlimb angle of 160 degrees, the fold must be gently plunging.
8. Similar fold is a fold where the thickness of the layers remains constant when measured parallel to the axial surface.
9. The fold closure indicates the direction in which the limbs converge. The shape of the fold closure depends on how the curvature of the folded surface changes around the hinge. In case of antiformal anticline, the plunge direction is towards the fold closure.
10. Reclined fold is a dipping neutral fold in which the axial plane dips between 10° and 80° and the pitch of the hinge line on the axial plane is more than 80°.
11. The sequence A-B-C-D-C-B-A is interpreted as folded strata as it traverses across the strike direction in an area. The repetition of strata in reverse direction indicate that the centre of the fold contains D bed and away from the centre there is C, B and A bed lies respectively.

Previous Year difficult Questions

1. In superimposed fold type 2, the axes and axial planes of the second fold are oriented at right angle to first fold.
2. The intersection of the limb of the first fold and the axial plane of the second fold will define a line which will be parallel to the axis of the second fold hence we can find at any point by looking this intersection.
3. The strata P, Q, R have folded into north plunging anticlinal antiform. North plunging due to the plunge of the axis is towards north, anticlinal because older bed lies in the core and limbs dip away from each other hence, antiform.
4. Granite pluton is unaffected by folding and unconformity so it was formed later than those of folding and unconformity.
5. Outlier- younger rocks surrounded by older rock
   Inlier- older rock surrounded by younger rock.
6. A synformal anticline is an anticline because the strata get younger away from its axial surface. At the same time, it has the shape of a synform, i.e. it is synformal. As truncation of cross bed in figure Y is towards outward direction hence it indicates the characteristics of anticline.
   Similarly, an antiformal syncline is a syncline because of the stratigraphic younging direction, but it has the shape of an antiform. In the figure X the cross bed shows younging direction towards center which is a characteristic of syncline.
7. If the plunge angle of the hinge line is equal to the dip angle of the axial surface the fold is called a reclined fold. Here in the stereographic projection it shows that axial plane dips between 10-80° and pitch of the hinge line on the axial plane. Hence it is a reclined fold.

8. Plunging antiform and synform are those folded structures whose axis tilted from the horizontal towards the center and away from the center respectively. A recumbent fold is one in which the axial plane is essentially horizontal and in case of reclined fold the pitch of the hinge line on the axial plane is more than 80°.
9. Buckle folds are formed when layers are compressed along their length due to ductile deformation. The sideways deflection from a median line of competent layers in a less competent matrix, due to mechanical buckling instabilities set up by layer parallel shortening.

Multiple Select questions

1. An anticline is an upward arched fold with the youngest rocks exposed along the hinge line. Oldest rock found in the core of the fold.
2. Both vertical and upright fold has vertical axial plane but upright fold have axis vertical which is varies in case of vertical fold. Reclined and inclined fold both have tilted axial plane.
3. Due to tensional force the strata stretching in opposite direction and because of necking when the instability in the material causes its cross section to decrease by a greater proportion than the strain hardens when undergoing tensile deformation and boudinage formed.
4. A synformal anticline is an anticline because the strata get younger away from its axial surface. At the same time, it has the shape of a synform, i.e. it is synformal.

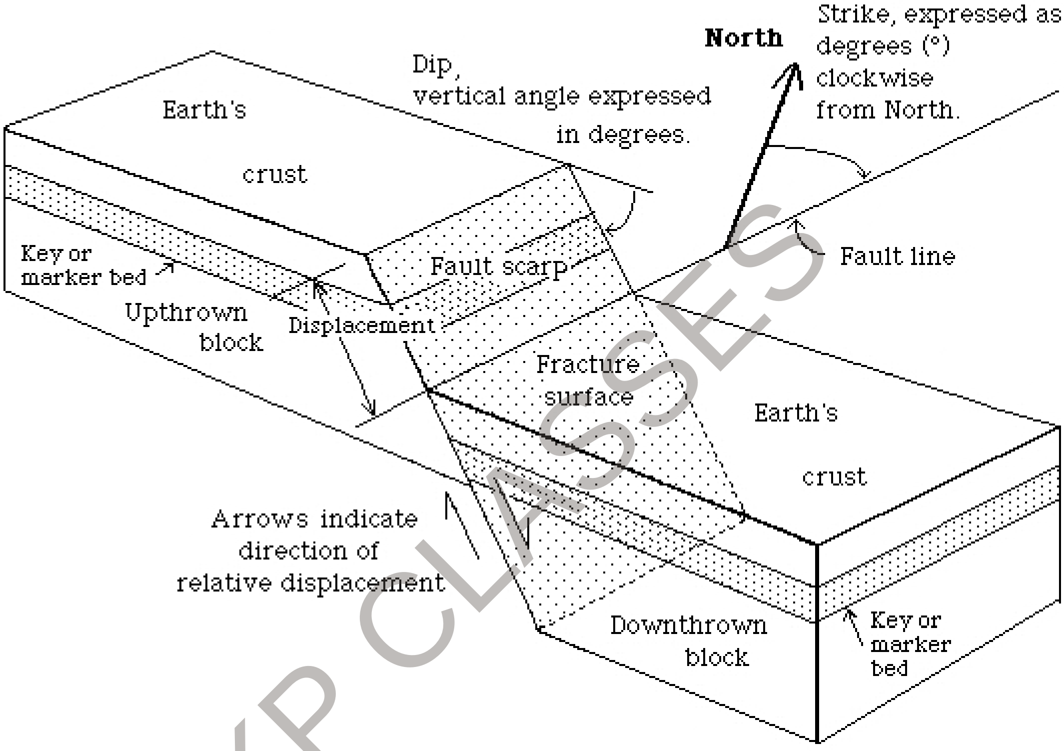
Chapter 4: Fault

- Faults are caused by short-term stress on rocks. They occur discontinuously along fault planes, and are the cause of most earthquakes.
- Faults are classified in terms of the type of force causing the fault which determines the direction of movement.
- A fault is a fracture in the earth's rock units along which there has been an observable amount of movement and displacement.
- Unlike folds which form predominantly by compressional stress, faults result from either tension, compression or shear.
- **Fractures** are planar discontinuities, i.e. interruption of the rock physical continuity, due to stresses.
- The geological fractures occur at every scale so that any large volume of rock has some or many. These discontinuities are attributed to sudden relaxation of elastic energy stored in the rock.
- The geological fractures have their economic importance. The loss of continuity in intact rocks provides the necessary permeability for migration and accumulation of fluids such as groundwater and petrol.
- Fractured reservoirs and aquifers are typically anisotropic since their transmissivity is regulated by the conductive properties of fractures, which the local stress field partially controls. Geological fractures may be partially or wholly healed by the introduction of secondary minerals, often giving rise to ore deposits, or by recrystallization of the original minerals.
- Planar discontinuities along which rocks lose cohesion during their brittle behaviour are:
    - **joints** if there is no component of displacement parallel to the plane (there may be some very small orthogonal parting; joints are extension fractures).
    - **faults** if rocks on both sides of the plane have moved relative to each other, parallel to the plane (faults are shear fractures).
    - **veins** if the fractures are filled with secondary crystallization.
- Joints and faults divide the rocks into **blocks** whose size and shape must be taken into consideration for engineering, quarrying, mining, and geomorphology.

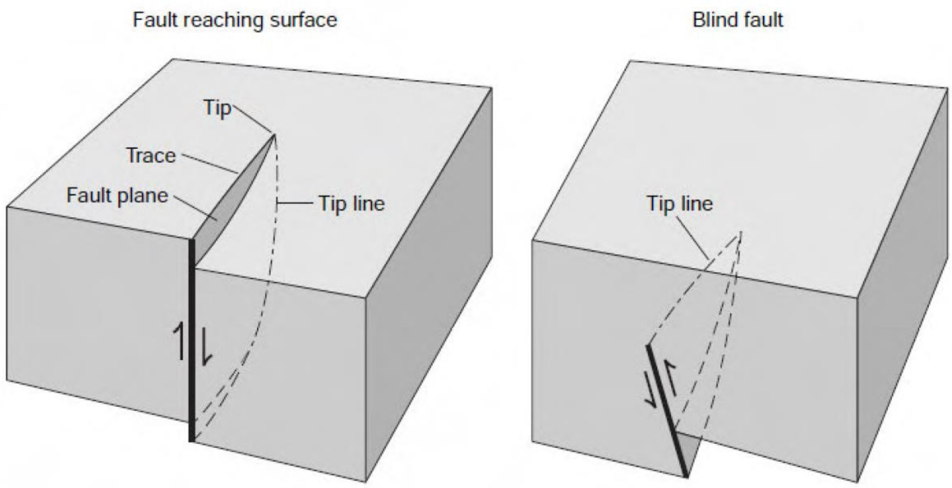
4.1: Fault terminology

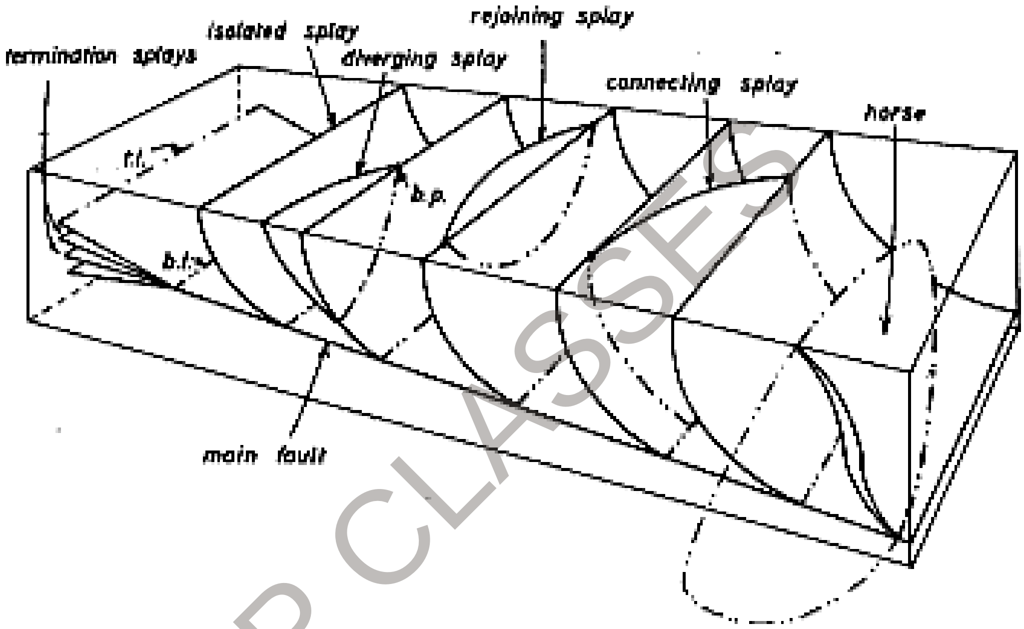
- In order to correctly describe a fault, it is essential to understand its components:
- The **fault plane**: Is the plane of dislocation or fracture along which displacement has occurred. The fault plane therefore separates one or more rock units into two **blocks**.
- The **Hanging wall** and **footwall** blocks: If the fault plane is not vertical, then the block lying on top of the fault plane is known as the hanging wall block, whereas that lying below this plane is known as the footwall block.
- **The downthrown** and **upthrown blocks:** The downthrown block is the one that has moved downwards relative to the other block, whereas the upthrown block is that which registers an upward relative movement.
- **The Dip** of the fault plane is the angle of inclination of the fault plane measured from the horizontal plane perpendicular to its strike.
- **Fault Throw:** Is the vertical displacement of a fault.
- **Heave:** It is the horizontal displacement of a fault.

- **Dip slip**: Is the amount of displacement measured on the fault plane in the direction of its dip.
- **Strike slip:** Is the amount of displacement measured on the fault plane in the direction of its strike.
- **Net slip:** Is the total amount of displacement measured on the fault plane in the direction of movement.
- N.B. In measuring the slip or throw of a fault, the displacement has to be measured using the same surface of the same unit affected by that fault.
- **Cut off lines**- The intersection between transected surface and fault plane is called the cutoff line of that marker horizon.



- The portion of a fault plane that passes relatively steeply through a layer is called the **steep** or **ramp**; and the section which is sub-parallel or parallel to the lithology is called the **flat**.
- Individual faults are of limited spatial extent. The boundary of a fault can take several forms. The fault displacement may die to zero.
- The line bounding the physically displaced walls at the end of a fault is then known as the **tip line**.
- The line where a fault plane cuts the ground surface is known as the **fault trace**, and this terminates at the **tip** or **tip point**.
- In certain geological situations the **tip line** does not reach the surface and the fault is then termed **blind**.
- Individual faults sometimes branch into a number of diverging **termination splays** at their ends.
- The term splays is also given to a fault which asymptotically branches off from another fault. The figure given below shows the different types of splays viz. **isolated-, diverging-, rejoining- and connecting-splay faults**.





- When rejoining splays isolate a lens shaped mass of rock bounded on all sides by faults the structure is called a **horse**.
- Where faults meet, the line of intersection of any two fault surfaces is known as the **branch line** and, if the faults crop out at the surface, this line will appear as the **branch point**.

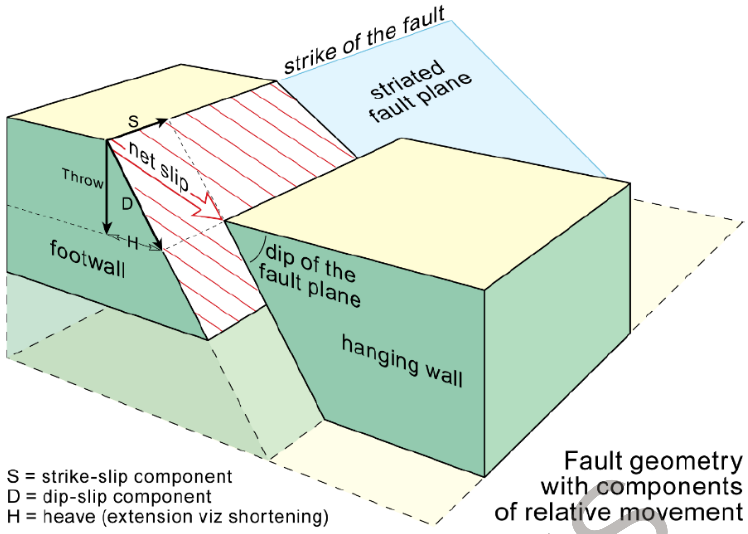
4.2: Definitions

- Faults separate two adjacent blocks of rock that have moved past each other because of induced stresses.
- The notion of localized movement leads to two genetically different classes of faults reflecting the two basic behaviors of rocks under stress: brittle and ductile.

4.2.1: Brittle fault

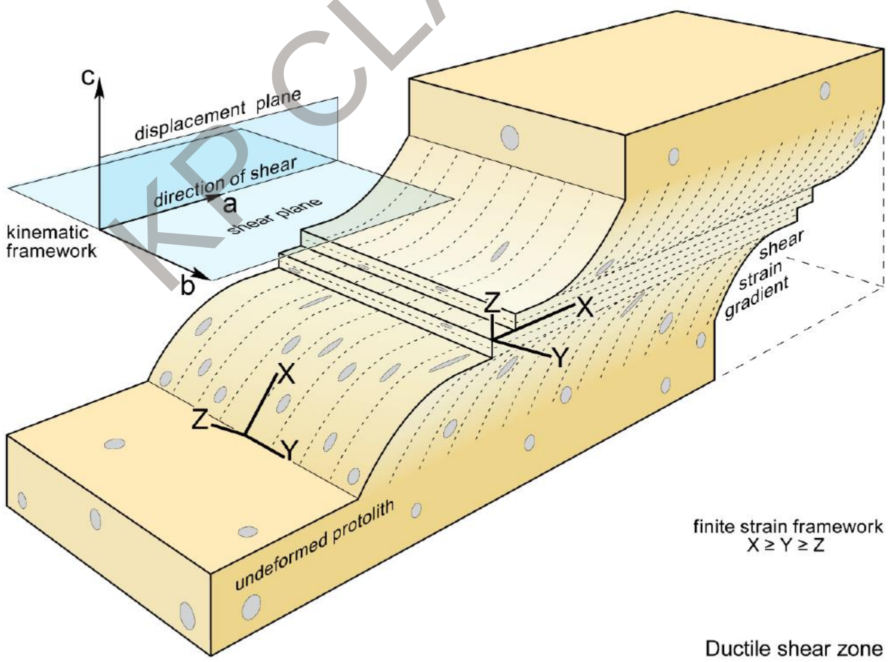
- A **fault** is a discrete fracture between blocks of rock displaced relative to each other, in a direction parallel to the fracture plane.
- A **fault zone** is a region containing several parallel or **anastomosing** (i.e. branching and reconnecting) faults.
- Any fault-bounded sliver in a fault zone is a **horse**.

- Fault and fault zones are identified where either an earthquake occurs or by geological mapping, showing that motion across a discontinuity has occurred in the past. Geologic maps usually show only faults that affect the outcrop pattern.



4.2.2: Ductile fault

- **Shear zones** are the analogues in a ductile material of faults in a brittle material. Shear zones are regions of localized but continuous ductile displacement, formed under conditions of elevated temperature and/or confining pressure, in contrast to fault zones that are regions of localized brittle deformation. Shear zones are thus ductile faults, by contrast to the brittle faults.

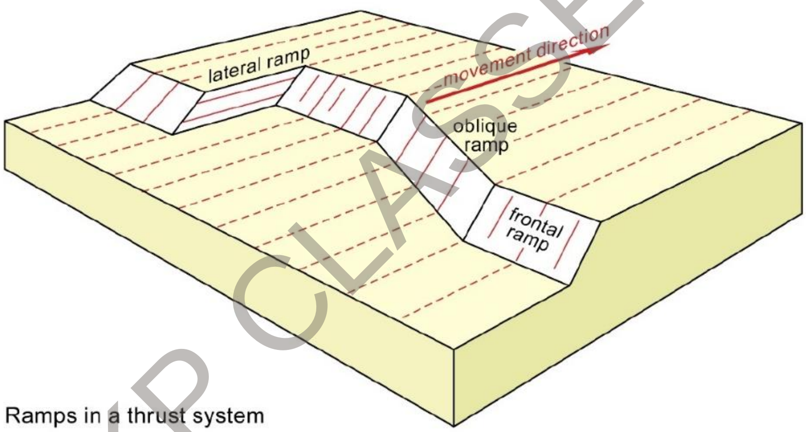


4.3: Geometrical classification

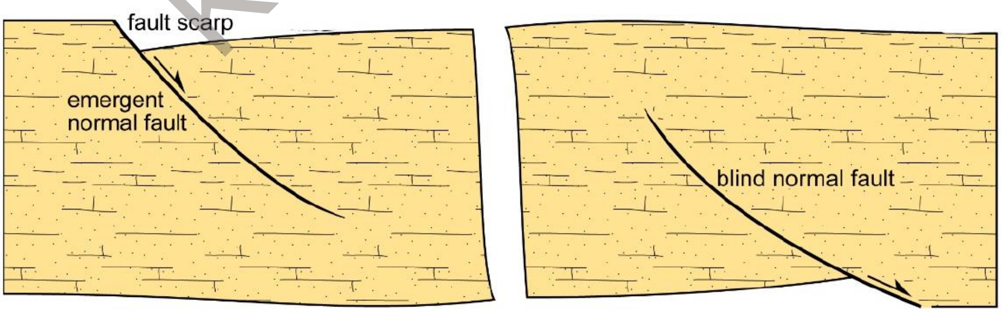
4.3.1: Fault plane

- **High angle faults** dip more than 45; Faults dipping less than 45° are **low angle faults**. Most long faults are **segmented**, each segment having its individual history; fault segments are usually not coplanar. In general, fault surfaces undulate, as commonly seen in 3D seismic data.

- The fault **corrugations** thereby identified are attributed to the linkage of fault-segments.
- A **listric fault** is curved, concave upward, that is, it gradually flattens with depth.
- Where low-angle faults affect a set of nearly horizontal bedded rocks, they generally follow a staircase path made up of alternating **ramps** and **flats**.
- The flats are where the overlying rocks slide along a relatively weak bedding plane also called a **décollement plane,** which refers to a surface across which there is a discontinuity in displacement, strain, and/or fold style.
- The ramps are fault sections climbing through the stratigraphic sequence, typically at around 30° to the horizontal, across stiff, competent layers.
- Ramps do not necessarily strike perpendicular to the movement direction (**frontal ramp**).
- They also can be **oblique** or parallel to the transport direction (**lateral ramp** or **tear fault**).
- The fault that intersected the ground surface while it was active is an **emergent** fault, by opposition to **blind** faults that did not break the surface.
- Emergent faults produce a topographic step, the **fault scarp**. Some blind faults are identified as seismogenic streaks with no corresponding fault plane mapped on the Earth's surface.



Ramps in a thrust system



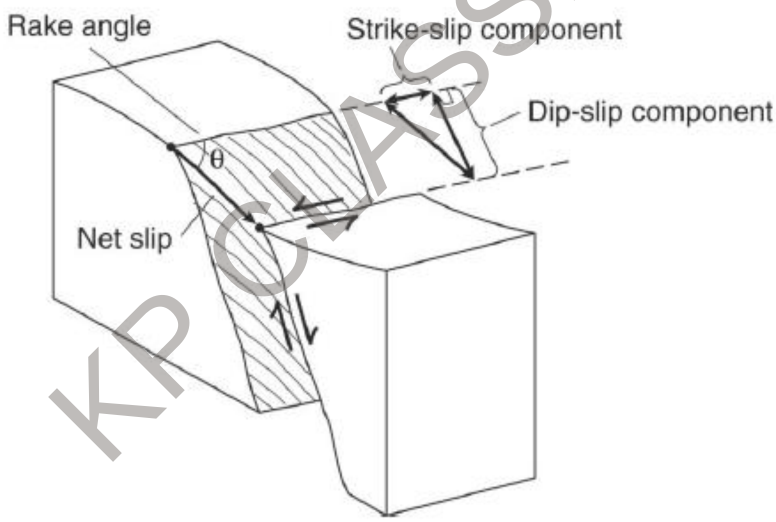
4.3.2: Fault blocks

- The **hanging-wall** and the **footwall** designate the rock immediately above and below a non-vertical fault or shear zone, respectively.
- Rocks that have been translated great distances away from their original site are **allochthonous**.
- Allochthonous rocks that have lost connection with their original site are **rootless**.
- They come to rest on **autochthonous** rocks, which have retained their original location. **Parautochthonous** refers to locally transported rocks.

4.4: Kinematic classification

4.4.1: Slip

- Slip is the direction of movement of one wall relative to the other.
- The **net slip** is the displacement vector connecting originally coincident points (the **piercing points**) on opposite sides of the fault plane.
- Its length provides the amount of displacement on the fault, which generally is the addition of several movements.
- The components of the net slip parallel to the strike and dip of the fault are the **strike-slip** and the **dip slip**, respectively.
- The **rake** is the angle measured within the fault plane down from the strike direction to the line of slip.
- The **plunge** is the angle measured in the vertical plane that contains the slip line between the horizontal in this plane and the slip line.
- The offset shown by a planar feature in a vertical cross-section perpendicular to the fault is the **dip separation**.
- The vertical component of the dip separation is the **throw** and the horizontal component (perpendicular to the fault strike) is the **heave**.
- Notice that the dip separation is not equivalent to the dip-slip, the former depending on the orientation of the offset surface as well as on the nature of the fault displacement.



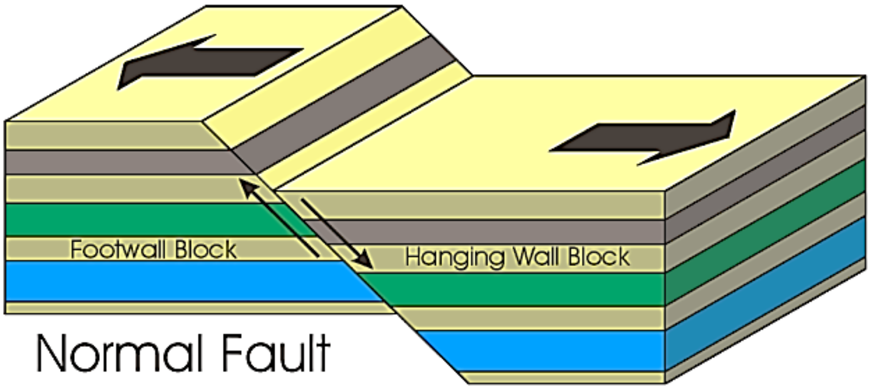
- Note: A bedding surface alone can never be used to determine slip.
- Faults are classified according to the direction of the relative movement between fault blocks, which is related to the type of stress causing the fault.

4.5: Types of Faults

4.5.1: Normal fault

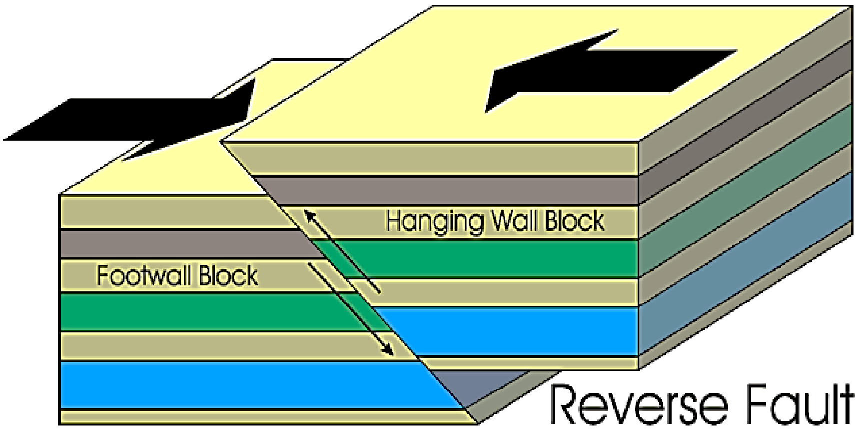
- A **normal fault** is a high angle, dip-slip fault on which the hanging-wall has moved down relative to the footwall. A normal fault brings younger rocks over older ones. (i.e. downthrown block = hanging wall block).
- Because of the separation of geological horizons, normal faults are also termed **extension faults**.

- Extensional ramps termed **detachments** cut down section in the direction of transport, although a typical detachment has no roots and follows a stratigraphic horizon.
- Some call a **lag** or **denudation fault** a normal fault with a dip less than 45°.



4.5.2: Reverse fault

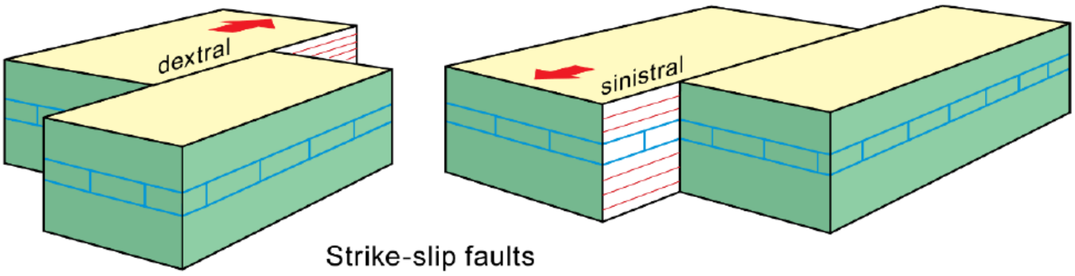
- A **reverse fault** is a dip-slip fault on which the hanging-wall has moved up and over the footwall. (i.e. upthrown block = hanging wall block). Consequently, old rocks lay over younger ones.
- Because the displacement in both normal and reverse faults occurs along the dip of the fault plane, they may be considered types of **dip slip faults**.
- Such faults produce a repetition or overlap of a geological horizon and are accordingly termed **compression fault**.
- A **thrust fault** is a low-angle reverse fault (< 45°) along which the hanging wall forms **thrust-sheets (nappes)** of allochthonous rocks emplaced over the autochthonous or parautochthonous footwall.
- Most common, thrust faults ramp up section towards the surface in the direction of tectonic transport.
- Thrusts are very common in mountain chains (fold and thrust belts) where they are characterized by transporting older rocks on top of younger ones over long distances.
- Thrust faults with a very low angle of dip and a very large total displacement are called **overthrusts** or **detachments**; these are often found in intensely deformed mountain belts.



4.5.3: Strike-slip fault

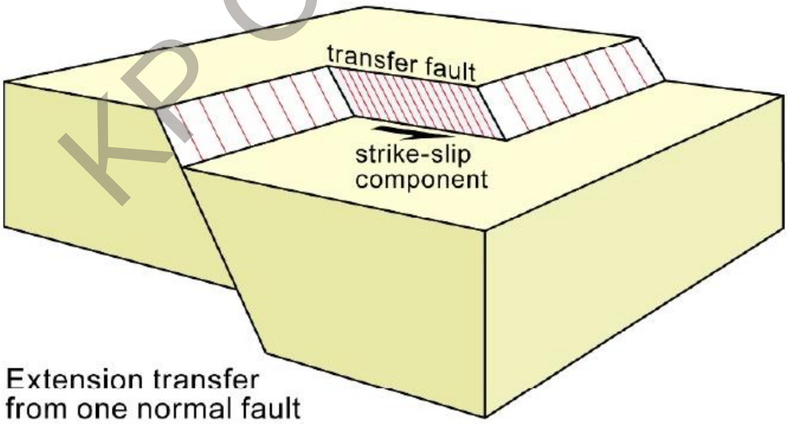
- **Strike-slip faults** usually have very steep or vertical dips and the relative movement between the adjacent blocks is horizontal, parallel to the strike of the fault plane.

- Large strike-slip faults are referred to as **transcurrent faults** and **wrench faults**.
- **The terms sinistral** (left-lateral) and **dextral** (right-lateral) describe the sense of the strike-slip displacement.
- A fault is sinistral if, to an observer standing on one block and facing the other, the opposite block is displaced to his left. Conversely, the fault is dextral if the movement is to the right.



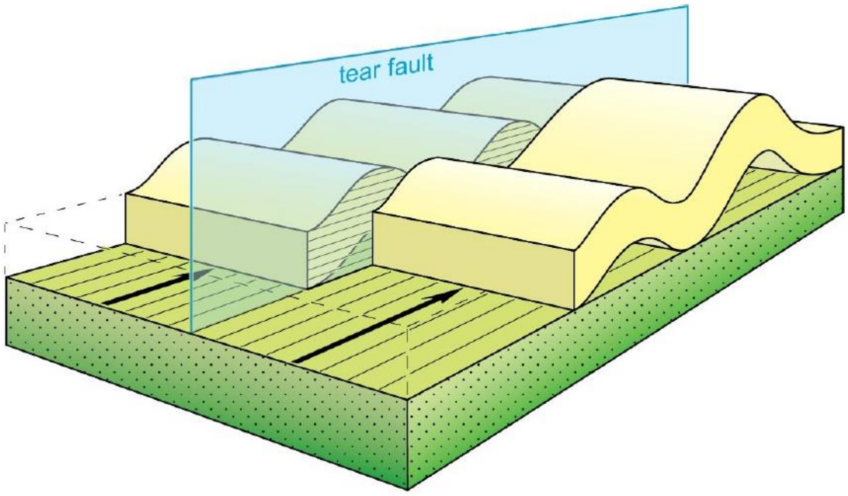
Strike-slip faults

- A **transfer fault** is a strike-slip fault that transmits displacement between two similarly oriented fault segments (e.g. two normal faults).
- Transfer faults are usually confined to hanging walls of detached systems (i.e. not affecting the basement) and terminate where they connect the linked faults.
- Transfer faults or zones are lateral ramps that may accommodate differential displacement and/or strain in adjacent blocks (different amounts of shortening or extension on both sides of the fault).
- Assuming that thrusts and normal faults strike at a high angle to the slip direction, transfer faults linking two thrusts or normal faults are therefore nearly parallel to the movement direction.
- Accordingly, transfer faults usually have strike-slip components that vary along strike if displacement changes across the transfer zone.



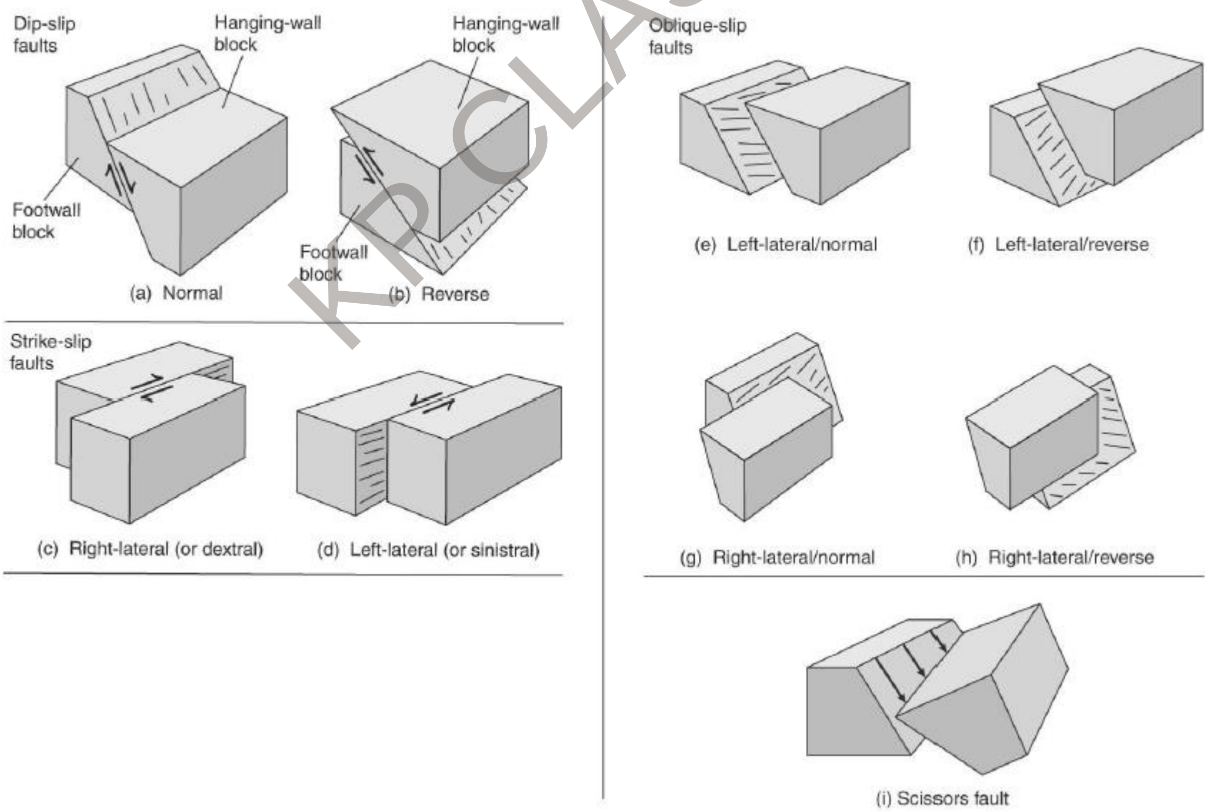
Extension transfer
from one normal fault
to another normal fault through a transfer fault

- A **tear fault** is a strike-slip fault that runs across the strike of a contractional or extensional belt and accommodates differential displacement between two segments of the belt. Like transfer faults, tear faults are usually confined to hanging walls of detached systems (i.e. not affecting their basement).



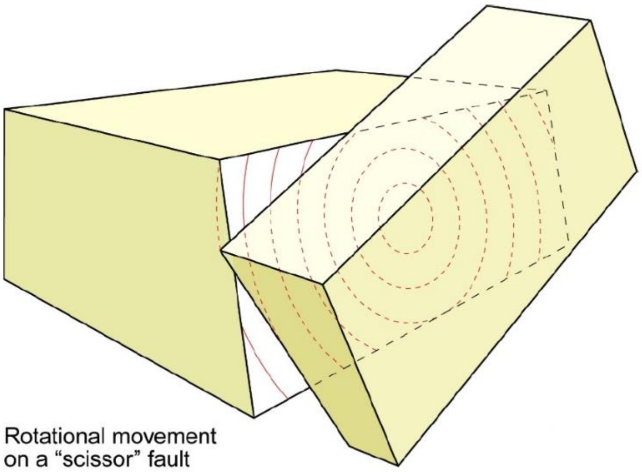
4.5.4: Oblique slip fault

- It is one in which the displacement was both in the strike and dip directions (i.e. the displacement has strike and dip components). Keep in mind that an oblique slip fault can also be either normal or reverse.
- The terms normal fault and reverse fault, while strictly defined for faults with zero strike-slip displacements, also apply to faults with small strike-slip components accompanying much larger dip-slip displacements.
- Where the strike-slip and dip-slip displacements have similar magnitude, the fault may be called an **oblique-slip** fault.



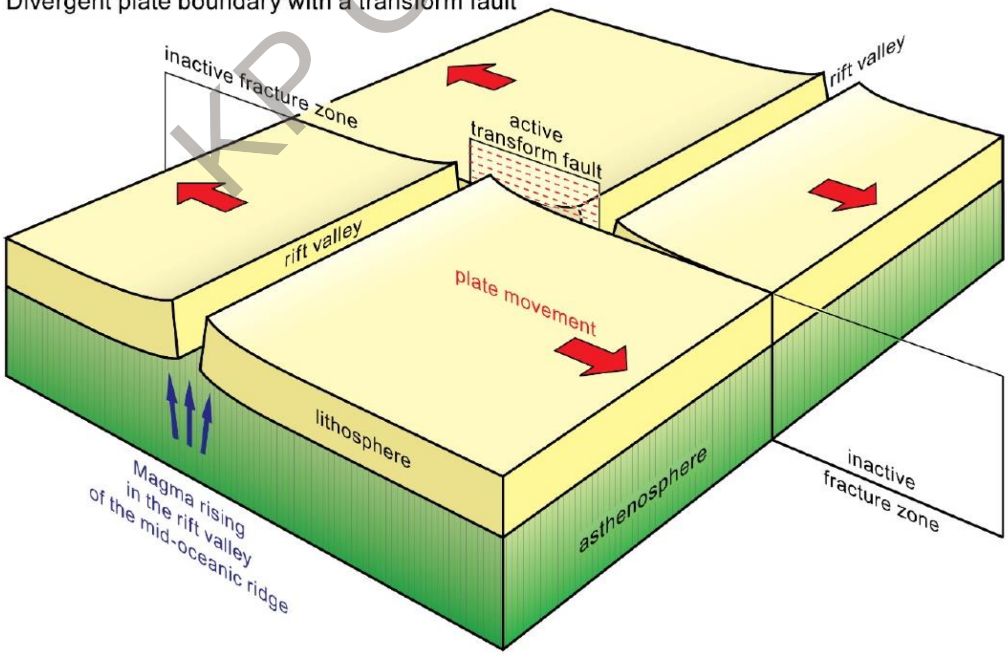
4.5.5: Scissors fault

- One fault block can rotate around an axis perpendicular to the plane of **scissors faults.**



4.5.6: Transform fault

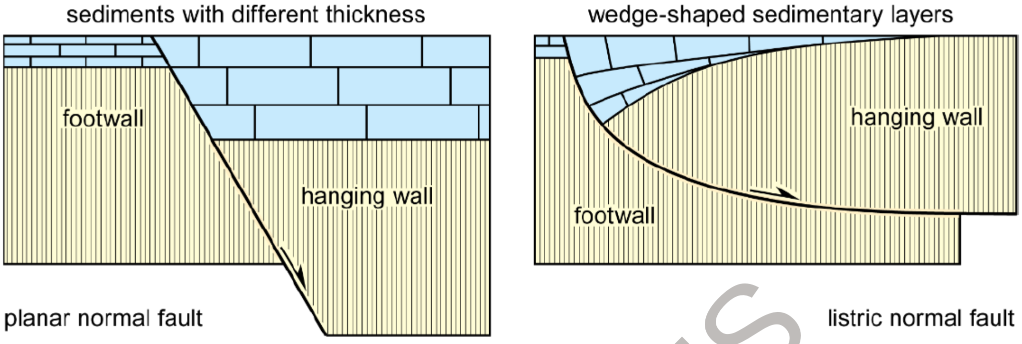
- A **transform fault** is a strike slip fault at plate boundaries. There are three types:
  - Ridge-Ridge transforms link two segments of a constructive plate boundary.
  - Trench-Trench transforms link two segments of a destructive plate boundary.
  - Ridge-Trench transforms link a constructive plate boundary to a destructive one.
- Ridge-Ridge transform faults are the most common. They are fracture zones striking at nearly right angles to the mid-oceanic ridges and seemingly offsetting the ridges.
- However, they differ from transcurrent faults in that the direction of horizontal movements is in the opposite direction to that required if the faults were strike-slip faults responsible for offsetting the ridges after formation of the latter.
- Transform faults are active between the ridges and dead beyond the offsets, and they are parallel to small circles centred at the poles of rotation of the plates.
- Displacement across them is much greater than the length of the active segment.



4.5.7: Growth fault

- A thicker stratigraphic sequence on the hanging-wall than sedimentary layers of the same age on the footwall of a fault indicates fault movement during sedimentation.

- **Growth faults** form characteristically, but not exclusively, in unconsolidated sediments deposited in basins actively growing in breadth and depth.
- A fault that flattens downward is called a **listric fault** (i.e. a convex-up surface), while downward-steepening faults are sometimes called antilistric.
- The terms **ramps** and **flats**, originally from thrust fault terminology, are used for alternating steep and sub horizontal portions of any fault surface.
- For example, a fault that varies from steep to flat and back to steep again has a ramp-flat-ramp geometry.

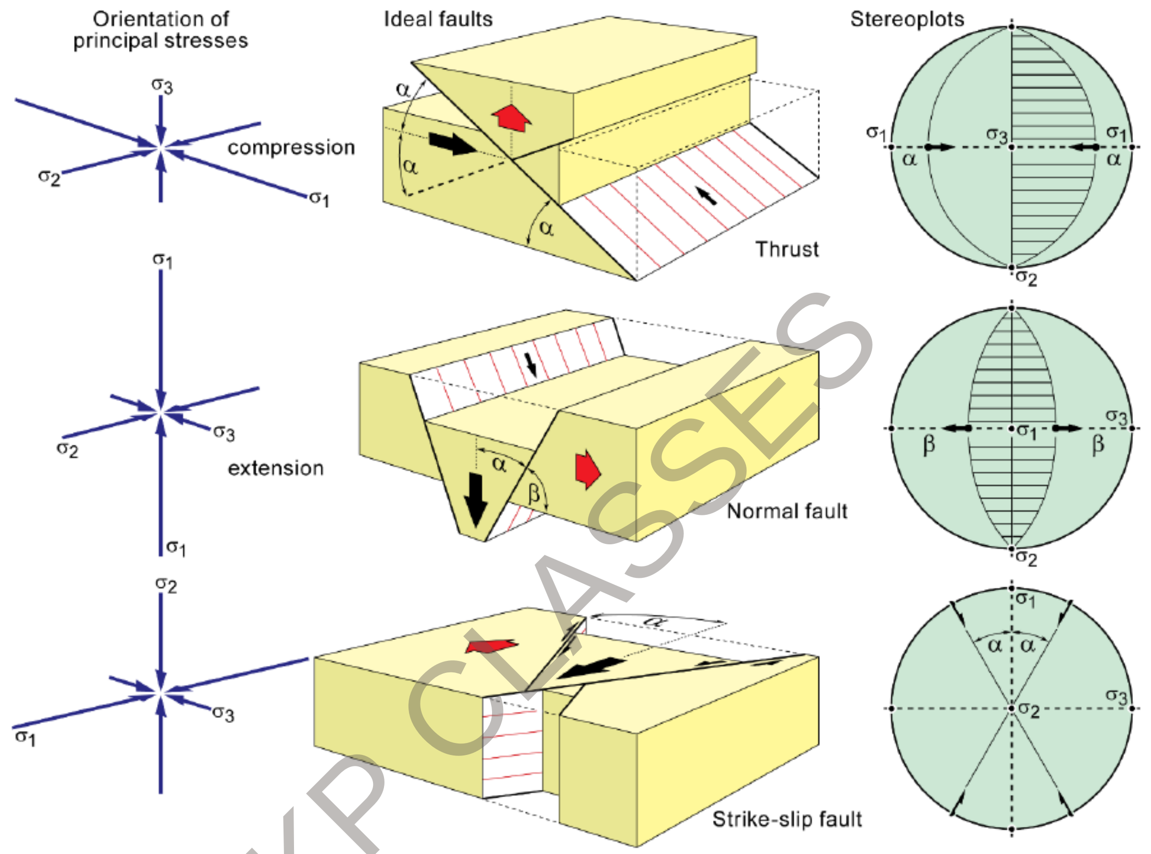


Growth normal faults with associated sedimentary basins

4.5.8: Conjugate faults

- Major blocks may be bounded by sets of **conjugate faults,** which means that faults of the same type and formed during the same deformation episode occur in two symmetric sets with parallel strikes, opposite dips and opposite or reciprocal sense of movement to each other.
- Triaxial experiments (the three principal stresses have non-zero magnitudes) show that Mohr-Coulomb shear fractures (i.e. faults) are oriented systematically with respect to stress directions.
  - Conjugate faults intersect in a line parallel to the intermediate principal stress axis $\sigma 2$.
  - The greatest principal stress $\sigma 1$ bisects the acute angle between the conjugate faults.
  - Striation orientations on a given fault are movement directions defined by the intersection of the fault surface with the ($\sigma 1$, $\sigma 3$) plane.
  - The material shortens parallel to $\sigma 1$ and expands parallel to $\sigma 3$.
- These observations are the basis for a dynamic interpretation of fault systems.
- In addition, Anderson emphasized that the earth surface is a free surface with a fluid, the air, and fluids are unable to support any shear stress (it is a physical definition of fluids).
- Therefore, the earth surface is a principal plane of stress (remember that a principal stress is per definition orthogonal to a no-shear plane).
- Assuming a bulk horizontal attitude of the surface of the earth (which is nearly true in low relief regions), one of the three principal stresses is close to the vertical.
- The type of conjugate fault that develops near the surface depends on which of the three principal stresses is sub-vertical:
  - **$\sigma 1$vertical**: Normal faults dipping about 60°.
  - **$\sigma 2$ vertical**: Vertical strike-slip faults.
  - **$\sigma 3$ vertical**: Thrusts dipping about 30°.

- This interpretation involves that the vertical stress is the lithostatic pressure and that regional stress variations are due to changes in the magnitude of the horizontal stresses relative to the vertical gravitational load.
- There are three possible ways:
  - Both horizontal principal stresses decrease by different amounts in magnitude.
  - Both horizontal principal stresses increase by different amounts in magnitude.
  - One horizontal principal stress increase while the other horizontal principal stress decreases



Dynamic interpretation of faults: Anderson's "standard" relationship between stresses and ideal faults

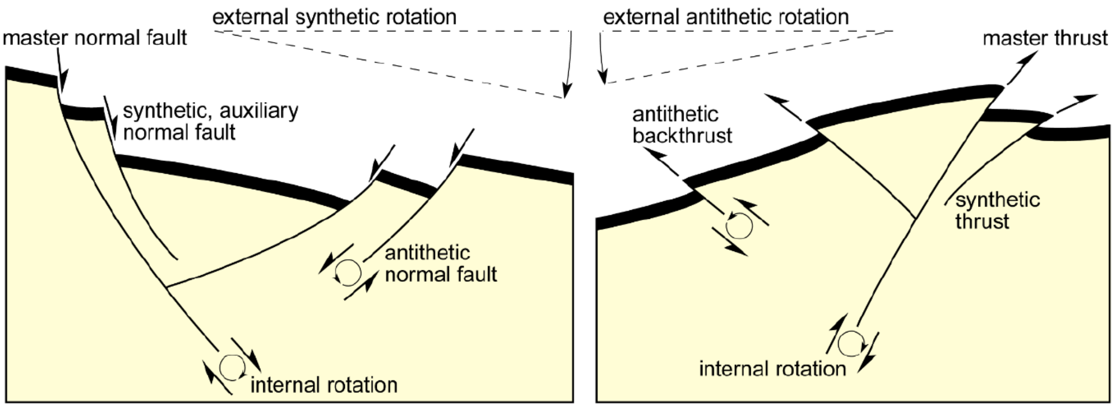
- This formulation explains many fault systems but low-angle normal faults and high-angle thrusts are cases that do not abide by **Anderson's rules**.
- Explanations can be the role of anisotropies or pre-existing fractures in natural rocks, which affect fault orientation, and possible strain along the σ2-direction.
- Other explanations involve the rotation of fault planes towards non-conventional attitudes.

4.6: Features associated with normal fault

4.6.1: Synthetic and antithetic faults

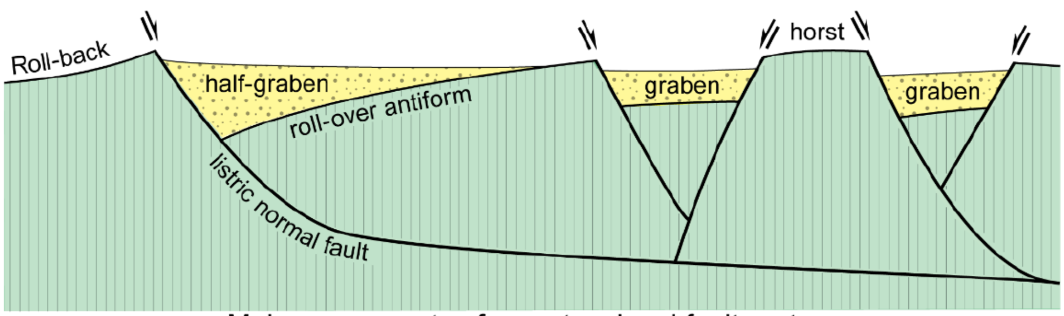
- The largest faults in a faulted area, called **master faults**, are associated with minor faults that may be **antithetic** or **synthetic**.
- An **antithetic** fault dips toward the master fault, while a **synthetic** fault dips in the same direction as the master fault.
- These expressions are relative and only make sense when minor faults are related to specific larger-scale faults.
- Not all extensional environments give rise to symmetrically oriented normal fault systems.

- **Synthetic faults** are parallel and have the same relative movement as the master fault.
- The subsidiary yet genetically related set of conjugate faults, dipping in the opposite direction to the master fault, is **antithetic**.



4.6.2: Horst and Graben

- Faults often occur in groups. If two normal faults have parallel strikes and share the same downthrown block, a trough-like structure results which is known as a **graben**.
- A **horst** is an uplifted block bounded by two normal faults that strike parallel to each other (and which share the same upthrown block ⇒ the horst).
- Grabens and horsts are common in areas of very early *rifting* (e.g. *the East African Rift Valley*).
- **Step faults** are several faults with parallel strikes and a repeated downthrow in the same direction giving the area an overall step - like appearance. They are common in rifted areas (e.g. on the flanks of the Red sea).
- **Horsts** and **graben** are sequences of crustal blocks that have moved along faults with respect to each other such that horsts are higher-standing blocks and graben are lower-standing flat valleys.
- These formations are commonly found in extensional regions as they are systems of opposite-facing normal faults. Graben formed alone are known as **half-graben**.
- Other fault formations include **fault scarps** (steep-sided regions where movement along a fault has offset the landscape), tilted fault-blocks (such as a **half-graben**), **rift valleys** (complex sequences of opposite-facing faults in an extensional setting, such as the East African Rift Zone).

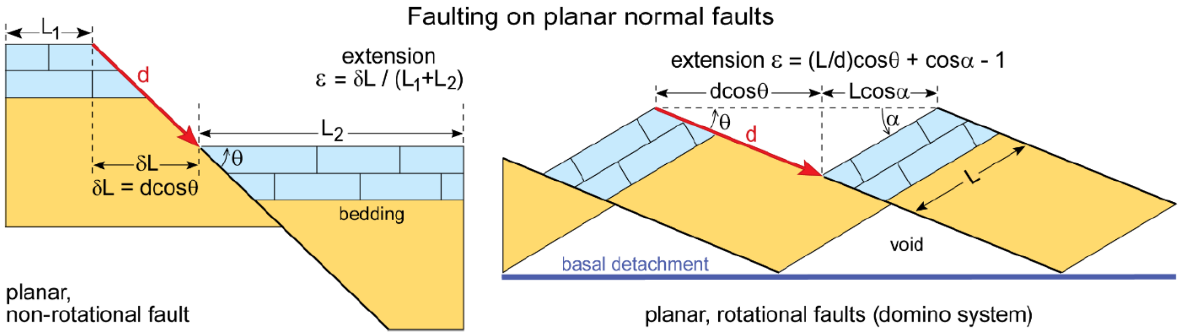


Main components of an extensional fault system

4.6.3: Planar faults

- Planar, rotational normal faults occur above a basal detachment or a brittle-ductile transition. They separate juxtaposed and tilted blocks without internal deformation.

- Both the faults and fault-blocks rotate simultaneously about an axis roughly parallel to the strike of the faults (rigid body rotation resulting in **domino** or **bookshelf faulting**).
- Each fault block has its half-graben. Each fault must have the same amount of displacement and tilt and/or voids open at the bottom of the system.
- Planar, rotational faults and blocks generally abut against transfer, scissors faults.

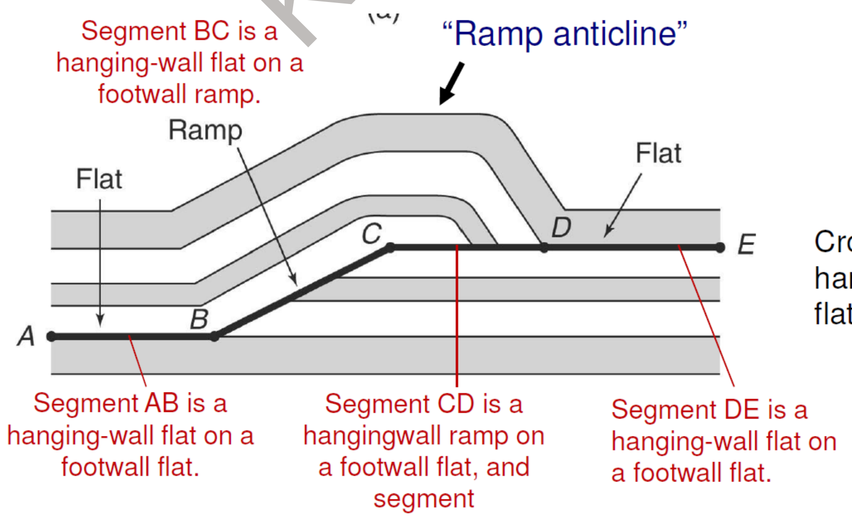


4.7: Features associated with thrust faults

- Two styles refer to the degree of basement involvement in the considered thrust system: **thin-skinned** and **thick-skinned** tectonics.

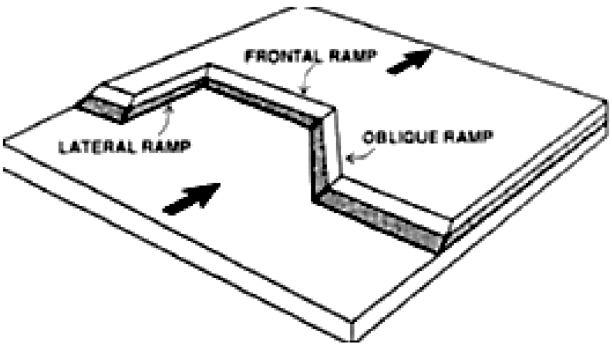
4.7.1: Thin-skinned tectonics

- In many foreland fold-and-thrust belts, bedding plays a controlling factor in generating staircase, flat–ramp systems.
- The sedimentary cover is detached from the basement typically along the **sole thrust**, which remains above the strong crystalline basement left undeformed. Thin-skinned tectonics describes this style of deformation.
- Thin-skinned tectonics implies large horizontal displacements whereby the stratigraphic sequence above the floor décollement can be piled up several times, thrust sheet upon thrust sheet.
- Thrust sheets are generally thin compared to their lateral extent. Thrust faults may develop in sequence either forward (which is termed **prograding**) or backward from the first thrust.

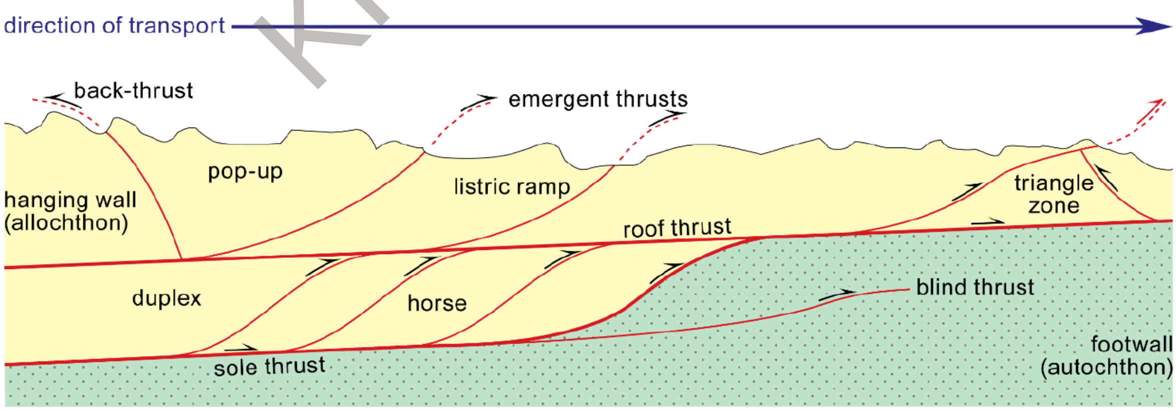


Cross section illustrating hanging-wall and footwall flats and ramps.

- **Frontal ramp:** A ramp in the thrust surface that is perpendicular to the direction of transport of the thrust sheet. Ramp angles are commonly between 10° and 30°.
- **Lateral ramp:** A ramp in the thrust surface that is parallel to the direction of transport of the thrust sheet. Ramp angles are generally between 10° and 30°.



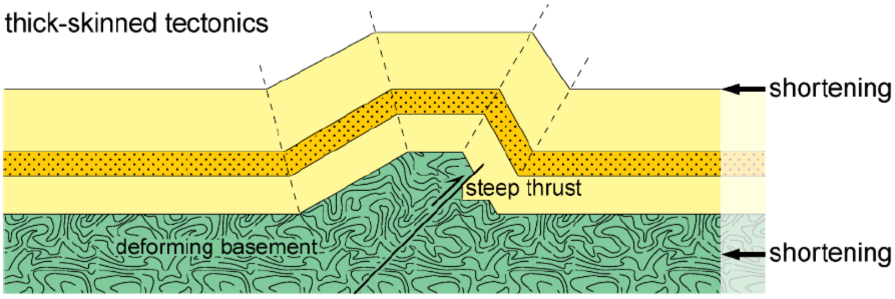
- (Note that if the lateral structure is vertical then it becomes a thrust transport parallel tear or strike-slip fault and should not be termed a lateral ramp).
- **Oblique ramp:** A ramp in the thrust surface that is oblique to the direction of transport of the thrust sheet. Ramp angles are generally between 10° and 30°.
- Where the younger thrust develops in the footwall of the original thrust, the earlier, higher thrust sheets are carried forward on the later, lower ones, which earned the name of **piggyback** thrusting.
- Conversely, if the thrust development migrates backward, an **overstep** sequence develops.
- Thrust sequences often result in the stacking up of a series of thrust sheets separated by subparallel thrust faults making up an **imbricate zone** or **schuppen structure**.
- When master thrusts or décollement surfaces delimit at the top and bottom of an imbricate zone, the whole package is a **duplex**.
- Individual imbricate sheets within the duplex are **horses**, typically lens-shaped in cross-section.
- The duplex structure, therefore, consists of a flat-lying **roof thrust** and a **floor thrust** (also **sole thrust**) enclosing a stacked-up pile of horses.
- **Backthrusts** are subsidiary thrusts with a displacement opposite to that of the main thrust. The uplifted hanging-wall block between a thrust and a backthrust forms a **pop-up**. If the backthrust truncates an earlier thrust, a **triangle zone** is formed.



4.7.2: Thick-skinned tectonics

- In metamorphic regions, thrusting is commonly associated with intense and distributed ductile deformation.
- The staircase, flat and ramp geometry is not respected. Major sole thrusts extend steeply down to the basement.

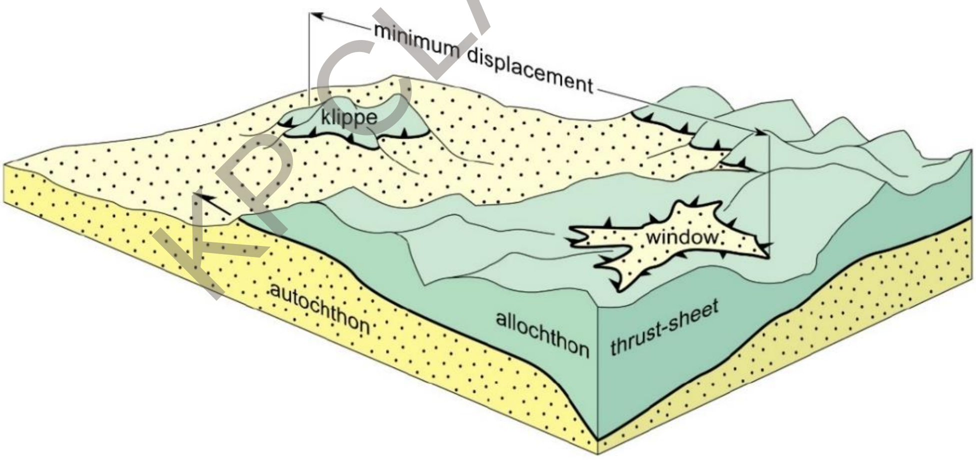
- Although thrust zones tend to follow surfaces of rheological contrast, they involve the basement. This style is termed thick-skinned tectonics.



4.7.3: Eroded thrusts

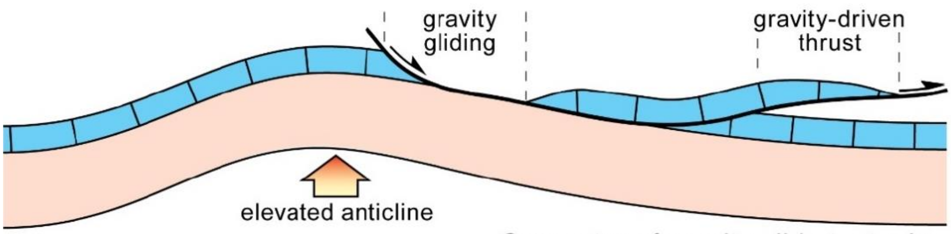
- A **window** (or **fenster**) is an erosion exposure of the rocks below a thrust fault surrounded by rocks above the thrust.
- A **klippe** is an isolated, erosion remnant of a thrust sheet surrounded by rocks of the footwall.
- ***Thrust nappe:*** *A* large thrust sheet which may have been generated from a recumbent fold in which the lower limb has been faulted out to form the sole thrust of the nappe.
- Thrust nappes may also be generated from detachment thrusting and from inversion structures or from inversion of ramp flat extensional fault systems.

Figure: Thrust Nappe



4.7.4: Gravity-driven thrusts

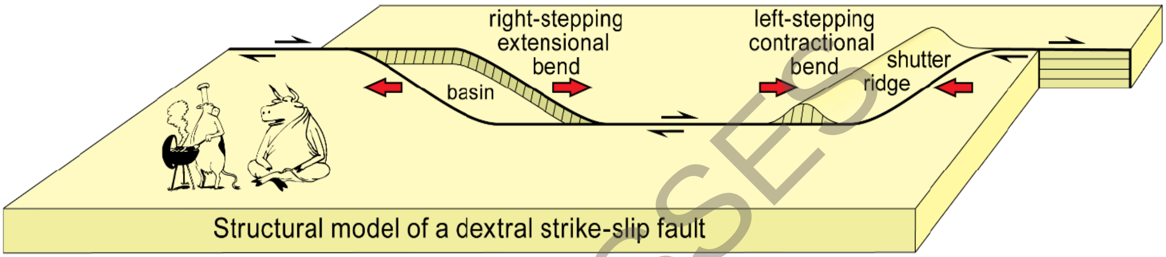
- **Slip-sheets** are coherent parts of a series slipped away, as gravity collapse, from an anticline to rest on an eroded surface within one of the adjacent synclines.



Geometry of gravity slide tectonics

4.8: Features associated with strike-slip faults

- These faults are usually steeply oriented, often vertical with differential displacement between the walls that is predominantly horizontal beds.
- The movements on a strike-slip fault are termed either **right-handed** (**dextral**) or **left handed** (**sinistral**), depending on the relative movement of the wall of the fault opposite to that of the observer.
- Strike slip faults have also been referred to as **wrench faults** by some authors.
- Strike-slip faults are in general vertical and develop at ca. 30° to the horizontal compression direction.
- Major strike-slip faults can be several hundred kilometres long and are not simple planar movement planes. They often develop a system of **right-stepping** and **left-stepping** faults.
- Where right stepping faults generate an extensional zone, left-stepping faults generate a compressive zone, and vice versa, according to the sense of displacement on the master fault.



- **Transform fault:** A plate bounding strike slip fault.
- **Transcurrent fault:** General term for strike slip faults which do not cut the lithosphere.

4.8.1: Strike-slip fault and transcurrent fault

Strike-slip fault	Transform fault
1. Terminate by splay faulting or the bending of the fault to its receding side	Terminate abruptly at special extensional or contractional features
2. Displacement varies, and decreases toward the fault termination	Equal displacement along the fault
3. Displacement smaller than 20% of fault length	Unlimited displacement
4. Adjacent parallel faults show similar displacement sense	Adjacent parallel faults can show opposite displacement
5. Formed as part of the internal strain pattern within continental plates.	Formed at plate contacts and found at ocean–ocean, ocean–continent, and continent–continent sites

4.8.2: Fault bends and Offsets

- Strike slip faults include **bends (**or **jogs),** and **step-overs (**or **offsets).**
- **Bends** are curved parts of a fault trace that connect two noncoplanar but approximately parallel segments of fault.
- **Step-overs** or **offsets** are regions where one fault segment ends and another **en echelon** fault segment of the same orientation begins.
- Bends and step-overs are described geometrically as being either right or left depending on whether the bend is toward the right or left as one progresses along the fault.
- This description is the same regardless the sense of shear on the fault zone. Bends are geometrically equivalent to frontal ramps on dip slip faults in that the displacement on the bend or ramp is approximately perpendicular to the line of intersection of the bend or ramp with the fault.

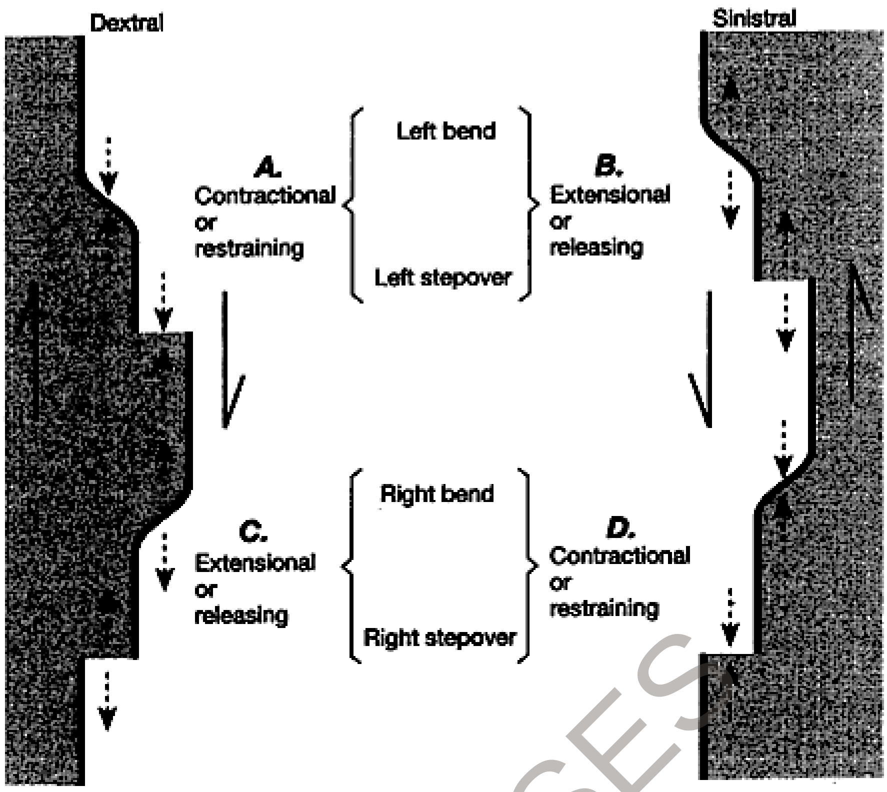
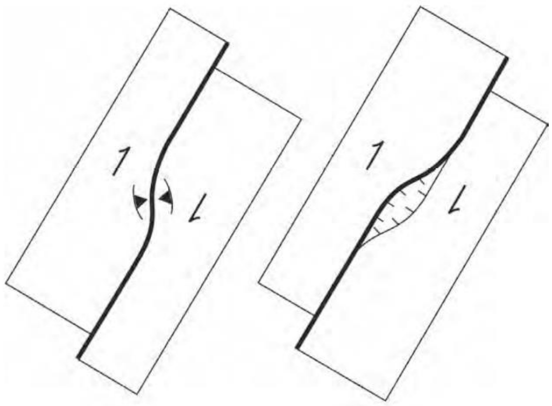


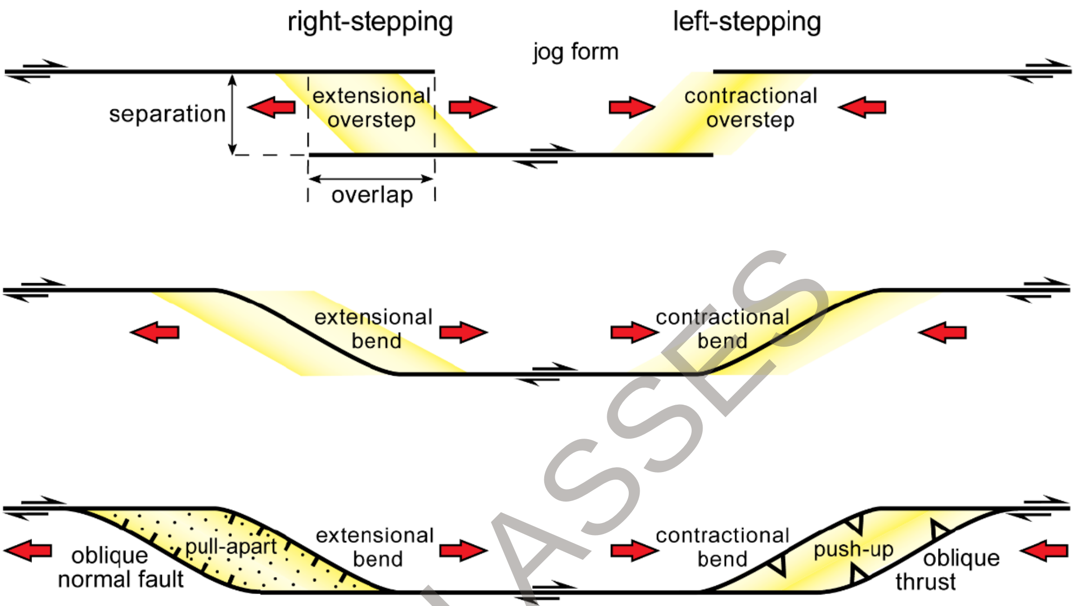
Figure: Bends and step-overs

- **Fault bends** (or **steps**) along strike-slip faults cause changes in the strike of the fault.
- To describe the orientation of such fault bends, imagine that you are straddling the fault and are looking along its strike; if the bend moves the fault plane to the left, you say the fault steps to the left, and if the bend moves the fault plane to the right, you say that the fault steps to the right.
- Note that the presence of bends along a strike-slip fault results in either contraction or extension across the step, depending on its geometry.
- Locations where the bend is oriented such that blocks on opposite sides of the fault are squeezed together are restraining bends, whereas locations where the bend is oriented such that blocks on opposite sides of the fault pull away from each other are releasing bends.
- Where movement across a segment of a strike-slip fault results in some compression, we say that **transpression** is occurring across the fault, and where movement results in some extension, we say that **transtension** is occurring across the fault.
- Note that a step to the left on a right lateral fault yields a **restraining bend**, whereas a step to the right on a right-lateral fault yields a **releasing bend**.
- During **transpression**, the compression is generally relieved by vertical uplift of the sector accompanied by the formation of thrusts and folds.



- These features may range from small scale pressure ridges of near surface superficial material to extensive thrust faults and folds and the development of rhomb-shaped horsts and uplift terrains on a regional scale.
- On the other hand, **transtension** leads to the formation of land surface depressions, **sag ponds** (locally the sites of temporary or permanent lakes), while on a large scale major crustal depression may be formed as **pull-apart basins**, **rhomb-shaped grabens** or **rhombo-chasms**.

Terminology of restraining (contractional) and releasing (extensional) stepovers and bends along a dextral strike-slip fault



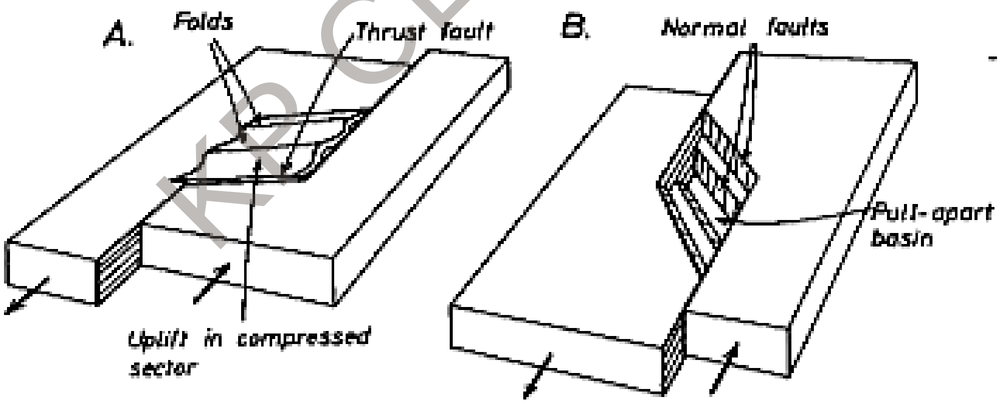
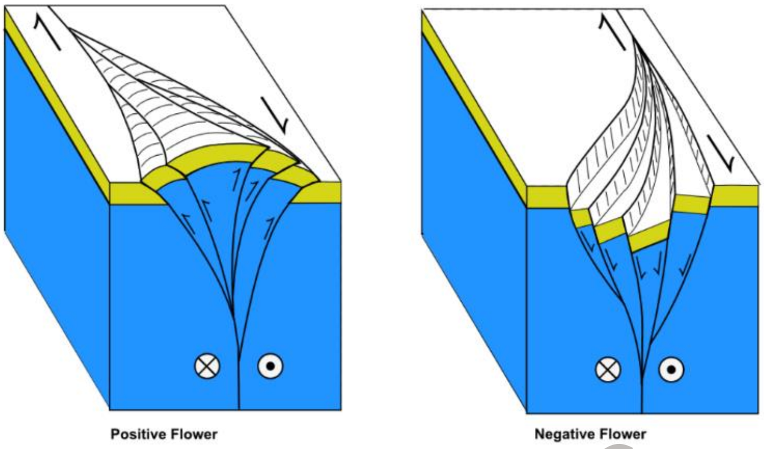


Figure: (A)Thrusting in transpression; (B)Pull-apart basins in transtension

4.8.3: Strike-slip duplexes

- Displacement along strike slip faults that have bends or step-overs produces a complex zone of deformation.
- Commonly the result is a **strike-slip duplex**, which is a set of horizontally stacked **horses** bounded on both sides by segments of the main fault.
- Such a duplex may be extensional or contractional depending on whether it forms at an extensional or contractional bend or step-over.
- In a strike-slip duplex, the shape of the faults on a vertical section normal to the main fault trace is referred to as a **flower-structure**.

- If the dip-slip component is normal, the faults tend to be concave up and form a **normal** or **negative flower structure**, also known as **tulip structure**.
- If the dip-slip component is reverse, the faults tend to be convex up and form a **reverse** or **positive flower structure** also referred to as a **palm tree structure.**



*The symbols **x** and **o** indicate motion **away** and **toward** an observer, respectively.*

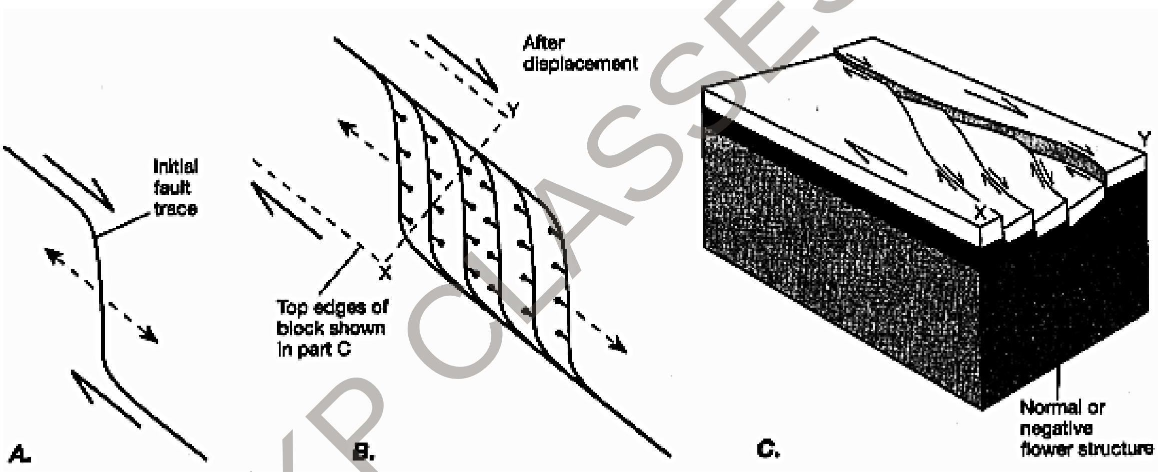


Figure: Negative flower structure

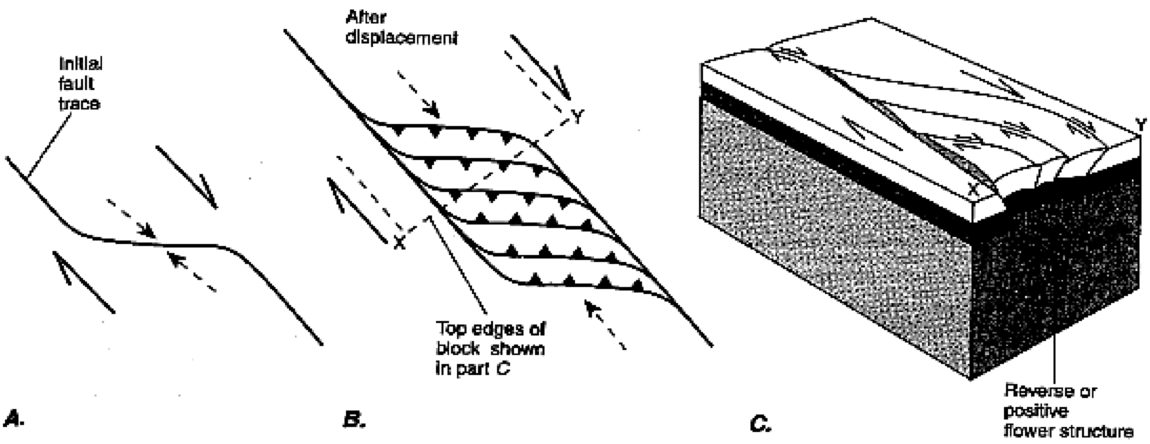
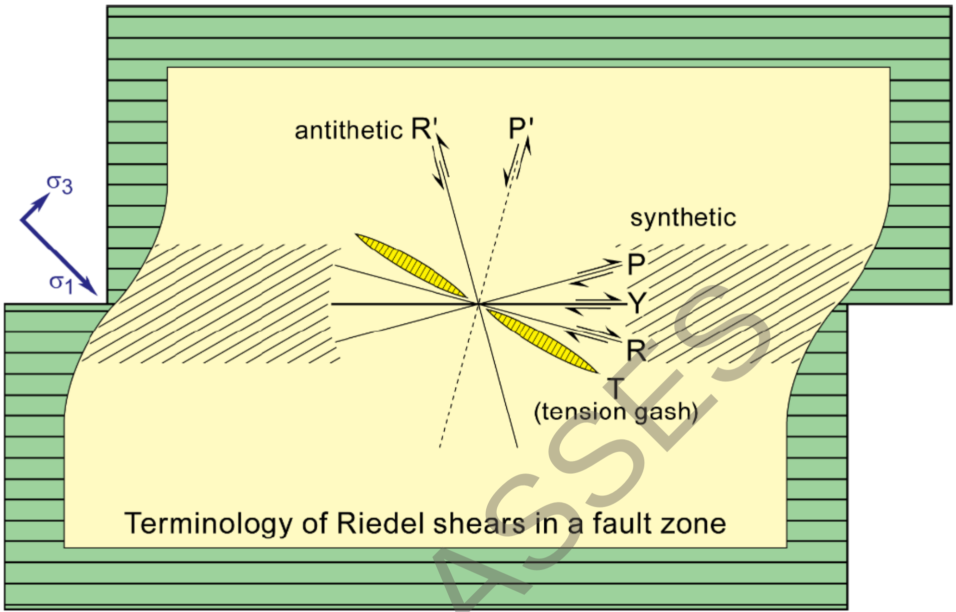


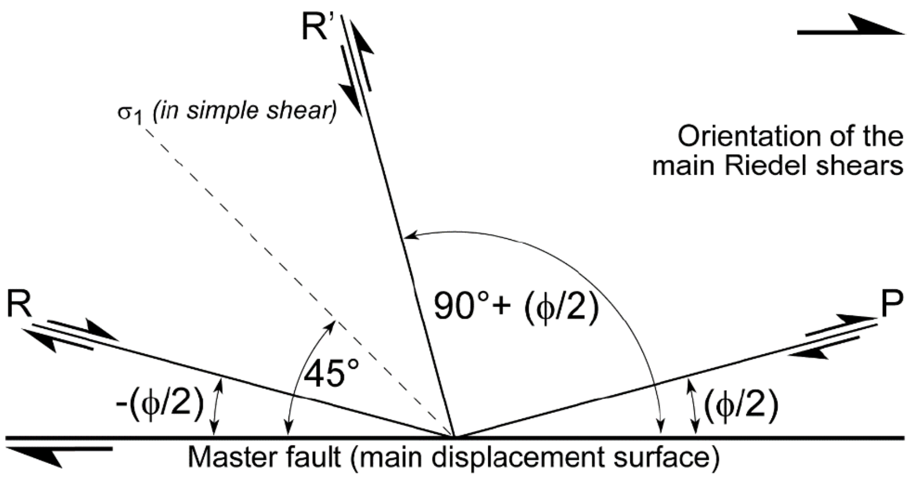
Figure: Positive flower structure

4.8.4: Subsidiary Faults

- Usually, subsidiary faults belong to the same class as the host master fault.
- Subsidiary **Riedel shear** fractures propagate a short distance out of the main fault and make a network commonly developed during the embryonic stages of faulting.
- Riedel shears form a systematic array apparently self-similar for a wide variety of materials over a wide scale-range.
- The basic geometry consists of conjugate R and R' fractures whose acute bisector is the direction of maximum compressive stress.



- **R Riedel shears** develop at a small angle (typically 10-20°) to the main fault, often in an *en échelon* array, and are synthetic to the main fault.
- *En-échelon* describes the aligned pattern of a series of parallel, short fractures arranged like rungs of a ladder seen in perspective.
- In simple shear, the principal stress σ1 is at 45° to the main slip plane. The Mohr-Coulomb failure criterion predicts that conjugate failure surfaces are optimally inclined at ± (45° - ϕ/2) to σ1, where ϕ is the angle of internal friction.
- The acute angle of R Riedel shears with the main fault is −ϕ/2. This angle points in the direction of the relative sense of movement on the master fault.



- **R' shears** are conjugate, antithetic to the (Riedel) shears (i.e. with offsets opposite to the bulk movement), oriented at a high angle [90°+ (ϕ/2)] to the main fault plane.
- They preferentially occur between two parallel R shears. R and R' shears intersect at an acute angle β=90° - ϕ.
- **P shears** are synthetic minor faults symmetrically oriented to the R shears with respect to the fault plane (at + ϕ/2 from the fault plane). P shears generally link R shears and tend to occur for large displacements.
- As for R Riedel shears, there may be **P' shears** conjugate with P shears (at - 45°− ϕ/2 from the fault plane) but these have relatively minor importance.
- **Y shears** are micro faults subparallel to and slipping coherently with the main fault.

4.9: Geomorphological features associated with faults

- Fault planes often result in the exposure of units that erode easily along the fault trace resulting in the development of valleys or the control of stream flow.
- In other cases, faults cause the offset of streams, causing them to bend sharply when they intersect the fault plane.
- The topography may also be strongly influenced by faulting so that the fault plane can be identified on the ground by a sudden and sharp change in elevation, known as a **fault scarp**.
- Faults cause repetition and displacement of beddings depending on the relative altitudes of beddings and fault planes.

4.9.1: Normal fault association with bedding

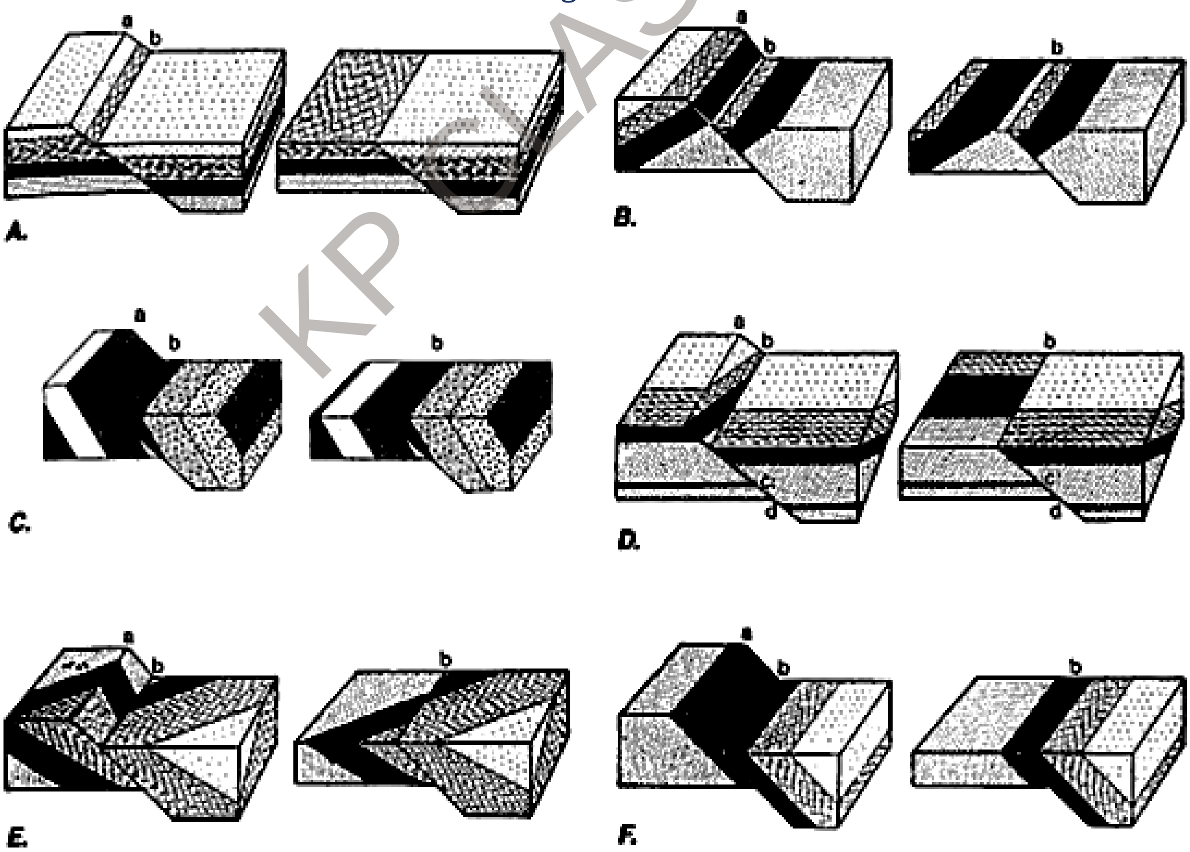
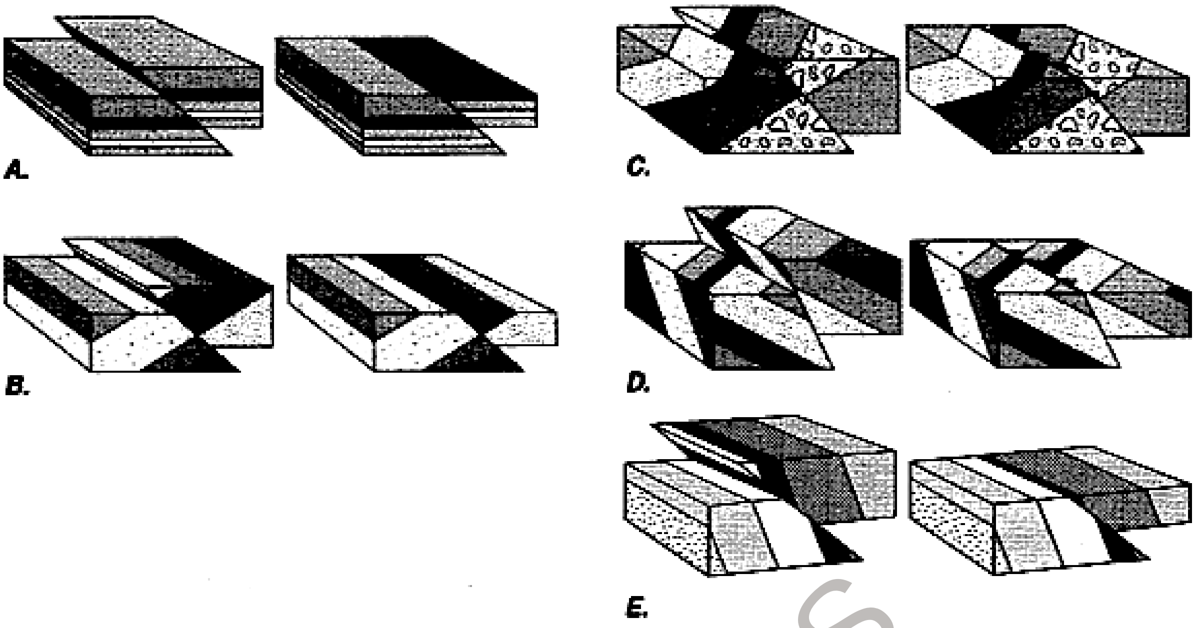
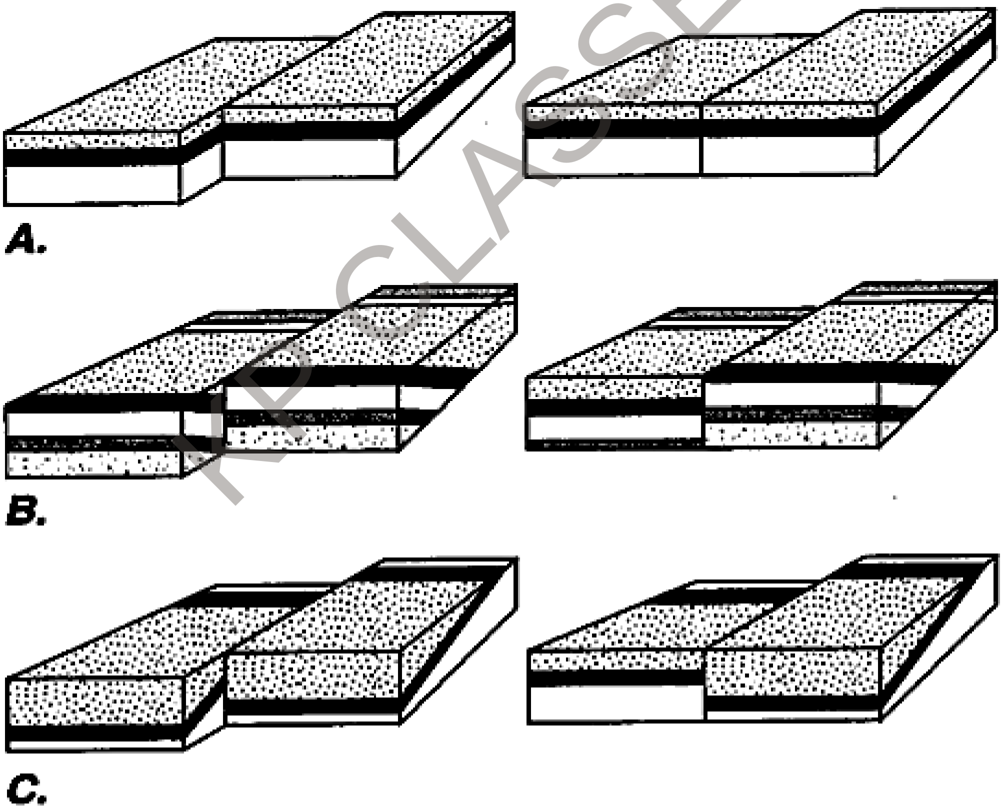


Figure: Faults affecting bedding (normal faults)

4.9.2: Thrust fault association with bedding



4.9.3: Strike slip fault association with bedding



4.10: Fault rocks

- Faulted rocks often fill fault zones. The accepted classification of fault rocks, i.e. rock types created by fault generation, uses cohesion at the time of fault movement and the presence of a planar fabric. There are two main types of fault rocks:
    - Incohesive fault rocks in brittle fault zones. These rocks have a random fabric.
    - Cohesive fault rocks in ductile shear zones. These rocks have a foliated fabric.

4.10.1: Incohesive, non-foliated fault rocks

- **Comminution** (grinding) of rocks characterizes faulting in the brittle field. The resulting incohesive, non-foliated fault rocks are **cataclasite.**

Description - Definition

- Cataclasites are randomly oriented aggregates of angular, broken fragments of the rocks composing the fault walls.
- The fragments range in size and may be held together by some cementing material, generally infilling minerals crystallized by precipitation from fluids circulating between the fragments.
- According to the size of the elements, one distinguishes**:**
- **Fault breccia** when visible, angular fragments constitute more than 30% of the rock volume. Breccia can be cemented or uncemented; rock fragments may range from sand-size to large boulder size and are commonly striated.
- **Micro breccia** if the fragments are microscopic;
- **Gouge** when more than 70% of the material consists of very fine-grained, clayey, and often dark powder containing small angular fragments.
- Clay minerals result from weathering and/or hydrothermal alteration of pulverized fault-wall rocks. Gouges and equivalent fine-grained fault wears are rarely consolidated.
- Late movements may impart a distinct planar fabric in these crushed rocks, which, however, fundamentally remain incohesive, i.e. unconsolidated.

Setting

- Major faults do not exhibit a discrete slip surface but a planar **core** up to several meters in thickness, essentially formed of wear detritus derived from the fault walls.
- Cataclastic and cracked rocks also constitute the damage zone, the broad volume of deformed wall rocks around the fault core.
- Many metalliferous veins occur in this setting, with hydrothermal minerals cementing the rock clasts.
- In that case, the cohesionless rock at the time of faulting has acquired a secondary cohesion.

Cataclasis

- Cataclasis results from the initiation, propagation, interaction, and build-up of slip along the fault.
- The incohesive fault rocks are essentially formed by **cataclasis**, the deformation process involving fracturing of grains and grain boundaries along with **dilatancy** allowing rigid-body rotation between granular elements.
- Cataclasis is thus the mechanical granulation, crushing, and/or milling down to powder any coherent rock.
- The process is common in the upper crust where strain rates are fast and confining pressures and temperatures relatively low (< 500 MPa, 200-300°C).
- The size-frequency of comminute particles is a measure of the energy used for cataclasis.
- Fault gouges show size frequencies with fractal dimensions > 1.6.

4.10.2: Cohesive, foliated fault rocks

- Cohesive, foliated, commonly lineated fault rocks belong to the **mylonite** series.

- They are characterized by a foliated or streaky structure, in thin section, and are typical of ductile shear zones.
- Grains of the parent rock have been reduced in size without the loss of primary cohesion.
- The fine grain-size and distinctive microstructure are due entirely to the ductile deformation (viscous creep) accompanied by recrystallization.
- Mylonite often contain larger fragments or relict minerals from the parent rock; these fragments are **porphyroclasts**.
- Mylonitization is a gradual process of grain size reduction in which three types of rocks are distinguished on the relative proportion of porphyroclasts to the fine-grain matrix:
- A **protomylonite** is a rock in the early stages of mylonitization, containing more than 50% porphyroclasts.
- A true **mylonite** contains 10-50% porphyroclasts.
- Extreme grain size reduction and dynamic recrystallization may produce a hard, flint-like, dark fault filling of ultramicroscopic grains containing less than 10% of tiny porphyroclasts. These rocks are **ultramylonites**.
- B**lastomylonite** describes extensively recrystallized rocks with strain grains annealed after mylonitization.
- **Phyllonite** is a mica-rich mylonite with the mesoscopic appearance of schist.

Fault rocks - Terminology

metamorphic conditions	very low grade		low grade	medium	high grade	
	Cataclasite			Mylonite		
Principal types of fault rocks	**incohesive**		**cohesive**			
	Fragments %				Matrix %	
	>30	Breccia		Protomylonite	<50	recrystallised Blastomylonite
		Microbreccia		Mylonite	50<<90	
	<30	Gouge		Ultramylonite	>90	
			Pseudotachylite (molten)		>85	

4.10.3: Pseudotachylite

- **Pseudotachylite** form thin, glassy, and dark veins of cohesive and non-foliated rock along some faults.
- They typically occur in a branching network of injection veins stemming from the fault zone into the usually crystalline wall rock.
- The glassy matrix, which contains rock inclusions and microscopic spherulites, attests that the vein was in a fluid state and abruptly chilled.
- In most cases, later devitrification has removed the glassy texture. Pseudotachylites are believed to form when a seismic movement and local decompression trigger swift melting followed by quenching and solidification of the molten material.
- Calculations of temperatures required for local friction melting of the wall rocks infer rapid movement (0.1 to 1 m/s) along the fault plane.
- Pseudotachylites are therefore recognized as indicators of paleo-seismic activity.

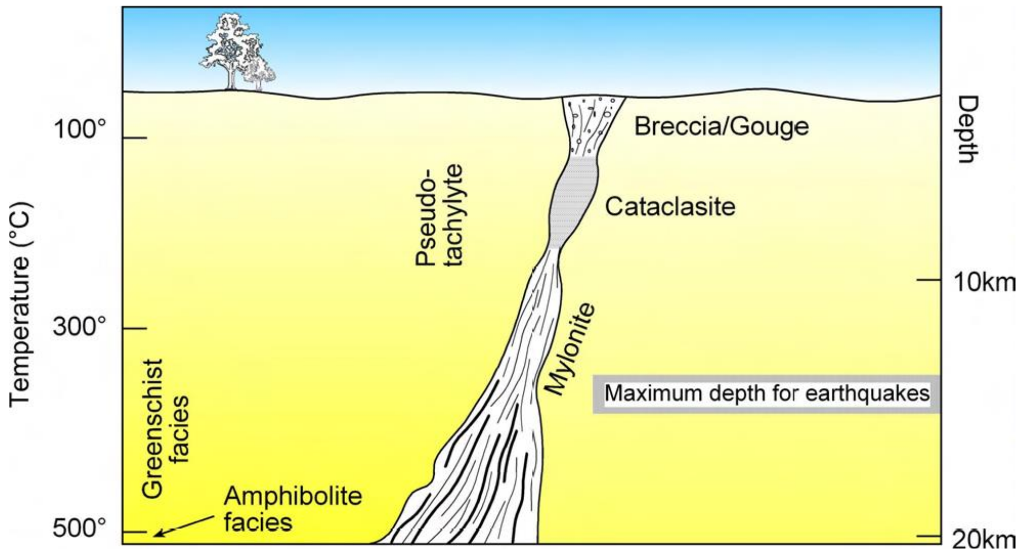
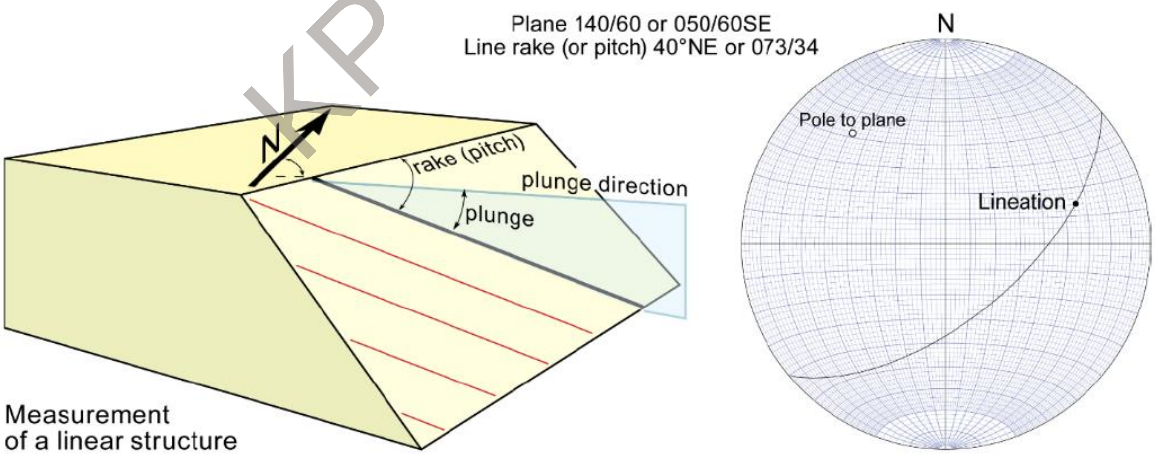


Figure: Change of fault zone rock with depth

4.11: Fault kinematic indicators

4.11.1: Slickensides

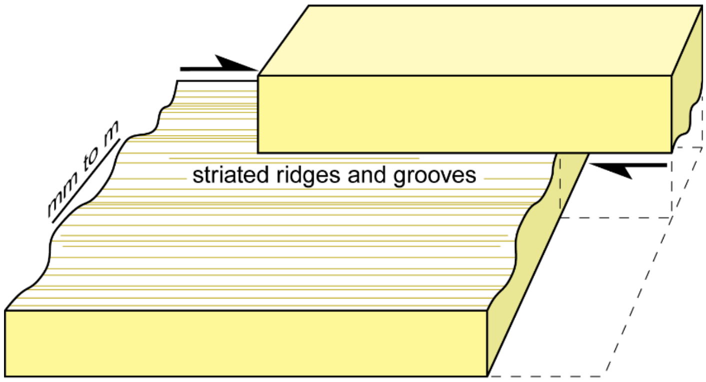
- Rocks in contact at a fault plane often have smooth, shiny, or polished surfaces of mineralized material known as **slickensides**.
- Slickensides are due to abrasive action, may be featureless, but sometimes feel smoother (under the finger) in the direction of slip.
- Parallel scratches **(striations)** are common on fault surfaces. These **cataclastic lineation** (**slicken lines**) are parallel to the slip vector on the fault.
- The angle measured within the inclined fault plane between the horizontal line (the fault strike) and the line marked by striations is the **pitch** or **rake**.
- Associated asymmetric surface features are **kinematic indicators** of the sense of slip.



4.11.2: Asperity plowing

- Slickensides commonly display a linear **striation** or **corrugation** (thereby describing parallel ridges and grooves that occur over a range of several scales) experimentally shown to be abrasion scratches parallel to the direction of relative fault movement. Mineral streaks in the fine-grained material along fault planes define most striations (**slicken lines**).

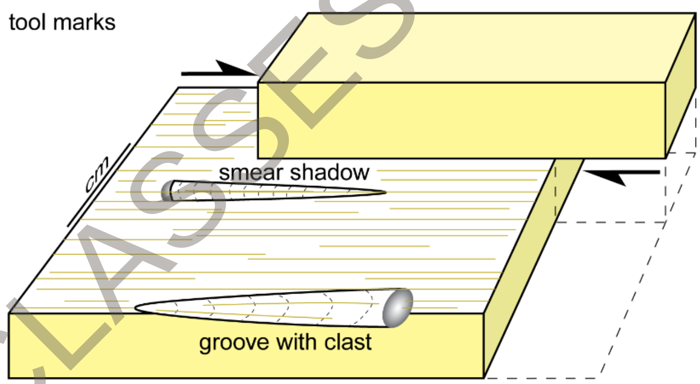
- Some **striae** may be **grooves** or **gutters** deeply furrowed on one side of a fault by hard particles drawn over it by the other side.
- **Ridges and grooves** can be long, linear, meter-scale undulations of the fault plane.
- On a microscopic scale, a dimensional preferred orientation of grains marks such lineations, in particular in soft sediments. These linear features indicate the slip direction but not its sense.



Movement structures within a brittle fault plane

4.11.3: Tool marks, tracks and debris streaking

- A striating, erosive object can be pinned in one wall of the fault plane while matching depressions or indentations are present on the opposing surface.
- A spoon-shaped depression around a hard clast provides the sense of relative movement, with the hard object at the distal end of the pit it carved.
- Conversely, debris can be deposited in the direction of slip behind a protruding asperity, erosion-sheltering creating a tail of lightly cemented gouge material accumulated behind hard asperities, which is the movement direction.



Movement structures within a brittle fault plane

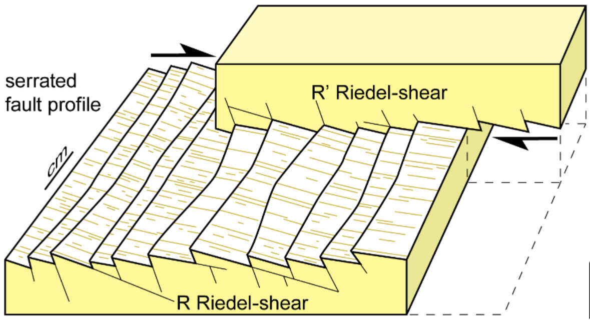
4.11.4: Steps

- **Chatter marks** are small, asymmetric **steps** facing in one direction and roughly perpendicular to the striations.
- These steps were traditionally interpreted as indicators of the sense of displacement, with the riser facing the relative displacement direction (**congruous steps**).
- However, experiments have shown that **incongruous** steps accompany frictional-wear striations or oblique-stylolite columns and form so that the risers of the steps are opposed to the movement vector.
- Therefore, there is no absolute rule about the kinematics significance of the steps alone.

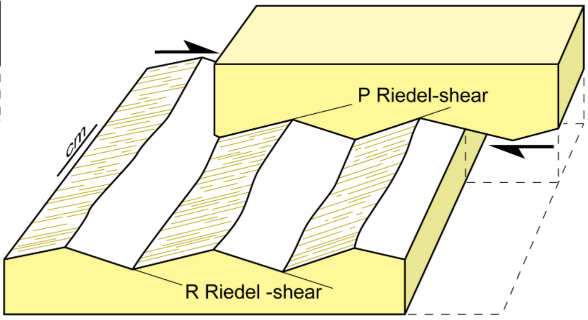
4.11.5: Riedel shears

- Small and striated fractures in Riedel-shear attitudes commonly truncate fault planes nearly orthogonal to the slip direction.
- R and R’ shears tend to be regularly spaced and impel a serrated profile to the fault plane, with steps facing the movement direction.

- Combinations of R and P-Riedel shears, intersecting nearly perpendicular to the slip direction, result in alternating striated surfaces (P-shears facing in movement direction) and non-striated surfaces (R-shears in the lee side of asperities).
- The intensity of striation or non-striation depending on the attitude of topographic irregularities on the fault plane is a common kinematic criterion.



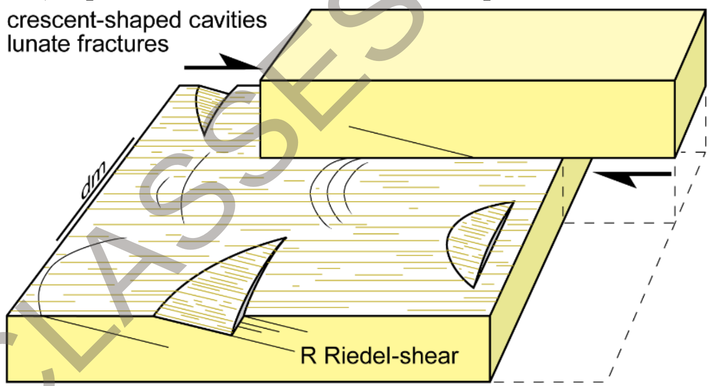
Movement structures within a brittle fault plane



Movement structures within a brittle fault plane

4.11.6: Friction fractures

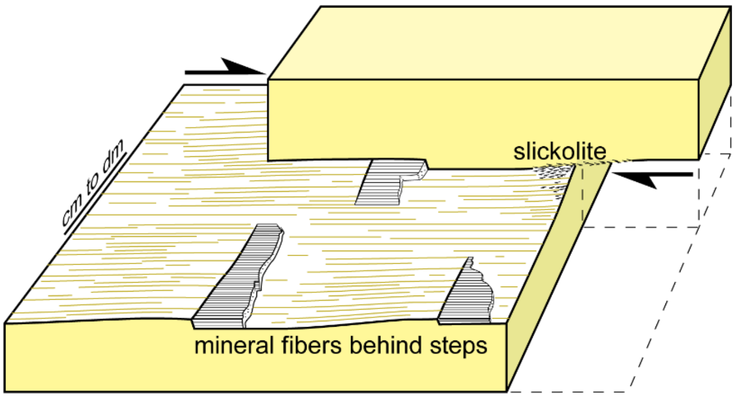
- Friction fractures (R-Riedel shears) dip forward into the fault with respect to the movement direction.
- They are concave so that their intersections with the fault surface have **crescent-shapes** with their long axis transverse to the direction of movement.
- The two crescent tips indicate the movement direction of the missing block.



Movement structures within a brittle fault plane

4.11.7: Accretionary mineral steps

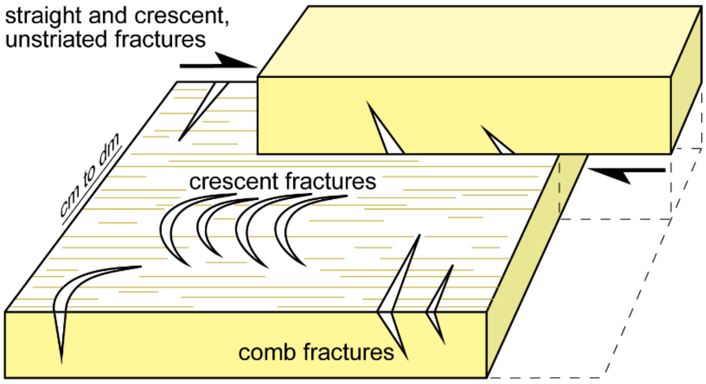
- Preferred directional growth of minerals produces fibrous crystals as walls separate during faulting.
- Such minerals have their long axes parallel to the prevailing direction of slip and fill cavities on the lee side of congruous steps and asperities on fault surfaces.
- The rock-to-fiber relationship across a step makes these **slicken fibers** (or **accretionary growth fibers**) particularly valuable to deduce the direction and sense of movement.
- Curved or superposed crystal fibers can preserve a record of changes in the instantaneous direction of fault displacement.
- By contrast, ordinary slickenside striations may be erased and overprinted if changes occur in the direction of fault displacement. If so, ordinary striations may record only the latest uniform displacement.



Movement structures within a brittle fault plane

4.11.8: Unstriated, mineralized fissures

- Straight, forward-dipping straight and lunate fractures form at a low angle to the fault plane and tend to rotate towards higher angle relationships during the deformation of wall rocks due to friction slippage.
- They open for secondary mineral crystallization during rotation. Straight fractures are named "**comb fractures**".
- The two horns of crescent fractures point in the direction of slip.



Movement structures within a brittle fault plane

4.11.9: Slickolites

- Surface irregularities or **asperities** may show a striated or stylolitic surface facing movement (compression) direction of the missing block and unstriated slopes towards the movement (extension) direction.
- Slickolite defines dissolution surfaces facing the displacement direction with micro stylolitic peaks pointing in the upstream direction at a low angle to the fault surface.

4.11.10: Tension gashes

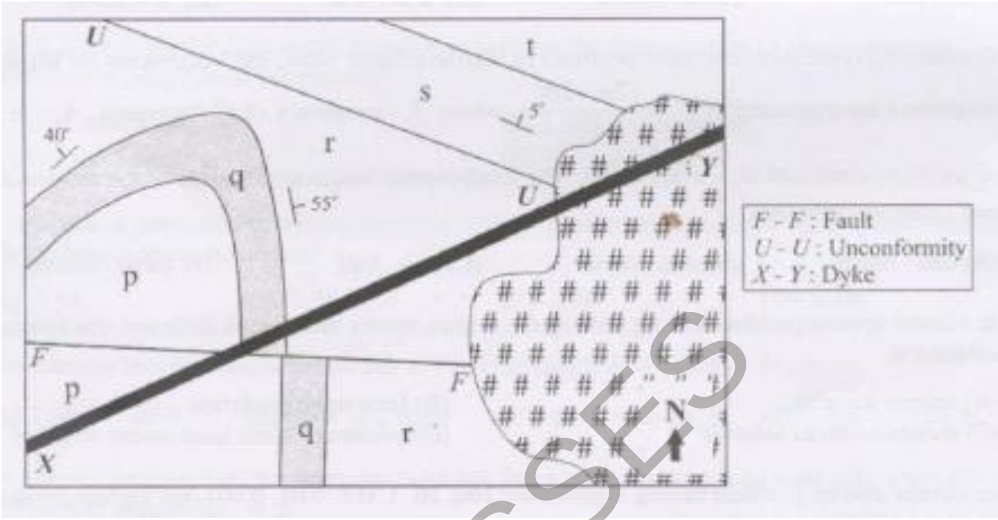
- **Tensile fractures** or **tension gashes** (T fractures) normally parallel to the regional maximum principal stress (compression) may appear at an angle typically less than 45° to the fault plane, near the fault plane.
- Their intersection with the fault surface is nearly perpendicular to the cataclastic lineation.
- Their angular relationship may be helpful to infer the sense of slip, as discussed for the pinnate joints.
- Besides, they may take S or Z shapes depending on the leftward or rightward sense of shear along the fault, respectively.

Practice Questions

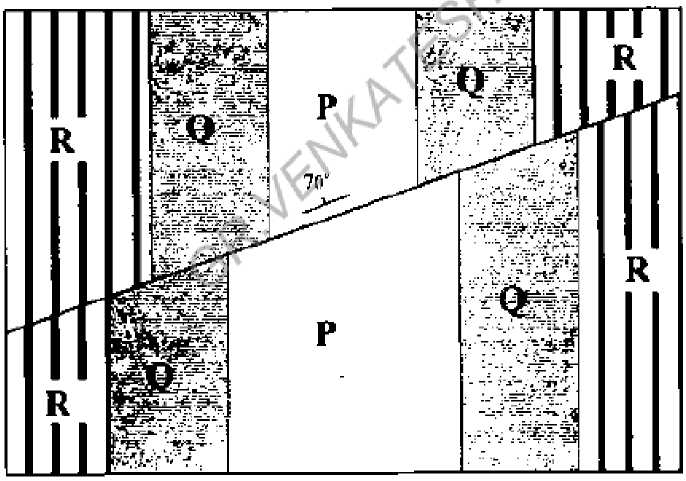
Previous year Difficult Questions

1. Rock 'X' is thrust over rock 'Y' subsequently, rock 'Y' is exposed to surface in the midst of rock 'X' by erosion. The exposure of rock surrounded by rock 'X' forms
   A. Inlier (GATE 2006)
   B. Klippe
   C. Outlier
   D. Window
2. In an earthquake affected area, the focal mechanism solution suggests a near vertical plunge of T-axis. It indicates (GATE 2006)
   A. A normal fault
   B. A strike slip fault
   C. An oblique fault with appreciable dip slip component
   D. A thrust fault

3. The dip slip of a fault is 200 m and the dip amount is 30 degree The throw of the fault (m) is (GATE 2008)
   A. 300
   B. 200
   C. 100
   D. 50
4. Common Data for Questions 4, 5 and 6: The following geological map shows exposures of sedimentary beds p, q, r, S, t and a batholith (hatched) in a flat terrain



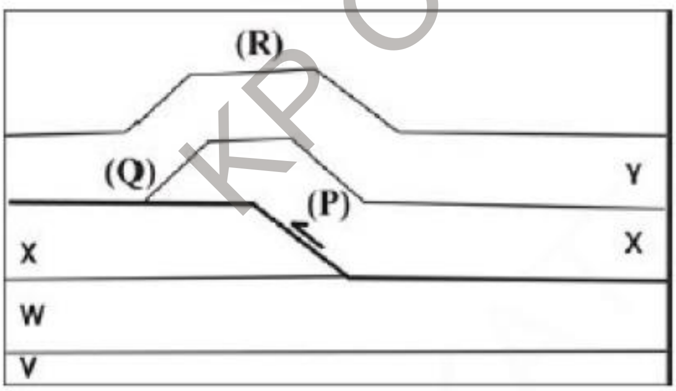
   The fold seen in the area is (GATE 2008)
   A. a synform plunging northerly
   B. a synform plunging southerly
   C. an antiform plunging northerly
   D. an antiform plunging southerly
5. If the fault dips 70° southerly, it is a (GATE 2008)
   A. normal fault with southern upthrown block
   B. right lateral strike-slip fault
   C. reverse fault will northern upthrown block
   D. reverse fault with southern upthrown block
6. The intrusion of dyke took place (GATE 2008)
   A. after deposition of beds 's' and ' t'
   B. before deposition of beds 's' and ' t '
   C. before faulting
   D. before folding
7. The following geological map exposes three beds, of which the bed P is the oldest and the bed R the youngest (GATE 2010)



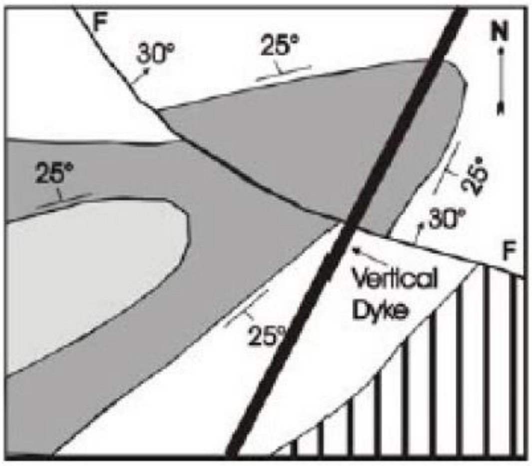
Why is bed P wider in the area south of fault?

A. Erosion has removed most of bed P to the north of fault
B. Folding has caused thinning of bed P to *the* north of fault
C. Deeper level of bed P is exposed due to faulting and erosion to the south of fault
D. Bed P had a variable thickness prior to faulting

8. What type of structure does the above map depict? (Follow question 7) (GATE 2010)
   A. Faulted anticline
   B. Folded strike-slip fault
   C. Faulted syncline
   D. Folded normal fault
9. The cross-section below shows a thrust fault with an associated fault related fold. For the hanging wall, which one of the combinations of (P), (Q) and (R) is correct? (GATE 2015)

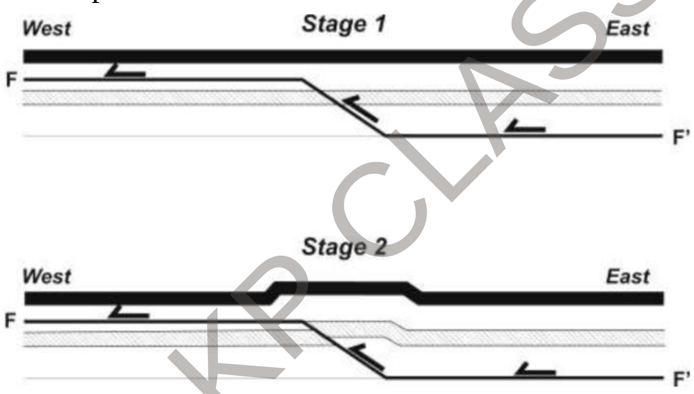


   A. Ramp (P), flat (Q), fault bend fold (R)
   B. Ramp (P), flat (Q), fault propagation fold (R)
   C. Flat (P), ramp (Q), fault bend fold (R)
   D. Flat (P), ramp (Q), fault propagation fold (R)
10. In the folded and faulted sequence of beds given in the map below, the fault F-F (dipping 30°NE) is which type of fault? (GATE 2015)



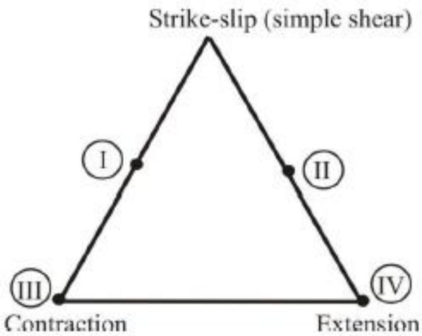
A. Sinistral strike- slip
B. Reverse
C. Normal
D. Dextral strike slip

11. The figure below is a schematic section showing the initial stages of development of a thrust fault (FF') having a typical ramp and flat geometry, with the thrust sheet being transported from east to west. With respect to the synform and antiform created in Stage 2, which one of the options below is CORRECT for the next increment of movement on the fault plane? (GATE 2018)



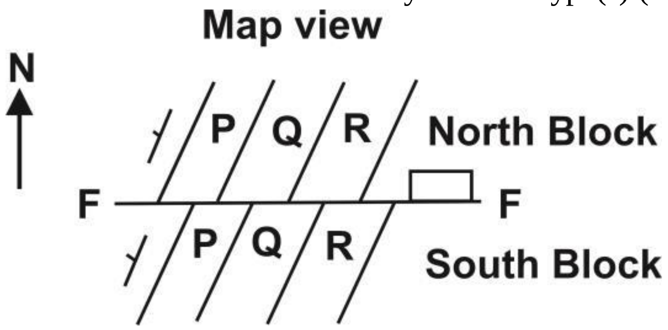
A. The synform and the antiform will both move westward.
B. The synform will remain in position, while the antiform will grow in amplitude.
C. Both synform and antiform will grow in amplitude.
D. The geometry will remain unchanged.

12. In the given diagram, which one of the combinations correctly lists structures typically developed at I, II, III, IV? (GATE 2019)



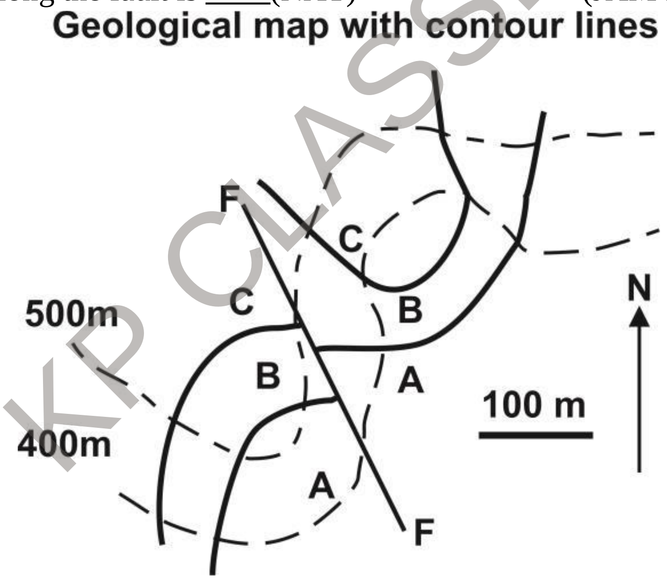
A. I-pressure ridge, II-thrust, III-horst, IV-pull apart basin
B. I-pull apart basin, II-thrust, III-horst, IV-pressure ridge
C. I-pressure ridge, II-pull apart basin, III-thrust, IV-horst
D. I-pull apart basin, II-pressure ridge, III-horst, IV-thrust

13. A northerly dipping fault (F-F) has displaced beds P, Q and R. The thickness of the beds across the fault is same. Identify the fault type(s).(MSQ) (JAM 2020)

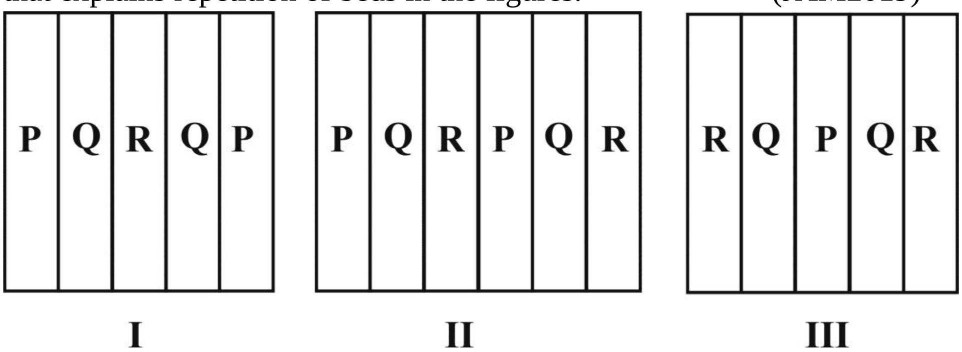


A. Dextral fault
B. Reverse fault
C. Normal fault
D. Sinistral fault

14. A set of sedimentary rocks A, B and C are affected by a fault F-F. The amount of vertical throw (in m) along the fault is ____(NAT) (JAM 2020)



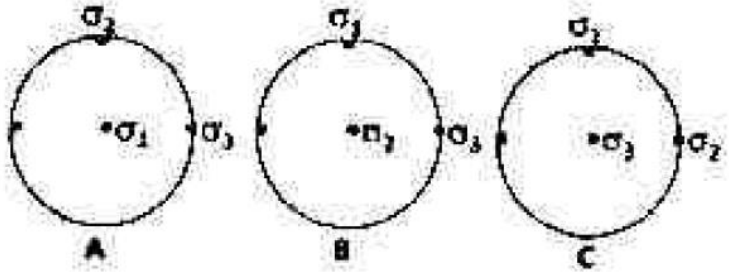
15. Figures I, II and III are the outcrop patterns of three inclined beds P, Q and R on a flat ground. P is the oldest and R is the youngest amongst these beds. Identify the correct option that explains repetition of beds in the figures. (JAM2019)



(A) I- anticline; II- syncline; III- fault

(B) I- syncline; II-anticline; III- fault
(C) I- fault; II- anticline; III- syncline
(D) I- syncline; II- fault; III-anticline

16. Throw and heave of a bed offset by a normal fault are 100 m and 200 m, respectively. The dip of the fault plane is _________ degree (one decimal place). (JAM 2019)
17. Stereogram A, B & C show three different orientations of the principal stresses σ_1, σ_2 *and* σ_3. Which one of the following is the correct match of stress orientations in A, B, C with the nature of faulting? (NET 2018)



A. A-Normal faulting, B-Strike-slip faulting, C-Thrust faulting
B. A-Strike-slip faulting, B-Normal faulting, C-Thrust faulting
C. A-Thrust faulting, B-Strike-slip faulting, C-Normal faulting
D. A-Strike-slip faulting, B-Thrust faulting, C-Normal faulting

Multiple Selected Questions

1. Which among the following is the result of normal fault?
   A. Horst
   B. Half graben
   C. Wrench fault
   D. Book shelf fault
2. Reverse fault occurs where
   A. There is horizontal shortening
   B. There is horizontal extension
   C. The hanging wall moves down
   D. The foot wall moves down
3. Tulip structure is formed due to
   A. Strike slip fault
   B. Normal fault
   C. Reverse faulting
   D. Ductile deformation
4. Which among the features associated with thrust fault?
   A. Klippe
   B. Schuppen structure
   C. Duplex
   D. Fenster

ANSWERS

Previous Year Easy Questions

1. A   2. B   3. A   4. D   5. C   6.B   7.A   8.A   9.B   10.B   11.D   12.A

13.A 14.D 15.C 16.D 17.B

Previous Year difficult Questions

1. D 2. D 3. C 4.C 5.D 6.A 7.C 8.D 9.C 10.B 11.B 12.C

13.B,D 14. 100 15.D 16. 26.5 17.A

Multiple Select questions

1. ABD 2. AD 3. AB 4. ABCD

EXPLANATIONS

Previous Year Easy Questions

1. Growth faulting is common feature of many deltaic environments and is vital in determining local sediment dispersal and accumulation.
2. A graben is a valley with a distinct escarpment on each side caused by the displacement of a block of land downward.
3. If the fault plane has a dip of less than 45°, then the reverse fault is called a thrust fault.
4. Heave is the horizontal component of dip-slip and throw is the vertical component.
5. Rake is the smallest angle between the strike line and the slickensides or only other line physically lying on the fault plane. Here rake is zero hence the fault was slipped into the strike direction of the rock, thus it is a strike-slip fault.
6. Horizontal component of Dip-slip fault is heave. Vertical component of dip-slip fault is throw. Angle of inclination of fault plane measured from vertical is called hade.
7. Rift valleys or grabens are long and relatively narrow fault throughs bounded by parallel high angle faults. The structure is produced when the two parallel normal faults hade towards each other and the rock beds between them are thrown down under the influence of gravity.
8. In duplex structure a rock body that is bounded by thrust faults from all the sides is called horse.
9. Horst and graben: - major uplifted or depressed blocks may be bounded by sets of faults of the same type but opposite sense of movement. A depressed block bounded by normal faults is termed as a graben and elevated one termed as horst.
10. In case of dip slip fault, the movement is essentially downward along the dip of the fault hence the rake would be 90°.
11. Flats are fault surfaces that form parallel to the strata, usually in weak rock units such as evaporites and shales. Ramps cur across more resistant rock units, for example sandstone and limestone forming a dip angle that is typically 30 to 45 degrees.
12. Normal fault as shown in the figure the hanging wall moves downward over the fault plane.
13. If two normal faults have parallel strikes and share the same downthrown block, a trough-like structure results which is known as a graben. A horst is an uplifted block bounded by two normal faults that strike parallel to each other.
14. Extensional setting indicates moving away of two plates from each other. Here normal fault, horst and rifts are the structure of extensional regime but thrust fault is the structure of compressional regime.
15. A transform fault is a strike slip fault at plate boundaries. Strike-slip faults usually have very steep or vertical dips and the relative movement between the adjacent blocks is

horizontal, parallel to the strike of the fault plane and formed along the conservative plate boundary.

16. Thrust faults are type of reverse fault in which the fault plane has a very shallow dip, typically much less than 45°. Thrust and reverse fault form by horizontal compressive stresses and so cause shortening of the crust.
17. Mid Oceanic ridges are formed due to the divergence of the plate boundaries and divergent plate boundary characterize by normal faults.

Previous Year difficult Questions

1. Window is a geologic structure formed by erosion on a thrust system. When erosion opens a hole and underlying rock is exposed window is formed.
2. Two classes of dip slip fault are distinguished depending on the sense of the vertical component of motion.
   Normal fault: T-axis is horizontal and P-axis is vertical. A special case of this type is the 'listric fault', in which the steepness of the fault surface is not constant but decreases with increasing depth.
   Thrust fault: The T- axis is vertical and the P-axis is horizontal.
3. Given dip slip = 200m
   Dip amount = 30°
   $\sin 30° = \frac{Throw}{200}$
   Throw = 100 meter
4. As chronology is unknown and limbs of the fold dips away from each other hence, the fold is an antiform and the plunging direction shows northerly dip.
5. If the fault dips 70° southerly, the q bed and its displacement indicate that it is a reverse fault and the southern block is up thrown.
6. Here the intrusion of the dyke shows that it happened at the end of the all geological events happened in the map.
7. Bed P wider in the area south of fault because of the upliftment and erosion of the southern part.
8. The structure in the map shows folded normal fault. The equal in lithology in the both side shows folded strata and displacement of down thrown block along dip direction shows normal fault.
9. Thrust faults particularly those involved in this skinned style of deformation have a so-called ramp geometry. Thrust mostly propagate along zones of weakness within a sedimentary sequence such as mudstone and salt layers. The parts of the thrusts are called flats.
10. Faulty FF caused the sheltering of the footwall side and broadening of the hanging wall side hence, it is reverse fault.
11. The synform will remain in position, while the antiform will grow in amplitude. This is a fault bend fold. Anticline grows in amplitude and the synform remains in position as the fold grows.
12. Reverse faults (thrusts) – contraction.
    Normal faults (horst and graben) – extension.
13. As the fault plane dipping northerly and bed are dipping westerly, the erosion of the topography after reverse faulting will look like northern block slightly displaced. As left side of the fault moving towards the observer, it would be sinistral fault.

14. If strike lines will be drawn for the bed lies in the both side of the fault, then it will be different in both side as the displacement happened along the fault.
    500 strike line which touches C bed contact in left side of the fault, 400 strike will touch the same contact in right side.
    Hence, it indicated that the vertical throw is 100m
15. Figure I show sequence of syncline as younger rock lies in the centre and older rock covers outward of the strata. Figure II shows sequence of fault as repetition of strata observed and figure III is the sequence of anticline due to appearance of older rock in the centre.
16. Throw = the vertical component = 100m
    Heave = the horizontal component = 200m
    Dip angle = $\tan^{-1}(100/200) = 26.5°$
17. According to Anderson's rule the principal stresses orientation determines the nature of faulting: **σ1vertical**: Normal faulting.
    σ2 vertical: Vertical strike-slip faults.
    σ3 vertical: Thrusts faulting

Multiple Select questions

1. Horst and graben are result of normal faulting, while the horst part lies the upthrown block and graben is in the downthrown block. Book shelf fault generated from the continuous faulting on the planar normal fault.
2. In case of reverse fault there is horizontal movement of two blocks towards each other. Hence shortening of the strata observed. This fault is a dip-slip fault on which the hanging-wall has moved up and over the footwall.
3. Tulip structure is the other name of negative flower structure which formed due to the combined movement of normal fault and strike slip fault. It shows concave up structure.
4. Al the structures are associated with thrust fault. Klippe is the thrust remain isolated and surrounded by foot wall rock. Fenster is the window structure results due the thrusting. Schuppen structure formed due to the stacking of series of thrust sheets.

Chapter 5: Fractures, Joints and unconformities

- Brittle structures such as joints and faults are found almost everywhere at the surface of the solid Earth.
- In fact, brittle deformation is the trademark of deformation in the upper crust, forming in areas where stress builds up to levels that exceed the local rupture strength of the crust.

- Brittle structures can form rather gently in rocks undergoing exhumation and cooling, or more violently during earthquakes.
- In either case, brittle deformation by means of fracturing implies instantaneous breakage of crystal lattices at the atomic scale, and this type of deformation tends to be not only faster, but also more localized than its plastic counterpart.
- Brittle structures are relatively easily explored in the laboratory, and the coupling of experiments with field and thin-section observations forms the basis of our current understanding of brittle deformation.

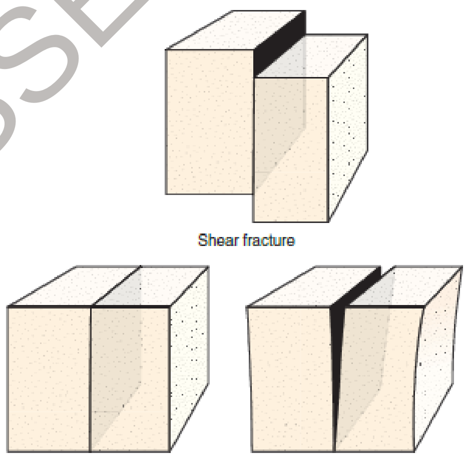
5.1: Fractures

5.1.1: What is fracture?

- Strictly speaking, a fracture is any planar or sub planar discontinuity that is very narrow in one dimension compared to the other two and forms as a result of external (e.g. tectonic) or internal (thermal or residual) stress.
- Fractures are discontinuities in displacement and mechanical properties where rocks or minerals are broken, and reduction or loss of cohesion characterizes most fractures.
- They are often described as surfaces, but at some scale there is always a thickness involved.
- Fractures can be separated into shear fractures (slip surfaces) and opening or extension fractures (joints, fissures and veins).

5.2: Type of fractures

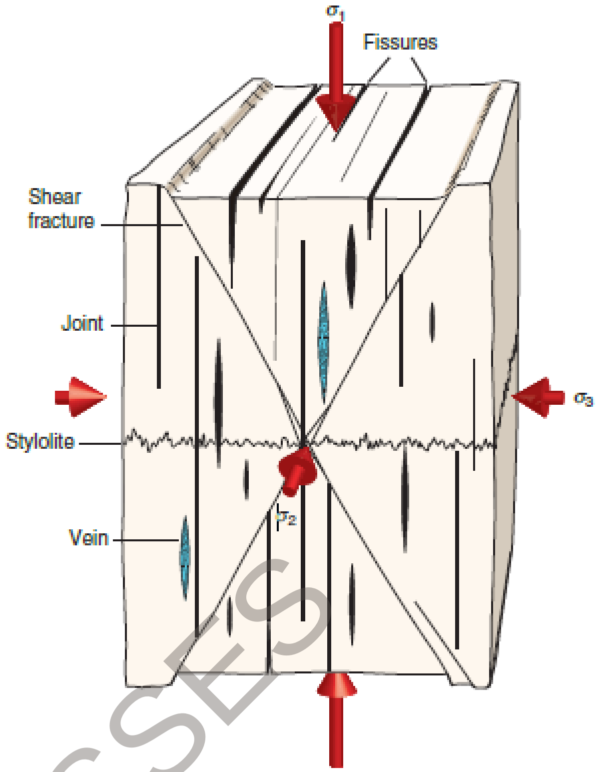
- Fractures are surfaces along which rocks or minerals have broken, creating two free surfaces where none existed before; they are therefore surfaces across which the material has lost cohesion.
- There are two basic types of fracture, **extension** and **shear fracture**, according to the relative motion that has occurred across the fracture surface during formation.



5.2.1: Shear fracture

- A **shear fracture** or **slip surface** is a fracture along which the relative movement is parallel to the fracture and typically develop at 20–30° to σ1.
- The term shear fracture is used for fractures with small (mm- to dm-scale) displacements, while the term fault is more commonly restricted to discontinuities with larger offset.

- The term slip surface is used for fractures with fracture-parallel movements regardless of the amount of displacement and is consistent with the traditional use of the term fault.
- Fractures are commonly referred to as cracks in material science and rock mechanics-oriented literature.

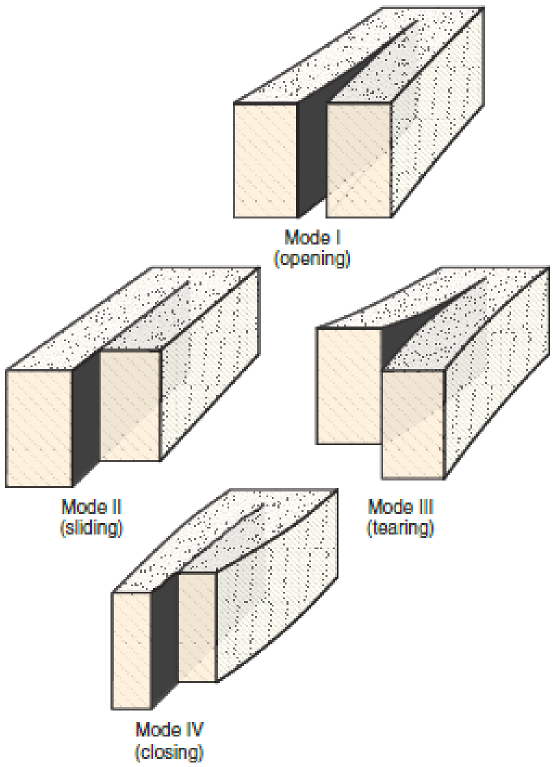


5.2.2: Extension fractures

- **Extension fractures** are fractures that show extension perpendicular to the walls.
- Joints have little or no macroscopically detectable displacement, but close examination reveals that most joints have a minute extensional displacement across the joint surfaces, and therefore they are classified as true extension fractures.
- Extension fractures are filled with gas, fluids, magma or minerals. When filled with air or fluid we use the term **fissure**.
- Mineral-filled extension fractures are called **veins**, while magma-filled fractures are classified as **dikes**. Joints, veins and fissures are all referred to as extension fractures.

5.2.3: Contraction fractures

- Contractional planar features (anticracks) have contractional displacements across them and are filled with immobile residue from the host rock.
- Stylolites are compactional structures characterized by very irregular, rather than planar, surfaces.
- Some geologists now regard stylolites as **contraction fractures** or **closing fractures**, as they nicely define one of three end-members in a complete kinematic fracture framework together with shear and extension fractures.
- Such structures are known as **anticracks** in the engineering-oriented literature.



5.3: Fracture mechanics

- In the field of fracture mechanics, it is common to classify the displacement field of fractures or cracks into three different modes.

- **Mode I** is the opening (extension) mode where displacement is perpendicular to the walls of the crack.
- **Mode II** (sliding mode) represents slip (shear) perpendicular to the edge and **Mode III** (tearing mode) involves slip parallel to the edge of the crack.
- Modes II and III occur along different parts of the same shear fracture and it may therefore be confusing to talk about Mode II and Mode III cracks as individual fractures.
- Combinations of shear (Mode II or III) fractures and tension (Mode I) fractures are called **hybrid cracks** or fractures.
- Furthermore, the term **Mode IV** (closing mode) is sometimes used for contractional features such as stylolites.
- The mode of displacement on fractures is an important parameter, for instance when fluid flow through rocks is an issue.

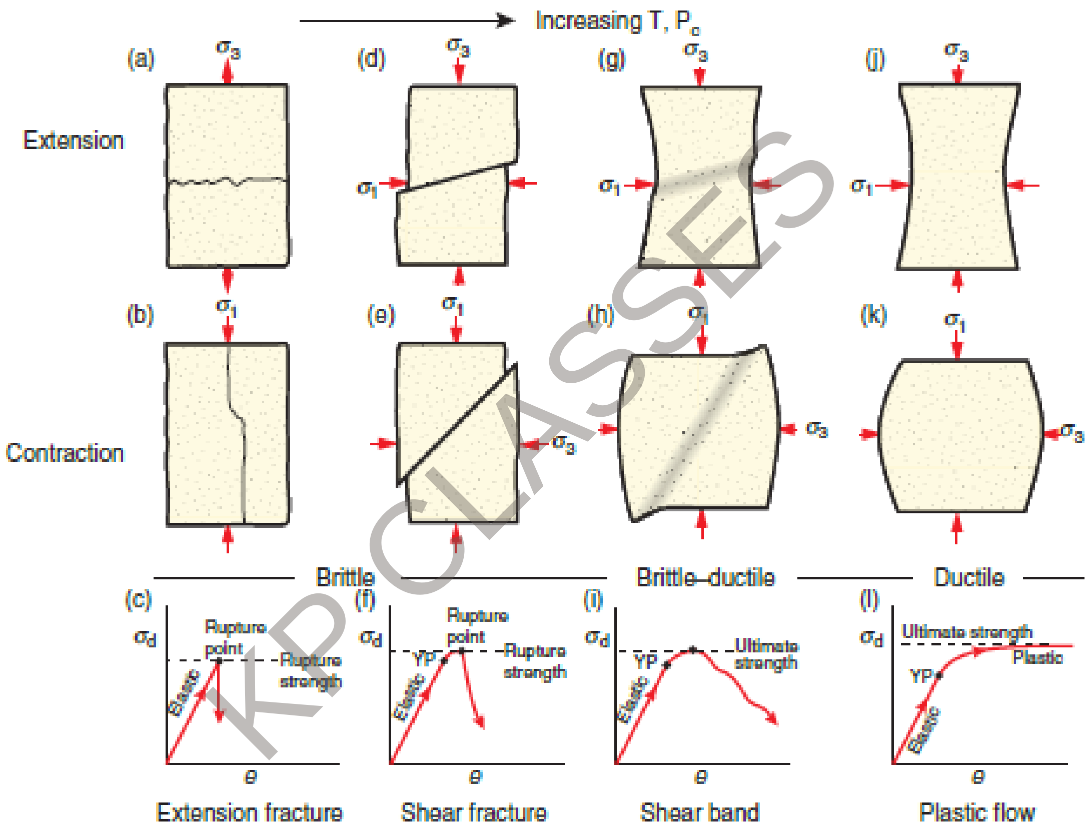


Figure: Experimental deformation structures that develop under extension and contraction.

5.4: Joints

- Joints (also termed **extensional fractures**) are planes of separation on which no or undetectable shear displacement has taken place.
- The two **walls** of the resulting tiny 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.
- They often form under high fluid pressure (i.e. low effective stress), perpendicular to the smallest principal stress.

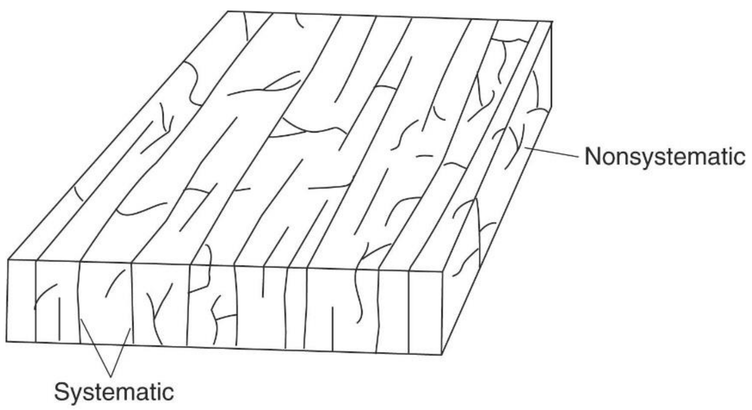
- The **aperture** of a joint is the space between its two walls measured perpendicularly to the mean plane.
- Apertures can be open (resulting in permeability enhancement) or occluded by mineral cement (resulting in permeability reduction). A joint with a large aperture (> few mm) is a **fissure**.
- The **mechanical layer** thickness of the deforming rock controls joint growth. If present in sufficient number, open joints may provide adequate porosity and permeability such that an otherwise impermeable rock may become a productive **fractured reservoir**.
- In quarrying, the largest block size depends on joint frequency; abundant fractures are desirable for quarrying crushed rock and gravel.

5.4.1: 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°.

5.4.2: Joint geometry

- The geometry of joint systems refers to the orientation (plotted on stereonets and rose-diagrams), the scale, the shapes and trajectories, the spacing, the aperture, the intersections and terminations of the studied joints.
- The mean orientation and orientation distribution, spacing and relative chronology are general characters used to define joint sets.
- In this respect, a three-dimensional observation is essential to avoid skewed sampling measurements due to simple geometrical reasons.
- **Bedding-contained joints** terminate at the top and bottom of beds.
- **Systematic** joints are characterized 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 generally terminate against systematic joints.

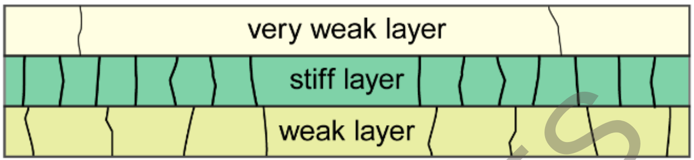


5.4.3: Joint spacing

- The sizes and **spacing** (the average orthogonal distance between neighbouring fracture planes) are essential characteristics of joint sets.
- In isotropic rocks (e.g. granite) joint spacing follows an approximately log-normal **frequency** (the number of joints occurring within a unit length) distribution.
- In anisotropic (layered) rocks, joint spacing differs according to several parameters.

Bed thickness

- For the same lithology, joints are more closely spaced in thinner beds. This is because the formation of joints relieves tensile stress in the layer over a lateral distance proportional to the joint length.
- Since joints end at layer boundaries, which are rock discontinuities, the longer joints in thicker layers need to be spaced less frequently.



Spacing of bedding-parallel joints
according to competence (elastic modulus) of layers

- However, systematic investigations have shown that the thickness of incompetent interlayers influences fracture separation within competent layers.
- Spacing is wider where interlayers are thicker than a critical value assessed to be ca 5 cm; conversely, fractures are closer to each other where weak interlayers are thinner than 5 cm.
- Spacing scaled with layer thickness is a tool to map lithological contacts, particularly in air-photo interpretation or in the surface mapping of heavily weathered or inaccessible exposures.
- Spacing may also reveal differences in the joint systems at limb and hinge positions on large folds or different distances from large faults.

Lithology

- Stronger, more brittle rocks have more closely spaced joints than weaker rocks.
- Similarly, rocks with low tensile strength show more joints than stiffer lithologies, because the strain is the same along layers of different types.
- Yet, higher stresses are required to achieve the same amount of strain in the stronger layers.
- Therefore, strong layers fracture more frequently. However, this response is particularly sensitive to local pore fluid pressure.

Structural position and strain

- The structural position (particularly within folds) and the magnitude of extensional strain also control joint spacing.

5.4.4: Joint patterns

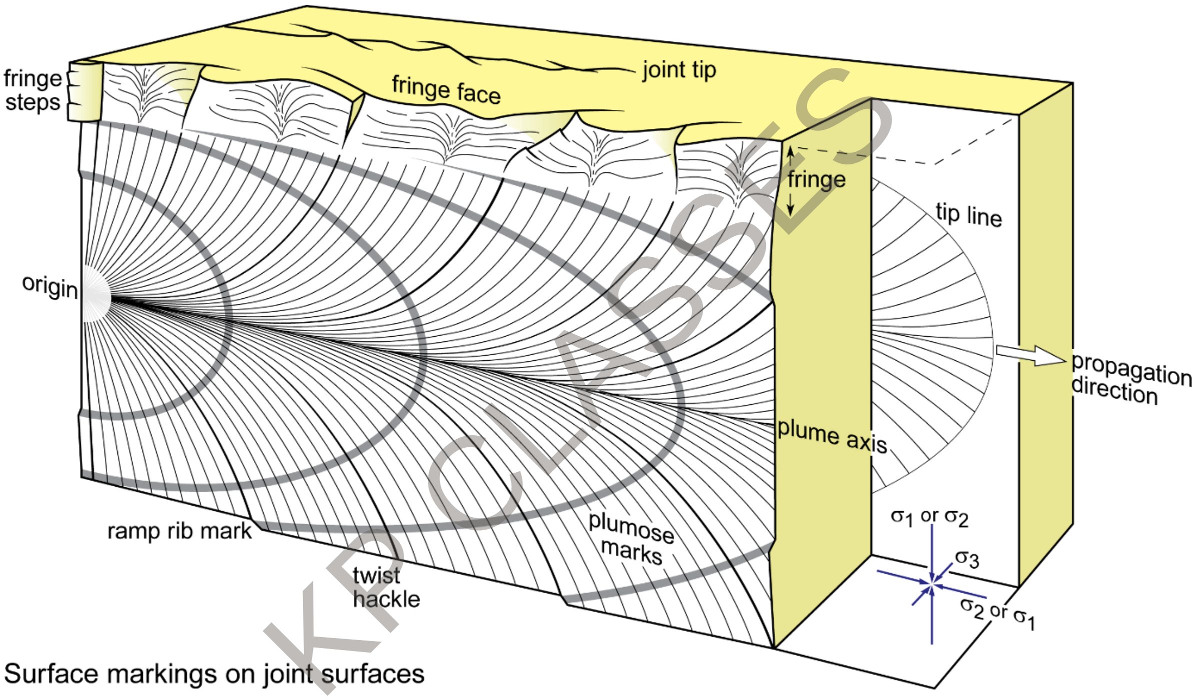
There are five main arrangements:

- Parallel sets are curved or straight
- Fans sets along fold or intrusion crests

- Radiate sets around intrusion centers
- Concentric sets around intrusion and collapse centers (cone, ring or cylindrical)
- Polygonal sets as columnar or prismatic.

5.5: Joint surfaces features

- Barren joints are characterized by clean, granular and jagged breaks.
- They are **conchoidal structures**, meaning that they are uneven surfaces with low relief convexities and concavities (like those of a clamshell) that do not follow any natural plane of separation.
- Such structures are typically seen when an amorphous material (glass, flint, obsidian, etc.) is fractured.
- Likewise, some joint surfaces display delicate ornaments falling into two groups: **plumose-marks**, the most common type, and **rib-marks**.
- Preservation of these delicate features specifies that the joint is not a shear fracture.



Surface markings on joint surfaces

5.5.1: Plumose structures

- Plumose structures are aggregates of gentle curvilinear undulations (the **hackle marks**) that radiate from the point where the joint originated and fan outward from a generally straight, more rarely curved axial line, then resembling the shape and imprint of a feather.
- The **origin** commonly is some rock heterogeneity such as ripples on bedding planes or inclusions (concretion, nodule, clast, fossil, etc.) in beds.
- Hackles are often very fine near the joint origin, while the differential relief may amplify lengthwise towards the joint margin (the **fringe**).
- Hackles diverge sharply at angles of about 30° from the central axis, gradually curving to angles of about 70° near the margins of the joint surface.
- The scale of plumose patterns seems to depend on the grain size of the rock.
- Markings similar to plumose structures occur on fracture surfaces in glass and other brittle materials.

- They are interpreted as surface irregularities due to local variations in the propagation of the fracture front in terms of velocity and heterogeneities in the rock.
- Experiments show that the diverging rays of the plumose structures always remain parallel to the direction of propagation of the fracture.
- Thus, constructing lines at right angles to these rays yields the position and shape of the fracture front at different times of its evolution.
- The fracture fronts form a series of concentric ellipses, the centre of which marks the site of fracture initiation.

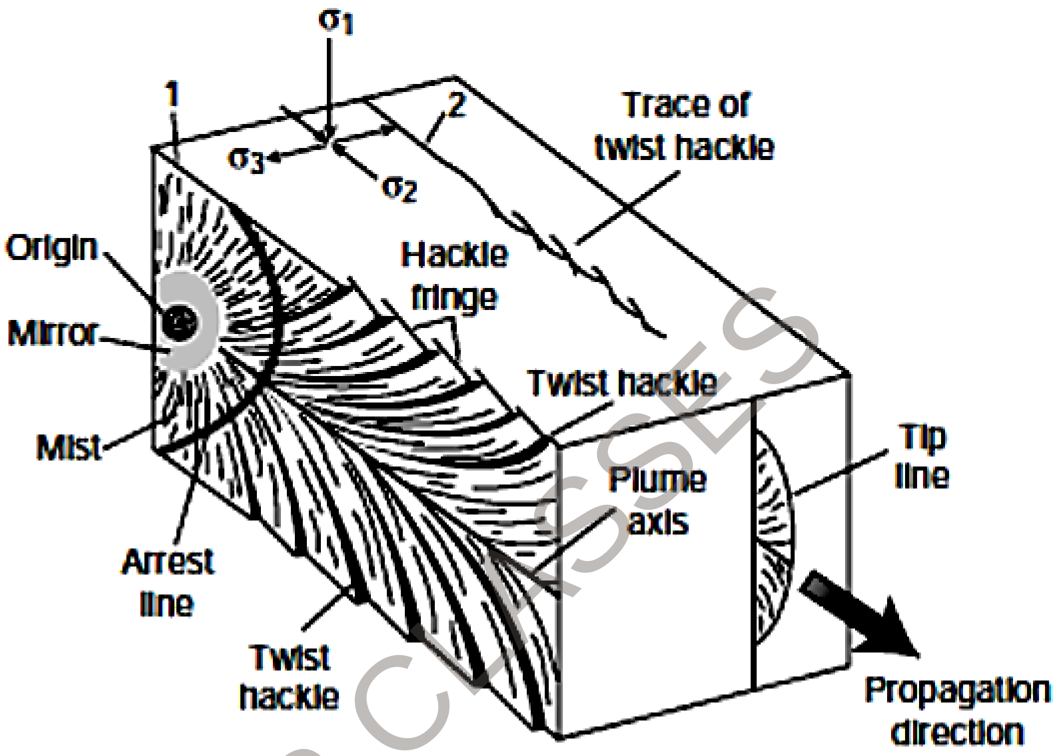


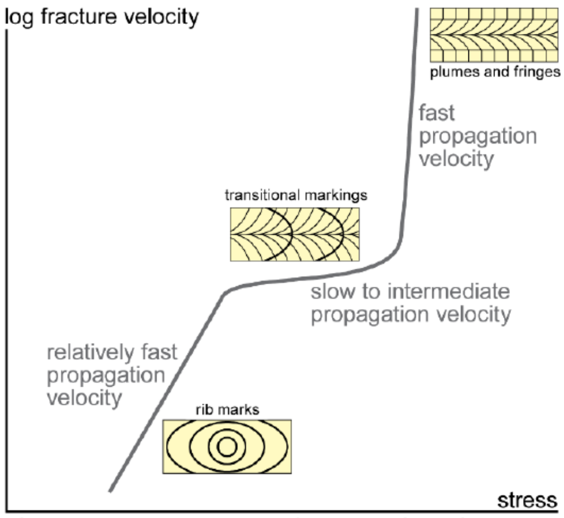
Figure: Block diagram showing plumose structure.

5.5.2: Rib-marks

- Rib-marks form a series of regular, concentric and arcuate changes or ramps in the orientation of the joint surface, giving cuspate, waveforms or rounded ridges or furrows.
- The central zone of rib-marks (the **mirror**) is often circular or elliptical. **Wallner lines** are similar to ribs but they occur as one or two sets oblique to the hackles.
- Rib-marks represent changes in fracturing direction as the stress field changes.
- Experiments have shown that those that are sinusoidal in profile and smooth on their crests record the location at which the velocity of propagation of relatively fast-propagating fractures cutting through a solid material diminishes (the stress field is vibrating).
- Strongly asymmetric rib marks, with sharp crests and occasionally deviating from parallelism (**arrest marks**) are associated with slow crack propagation.
- They are old joint terminations, mapping successive temporary arrests of the crack front during repeated crack growth under recurring loading/unloading conditions.

5.5.3: Interpretation

- Plumose and rib marks can be superposed on a joint plane and generally are orthogonal to each other.
- Such delicate features interlock on opposed faces of joints, and this precludes shear movement (hence, joints are mode 1 fractures parallel to the (σ1; σ2) plane).
- Plumose and rib marks are a direct expression of the joint path because the edges of the fracture constantly twist and tilt as they advance.



Qualitative distribution of joint surface features with respect to stress intensity and fracture propagation velocity

- Plume axes develop parallel to the main propagation direction, commonly parallel to bedding.
- Considerations in linear fracture mechanics suggest that fracture velocity and /or stress intensity control these surface structures.
- The average propagation velocity has been measured to be half speed of sound. Experiments further suggest that propagation velocities of cracks with plumose ornamentation may exceed half the speed of sound.

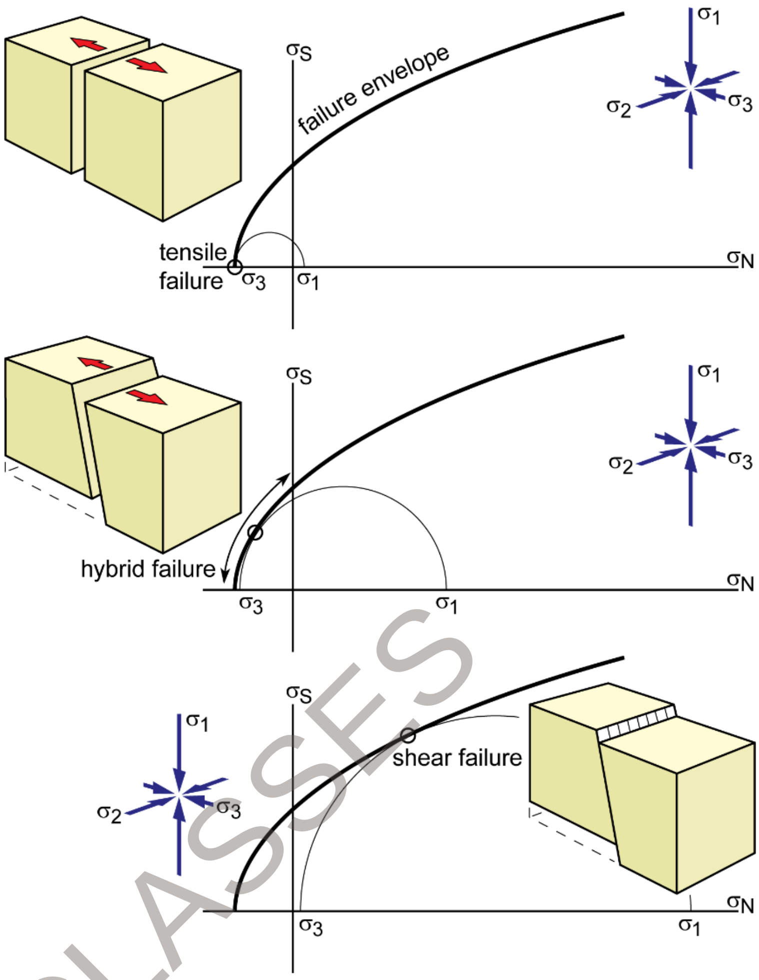
5.6: Type of Joints

- A genetic classification of joints is based on the size of inferred, imperceptible displacement related to the three principal stress axes of a region.
- If the total displacement is normal to the fracture surface, it is an **extension** or **dilatant joint** (mode 1 fracture).
- If the shear component has some finite, yet negligible value, the fracture called a **shear joint** is really a fault (modes 2 and 3 fracture), keeping in mind that the shear component may have accumulated after the formation of a former dilatant joint.

5.6.1: Extension joints

- Linear elastic fracture mechanics predicts that the orientation of dilatant joints (genuine mode 1 fractures) in a relatively isotropic rock is controlled by the remote stress field at the time of fracture propagation: joints are gaping planes parallel to the maximum compressive stress σ1 and perpendicular to the direction of the least principal stress σ3.
- In other words, they form in the plane containing σ1 and σ2. Otherwise, there would be a shearing stress and a corresponding finite shear displacement on the joint plane.
- Triaxial experiments on brittle isotropic rocks confirmed this theoretical consideration.
- Thus, regionally consistent joint sets are taken as effective proxies for stress trajectories during joint growth: relatively closely spaced, parallel and linear joints suggest that the regional principal stress trajectories are rectilinear and remained parallel across the fractured area; alternatively, complex joint orientations are related to stress trajectory variability.

- The pattern of dilatant joints is commonly T-shaped, the younger joint abutting the older one.
- Given suitable anisotropy of the tensile strength, it is, however, possible to get joints normal to σ2 or even σ1.



5.6.2: Hybrid joints

- **Hybrid** joints show components of both extension and shear components.
- They are interpreted as failure surfaces initiated in the transition from tensile to shear failure.
- They form when the stress circle touches the (Griffith) failure envelope in the tensile (negative normal stresses) side of the Mohr diagram.
- Dihedral angles between conjugate hybrid fractures are typically smaller than between shear fractures (faults).

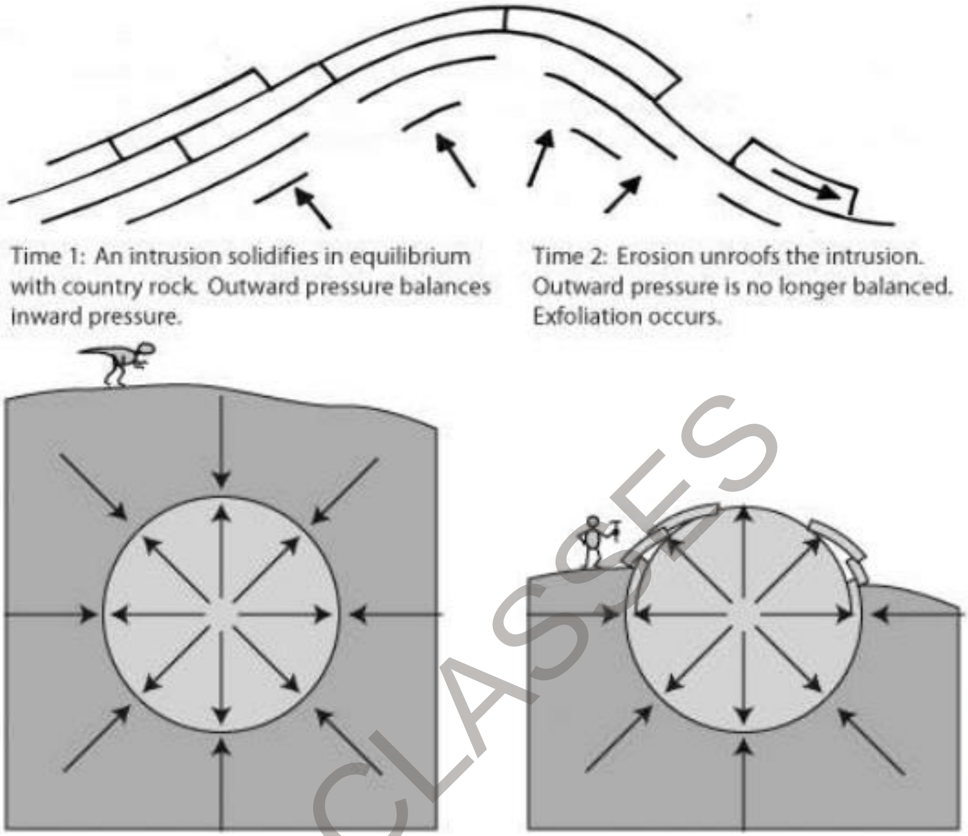
5.6.3: Shear joints

- This term is unfortunate and ambiguous because shear joints actually are small faults. Conjugate "shear joints" generally define X, Y or V shapes.
- The acute bisector of these shapes is parallel to σ1, unless these patterns represent unrelated crosscutting or abutting fractures.

5.6.4: Sheet (exfoliation) joints

- Erosion relieves vertical stress, which must approach one atmosphere, but lateral stress (at least the lithostatic pressure) is not reduced proportionally.
- Therefore, the state of stress becomes non-hydrostatic and the vertical stress becomes minimum principal stress σ3 so that joints form approximately parallel to the earth's surface.
- Dilatant joints formed during erosion of homogeneous rocks such as granite are sub-parallel to the topography, and this orientation results in sets of flat-lying, curved and large joints referred to as **sheeting** or **sheet structure**.
- Spacing between sheet joints increases with depth, down to 50-100 m. Deeper sheet joints have a larger radius of curvature.
- As soon as the stress is relieved in the vertical σ3 direction, the original σ2 becomes the greatest tensile stress.

- When the tensile strength is exceeded once more, a set of extension fractures perpendicular to the original set will form, generally somewhat less well developed than the first.
- The amount of expansion to be expected from the release of stored stress consequent on burial is indicated by the values of the **compressibility** of rocks, the ratio of volume change to pressure change.



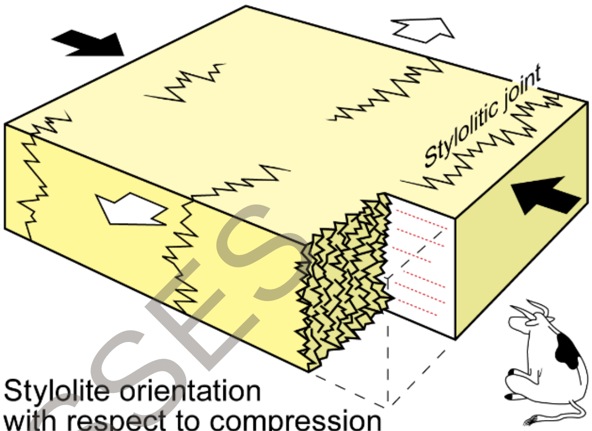
5.6.5: Bedding-parallel and bedding-contained joints

- Pressure changes of 200 MPa, corresponding with depth changes of about 6 km, lead to volume changes ranging from a few percents to a few tenths of a percent.
- If such volume changes are accomplished mainly by vertical extension, and if this extension takes place fast enough, horizontal dilatant joints may form.
- Parting of **bedding-parallel joints** is also related to unloading. Decompression joints may also form vertically.
- They commonly abut against layer boundaries and dissect layered rocks in blocky elements.
- Such **bedding-contained joints** exhibit different spacing from bed to bed, which likely reflects differences in compressibility between different layers.
- In homogeneous and isotropic rocks such as granite and sandstone, horizontal and vertical joints dissect rocks in near cubic elements.
- Weathering along these joints may lead to extreme rounding, which results in **boulders**.

5.6.6: Stylolitic joints

- **Stylolitic joints** have a characteristic saw-tooth profile and an interdigitating cone-like form in three dimensions.

- The interlocking 'teeth' are normal or oblique to the joint surface. Stylolitic joints are surfaces along which relatively soluble rock material has been removed by pressure-induced chemical dissolution to accommodate shortening.
- Shortening is parallel to the teeth direction. Stress concentration at the contact between grains triggers dissolution.
- Relatively insoluble residues (clay, iron oxides, etc) remained accumulated in the joint. This deformation mechanism is called **pressure solution**. Stylolites are particularly common in limestone.
- Assuming that stylolitic joints initiate as flat planes and do not propagate out of plane, their amplitudes represent a minimum estimate of the amount of shortening (compaction) that has occurred.
- Assuming that insoluble material initially was evenly distributed in the rock and that there has been no contamination by circulating fluids, the thickness of insoluble residue along a stylolitic joint would be proportional to the amount of material dissolved and would, therefore, be proportional to the shortening displacement across the stylolitic joint.

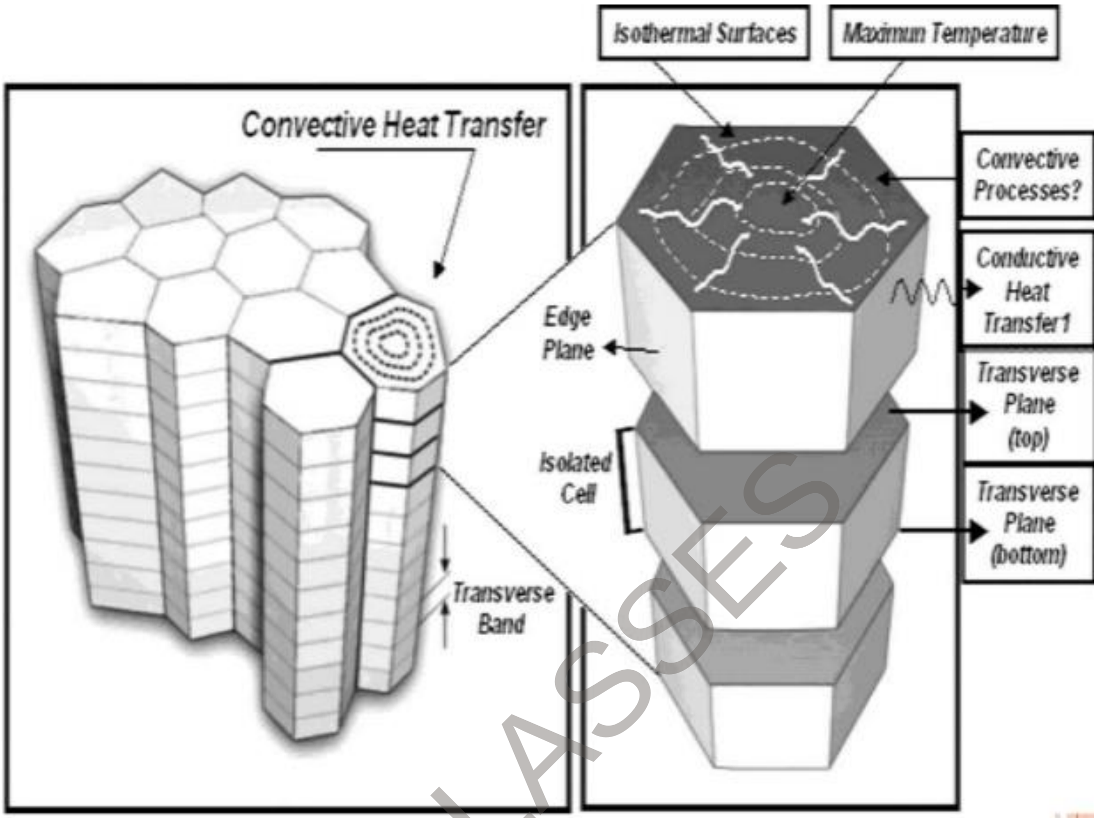


- Owing to this mode of displacements some authors call them **anticracks** or **mode 4 (closing mode) fractures**.

5.6.7: Columnar joints

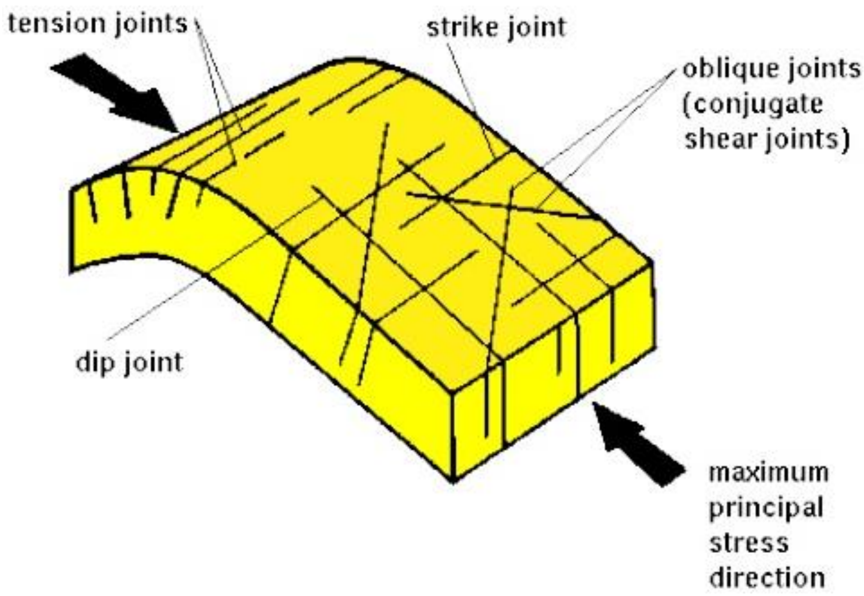
- **Columnar joints** are most prominent in basaltic sills and lava flows. They form a three-dimensional network of interconnected fractures that dissect the rock in long and spectacular polygonal (commonly five- or six-sided) columns.
- Minor, column-normal joint sets segment columns along their length and generally terminate at the column-bounding joints.
- Thermal contraction during cooling causes these column-bounding and column-normal joint sets to form and propagate perpendicular to isotherms.
- No stress occurs if the temperature of a homogeneous, isotropic, and unconstrained body changes.
- Stresses arise if the body is prevented from expanding or contracting, or if there is an uneven temperature distribution, as it is the case from the cold top to the warm bottom of a lava flow.
- A joint begins to form when the local stresses are equal to or exceed the tensile strength of the rock (up to 485 MPa for basalt).
- Fracturing relieves thermal stresses along the joint sides, perpendicular to the fracture plane, but concentrates stresses at its tip.
- Column-bounding fractures propagate in the direction of the thermal gradient, following it as it moves through the cooling lava from the cool outside to the hotter lava.
- Thus, fractures grow by the successive addition of new segments to previous ones.
- Propagation occurs whenever the stress concentration at the fracture tip is greater than or equal to the tensile strength of the rock.

- Fracture growth ceases when insufficient thermal stress exists for propagation or when the strain rate is too low to overcome viscous relaxation of stress where the fracture tip is close to the cooling front, which is the transition between the cooled, brittle and the warm, viscous or visco-elastic lava.



5.6.8: Joints in folded region

- Joints are often a part of the deformation in regions where rocks have been folded.
- Although joints normally are nearly perpendicular to bedding, they commonly form in a predictable pattern with respect to the hinge trends.
- **Longitudinal joints** are roughly parallel to fold axes and often fan around the fold.
- **Cross-joints** are approximately perpendicular to fold axes. They are common and indicate axis-parallel extension.
- **Diagonal joints** generally occur in paired, conjugate sets oblique to the fold axes, more or less symmetrically arranged about the longitudinal and cross-joints.
- **Strike joints** are parallel to the strike of fold axial planes, whereas **cross-strike joints** cut across the axial plane.
- **Gaussian Curvature** or stress history analysis can predict the orientation and relative intensity of fracturing within folded structures.
- The Gaussian curvature is the product (K) of the principal curvatures (k1 and k2), which follow the trends of the principal strain axes (X and Z).
- Extensional fractures will lie parallel to one of the principal curvatures, dependent on the stress field that formed the fold.
- The intensity of fracturing is proportional to the degree of curvature (bending) of the strata.

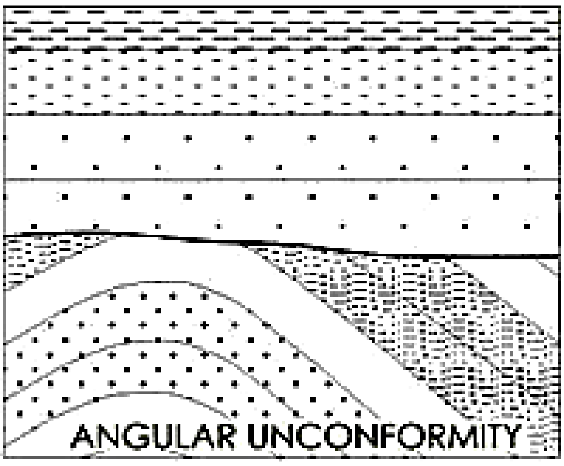


5.7: Unconformities

- An unconformity is a surface (or contact) along which there was no fracturing (i.e. not a fault or joint) and which represents a break in the geologic record.
- An unconformity therefore indicates a lack of continuity of sedimentary deposition in an area, resulting in rocks of widely different ages occurring in contact with each other.
- Unconformities usually result from changes in the sedimentary history of an area, which may be due to vertical movements (e.g. uplift followed by erosion and deposition), deformation (also followed by deposition), changes in sea level (which may be due to climatic changes, among other things), ...etc.
- In many cases, unconformities represent a buried erosional surface. In such cases, erosion of the older units results in their fragmentation into smaller pieces.
- As soon as deposition resumes, these fragments may consolidate to form a rock known as breccia (if the fragments are angular) or conglomerate (if the fragments are rounded).
- Because the breccia or conglomerate occur at the base of the younger units lying on top of the unconformity surface, and because their fragments are derived from the units below this surface, the conglomerates or breccias are known as **basal conglomerates** or **basal breccias.**

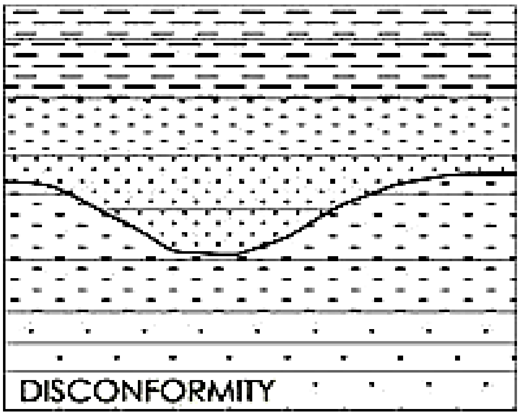
5.8: Type of unconformities

5.8.1: Angular unconformity



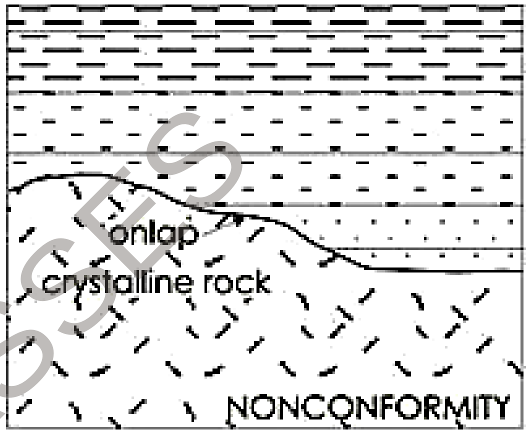
- In this case sediments are both above and below the contact, but the ones below meet the contact at an angle. (the ones above are roughly parallel to it).
- This is called an ***angular unconformity*** because the dips of beds above and below it are different.
- In this case the unconformity represents the time during which the underlying beds were tilted (folded, actually) and eroded.
- The overlying beds were then deposited on top of that flat erosional surface.

5.8.2: Disconformity



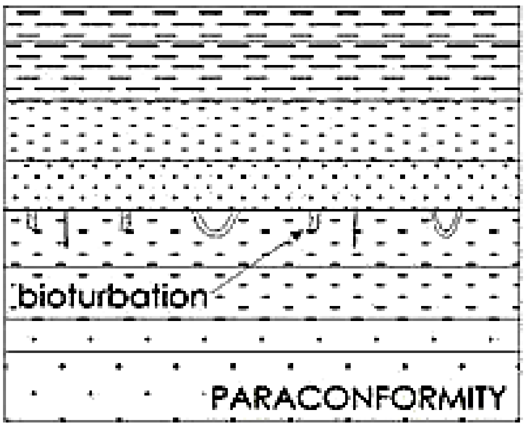
- In this case, once again, there are sedimentary rocks above and below the unconformity.
- Unlike the angular unconformity, however, the beds on both sides are essentially parallel to the contact.
- The unconformity in this case represents either a simple lapse in the continuity of sedimentation OR that plus erosion of the underlying layer. The first type can be devilishly hard to recognize, that latter type is easier.

5.8.3: Nonconformity



- One way of course is for the sediments to be the ***country rock*** or ***host rock*** for the intrusion.
- The other way, and the one that now interests us, is for the original host rock and part of the intrusion to be eroded away, ***at the surface***, before the sediments are laid down above them.
- The unconformity (symbolized by the wavy line) represents the time of erosion of the host rock and intrusion.
- This type of unconformity is called a ***nonconformity***. Sediments overlie igneous (or metamorphic) rocks.

5.8.4: Paraconformity

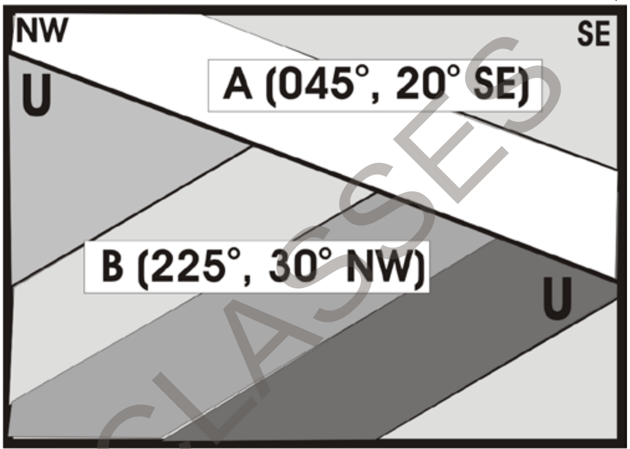


- A paraconformity (also called a **diastem**) occurs when erosion does not come into play: if sedimentation rates become very small, or even drop to zero, there is no sedimentary record (depending on the resolution we are looking for) for that time interval.
- Hence, even without erosion, simple non-deposition causes a gap in time, that is an unconformity.
- A paraconformity (diastem) implies that:
  - a sequence of sedimentary rocks was deposited horizontally
  - sedimentation stopped because of changed conditions at the bottom of the basin
  - sedimentation started again, after a time interval during which there was no deposition (a gap in the record)

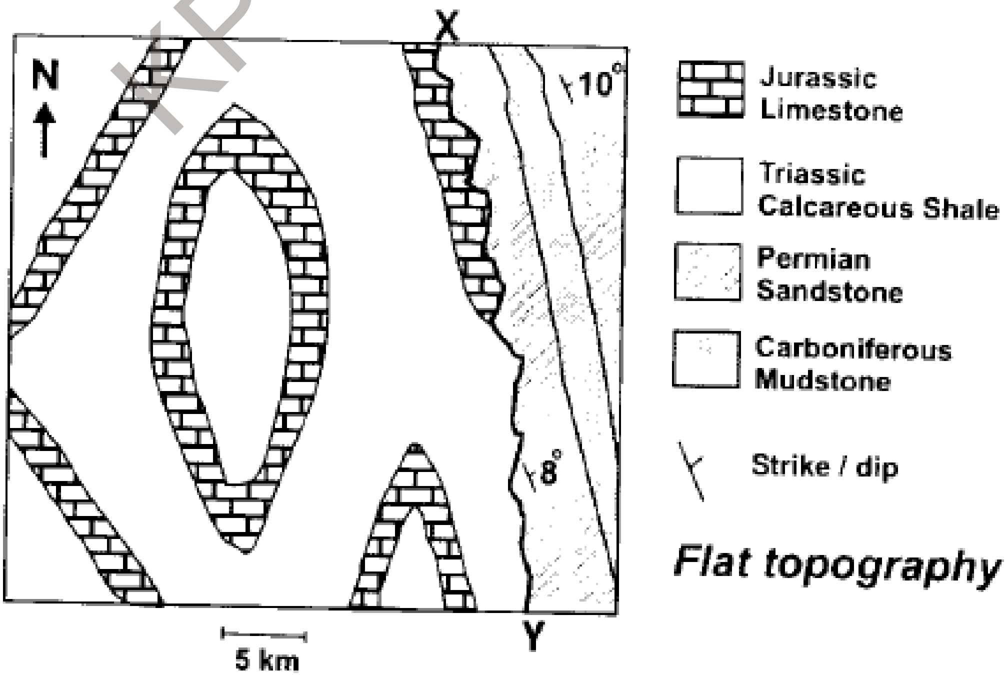
Practice Questions

Previous year Easy Questions

1. If plutonic rocks are unconformably overlain by younger sedimentary rock, the resulting discontinuity surface will be called (GATE 1997)
    A. An angular unconformity
    B. A nonconformity
    C. A disconformity
    D. A paraconformity
2. Columnar joints in igneous rock are formed due to (GATE 1998)
    A. Diastrophic movement
    B. Chemical weathering
    C. Thermal relaxation
    D. Pressure release
3. Attitudes of beds in sequences A (younger) and B (older), separated by an unconformity UU, are given in the following sectional view. If UU was horizontal when sequence A was deposited, the dip amount of beds in sequence B at that time was _____ (answer in one decimal place). (JAM 2018)



4. In the given map, the X-Y surface has the same orientation as in the Palaeozoic sequence. X-Y represents (JAM 2017)

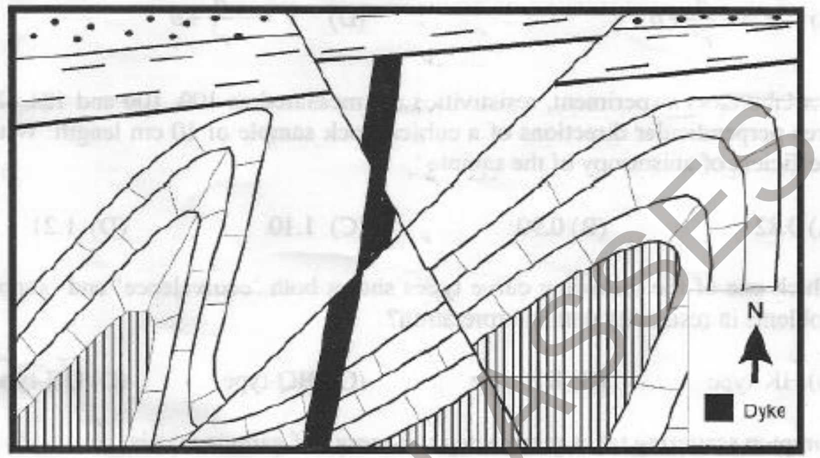


    A. Angular unconformity

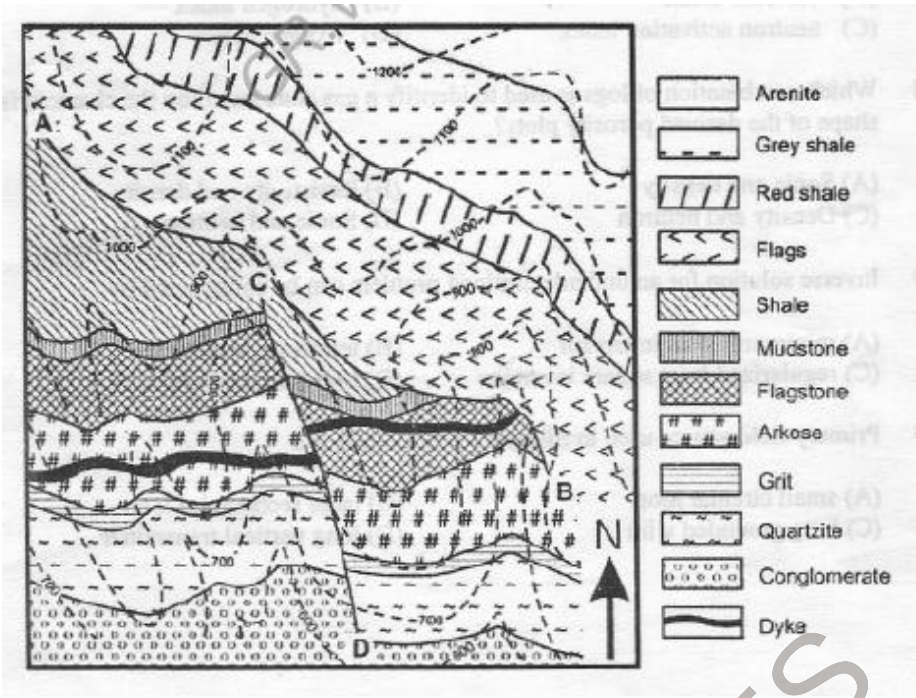
B. Non-conformity
C. Normal fault
D. Thrust

Previous year Difficult Questions

1. A hill face runs east- west and slopes at an angle of 35°N. which one of the following joints is done to cause landslides? (GATE 2004)
   A. Joints dipping towards N 10°E
   B. Joints dipping 35° due south
   C. Joints dipping 50° due north
   D. Joints dipping 50° due east
2. Geological map of an area is given below in the standard format. Based on this, attempt the question 2, 3 and 4. (GATE 2006)



   The map indicates which type of unconformity?
   A. Angular unconformity
   B. Disconformity
   C. Nonconformity
   D. Paraconformity
3. The nature of the conjugate set of faults is (GATE 2006)
   A. Normal fault
   B. Reverse fault
   C. Strike-slip fault
   D. Thrust
4. The correct sequence (oldest to youngest) of geological events is (GATE 2006)
   A. Faulting → folding → dyke intrusion → unconformity
   B. Folding → dyke intrusion → unconformity → faulting
   C. Folding → faulting →dyke intrusion → unconformity
   D. Faulting → folding → unconformity → dyke intrusion
5. The figure below represents the geological map of an area. Based on the map, attempt questions 5 and 6. Contours depicted are in metre. (GATE 2007)

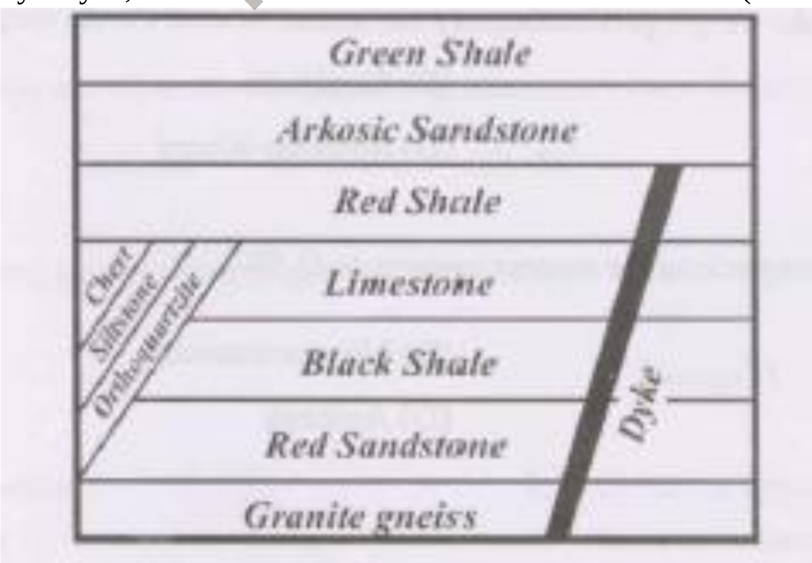


What is the nature of the discontinuity AB?

A. Fault
B. Disconformity
C. Paraconformity
D. Angular unconformity

6. The discontinuity CD represents a (GATE 2007)
   A. Normal fault
   B. Reverse fault
   C. Strike slip fault
   D. Strike fault

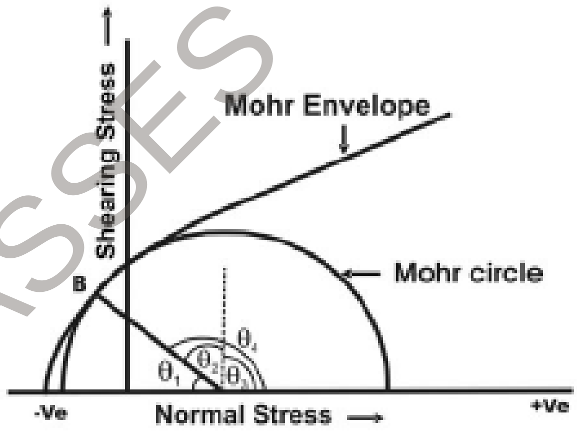
7. Common Data for Questions 7 and 8
   Examine the given geological section, which contains sedimentary successions interrupted by a dyke, and which contains no tectonic discontinuities (GATE 2009)



How many unconformities can be identified in the section?

A. 3
B. 4
C. 5
D. 6

8. Which of the following contacts is a nonconformity? (GATE 2009)
   A. Granite gneiss - Red Sandstone
   B. Black Shale – Limestone
   C. Limestone - Red Shale
   D. Red Shale - Arkosic Sandstone
9. The following figure gives Mohr envelope for a rock and Mohr circle in a particular stress condition. Fracturing occurs when the Mohr circle touches the Mohr envelope at B. What type of fractures will develop in the rock? (GATE 2012)
   A. Extension fractures
   B. Conjugate shear fractures
   C. Columnar fractures
   D. Hybrid extension-shear fractures
10. What is the dihedral angle in the above figure? (GATE 2012)
   A. θ1
   B. θ2
   C. θ3
   D. θ4



Multiple Selected Questions

1. Name the unconformities which have parallel relationship among top set and bottom set bed?
   A. Disconformity
   B. Buttress unconformity
   C. Paraconformity
   D. Angular unconformity
2. Unconformity which possess any erosional surface.
   A. Parallel unconformity
   B. Angular unconformity
   C. Paraconformity
   D. Buttress unconformity
3. Which of the following criteria used for the recognition of unconformities in the field?
   A. Structural discordance
   B. Topographic relief

C. By plotting attitude
D. All of these

4. Find out the correct statement regarding mural joint?
   A. Comprises of three sets of joints
   B. Joints are parallel to strike of the bedding
   C. Mostly seen in granitic rocks
   D. All of the above

ANSWERS

Previous Year Easy Questions

1. B 2. C 3. 50 4.D

Previous Year difficult Questions

1.C 2.A 3. B 4.B 5.D 6.A 7.A 8.A 9.D 10.B

Multiple Select questions

1. AC 2. ABD 3. AC 4. AC

EXPLANATIONS

Previous Year Easy Questions

1. A nonconformity exists between sedimentary rocks and metamorphic or igneous rocks when the sedimentary rocks lies above and was deposited on the pre-existing and eroded metamorphic and igneous rock.
2. Columnar joints are geological structure where sets of intersecting closely spaced fracture referred to as joints results in the formation of a regular array of polygonal prisms or columns. Mainly forms when the rock cools or contracts.
3. Strike of A bed is 045° and B bed is 225°, which is exact opposite of bed A. so it is clear that both the bed having strike NE-SW. now the dip of bed A is 20° and bed B is 30° but above the unconformity the bed A was horizontal means dip was 0°, so the dip of the bed in sequence B was = 20+30 = 50° at that time.
4. The western side of the surface X-Y showing deposits of Jurassic and Triassic period but the eastern side shows Permian and carboniferous sediments. Here the dip of the bed is towards eastern side and older rock is found in the dip direction, hence the X-Y surface is a thrust.

Previous Year difficult Questions

1. As the hill face running ease- west direction and slope is towards north, the joints dipping towards north is quite prone to land slide and 50° dipping amount is a steep angle to cause landslide.
2. The map shows angular contact between younger and older strata where lower part is strata folded and upper part partially inclined. Hence, the unconformity is angular.
3. The overlying strata is going upward in case of both the joints and the hanging wall rests over the fault plane. Hence, reverse fault.
4. From older to younger the sequence of geological events are folding → dyke intrusion → unconformity → faulting.

5. Sedimentary layers terminating along the discontinuity AB. Hence, it is an angular unconformity.
6. Along the discontinuity CD the beds are going downward in the hanging wall side. Hence, it is a normal fault.
7. There are 3 unconformities identified in this section. One is below red shale, second one is below orthoquartzite and third one is between red sandstone and granite gneiss.
8. A non-conformity is characterised by igneous or metamorphic succession below and sedimentary succession above it. Granite gneiss- red sandstone showing such contact.
9. At point B, the normal stress is negative and the shear stress is also present. Hence, the fracture is hybrid extension shear fracture.
10. Dihedral angles between conjugate hybrid fractures are typically smaller than between shear fractures (faults) and are angle between joint sets.

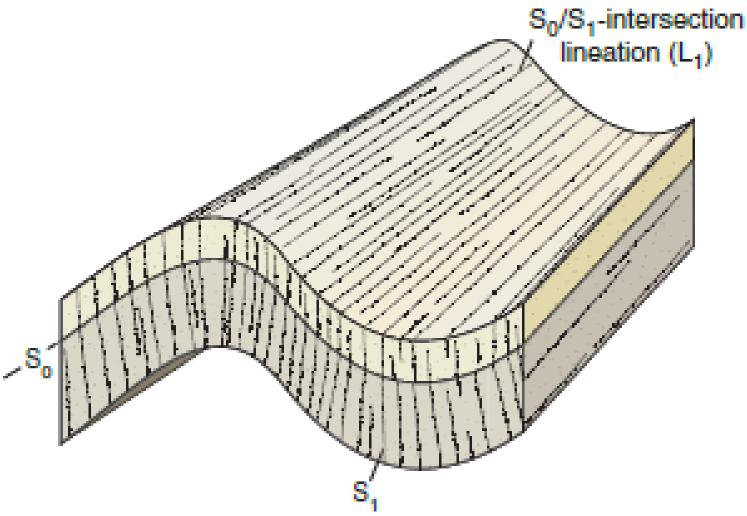
Multiple Select questions

1. Disconformity and paraconformity shows parallel relationship among the top set and bottom set bed lies in the both side of unconformity. While disconformity have erosional surface at the contact.
2. Paraconformity is the short gap in deposition where erosion does not come into play. If the sedimentary record is very small or zero then the small depositional gap creates this unconformity.
3. Structural disturbances used in case of angular unconformity and nonconformity while by plotting the attitude of the bed we can recognize unconformity in the field.
4. Granites commonly show three sets of joints mutually perpendicular to each other and divide the rock mass into more or less cuboidal blocks.

Chapter 6: Lineation, Foliation and Cleavage

6.1: Lineation

- **Lineation** is a term used to describe linear elements that occur in a rock, such as the linear structures seen in the gneiss.
- 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, although primary structures may also be involved, such as in the formation of S0–S1 intersection lineations (see below).



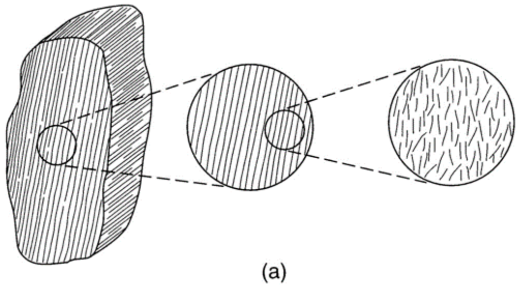
6.2: Fabric

- To a structural geologist, the **fabric** of a rock is the geometric arrangement of component features in the rock, seen on a scale large enough to include many samples of each feature.
- The features themselves are called **fabric elements.** Examples of fabric elements include mineral grains, clasts, compositional layers, fold hinges, and planes of parting.
- Fabrics that form as a consequence of tectonic deformation of rock are called **tectonic fabrics,** and fabrics that form during the formation of the rock are called **primary fabrics.**
- If there is no preferred orientation (i.e., alignment) of the fabric elements, then we say that the rock has a **random fabric.**
- Undeformed sandstone, granite, or basalt are rocks with random fabrics. Deformed rocks typically have a **nonrandom fabric** or a **preferred fabric,** in which the fabric elements are aligned in some manner and/or are repeated at an approximately regular spacing.
- There are two main classes of preferred fabrics in rock. A planar fabric, or **foliation** is one in which the fabric element is a planar or tabular feature (meaning it is shorter in one dimension than in the other two), and a linear fabric, or **lineation**, is one in which the fabric element is effectively a linear feature (i.e., it is longer in one-dimension relative to the other dimensions).

6.2.1: Penetrative fabric

- This leads in to a second important concept: the idea of a **penetrative** fabric. A fabric is penetrative *if it is present everywhere in the rock.*
- For example, some slates can be split almost anywhere: there's effectively an infinite number of cleavage planes. In others, the cleavage planes are visibly spaced.

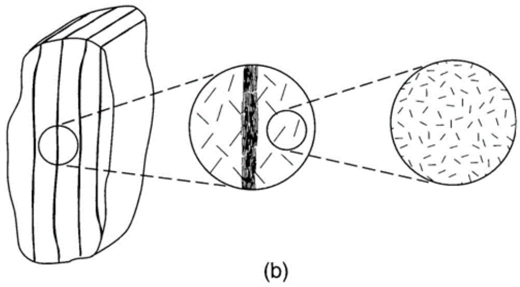
- A fabric is penetrative if
  - It is present throughout the rock
  - It is not possible to count the number of fabric planes or lines
  - It is not possible to see spaces between the fabric planes or lines



(a)

6.2.2: Non-Penetrative fabric

- A fabric is non-penetrative if
  - The fabric planes or lines are spaced apart within the rock
  - It is possible to see spaces between the fabric planes or lines where no fabric is present
  - The fabric planes or lines can be counted.

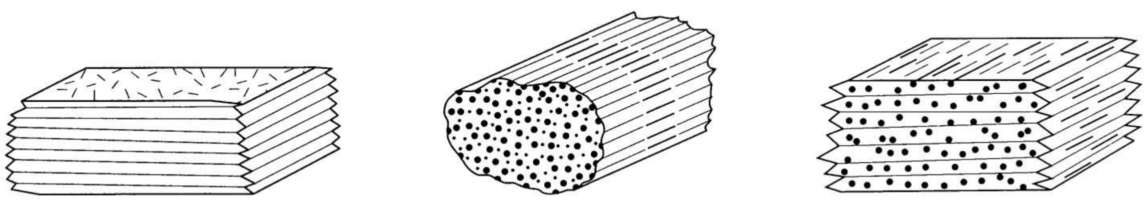


(b)

- Note that penetrative character is a scale dependent concept: - a fabric that is penetrative at map and outcrop scale may prove to be non-penetrative in thin section.

6.3: Tectonites

- Penetrative lineations are found almost exclusively in rocks deformed in the plastic regime.
- Where the lineation forms the dominating fabric element so that the S-fabric is weak or absent, the rock is classified as an **L-tectonite**.
- It can be seen from rocks with strain markers that most L-tectonites plot in the constrictional field of the Flinn diagram, i.e. $X >> Y \geq Z$.
- A balanced combination of a foliation (S-fabric) and a penetrative lineation (L-fabric) is more common, and such a rock is referred to as a **LS-tectonite**.
- LS-tectonites tend to plot close to the diagonal in the Flinn diagram.
- **S-tectonites**, which have no or just a hint of linear fabric, typically plot in the flattening field of the Flinn diagram.
- Fabrics may be planar or linear. Planar fabrics are also called **foliations.** Rocks with a strong secondary planar fabric are sometimes called **S-tectonites**. (The S is for schistosity.)
- Linear fabrics are called **lineations**. Rocks with a strong secondary lineation are sometimes called **L-tectonites**. Rocks with both types of fabric elements are called **LS-Tectonites.**
- It is common to find a lineation that lies parallel to (or in the plane of) a planar fabric. Rocks with a strong tectonic lineation that lies in the plane of a tectonic foliation are sometimes called **LS-tectonites.**



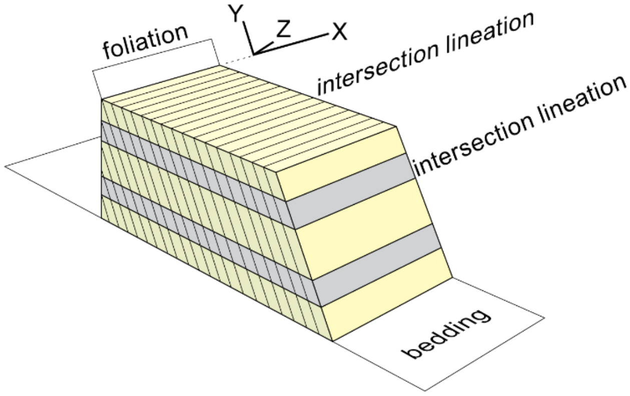
(a) (b) (c)

Figure: (a) S-tectonite, (b) L-tectonite and (c) LS-tectonite

6.4: Descriptions of different lineations

6.4.1: Intersection lineations

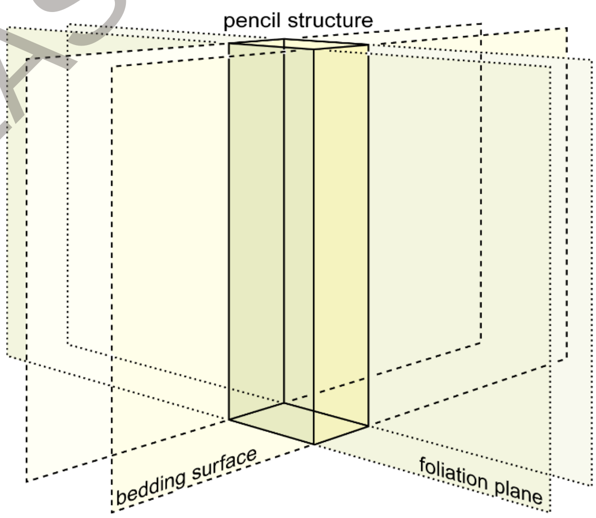
- Since any two planar surfaces intersect in a line, most rocks folded with concomitant development of an axial plane foliation display the **intersection lineation** between bedding and the axial plane foliation.
- The trace of bedding on an intersecting foliation plane commonly appears as colour stripes generally parallel to local fold axes (hence it is sometimes called **striping lineation** to avoid using a genetic term).



- Two non-parallel foliations can also produce an intersection lineation; for example, the intersection of a crenulation cleavage and the earlier foliation.
- The more planar surfaces there are in an exposure, the more potential intersections there will be.
- **Note:** The linear trace of any plane on a random joint surface has no significance in structural analysis; a lineation must be measured on and only on the foliation plane of the same deformation episode. Intersection lineation, however, may also be measured on the bedding plane.

6.4.2: Pencil structure

- When the fissility of both a foliation and bedding (or yet another foliation) is prominent, the rock tends to break up along elongate fragments sub-parallel to the local fold hinges.
- The resulting geometry, with rectangular or prismatic cross-sections, is a **pencil structure**.

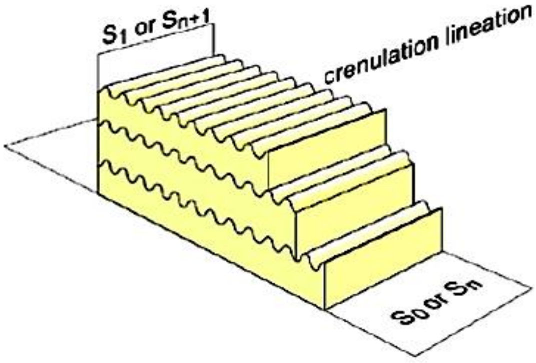


- The formation of pencil structures occurs as a result of discrete interference between compaction cleavage and a subsequent tectonic cleavage, or between two equally developed tectonic cleavages.
- Pencil structures have a preferred orientation and form a lineation in unmetamorphosed and very low-grade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

6.4.3: Crenulation lineation

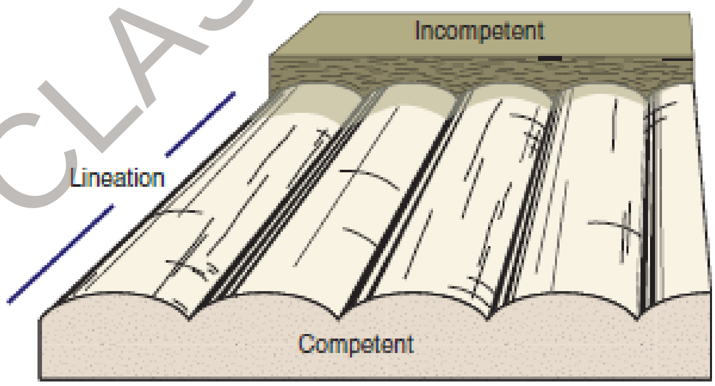
- Small scale rippling of an earlier foliation (and occasionally bedding) produces an obvious linear array parallel to the closely spaced and regular wrinkle hinges.

- The **crenulation lineation** is the fabric element parallel to the tightly spaced hinges. Many schists exhibit this type of lineation. It generally is a good indication of superposed deformation.
- Two or more sets of crenulation lineation may intersect one another, sometimes in a conjugate manner, forming all sorts of small-scale interference patterns.
- Rolling of some minerals during deformation may produce a wrinkling of an existing part of the foliation.
- If carried out far enough, this may produce some kind of chevron folds parallel to the rotation axis of the minerals, the resulting crumples trending across the general direction of flow.



6.4.4: Mullions

- **Mullions** are coarse corrugation of the bedding surface between a competent and an incompetent layer.
- The term stems from the old French "*moinel*", designing the vertical columns in tall windows of Gothic architecture.
- Mullions form at any size in the original rock material as opposed to segregated or introduced material.
- Their ribbed or grooved appearance is often due to broad, smoothly curved convex surfaces of the competent layer rather regularly separated by narrow, sharp, inward-closing hinges.
- 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.



- These long, convex and cuspate structures are remarkably cylindrical and surface features are very persistent along the length of the mullions.
- Characteristically, micas coat mullions, but polished or longitudinally striated surfaces have been described.
- Mullions most commonly represent the intersection between bedding and a spaced foliation in the competent layer.

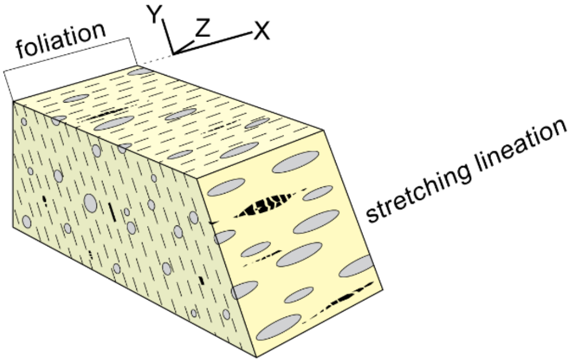
6.4.5: Rods

- **Rod** is a morphological term for elongate, cylindrical and monomineralic bodies of segregated mineral (quartz, calcite, pyrite, etc.) in metamorphic rocks of all grades.
- Rods may have any profile outline, from elliptical to irregular, dismembered rounded structures.

- Rods are generally parallel to local fold axes and often are isolated fold hinges detached from their limbs.

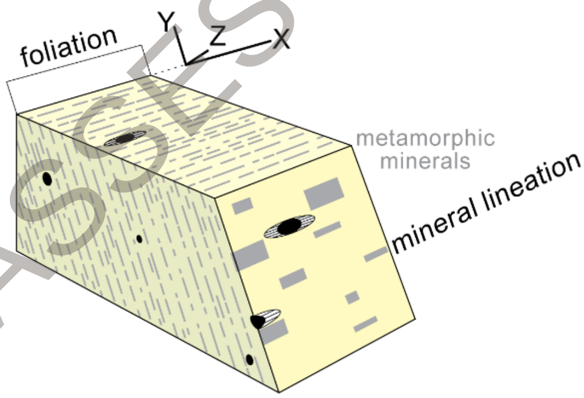
6.4.6: Stretching lineations

- The parallel alignment of individual grains, aggregates or fragments of any size that have been elongated and/or rotated during deformation is an important type of lineation.
- Ellipsoidal ooids and spherulites must have been deformed since they generally are originally almost spherical and their long axes define the **stretching** (**extension** or **elongation**) **lineation**.
- Deformed pebbles or boulders also define such lineations. Elongated grains or grain aggregates define a **preferred shape orientation**.



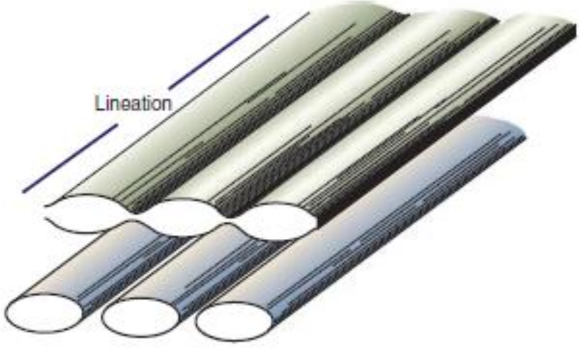
6.4.7: Mineral lineations

- Metamorphic minerals often grow with a preferred crystallographic and dimensional orientation, i.e. with their long axes in parallel alignment.
- The long axes of individual, elongate crystals (for example amphibole crystals, sillimanite needles) or mineral aggregates aligned and sub-parallel within a foliation plane delineated **mineral lineations**.

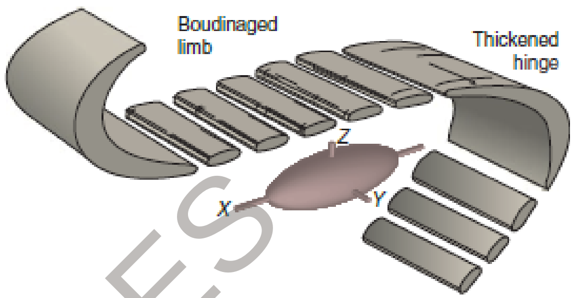


- They are a penetrative element of the rock fabric, commonly coincident with other types of lineation, and serve to reinforce them.
- Mineral lineations may be parallel or inclined to the axes of related folds. They indicate a stretching direction if the involved minerals are segmented along the lineation.
- They also can define the intersection between foliation planes and rotation axes of rotating minerals.
- "**Pressure shadow**" or "**pressure fringe**" structures comprise spindle-shaped aggregates of new grains crystallized on opposed sides of a host porphyroblast or competent, clastic objects.
- The new grains form when material dissolved by pressure solution is re-precipitated, occasionally as fibers, in the regions sheltered from strain on either side of the rigid grains.
- The fibers generate tails filling openings in the extending direction between grain and matrix, during deformation.
- The central grain and the tails produce an elongate structure contained in the foliation; this structure and the fiber crystals thus define a lineation.
- Circular fringes with radial fibers on the foliation, however, characterize pure shear without stretching direction (pan-cake finite strain ellipsoid).
- Similarly, the oriented growth of mineral fibers in tensions gashes and veins indicates the local extension direction and may record incremental strain directions.

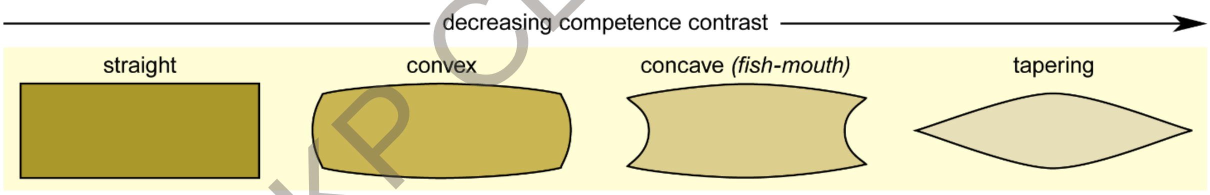
6.4.8: Boudinage



- Boudins are competent rock layers that have been stretched into segments.
- Individual boudins are commonly much longer in one dimension than the other two and thus define a lineation.
- Such linear boudins form where the X-axis of the strain ellipsoid is significantly larger than Y.
- The geological **boudins** (blood sausage in French) are side-by-side segments of a layer or object sandwiched in a less competent (i.e more deformable) matrix**.**

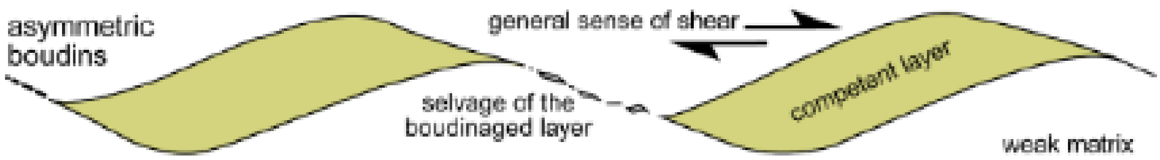


- **Boudinage** describes the process of stretching, necking and eventually segmentation and separation of these segments; this is produced in general by extension parallel to the bedding plane and failure of the competent, boudinaged layer during the ductile flow of the less competent host. Objects such as fossils, pebbles, and minerals can also be boudinaged (**linear streaking of minerals**).
- Boudinage ranges from micro- to macroscopic scales; typically, a strong layer or dike is broken up at regular intervals into a series of elongate and aligned blocks whose profiles, seen orthogonal to the long axis of boudins, are the basis for the classification of boudinage structures.



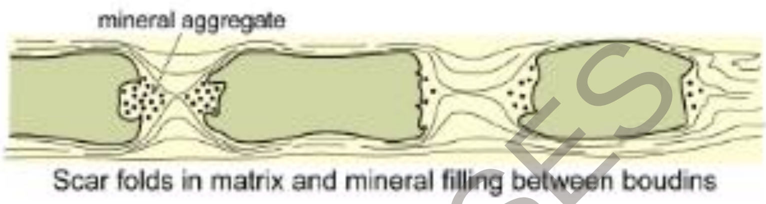
Description of boudins extremities

- Boudin profiles are variable, symmetrical or asymmetrical. Long faces, usually layer boundaries of the boudins, can be concave (bone-shaped boudins), convex (barrel-shaped boudins) or parallel to each other (blocky boudins).
- These shapes reflect ductility contrasts between layer and matrix. Large contrasts produce boudins with sharp edges, and small contrasts produce rounded boudins.
- At higher grades, and in unconsolidated rocks, the competent layers have generally not broken through; narrow thinned **necks** separate and alternate with relatively thicker swells. The resulting wavy structure is called **pinch-and-swell**.
- **Asymmetric boudins** are common in medium to high-grade metamorphic rocks. Such boudins have often lozenge shapes pinched and stretched at diagonally opposed corners; this shape is frequently used as a sense of shear indicator, consistent with the pinched corners.



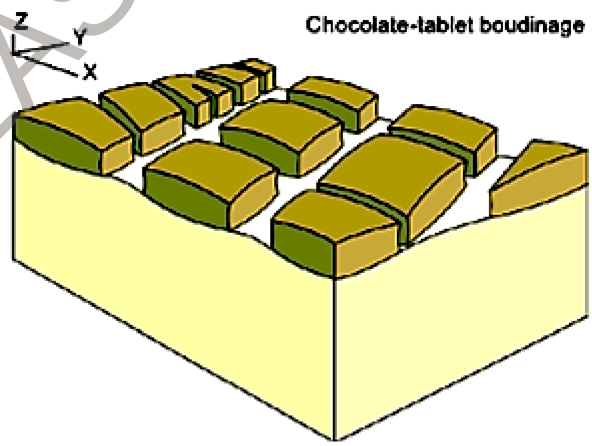
Inter-boudin zone

- Boudins are separated by the material that originally lay on either side of the segmented layer or by mineral aggregates that have grown in situ while individual boudins moved apart.
- The surrounding ductile layers that flow in the space between boudins form **scar folds** (or **neck folds,** also called **flanking structures**).
- Quartz, micas and carbonate and, in high-grade rocks, pegmatite and leucosome veins represent material transfer into scar zones.



Scar folds in matrix and mineral filling between boudins

- Boudins are commonly linear and separated by a single set of tension fractures; their long axes are often parallel to the axes of related folds.
- However, layer-parallel extension may take place in two or more directions. Segmentation and opening of extension gaps in two directions produce nearly equidimensional rather than elongate boudins.
- The three-dimensional, blocky fragmentation of layers is called **chocolate-tablet boudinage**.

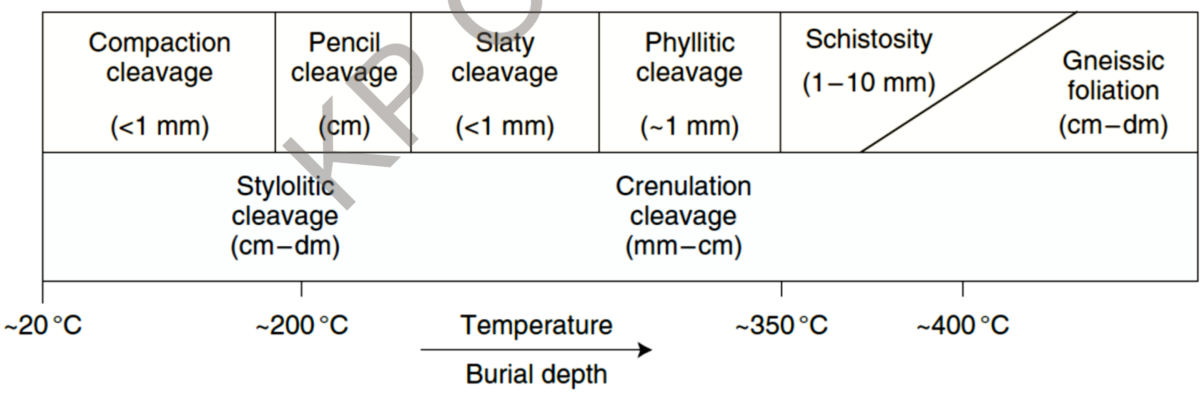


6.5: Foliation

- Foliation: It generally refers to any plane structure developed in a geological body, normally divided into two origins, primary and secondary.
- It is typically formed by sedimentation, metamorphism, magma activities and tectonic movement.
- It is, in fact, concerned with foliation, flow surface, schistosity, gneissosity, cleavage and various fracture planes.
- It commonly characterizes the mineral composition, grain size variation, mineral orientation pattern and microstructure associations.

6.5.1: Definition

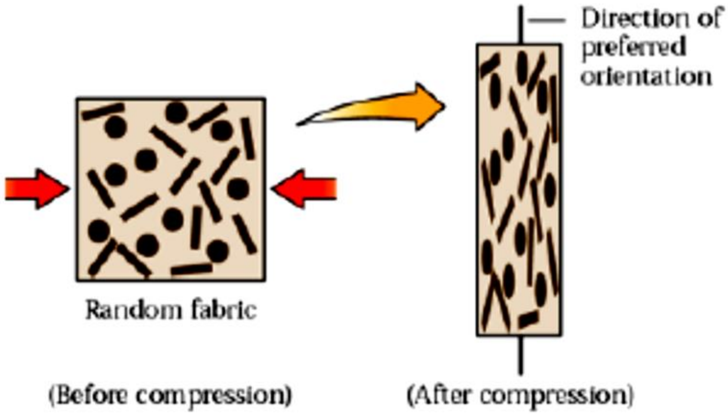
- **Foliation** is the general term describing the arrangement of any kind of sub-parallel, closely-spaced and low-cohesion surfaces that are no strata in deformed rocks (and glaciers).
- These generally regularly spaced surfaces impart to foliated rocks the facility to split into leaf-like (*folia* = leaf in Latin) planar elements other than bedding.
- **Foliation planes** are reported for a wide range of temperature and pressure conditions, from shallow crustal to deep mantle conditions. Any plane is referred to as **S-surface**.
- Where S-surfaces of different generations can be distinguished by type and age (cross-cutting relationships, overprinting, absolute age of mineral components), they are given numerical suffixes according to relative age: S0 is the primary surface, generally bedding, and S1, S2 … Sn for secondary foliation planes in order of determined superposition.
- Such a foliation-related reference frame helps unravelling the tectonic and metamorphic evolution of the area where **S-surfaces** are present.
- 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 the next figure.



6.5.2: Formation Mechanisms

- Foliation is usually formed by the preferred orientation of minerals within a rock.
- Typically, this is a result of some physical force, and its effect upon the growth of minerals.
- The planar fabric of a foliation typically forms at right angles to the minimum principal strain direction.
- In sheared zones, however, planar fabric within a rock may not be directly perpendicular to the principal stress direction due to rotation, mass transport and shortening.

- Foliation may be formed by realignment of micas and clays via physical rotation of the minerals within the rock.
- Often this foliation is associated with diagenetic metamorphism and low-grade burial metamorphism.
- Foliation may parallel original sedimentary bedding, but more often is oriented at some angle to it.



- The growth of platy minerals, typically of the mica group, is usually a result of prograde metamorphic reactions during deformation.
- Often, retrograde metamorphism will not form a foliation because unroofing of a metamorphic belt is not accompanied by significant compressive stress.
- Thermal metamorphism in the aureole of a granite is also unlikely to result in growth of mica in a foliation, although growth of new minerals may overprint existing foliation(s).
- Alignment of tabular minerals in metamorphic rocks, igneous rocks and intrusive rocks may form a foliation.
- Typical examples of metamorphic rocks include porphyroblastic schists where large, oblate minerals form an alignment either due to growth or rotation in the groundmass.
- Igneous rocks can become foliated by alignment of cumulate crystals during convection in large magma chambers, especially ultramafic intrusions, and typically plagioclase laths.
- Granite may form foliation due to frictional drag on viscous magma by the wall rocks. Lavas may preserve a flow foliation, or even compressed eutaxitic texture, typically in highly viscous felsic agglomerate, welded tuff and pyroclastic surge deposits.
- Metamorphic differentiation, typical of gneisses, is caused by chemical and compositional banding within the metamorphic rock mass.
- Usually this represents the protolith chemistry, which forms distinct mineral assemblages.
- However, compositional banding can be the result of nucleation processes which cause chemical and mineralogical differentiation into bands.
- This typically follows the same principle as mica growth, perpendicular to the principal stress. Metamorphic differentiation can be present at angles to protolith compositional banding.

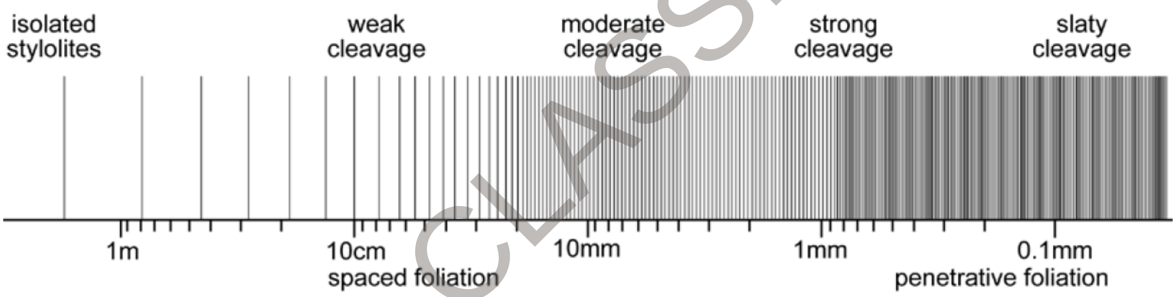
6.6: Classification of foliation

- Morphological features used in the description and classification of foliations are those used for planar geometries. They refer to:
  - Spacing between the planes or planar domains.
  - Shape of the planes (rough, smooth, wriggly, etc.).
  - Spatial relationship between planes (parallel, anastomosing, conjugate, cross-cutting…).
  - Characteristics of the boundaries of planar domains (gradational, sharp, discrete, etc.).
  - Fabric of the rock between foliation planes (planar, folded, etc.).

- The morphology of foliations reflects formation processes. For example, bedding-parallel foliation may reflect **compaction**, i.e. volume reduction due to pore-water expulsion from fresh sediments under the increasing weight of overburden load.
- In deeper crustal levels, the foliation morphology varies with metamorphic grade (the temperature and pressure conditions existing during foliation development), with position in folds and with rock type and composition.
- Foliation is classified by mechanisms of formation into two broad types and several end-members.
- Morphological gradations between the descriptive terms classified below exist and provide a wide spectrum of intermediate forms.

6.6.1: Spaced foliation

- Spaced foliation planes are discrete, tabular **domains** separated by thin slabs of rock without fabric or with a differently oriented, older, primary (original) or secondary fabric.
- These rock slabs which are thick enough (> ca. 1mm) to be distinguished in hand specimen or in outcrop, are called **microlithons**.
- Foliation domains (the *foliae*) are heterogeneously distributed lamellae where the fabric and mineralogy of the host rock has been altered (usually concentration of phyllosilicates and opaques) so that minerals show a preferred shape and/or crystallographic orientation.
- Foliation domains are those thin planar regions along which the rock splits.



Qualitative classification of foliation based on domain spacing

6.6.2: Penetrative (continuous, pervasive) foliation

- In penetrative foliation, all platy grains have a statistically preferred planar orientation.
- Penetrative means that these fabric elements (equally spaced surfaces that are approximately planar and parallel) appear everywhere throughout the entire rock mass and tends to persistently obliterate earlier structures.
- Imagine sheets of a book to envision a penetrative foliation. Planes are defined by discontinuities, preferred dimensional orientation of platy minerals, laminar mineral aggregates, or some combination of these structures.
- The fabric is visible down to the scale of individual grains and intervals between the foliation planes (or **cleavage)** are seen on a microscopic scale (< ca. 1 mm).

6.6.3: Fracture cleavage

- **Fracture cleavage** consists of evenly spaced, planar discontinuities that sharply divide the rock into a series of plate-shaped microlithons that display essentially no internal deformation.
- Fracture cleavage can be envisioned as a dense population of joints or micro faults generally formed in low metamorphic grade, competent rocks such as sandstone and

limestone, where fracture cleavage may coexist with and grade into slaty cleavage in interlayered pelites.

- Microscopic to metre scale sets of foliation-like, closely spaced yet non-penetrative fractures may be confused with dense sets of joints. Disjunctive fracture cleavage with shear movement is not a "true" foliation in terms of finite strain: it is a **false cleavage**.

6.6.4: Solution cleavage

- **Solution cleavage** consists of regularly spaced dissolution surfaces (e.g. **stylolitic joints**) that divide the rock into a series of microlithons without internal deformation.
- Dissolution surfaces, along which some rock mass has been removed, often contain dark seams of insoluble residues that may impart a prominent striping to the rock.
- Stripes denote the spatial variation in mineral composition and/or grain size. Mineral overgrowths, pressure shadows and veins record local mass transfer.
- Solution cleavage is generally formed in low metamorphic grade rocks rich in fluids and is common within limestone as regularly spaced stylolitic planes.

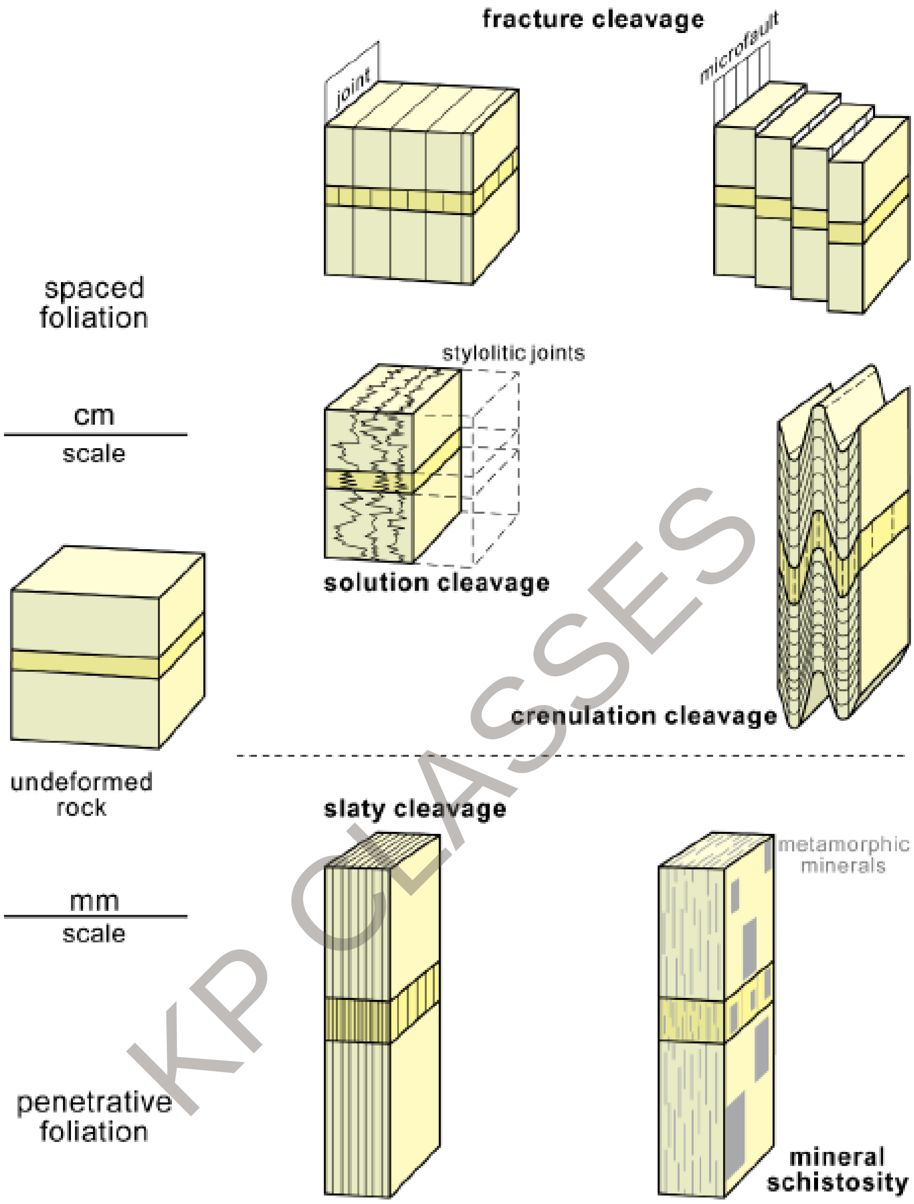
6.6.5: Crenulation Cleavage

- **Crenulation cleavage** is created when an earlier foliation is folded (**crenulated**) on a meso- to micro-scale.
- The small, regular crinkle folds (10-1-101 mm) may be symmetric but are most commonly asymmetric.
- The crenulation cleavage is defined by the parallel alignment of grains in the limbs of the tight to isoclinal microfolds whose wavelength controls the spacing of successive foliation planes.
- Where microfolds are asymmetric, the short limb usually becomes the cleavage plane.
- Crenulation cleavage is sometimes defined by micro faults parallel to the microfold limbs and then referred to as **strain slip cleavage**, but the non-genetic name "crenulation cleavage" is preferable.
- A **discrete crenulation cleavage** truncates the pre-existing cleavage. Conversely, the pre-existing fabric can be followed from microlithons through a **zonal crenulation cleavage**.
- Dissolution of soluble material often takes place along the microfold hinges, leaving a concentration of insoluble residue along these limbs while soluble material (generally quartz) is transported and precipitated in hinges.
- Crenulation cleavages are found in all metamorphic grades.

6.6.6: Differentiated layering

- Crystallization of metamorphic minerals, metamorphic recrystallization of older minerals, and pressure solution may create independently or together a new "layering" defined by alternating layers of different composition and/or grain size.
- Indeed, metamorphism reorganises the chemical components of a rock and produces new minerals in new orientations governed by evolving strain.
- The resulting compositional, **differentiated layering** is visible as distinct light and dark-coloured bands in hand specimen.
- Differentiated layering is found in medium to coarse-grained, granular metamorphic rocks of all grades. Slaty cleavage, crenulation cleavage, and schistosity can be differentiated.
- In high-grade rocks, differentiated layering is customarily described as **gneissic layering**, also commonly defined by alternating mafic (dark-coloured) and felsic (light-coloured) layers.

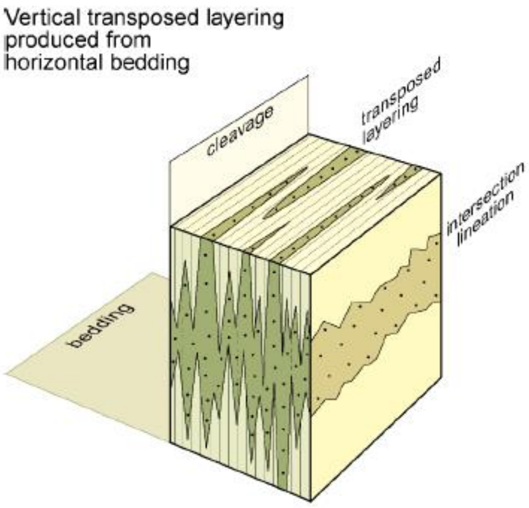
- The resulting lithological banding may be more or less modified bedding, and thus reflects initial sedimentary compositional differences or a foliation entirely due to differentiation during deformation.



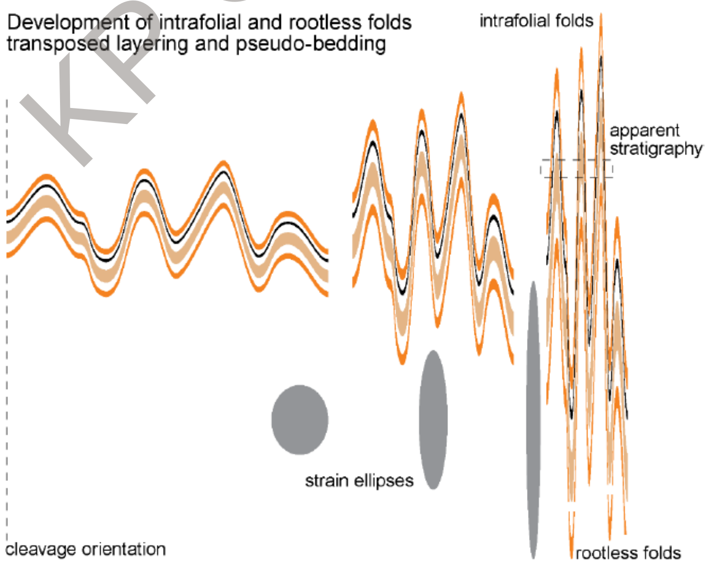
Morphological classification of foliations

- Gneissic layering can also result from oriented melt segregation during partial melting and/or intimate injection of subparallel igneous veins.
- Strongly sheared rocks develop a **mylonitic foliation**, which is both a mineral foliation due to the preferred orientation of platy mineral grains and aggregates and a planar shape fabric defined by the flattened crystals (called ribbons).

6.6.7: Transposed layering



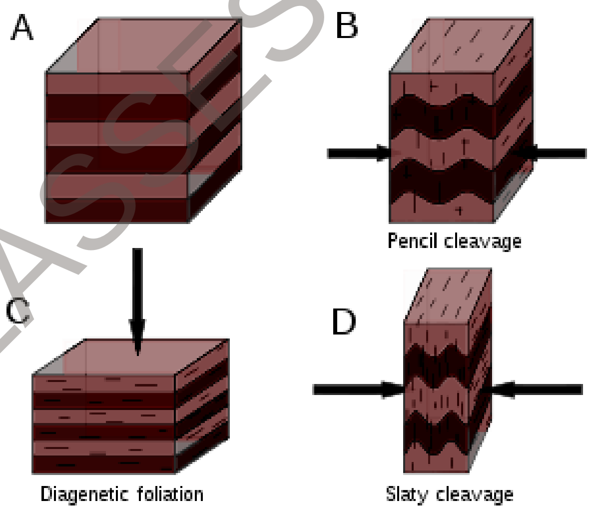
- **Transposition layering** is defined by parts of a pre-deformation surface (bedding or an older foliation) which are rotated independently into a new orientation; after intense deformation all of these parts become subparallel.
- In a laminated sequence of rocks, successive layers generally have different competences.
- Intense deformation produces appressed to isoclinal folds through rotation and stretching/thinning of limbs until these coincide with the foliation plane.
- Fold hinges are sharp and folds are **intrafolial**. Hinges may be teared apart along the stretched limbs that ultimately disappear.
- The intrafolial folds are **rootless** where hinges are completely detached from the limbs and relic bedding appears to be restricted to very local occurrences in obscured fold hinges.
- There is then practically no variation in the orientation of the transposed bedding. A transposed sequence may be mistaken for a normal sedimentary succession. Nevertheless, the **pseudo-bedding** has no stratigraphic significance.
- Recognition criteria for transposition are
  (1) foliation parallel to bedding,
  (2) isolated, intrafolial fold hinges,
  (3) isolated boudins of competent layers,
  (4) extreme flattening of strain markers and
  (5) reversals of younging criteria and asymmetry of parasitic folds in close proximity.



6.7: Cleavage

- Cleavage, in structural geology and petrology, describes a type of planar rock feature that develops as a result of deformation and metamorphism.

- The degree of deformation and metamorphism along with rock type determines the kind of cleavage feature that develops.
- Generally, these structures are formed in fine grained rocks composed of minerals affected by pressure solution.
- Cleavage is a type of rock foliation, a fabric element that describes the way planar features develop in a rock.
- Foliation is separated into two groups: primary and secondary. Primary deals with igneous and sedimentary rocks while secondary deals with rocks that undergo metamorphism as a result of deformation.
- Cleavage is a type of secondary foliation associated with fine grained rocks. For coarser grained rocks, schistosity is used to describe secondary foliation.
- Cleavages are mostly developed in the rocks that are strongly deformed and slightly metamorphosed.
- With obvious anisotropy, they are usually closely related to folds, faults (shear zones) and regional rheologic structures in geometry or in origin.
- Particularly in strongly deformed areas, various types of cleavages often exist in large scale folds, faults and ductile shear zones.
- Cleavage is related with deformation and metamorphism, and developed in rock layers or rock bodies. It characterizes the densely patterned micro fractures or potential plane structures.
- Constituents: Cleavage field mainly consisting of dark strips developed in micro fractures or micro structural metamorphosed strips. It is generally composed of newly formed mica and sub-melted residual minerals.



6.8: Type of cleavage

- The presence of fabric elements such as preferred orientation of platy or elongate minerals, compositional layering, grain size variations, etc. determines what type of cleavage forms. Cleavage is categorized as either continuous or spaced.

6.8.1: Continuous Cleavage

- Metamorphosed shale depicting slaty cleavage. Note the grains of mica, quartz, and ilmenite aligned with a preferred orientation.
- Continuous or penetrative cleavage describes fine grained rocks consisting of platy minerals evenly distributed in a preferred orientation.
- The type of continuous cleavage that forms depends on the minerals present. Undeformed platy minerals such as micas and amphiboles align in a preferred orientation, and minerals such as quartz or calcite deform into a grain shape preferred orientation.
- Continuous cleavage is scale dependent, so a rock with a continuous cleavage on a microscopic level could show signs of spaced cleavage when observed on a macroscopic level.

6.8.2: Slaty Cleavage

- Slaty cleavage refers to fine continuous foliation characteristic of slates. Slates are very fine grained low-grade metamorphic rocks that contain abundant sheet silicates (generally clays, chlorites and micas).
- The foliation provides a very strong cleavage to the rock, along which the rock breaks easily and tends to weather preferentially.
- Since the nature of cleavage is dependent on scale, slaty cleavage is defined as having 0.01 mm or less of space occurring between layers.
- Slaty cleavage often occurs after diagenesis and is the first cleavage feature to form after deformation begins.
- The tectonic strain must be enough to allow a new strong foliation to form, i.e. slaty cleavage.
- 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.
- The letters Q, F and M relate to quartz, feldspar and mica, and we need a microscope to discern the individual domains, which are considerably thinner than 1mm.
- The QF-domains are typically lozenge- or lens-shaped while the M-domains form narrower, enveloping zones.
- As shown below, many types of cleavages and foliations show such domainal structures, and they can all be referred to as domainal cleavages.

6.8.3: Phyllitic Cleavage

- Phyllitic cleavage resembles slaty cleavage except that the grain size of the rock is slightly coarser.
- It characterizes phyllites, which are low-grade metamorphic (greenschist), fine-grained metamorphic rocks containing abundant micas, chlorite, or both.
- In hand samples, the surface of the foliation has a sheen to it, and individual sheet silicate flakes may just be resolvable with a hand lens.
- The foliation is generally intermediate between fine and coarse continuous foliation, although some phyllitic cleavages may be smooth disjunctive foliations.

6.8.4: Spaced Cleavage

- A thin section depicting spaced cleavage. The cleavage domains are darker biotite grains, and the microlithons between consist of mostly muscovite and quartz.
- The grains in the microlithons are starting to align in a preferred orientation. A new foliation overprinted an old, showing the beginning signs of a crenulation cleavage.
- Spaced Cleavage occurs in rocks with minerals that are not evenly distributed and as a result the rock forms discontinuous layers or lenses of different types of minerals.
- Spaced cleavage contains two types of domains; cleavage domains and microlithons. Cleavage domains are planar boundaries subparallel to the trend of the domain, and microlithons are bounded by the cleavage domains.
- Spaced cleavages can be categorized based on whether the grains inside the microlithons are randomly oriented or contain microfolds from a previous foliation fabric.

- Other descriptions for spaced cleavages include the spacing size, the shape and percentage of cleavage domains, and the transition between cleavage domains and microlithons.

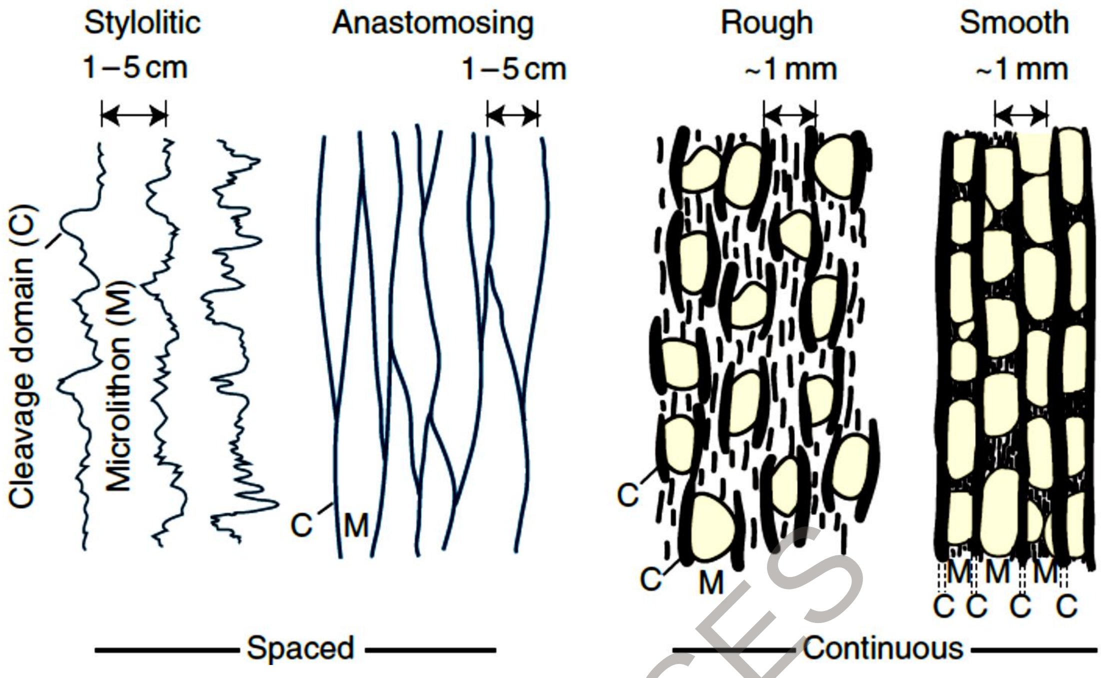


Figure: Disjunctive cleavage types. Stylolitic (limestones) and anastomosing (sandstones) cleavage are usually spaced, while continuous cleavages in more fine-grained rocks are separated into rough and smooth variants, where the rough cleavage can develop into the smooth version. All disjunctive cleavages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

6.8.5: Crenulation Cleavage

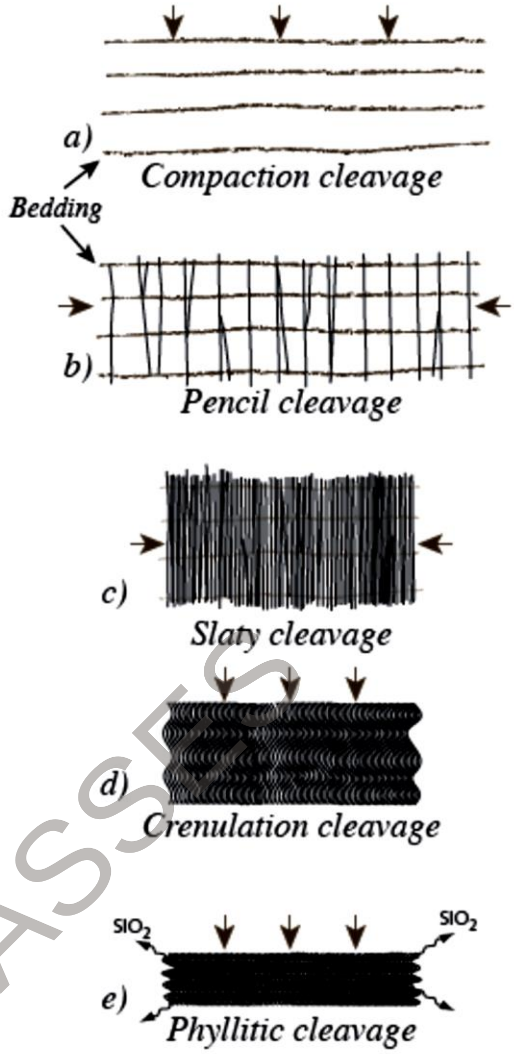
- Crenulation cleavage contains microlithons that were folded by a previous foliation.
- Folding occurs when there are multiple phases of deformation, the latter one causes symmetric or asymmetric microfolds that deform previous foliations.
- The type of crenulation cleavage pattern that forms depends on lithology and degree of deformation and metamorphism.

6.8.6: Disjunctive Cleavage

- Disjunctive cleavage describes a type of spaced cleavage where the microlithons are not deformed into microfolds, and formation is independent from any previous foliation present in the rock.
- A common outdated term for disjunctive cleavage is fracture cleavage. It is recommended that this term be avoided because of the tendency to misinterpret the formation of a cleavage feature.

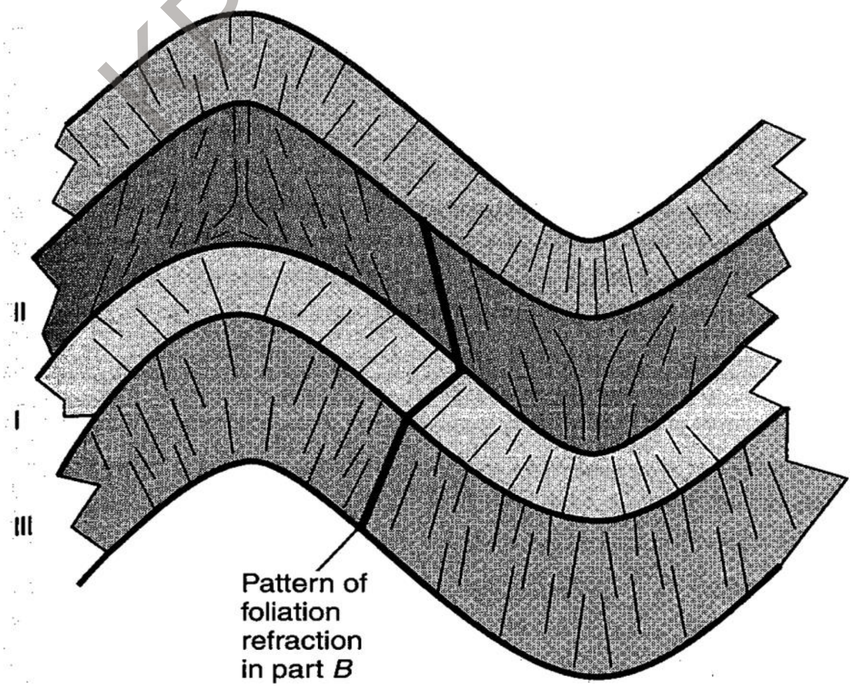
6.8.7: Transposition Cleavage

- When an older cleavage foliation is erased and replaced by a younger foliation due to stronger deformation and is evidence for multiple deformation events.

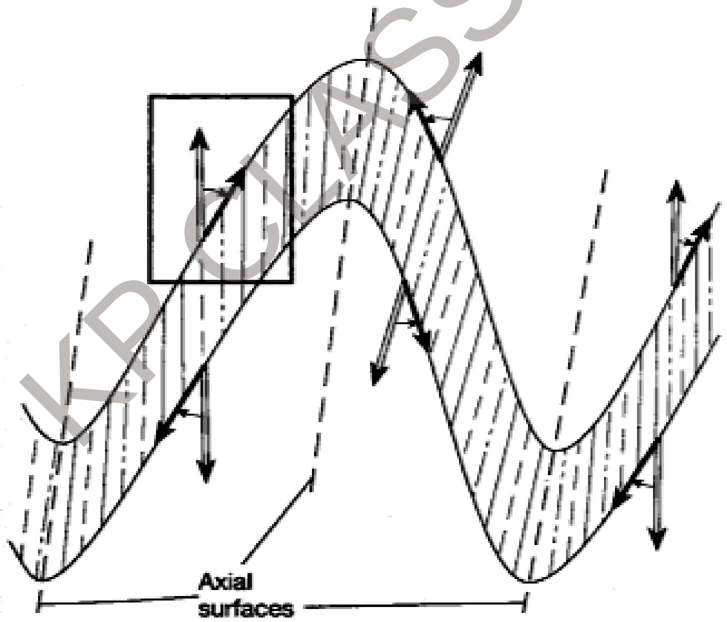


6.9: Relationship of cleavage to fold

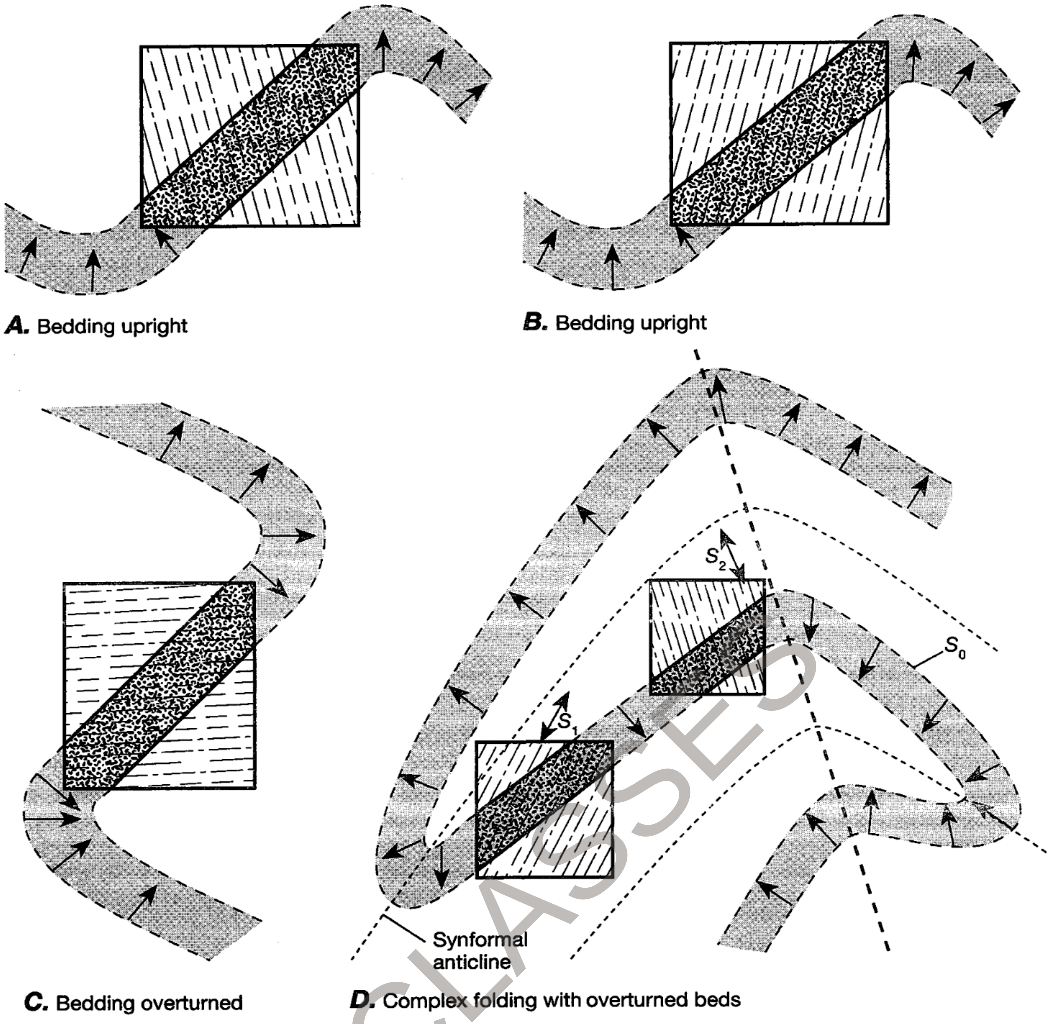
- **Secondary foliation** occurs so commonly parallel or sub-parallel to the axial surfaces of folds that the association is almost axiomatic.
- Such foliations are called **axial surface foliation** or **axial planar cleavages**.
- The orientation of such foliations characteristically changes progressively from one side of the fold to the other, or fans across the fold, and is actually parallel to the axial surface only at the hinge surface.
- Foliation fans are convergent or divergent, depending on whether, in passing from the convex to concave side of a fold, the foliation orientations converge towards one another (layers I and III in the following figure) or diverge from one another (layers II in the following figure).



- The extent of fanning of an axial surface foliation is commonly dependent on the composition of the rock in which the foliation develops.
- Foliations tend to be most strongly convergent across folds in rocks containing only small proportions of platy minerals such as sandstones, and they are least convergent or divergent in rocks rich in platy minerals such as schists and slates.
- The orientation of the foliation changes significantly at lithologic contact; this feature is called **refracted foliation** or **refracted cleavage**.
- The relationship of foliations subparallel to the axial plane of folds is so consistent that it can be used to determine the geometry of folding.
- In an area that has been subjected to only one generation of folding, it also can be a valuable indicator of whether sedimentary beds are **overturned** or **right side up**, because a given surface of axial foliation may cut a particular folded surface only once.
- Thus, the relative orientations of bedding and foliation permit us to determine the general location and direction of the fold closures.
- A useful thumb rule by which to remember this relationship is to imagine an arrow drawn along the foliation surface and then rotated through the acute angle between the foliation and the bedding (see the following figure).
- The sense of rotation changes across an axial surface. Thus, it can be used to map the locations of axial surfaces and to infer the direction of closures of the larger fold, even if the exposure does not permit direct observation of these features.



- Inferring the location of the fold closures as described in the preceding paragraphs allows one to deduce whether the bed is overturned or not, provided only one generation of folds has affected the rocks.
- If bedding and foliation dip in opposite directions, the bedding must be upright ; if bedding and foliation dip in the same direction, the bedding is upright if it has a shallower dip than the foliation, and is overturned if it has a steeper dip than the foliation (following figure).
- This method for determining the stratigraphic-up-direction does not work if multiple generations of folding have affected the rocks.



6.10: Strain significance of the cleavage

- In strong deformation areas, most of the cleavage develops with folds synchronically. While the cleavage are approximately parallel with the fold axial plane.
- Meanwhile, this indicates that the occurrence of the cleavage is generally perpendicular to the maximum compression orientation.
- Relation of cleavage with folds and rock associations: In the intensely deformed areas, the deformation media are typically soft and hard or characterized by interbeds.
- Moreover, the cleavages developed in the strong rocks usually form fan-shaped cleavages convergent to the core of the anticline.
- In contrast, the cleavages developed in weak rocks often shaped as the reverse fan spreading to the core of the anticline's core.
- **Cleavage refraction**: This phenomenon strongly proves that the cleavage development characteristics are related to the mechanical properties of the rocks.
- Usually, the cleavages found in the hard rocks are generally low frequency fracture or spaced cleavages whose occurrence is at a great angle with the rock bedding.
- However, the cleavages seen in the soft rocks are generally high frequency flow or continuous cleavages whose occurrence is at a small angle with the rock bedding.
- Cleavage is an important object for structural study and one of the common types of well-developed plane structures, or simply foliation. Hence, it is necessary to know foliation in order to understand cleavage.

Practice Questions

Previous year Easy Questions

1. Which of the following statements is true? (GATE 2012)
   A. Transposition foliation is an indication of superposed folding
   B. Stratigraphic information is retained in transposition structures
   C. Transposition foliation develops parallel to axial plane of tight folds
   D. Fold closures can be well identified in transposition structures
2. The best developed lineation and foliation traces in a L-S tectonite will be observed on a plane (GATE 2019)
   A. Parallel to the lineation and foliation
   B. Perpendicular to the lineation and foliation
   C. Perpendicular to the foliation but parallel to the lineation
   D. Perpendicular to the lineation but parallel to the foliation

Previous year Difficult Questions

1. In a deformed area bedding (S0) and axial plane schistosity (S1) measured in a quartzite band, dip to the south, but the dip of S0 is 82° and the dip of S1is 65°. This indicates that the quartzite band is the (GATE 1998)
   A. Gently- dipping limb of an asymmetrical fold
   B. Steeply dipping limb of an asymmetrical fold
   C. Normal limb of an overturned fold
   D. Inverted limb of an overturned fold
2. A bed is overturned if the dip of axial plane cleavage and the dip of the bed are in
   A. The same direction and the bed is steeper (GATE 2000)
   B. The same direction and the cleavage is steeper
   C. Opposite direction and the bed is steeper
   D. Opposite directions and the cleavage is steeper
3. The relationship between X,Y and Z of deformed pebbles in a conglomerate and the axial plane schistosity (S1) is such that on S1 (note $X \geq Y \geq Z$) (GATE 2001)
   A. X and Z of pebbles always lie
   B. Only X of pebbles lie
   C. Y and Z of pebbles always lie
   D. X and Y of pebbles always lie
4. The stretching lineation on the axial plane (S2) of a reclined fold on the S1 foliation makes an angle of 30° with the S1/S2 intersection lineation. The rake of the stretching lineation on the axial plane in degrees is _______________. (GATE 2018)
5. Which of the following change(s) when a dipping bed with a plunging lineation is rotated about a vertical axis? (MSQ) (JAM 2018)
   (A) Dip amount of bed
   (B) Plunge amount of lineation
   (C) Plunge direction of lineation
   (D) Strike of bed

Multiple Selected Questions

1. Which cleavage and bedding relation satisfies overturned fold?
   A. Cleavage and bedding dip in the same direction

B. Cleavage and bedding dip in the opposite direction
C. Bedding is steeper dip than cleavage
D. Cleavage is steeper dip than bedding

ANSWERS

Previous Year Easy Questions

1.C 2.C

Previous Year difficult Questions

1. D 2. A 3. D 4.60° 5.CD

Multiple Select questions

1. AC

EXPLANATIONS

Previous Year Easy Questions

1. Transposition foliation develop parallel to the axial plane of tight folds which are rotated independently into a new orientation; after intense deformation all of these parts become subparallel.
2. Best plane would be that which shows the maximum dimensions of both lineations and foliations.

Previous Year difficult Questions

1. When the dip of the bedding is greater than the axial plane schistosity, the limb is inverted and fold indicates overturned.
2. An overturned limb of a fold in interpreted when bedding and cleavage dipping in the same direction, through bedding is dipping more steeply than cleavage.
3. As X and Y direction of the pebble is larger compared to Z direction, the schistosity plane will contain X and Y of the deformed pebble.
4. Since the fold is a reclined fold, the hinge line dips along the axial plane with the same plunge as the dip of the axial plane. Intersection of the foliation (S1) and the axial plane (S2) is basically the hinge line. The stretching lineation forms an angle of 30° with the hinge line. It is clear that the rake of the stretching lineation on the axial plane is 60 degrees. Remember, rake of a line on a given plane is the angle made by the line with the strike of the plane, measured on the plane itself.
5. When a plunging lineation in a dipping bed rotated about a vertical axis, the plunging direction will change and strike of the bed will change. As it is moving with respect to vertical axis the plunge and dip amount will be remain same.

Multiple Select questions

1. If bedding and cleavage dips in same direction and simultaneously bedding has steeper dip than cleavage then it indicated as overturned fold.