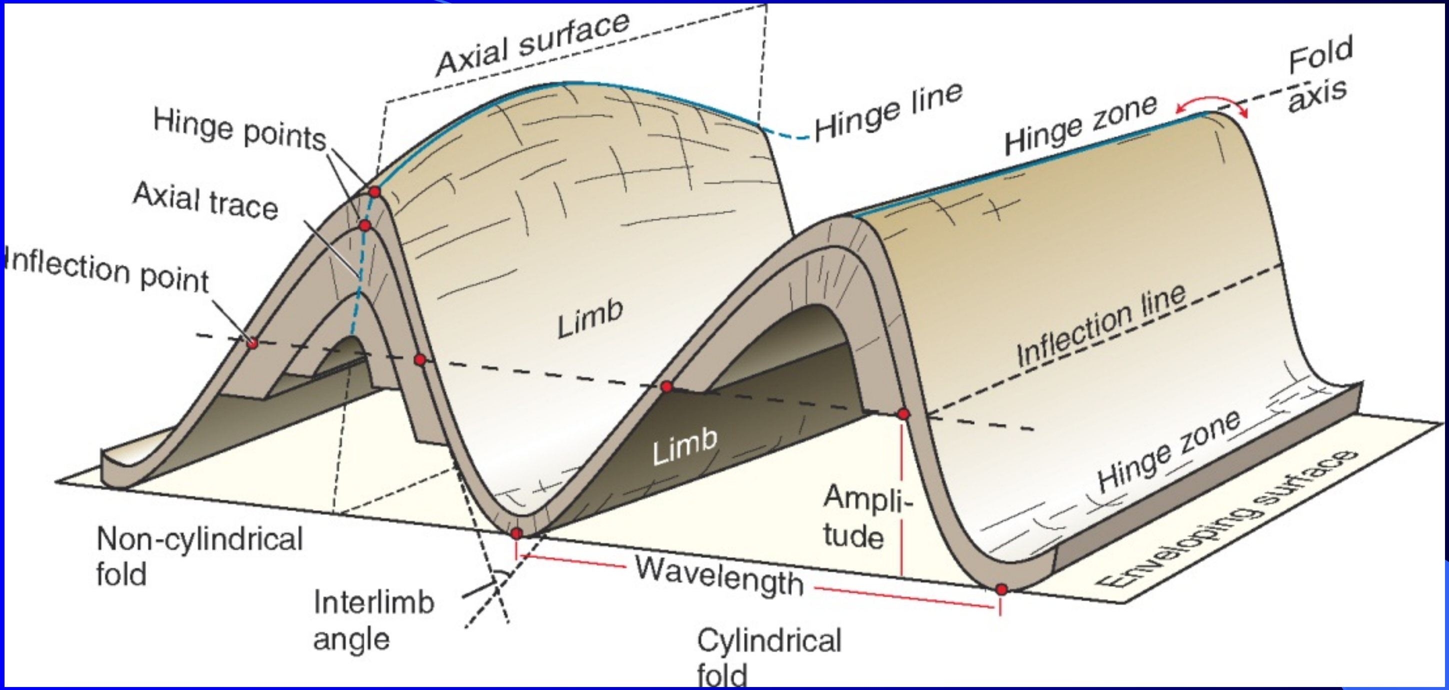
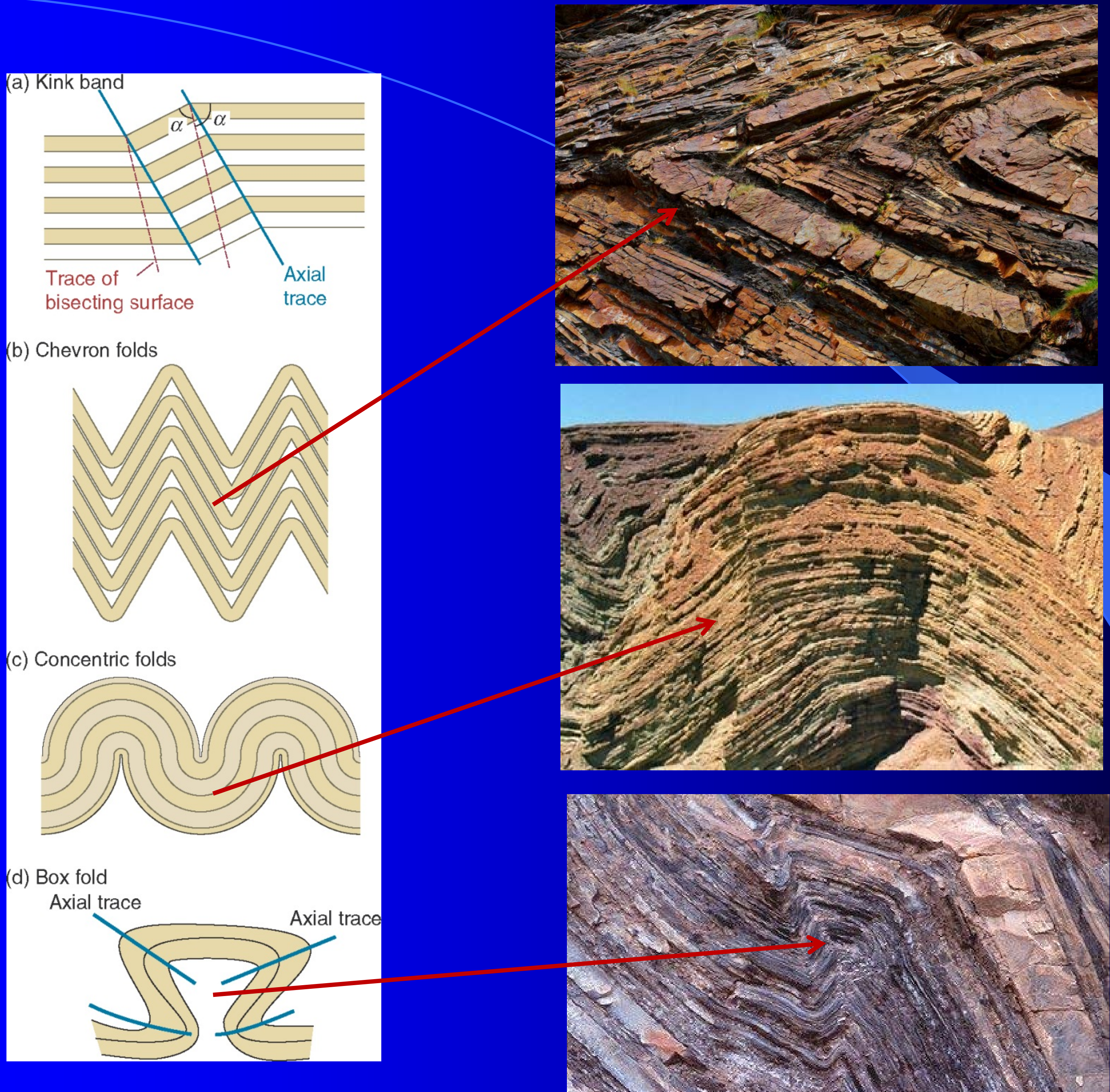
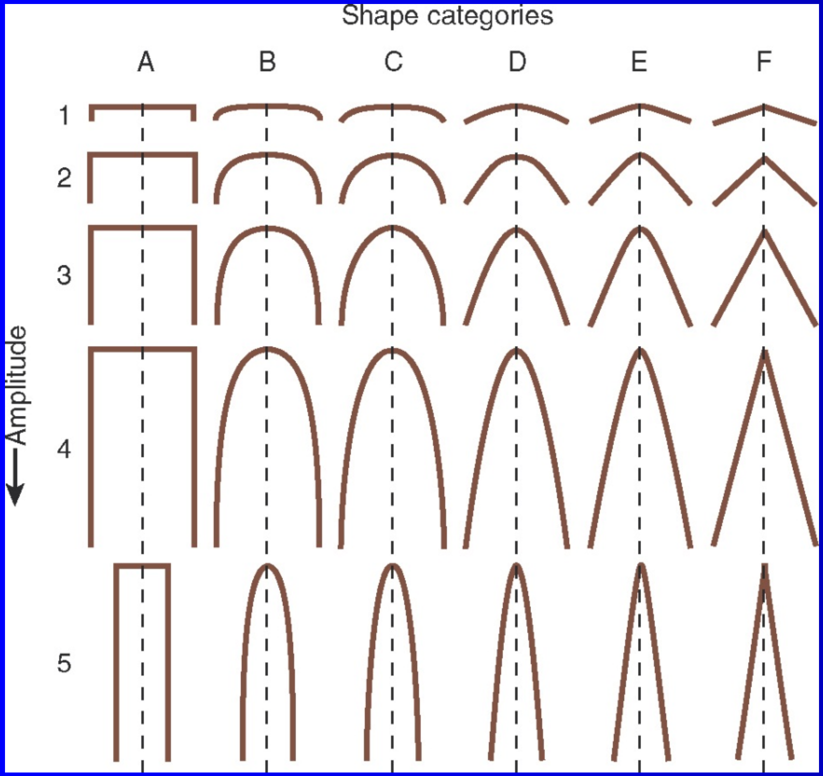
# Folds and Folding

# Folding – Geometric Description:

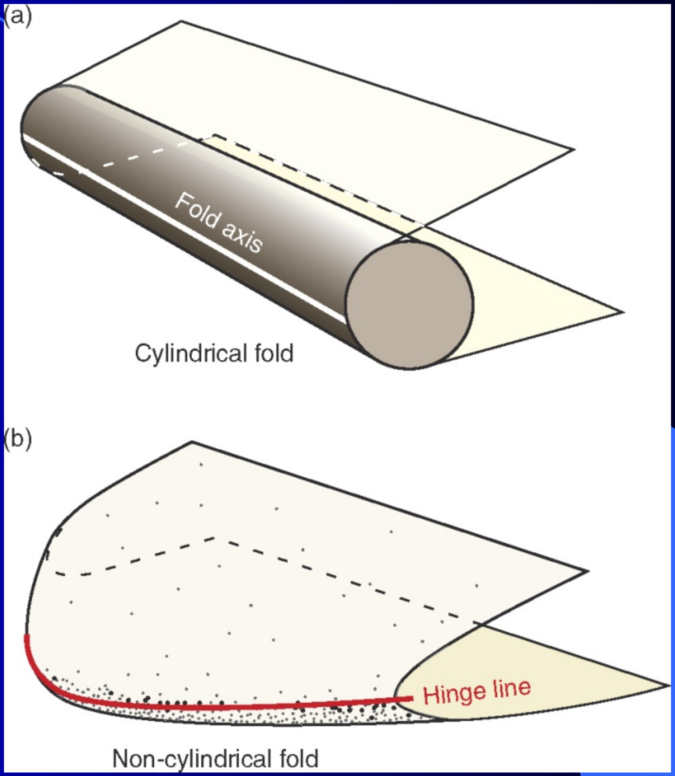



- The hinge connects the two limbs of a fold.
- The hinge point is the point of maximum curvature and is located in the center of the hinge zone.
- The hinge line is the three-dimensional equivalent of the hinge point.
- If the hinge line appears as a straight line it is called a fold axis.
- The axial surface (or axial plane when approximately planar) connects the hinge line of two or more folded surfaces.
- The axial trace represents the intersection between the axial plane and the surface of observation.
- The inflection point (inflection line) is where there is a change in curvature of a fold limb.
- The interlimb angle is the angle enclosed by the two limbs of a fold.
- The enveloping surface is the surface tangent to individual hinges along a folded layer.

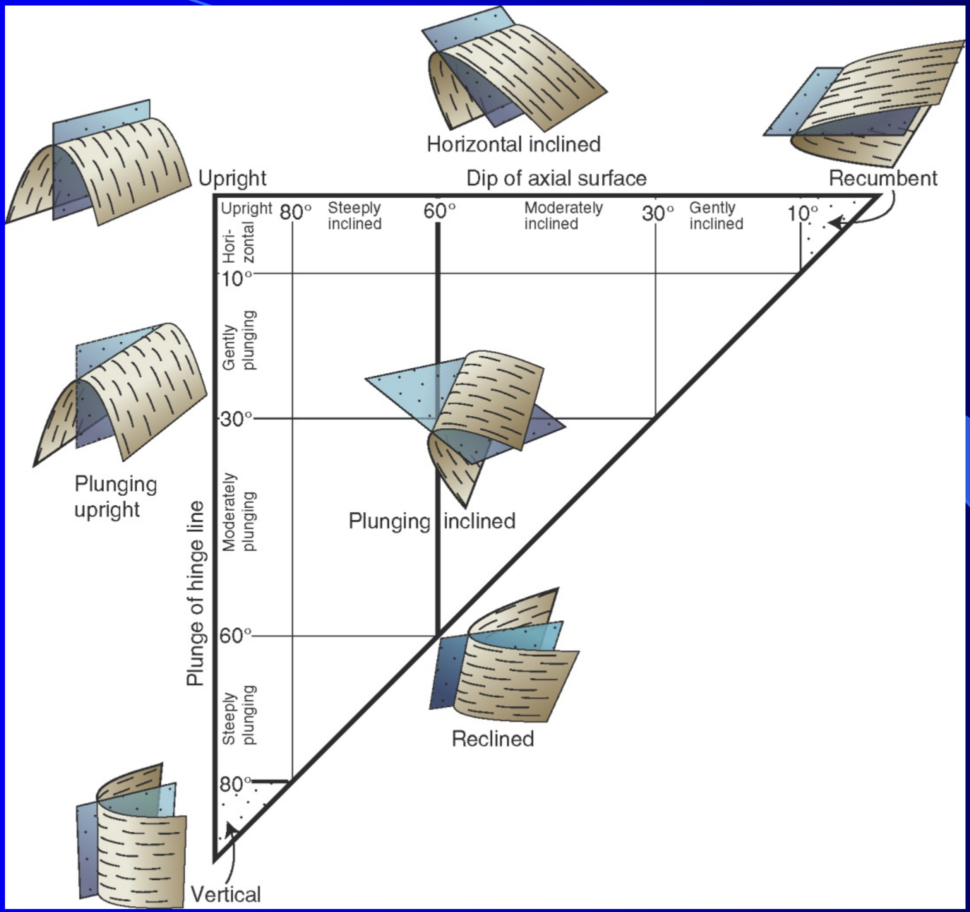

(a) Kink band
α
α
Trace of
bisecting surface
Axial
trace
(b) Chevron folds
(c) Concentric folds
(d) Box fold
Axial trace
Axial trace



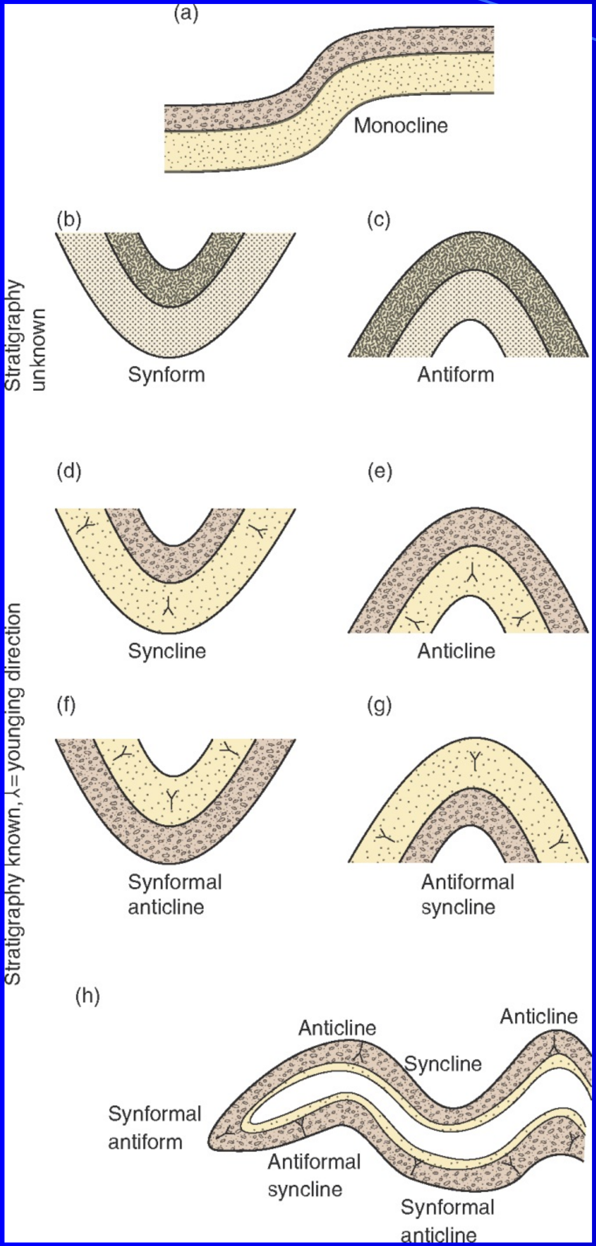

Fold classification based on shape



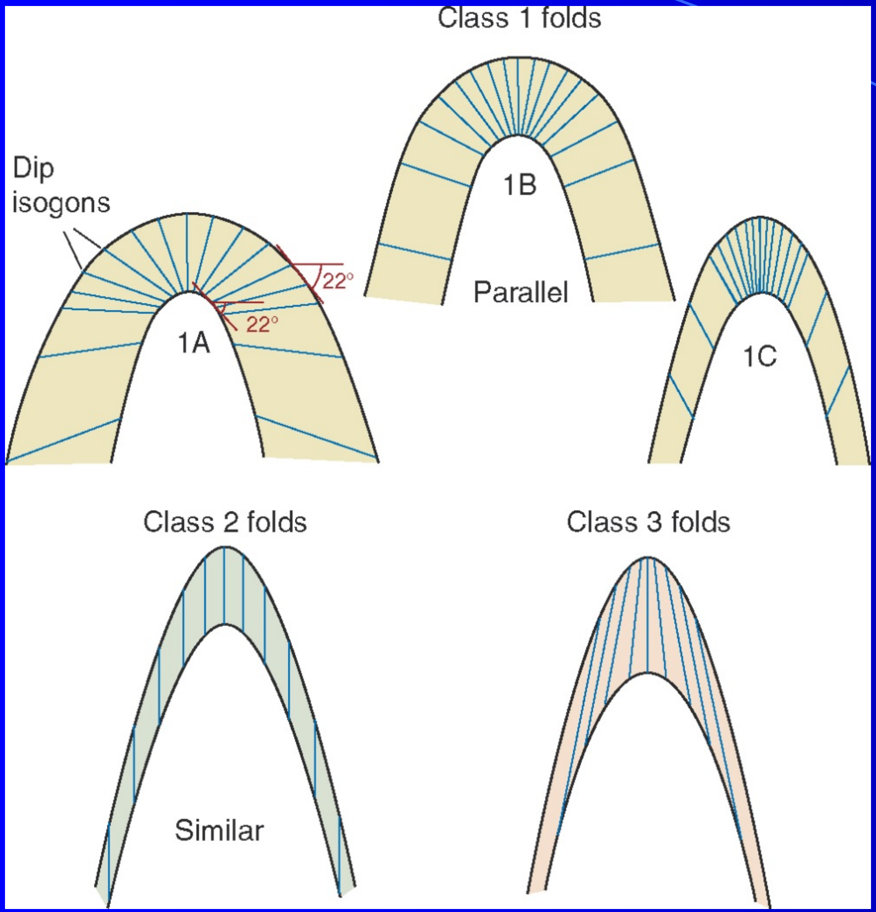

Cylindrical and non-cylindrical folds

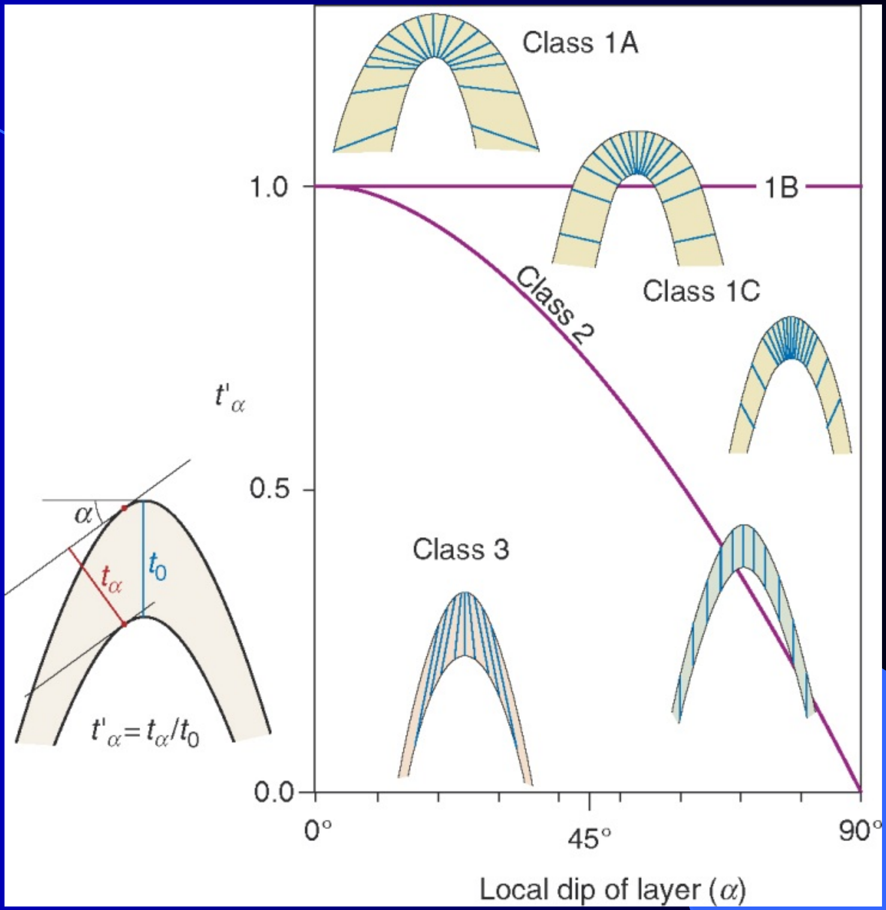



Classification of folds based on the orientation of the hinge line and the axial surface. Plunge is the dip of the hinge line.




- Monocline – a sub-cylindrical fold with only one inclined limb
- Synform – structure where limbs point up
- Antiform – structure where limbs point down
- Syncline – younger rocks in the center
- Anticline – older rocks in the center
- Synformal anticline – inverted anticline
- Antiformal syncline – inverted syncline
- Upright fold – vertical axial plane and horizontal hinge line.
- Recumbent fold – horizontal axial plane and hinge line.



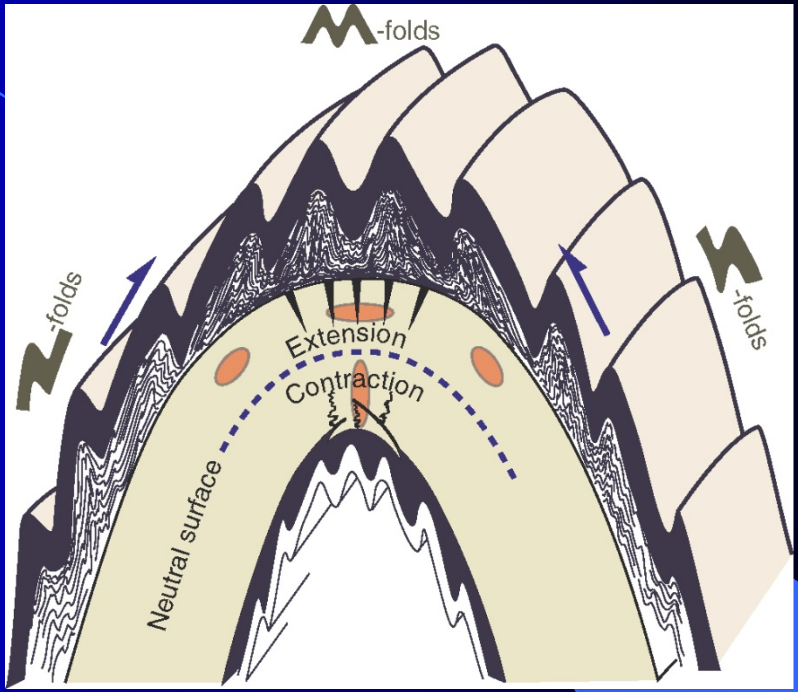




Ramsay's (1967) classification of folds (l). Dip isogons are lines connecting points of identical dip for vertically oriented folds. Mathematical representation (r) of the Ramsay classification. The plot shows the relationship between the dip of a particular layer and the thickness of that layer at different locations on the limb of the fold relative to the thickness of the layer in the fold axis.

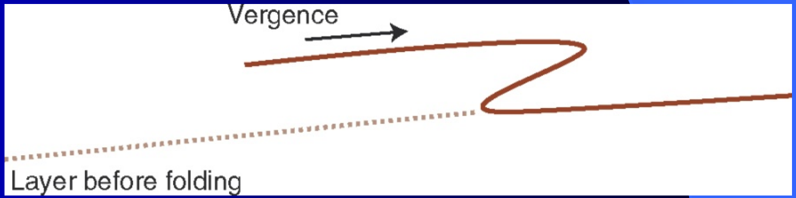
# Fold Symmetry

Symmetric folds – in a cross-section perpendicular to the axial surface the two side of the axial trace are mirror images (M-folds).
Asymmetric folds – in a cross-section perpendicular to the axial surface the two sides of the axial trace are NOT mirror images (Z- or S- folds).

- Z-folds – short limbs appear to have been rotated clockwise.
- S-folds – short limbs appear to have been rotated counterclockwise.



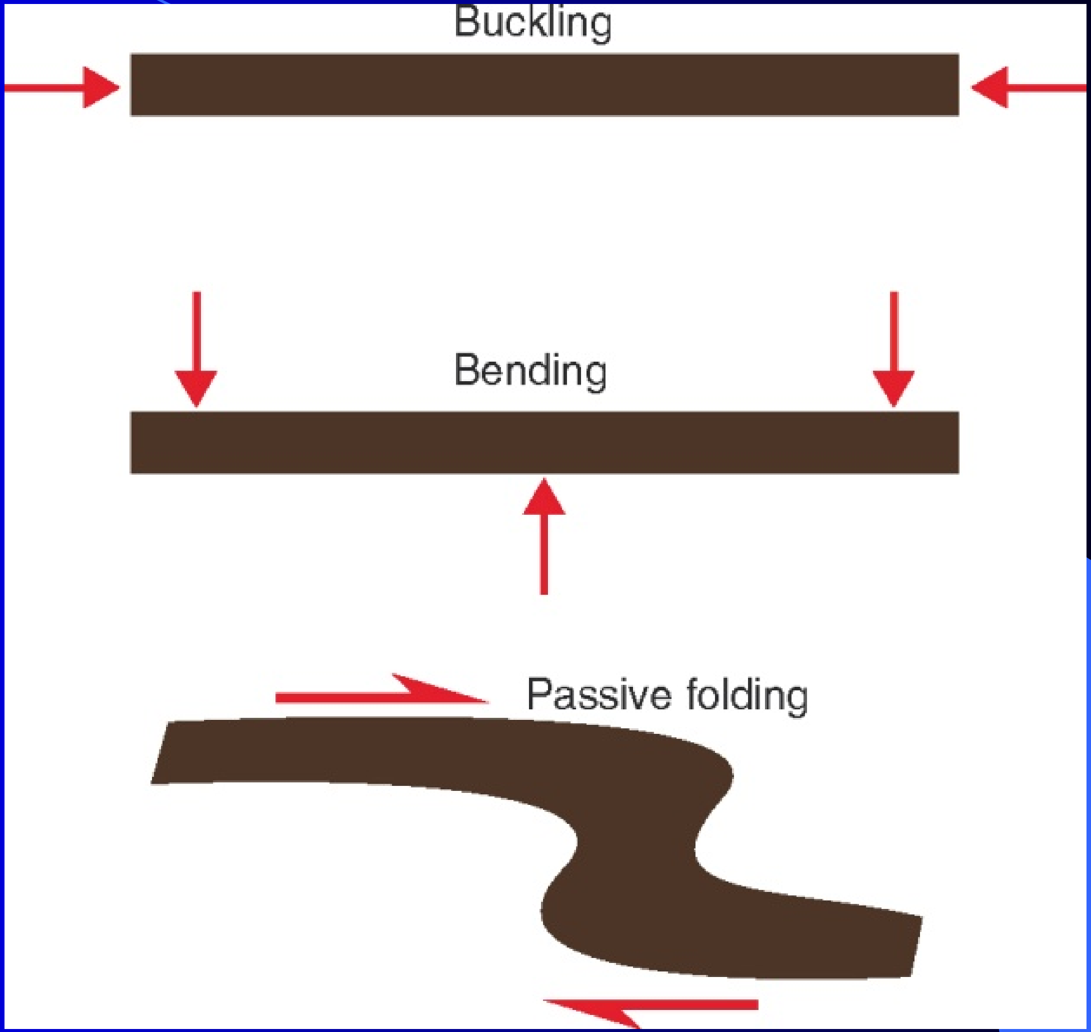

Fold systems with a consistent asymmetry display vergence. The vergence direction is given by the sense of displacement of the upper limb relative to the lower limb. Second, third, … order folds are called parasitic folds and have a vergence directed towards the hinge zone.



# Folding Mechanisms

Types of folding:

- Buckling – active folding. There is a viscosity contrast between the folding layer and its host rock. Forces are applied parallel to the layer
- Bending – forces are applied across the layer.
- Passive folding – layers are simply passive markers with no rheological influence



# Active folding (buckling) – Class 1B folds

Buckling occurs when a competent layer in a less competent layer is shortened parallel to the length of the layer. There must be irregularities on which folds can nucleate .

Top figure:

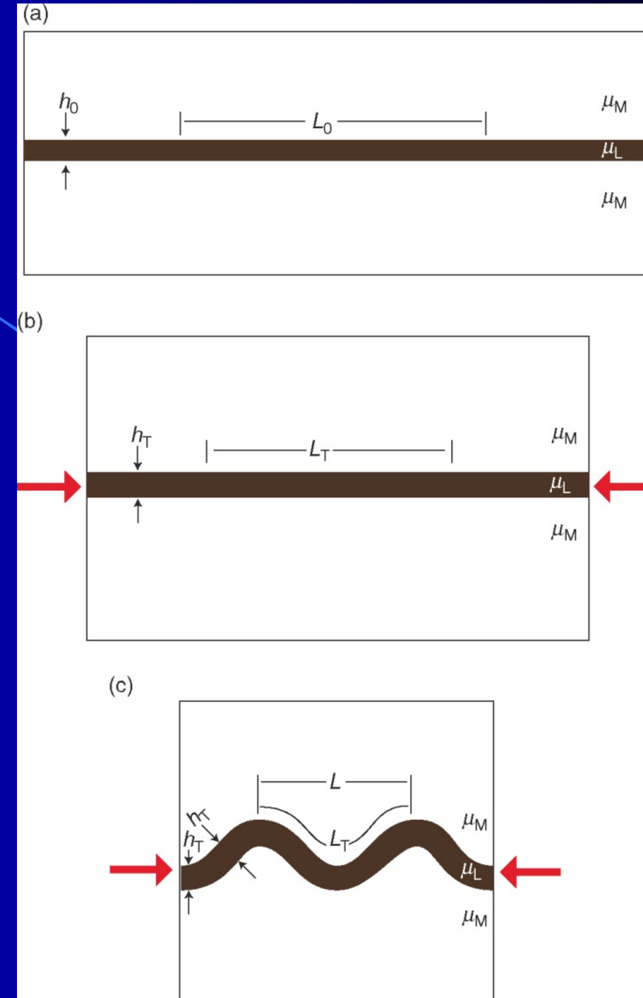
$L_o$ = length of the original layer
$h_o$ = thickness of the original layer

$L_T$ = length of layer after initial shortening
$h_T$ = thickness of original layer after initial shortening

$\mu_L$ = viscosity of layer
$\mu_M$ = viscosity of matrix

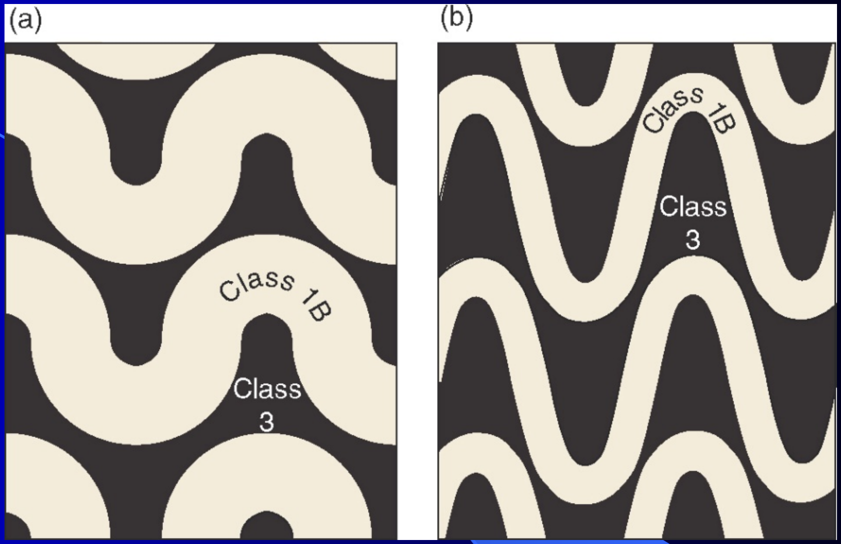
L = wavelength of fold

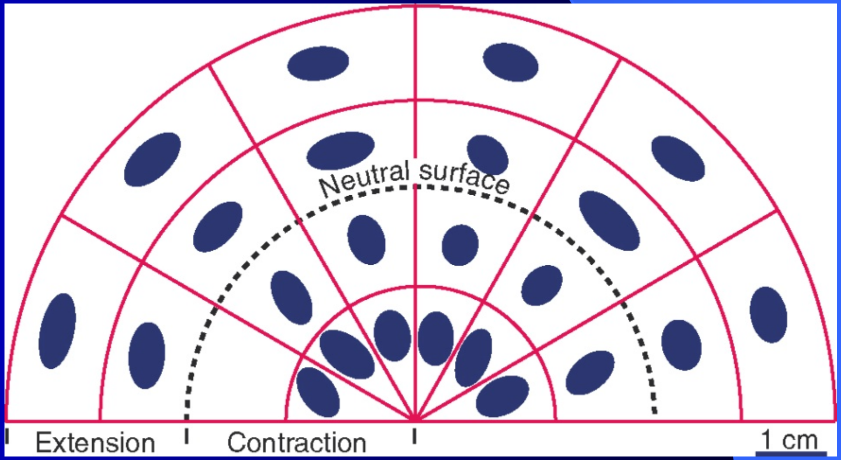
Bottom figure: Two folded layers of different thicknesses. The upper and thinner one shows a smaller dominant wavelength than the lower one.




## Single layer folds formed by buckling:

- 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 (picture previous slide)
- 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 (top figure). Cusps point to the more competent layers.
- The outer part of the competent layer is stretched while the inner part is shortened (bottom figure).



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 –

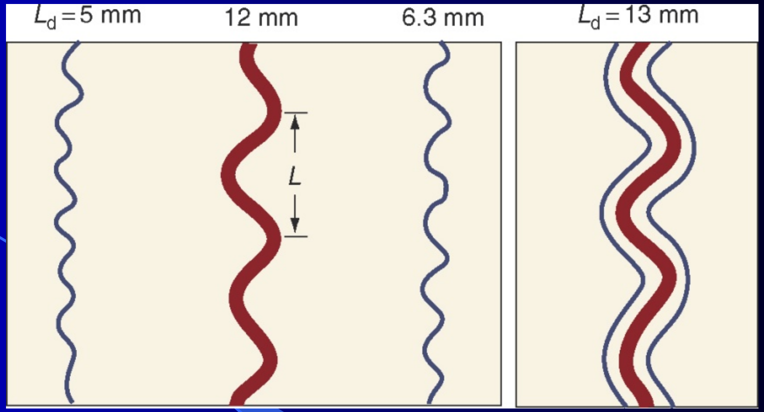
Ld = dominant wavelength

h = layer thickness

$L_{dT}$ = dominant wavelength taking into account thickening

$h_T$ = layer thickness after shortening

T = strain ratio X/Z = $(1 + e_1)/(1 + e_3)$




Folding of multilayered rocks. Far apart layers act as individual layers (left). The closer they get the more they behave as a single layer.

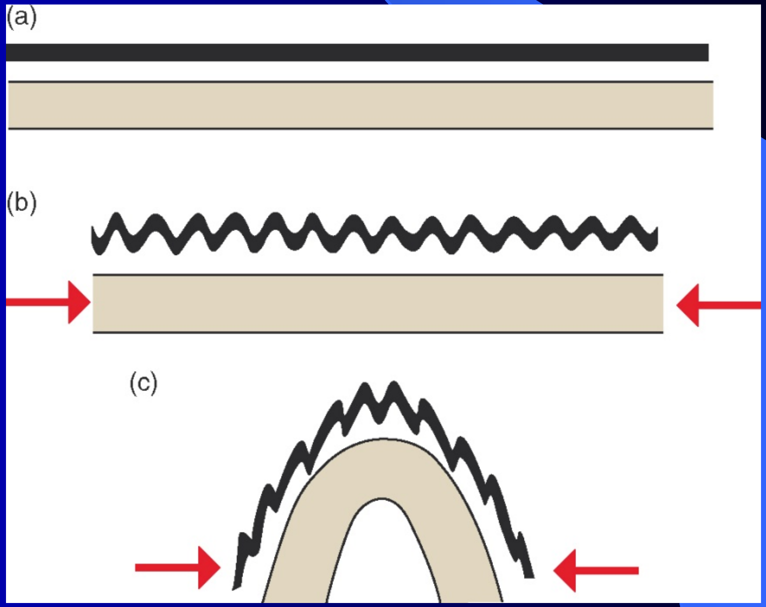


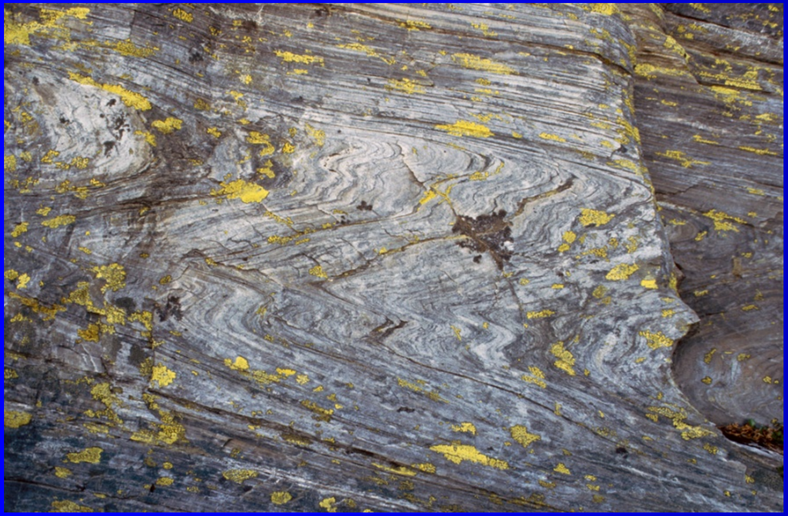

Illustration of how folding initiates in thin layers. Once the thicker layers start to fold the smaller folds become parasitic and asymmetric.

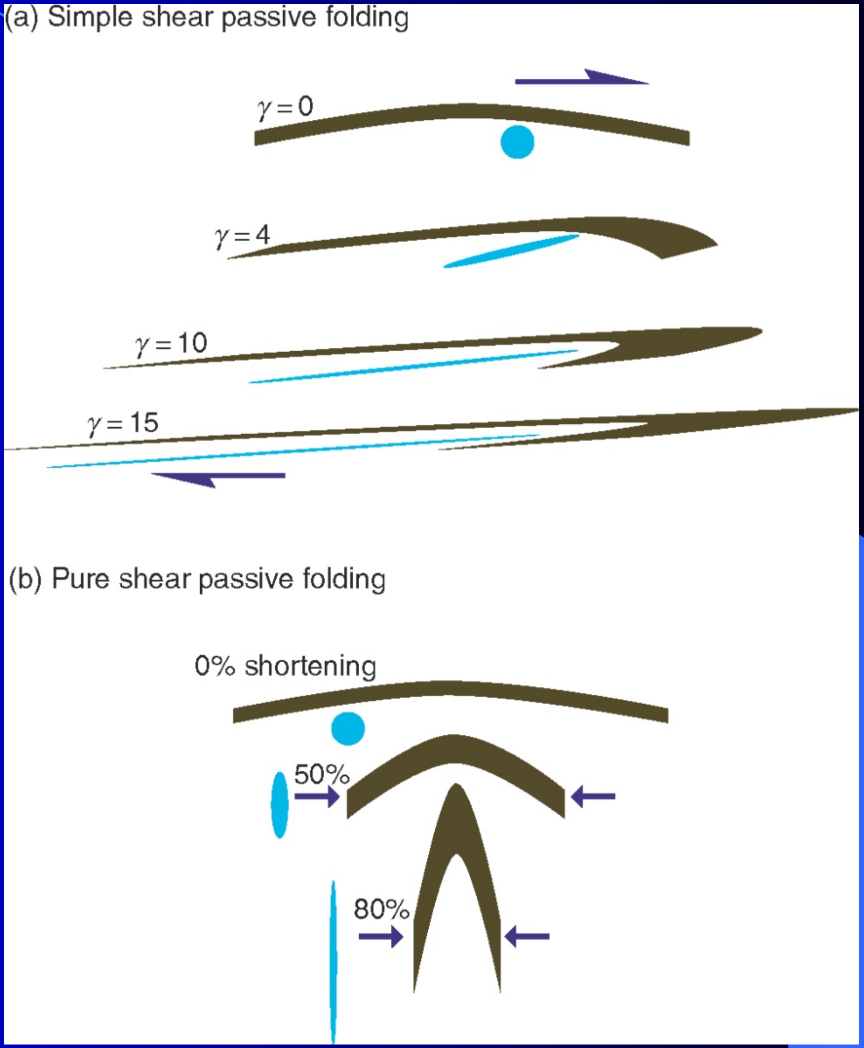
Buckled multilayers. Note how the largest folds affect the entire layer package.

# Passive (class 2 folds) folding

Passive folding produces harmonic folds where the layering plays no mechanical role and therefore has no influence on the shape of the fold.

Passive folds can form in response to any kind of ductile strain – simple shear, subsimple shear, transpression, and pure (coaxial) shear.





# Bending

Bending occurs when forces act across a layer at high angle.

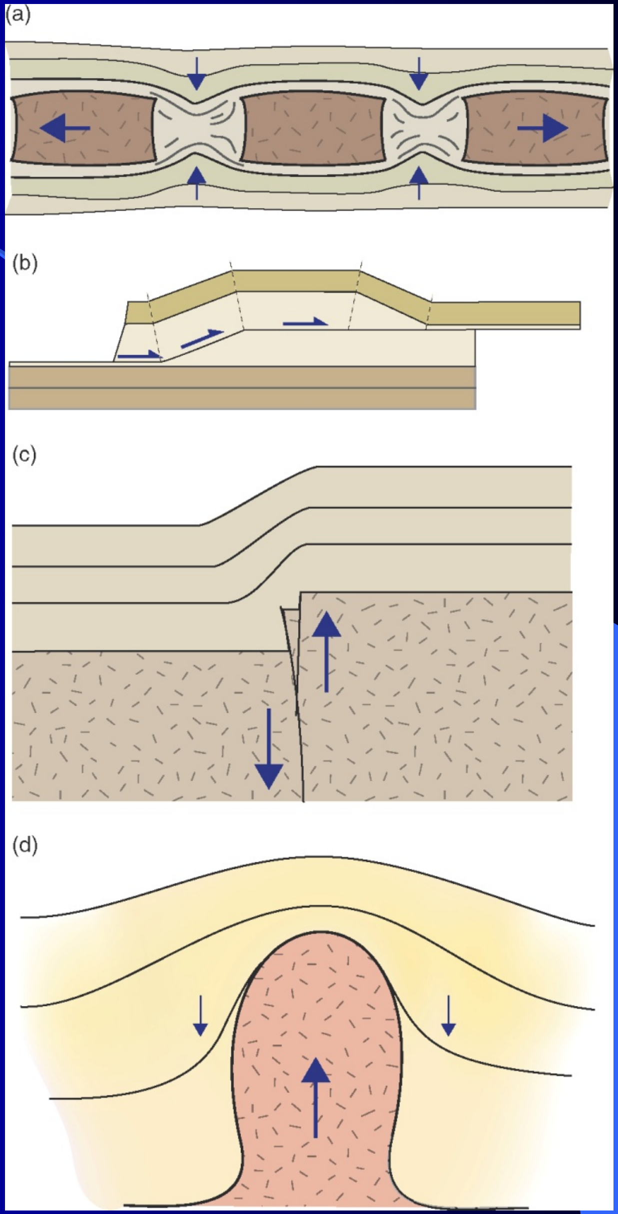
Examples of bending:

a) Between boudins

b) Above thrust ramps

c) Above reactivated faults

d) Above shallow intrusions or salt diapirs

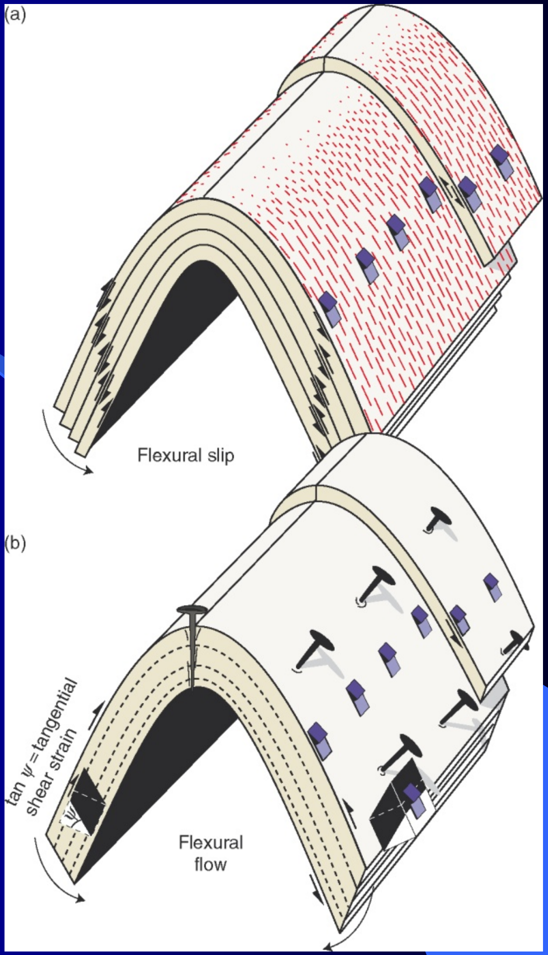


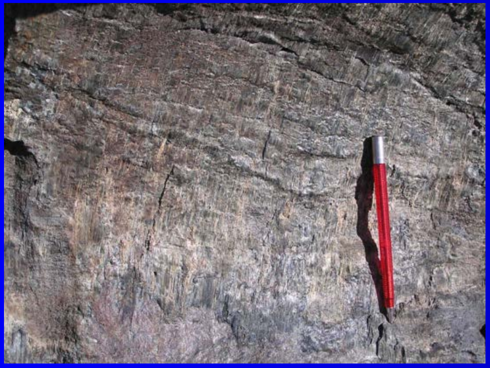
# Flexural slip, flexural flow, orthogonal flexure (Class 1B)

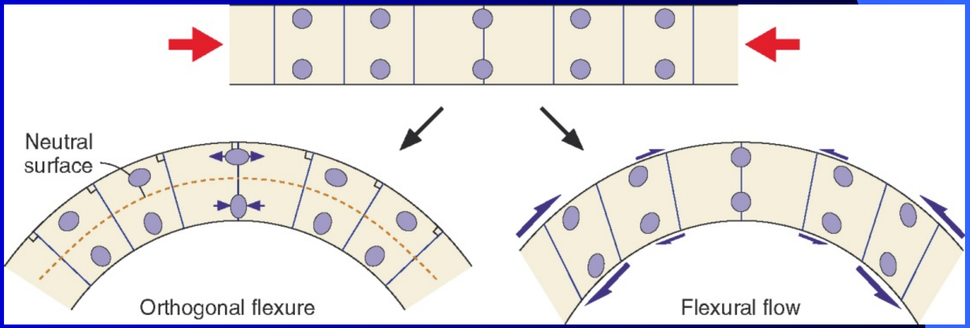
Flexural slip – deforming medium is layered or has a strong mechanical anisotropy (peanut butter and jelly sandwich). Slickenlines on folded weak layers and constant bed thickness are indicative of flexural slip.

Flexural flow – strain becomes more evenly distributed in the limbs. More common in the plastic regime. Shear increases down the limbs because there is a change in orientation (paperback book). Pure flexural folds have no neutral surface and strain increases away from the hinge zone.

Orthogonal flexure – all lines originally orthogonal to the layering remain so throughout the deformation history. Orthogonal flexure produces parallel folds with a neutral surface.



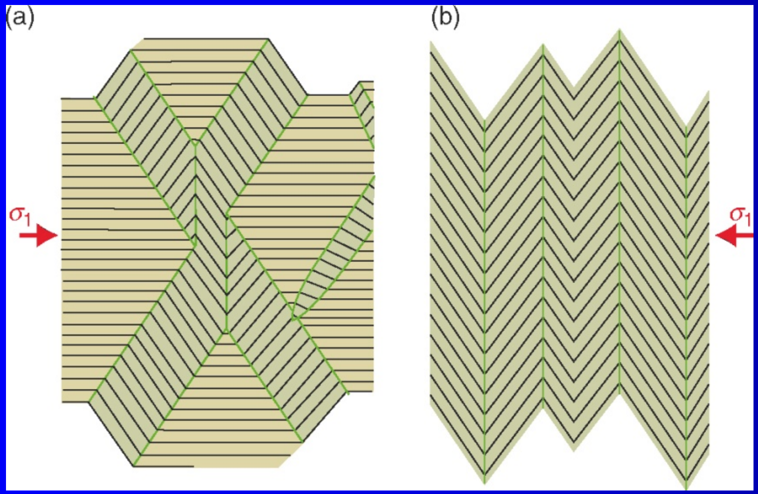


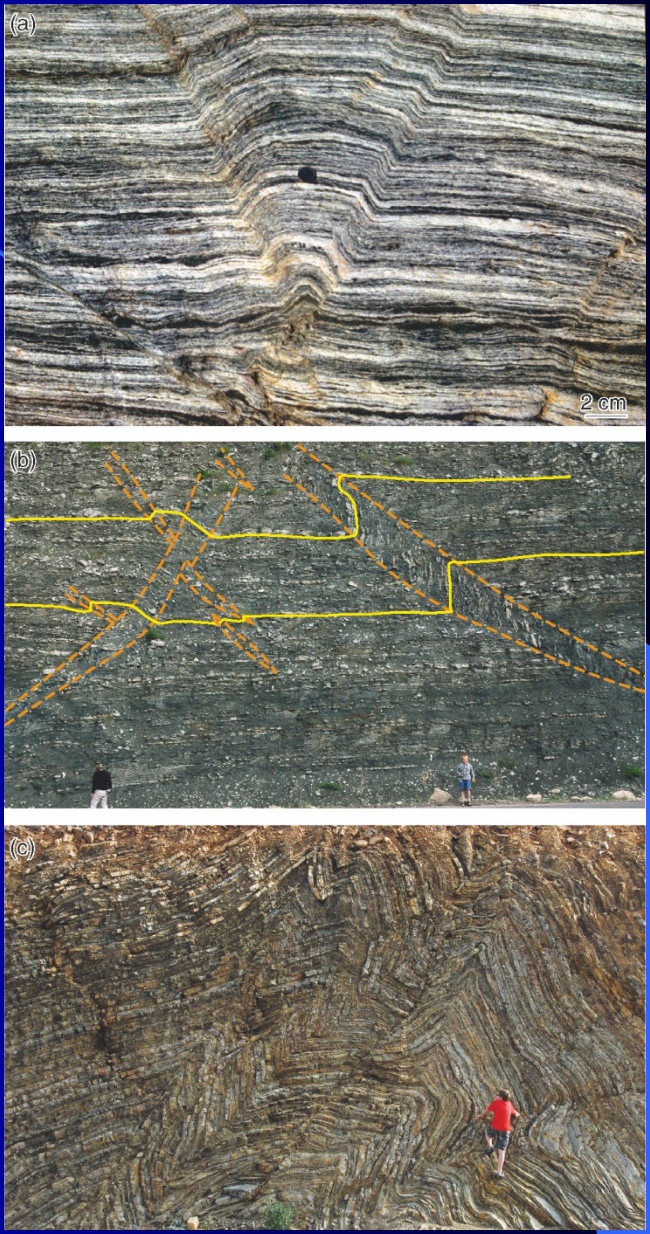
# Kink bands (Class 2)

Kink bands – centimeter to decimeter wide zones or bands with sharp boundaries across which the foliation is abruptly rotated.

Figure (right): (a) conjugate kink bands in mylonitized anorthosite gabbro; (b) kink folds related to Laramide thrusting in north Wyoming; (c) kink like folds in oceanic sediments.

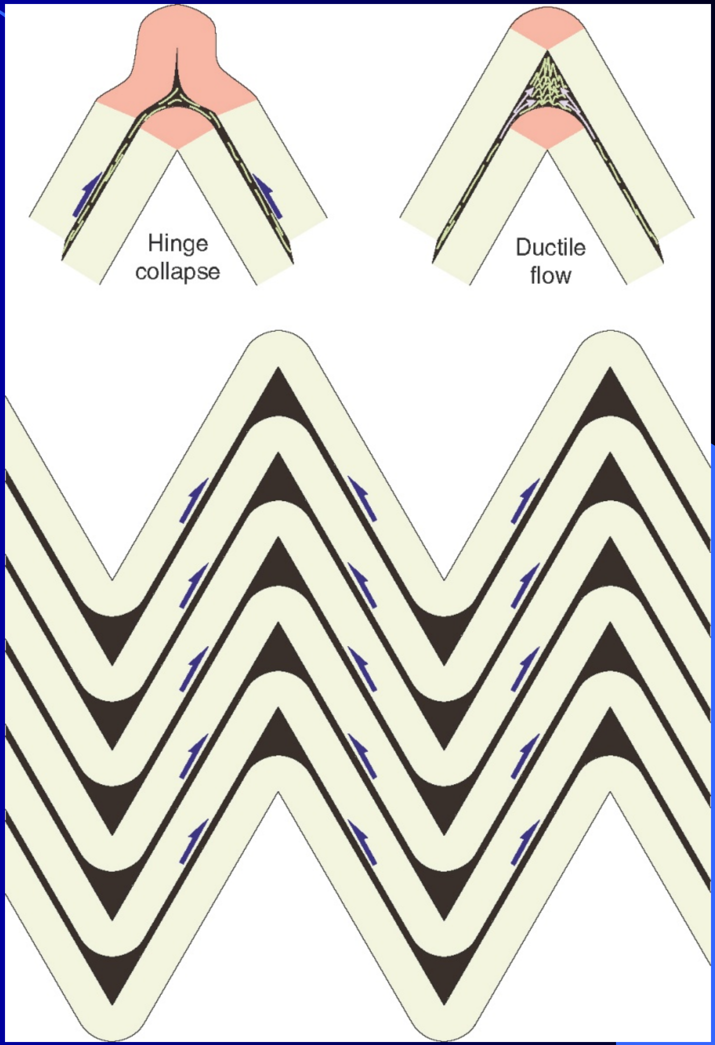
Figure (below): (a) the orientation of $\sigma_1$ can be determined from the orientation of conjugate sets of kink bands; (b) continued kink band growth can produce chevron folds.



# Chevron folds (Class 2)

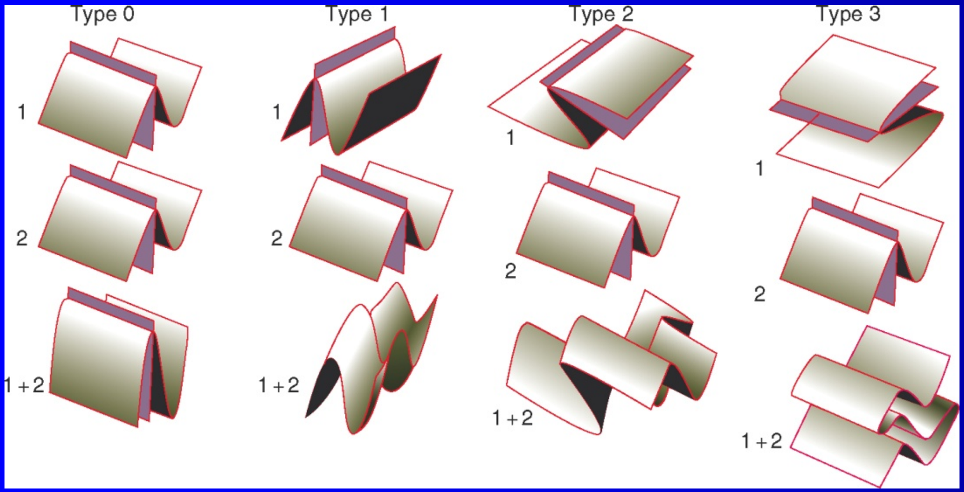
Chevron folds most likely form by flexural slip of multilayered rocks during layer-parallel shortening. Typically competent layers are separated by thin incompetent layers. The space problem in the hinge zone is resolved by ductile flow of the incompetent (dark) layers or collapse of competent layers in the hinge zone. Strained parts of competent layers are marked in red, showing that layer thickness is maintained on the limbs.



# Fold interference patterns and refolded folds

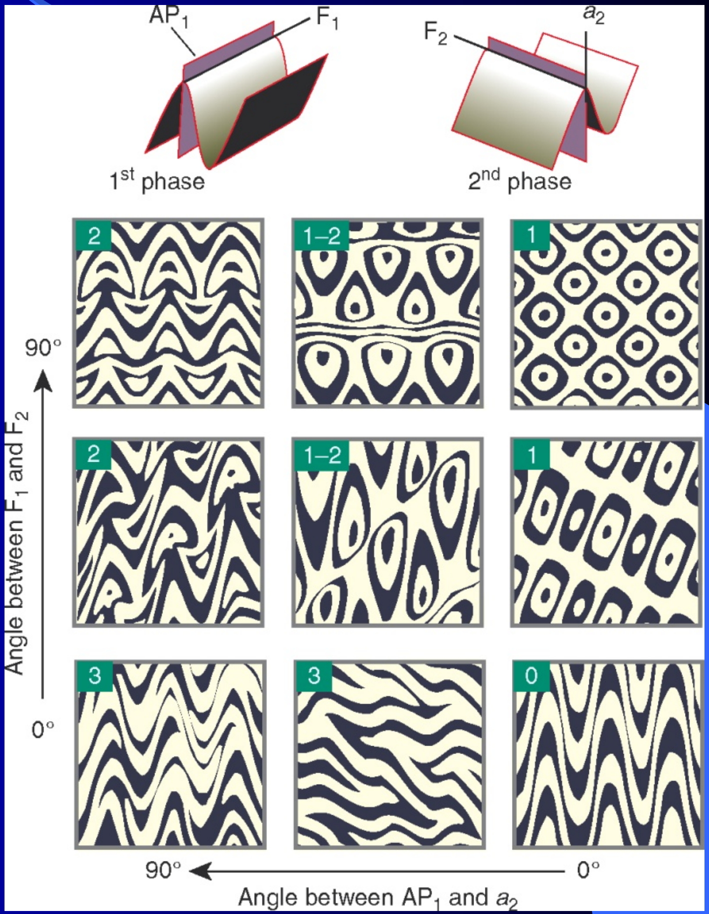
Refolded folds – modified by a later fold phase.

Fold interference patterns are produced during refolding.




Superposition of fold system 2 on fold system 1.

Fold interference patterns of cylindrical folds classified according to the relative orientation of fold axes (vertical direction) and the angle between the first axial plane and the direction $a_2$ indicated in the upper part of the figure. Type 0 pattern represents two identical but temporally separate fold systems.



Development of sheath folds (highly non-cylindrical folds) by amplification of a preexisting irregularity. Note that it takes high shear strains to form sheath folds by simple shear. Shear strain increases from (a) to (c).