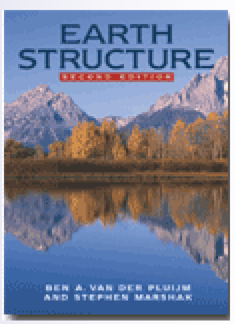
Lecture 9

Folds and Folding



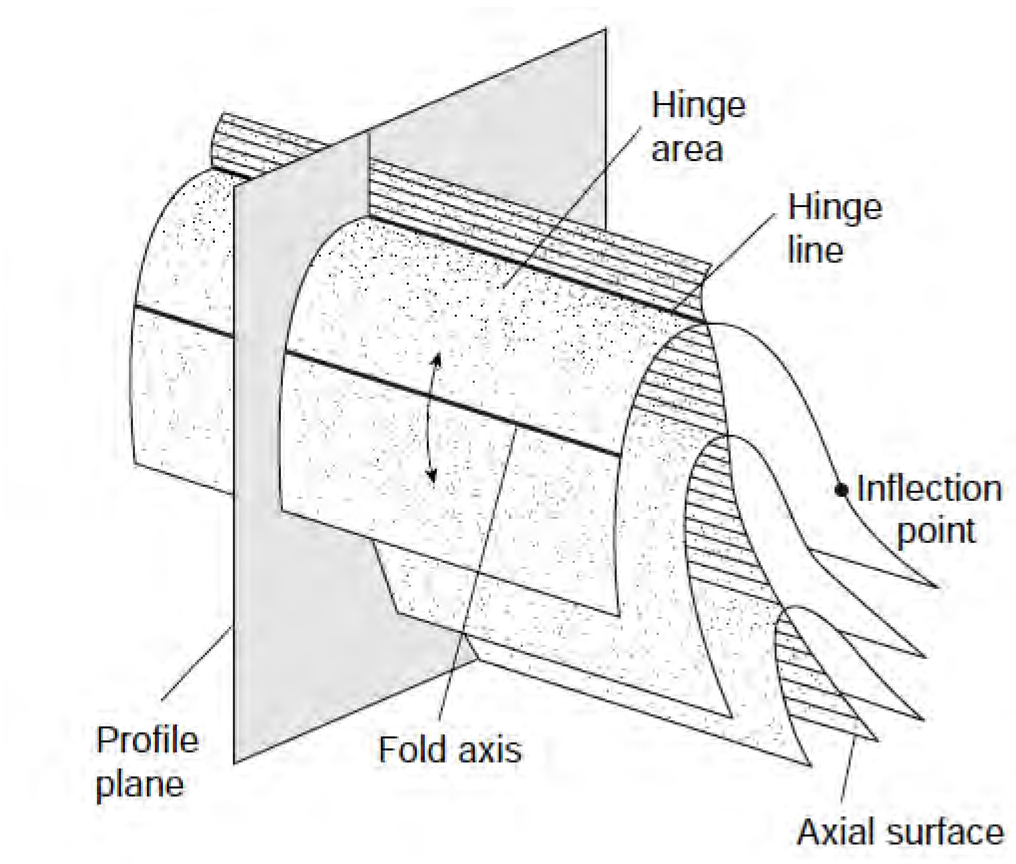
Earth Structure (2nd Edition), 2004
W.W. Norton & Co, New York
Slide show by Ben van der Pluijm

Fold Classification

- Beds in an **anticline** *are oldest in the core;*
- Beds in a **syncline** *are youngest in the core;*

*In both cases the younging direction points (or faces) upward,

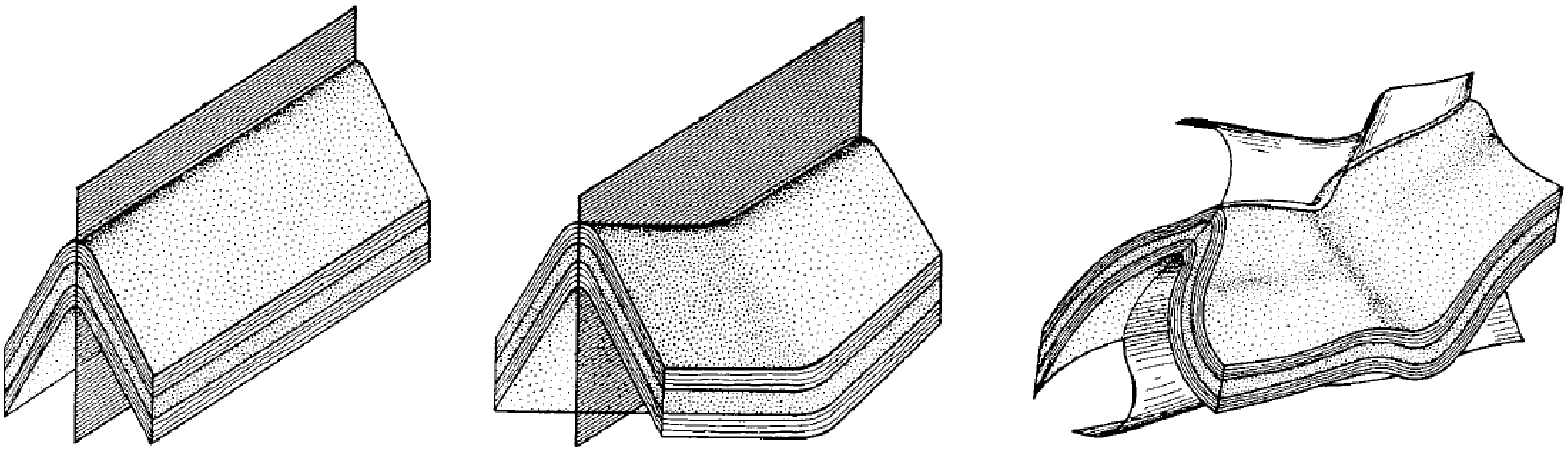
Anatomy of a folded surface Sec 10.2



- The **hinge area** is the region of greatest curvature and separates the two limbs.
- The line of greatest curvature in a folded surface is called the **hinge line.**
- A **limb** is the less curved portion of a fold.
- In a limb there is a point where the sense of curvature changes, called the **inflection point.**

- *The surface containing the hinge lines from consecutive folded surfaces in a fold is the **axial surface***

Cylindrical and non-cylindrical folds Fig. 10.3

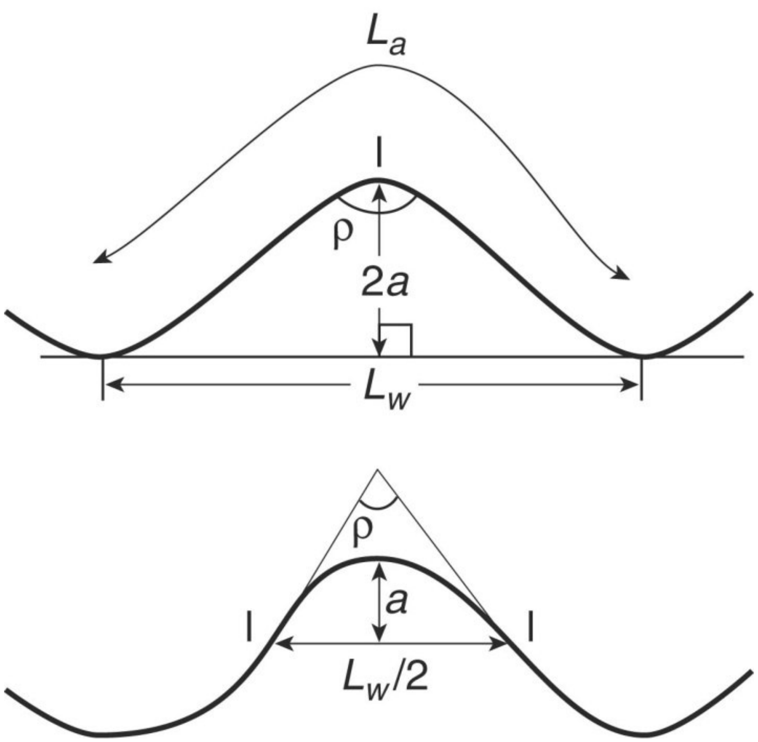


A **cylindrical fold** is characterized by a straight hinge line and a uniformly plunging fold axis

Noncylindrical folds can have planar or curved axal surfaces but have a variably plunging fold axis

FIGURE 10.7 An asymmetric, plunging fold (the Sheep Mountain Anticline in Wyoming, USA).

Fold geometry Fig. 10.4



- The interlimb angle (ρ)
- The wavelength (L_w)
- The amplitude (a)
- The arc length (L_a) of a fold system ***in profile***.

TABLE 10.3	FOLD CLASSIFICATION BY INTERLIMB ANGLE
Isoclinal	0°–10°
Tight	10°–60°
Open	60°–120°
Gentle	120°–180°

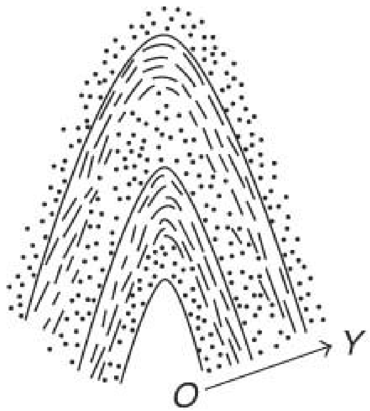
- *The reference plane used to describe fold shape is called the* ***fold profile plane,*** *which is perpendicular to the hinge line (Figure 10.2).*

TABLE 10.1 VOCABULARY OF A FOLD

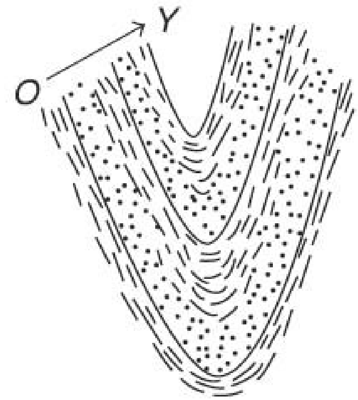
Amplitude	Half the height of the structure measured from crest to trough
Arc length	The distance between two hinges of the same orientation measured over the folded surface
Axial surface	The surface containing the hinge lines from consecutive folded surfaces
Crest	The topographically highest point of a fold, which need not coincide with the fold hinge
Cross section	A vertical plane through a fold
Culmination	High point of the hinge line in a noncylindrical fold
Cylindrical fold	Fold in which a straight hinge line parallels the fold axis; in other words, the folded surface wraps partway around a cylinder
Depression	Low point of the hinge line in a noncylindrical fold
Fold axis	Fold generator in cylindrical folds
Hinge	The region of greatest curvature in a fold
Hinge line	The line of greatest curvature
Inflection point	The position in a limb where the sense of curvature changes
Limb	Less curved portion of a fold
Noncylindrical fold	Fold with a curved hinge line
Profile plane	The surface perpendicular to the hinge line
Trough	The topographically lowest point of a fold, which need not coincide with the fold hinge
Wavelength	The distance between two hinges of the same orientation

Fold facing

upward facing
antiform or
anticline



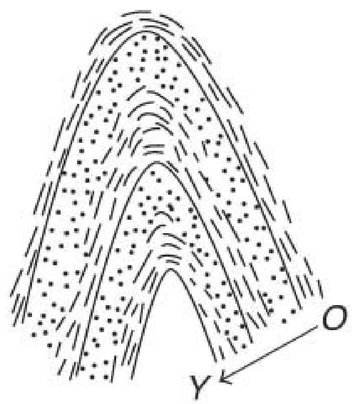
(a)



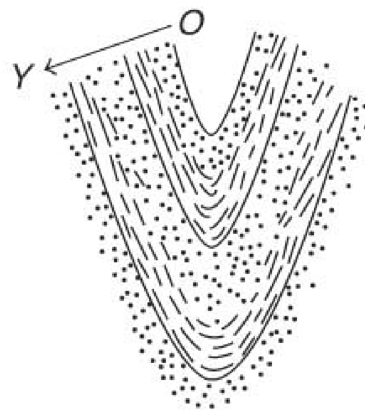
(b)

upward facing
synform or
syncline

downward-facing
antiform or
antiformal
syncline



(c)



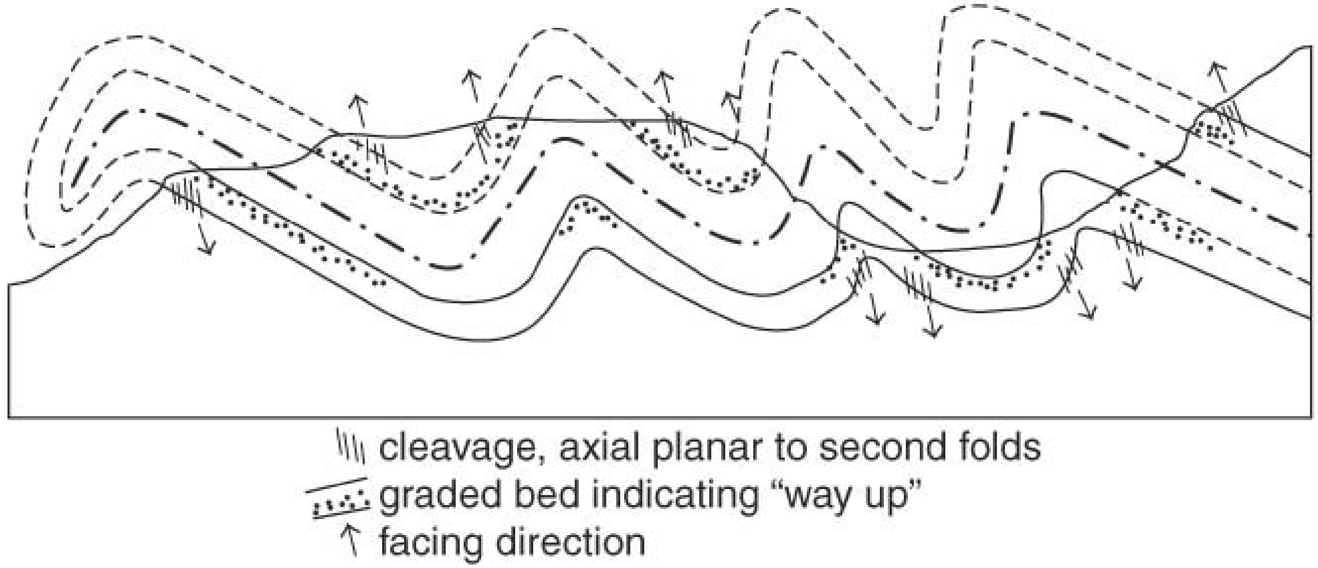
(d)

downward-
facing
synform or
synformal
anticline

Downward-facing folds reflect a complex and repeat fold history that placed the beds upside down prior to refolding.

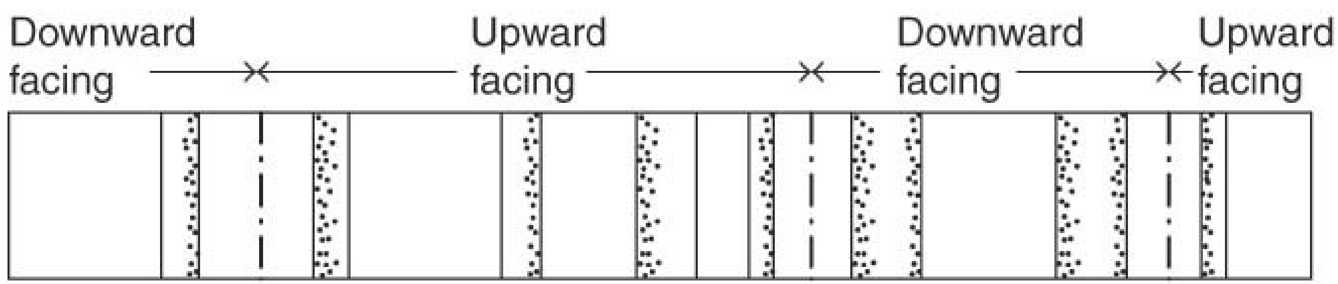
Fold facing Fig. 10.6

The corresponding facing in map view across this area is shown in (f).



(e)

Younging direction is indicated by O→Y arrow.



(f)

Fold orientation Fig. 10.9

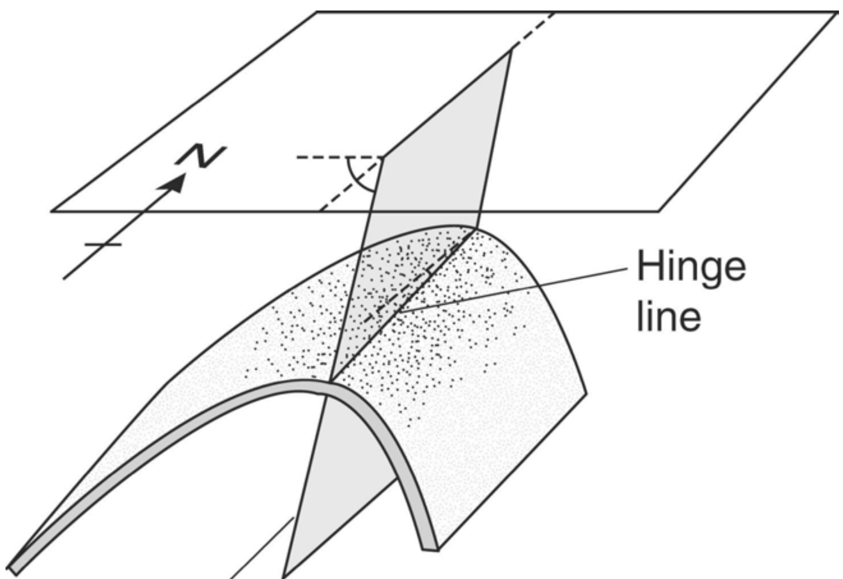
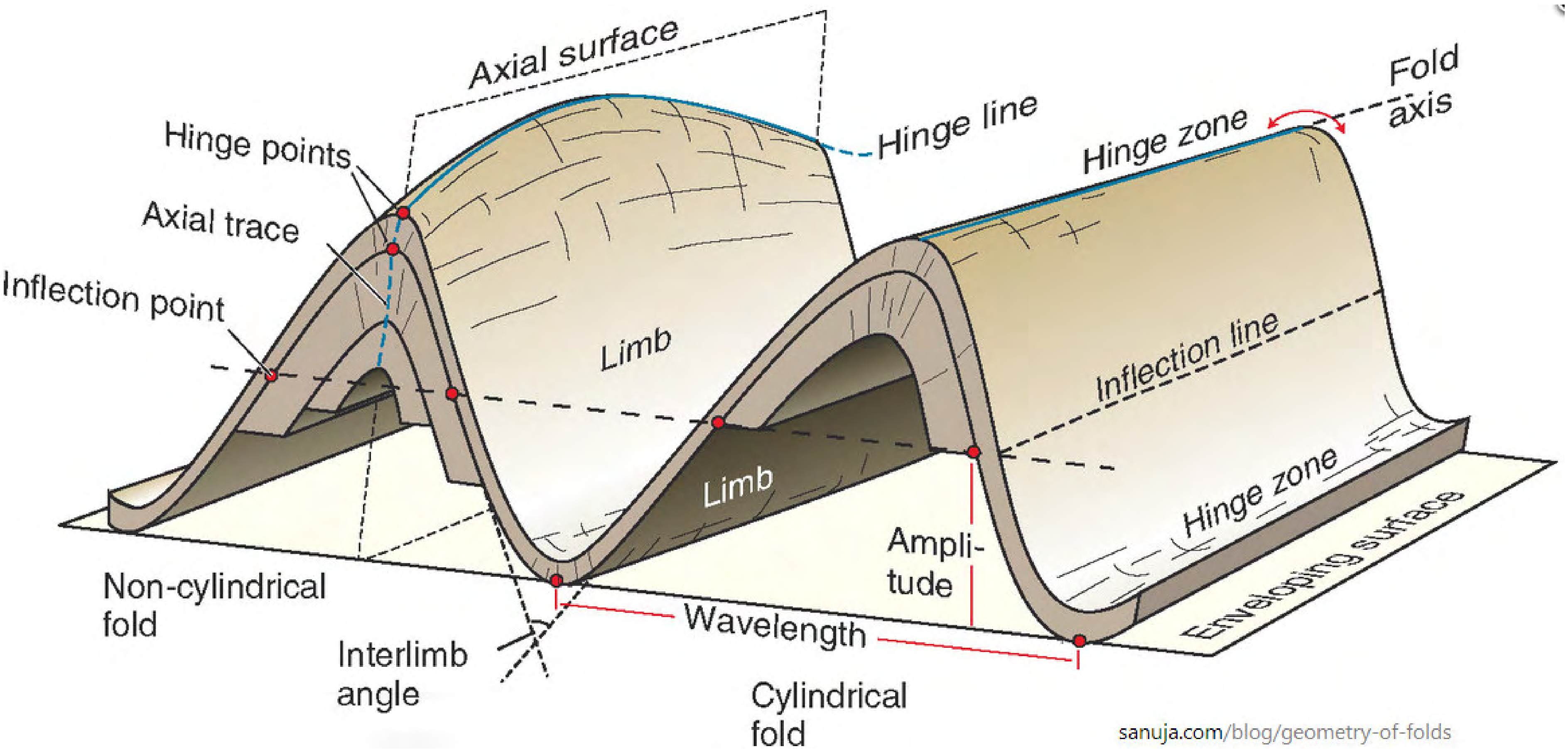


TABLE 10.2	FOLD CLASSIFICATION BY ORIENTATION
Plunge of Hinge Line	Dip of Axial Surface
Horizontal: 0°–10°	Recumbent: 0°–10°
Shallow: 10°–30°	Inclined: 10°–70°
Intermediate: 30°–60°	Upright: 70°–90°
Steep: 60°–80°	
Vertical: 80°–90°	

*Note that the **axial surface is a plane** whose orientation is given by dip and strike (or dip direction), whereas the **hinge line** is given by plunge and bearing.*



Note the curved hinge line on the left side fold is NOT a fold axis.

Fold orientation Fig. 10.10

Fold classification based on the orientation of the hinge line and the axial surface (shaded).

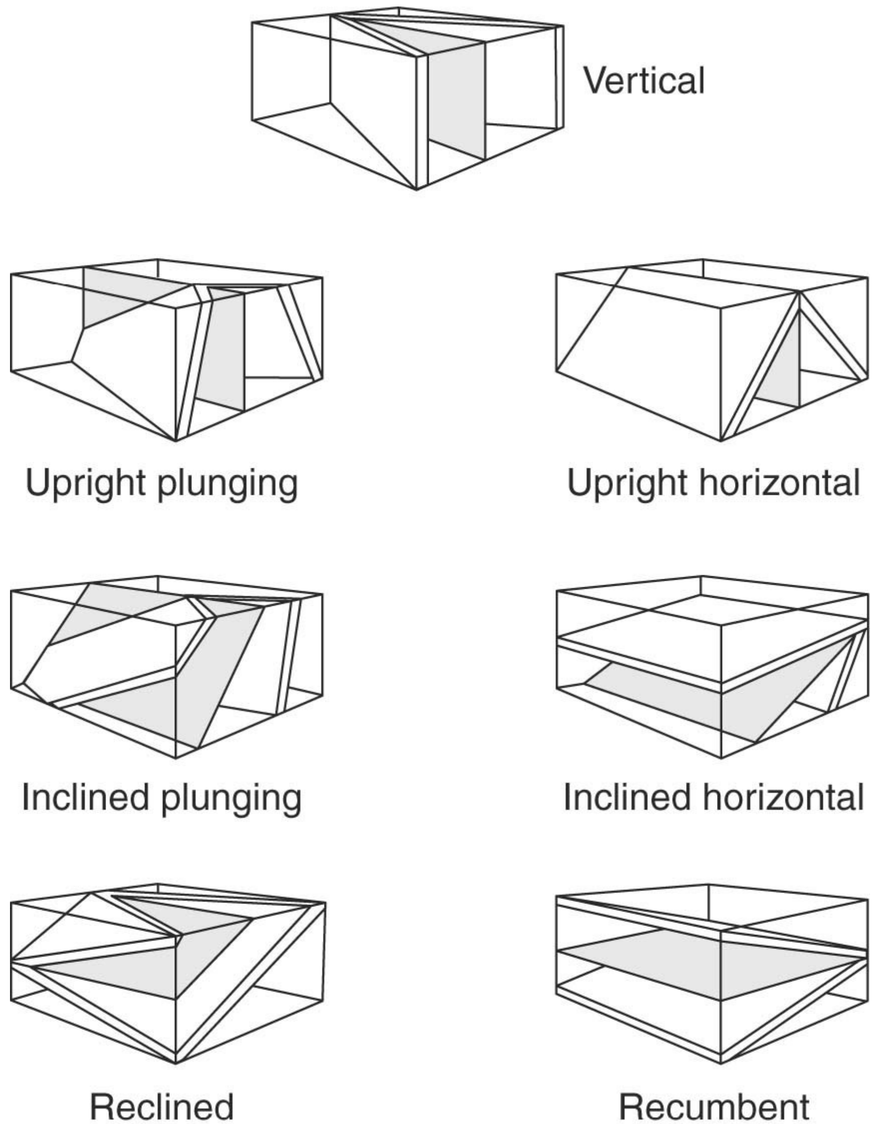


FIGURE 10.1 Large-scale recumbent fold in the Caledonides of northeast Greenland. The height of the cliff is about 800 m and the view is to the Northwest. *(Kildedalen)*

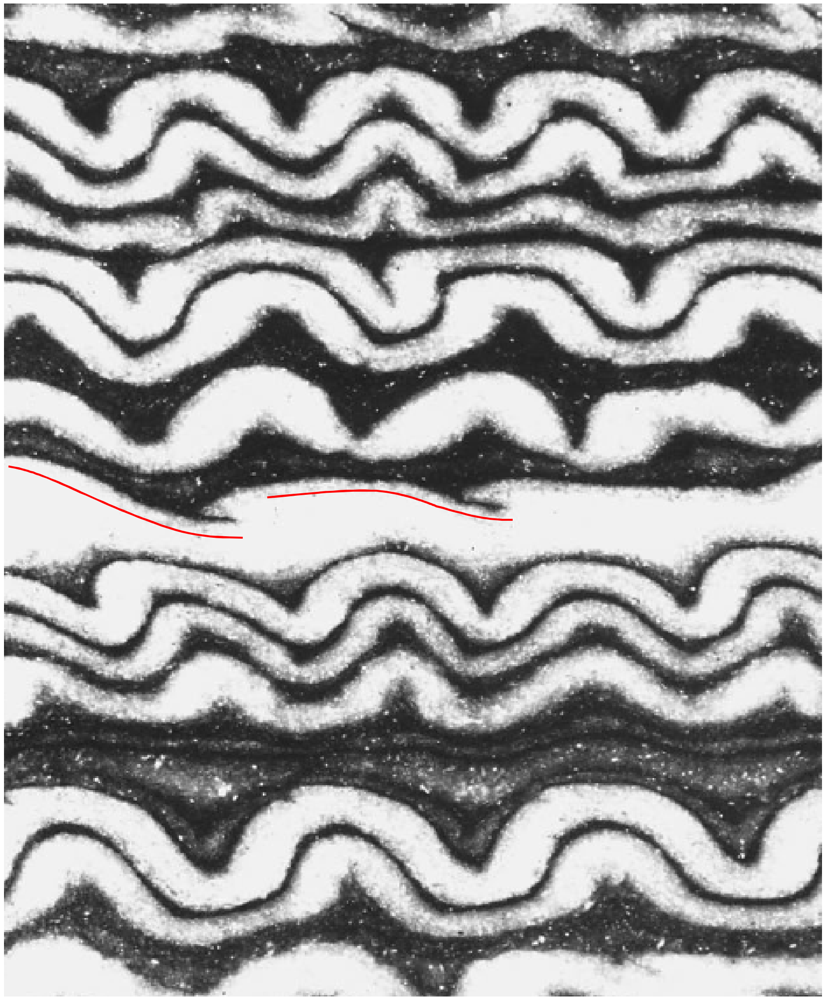
Fold Shape

similar fold

parallel fold

ptygmatic folds

Harmonic and disharmonic folds



Small-scale folds in anhydrite of the Permian Castile Formation, TX. White layers are anhydrite; dark layers are rich in calcite and organic material

Harmonic folds have approximately the same wavelength and amplitude within stacked strata

Disharmonic folds have different wavelengths and/or amplitudes

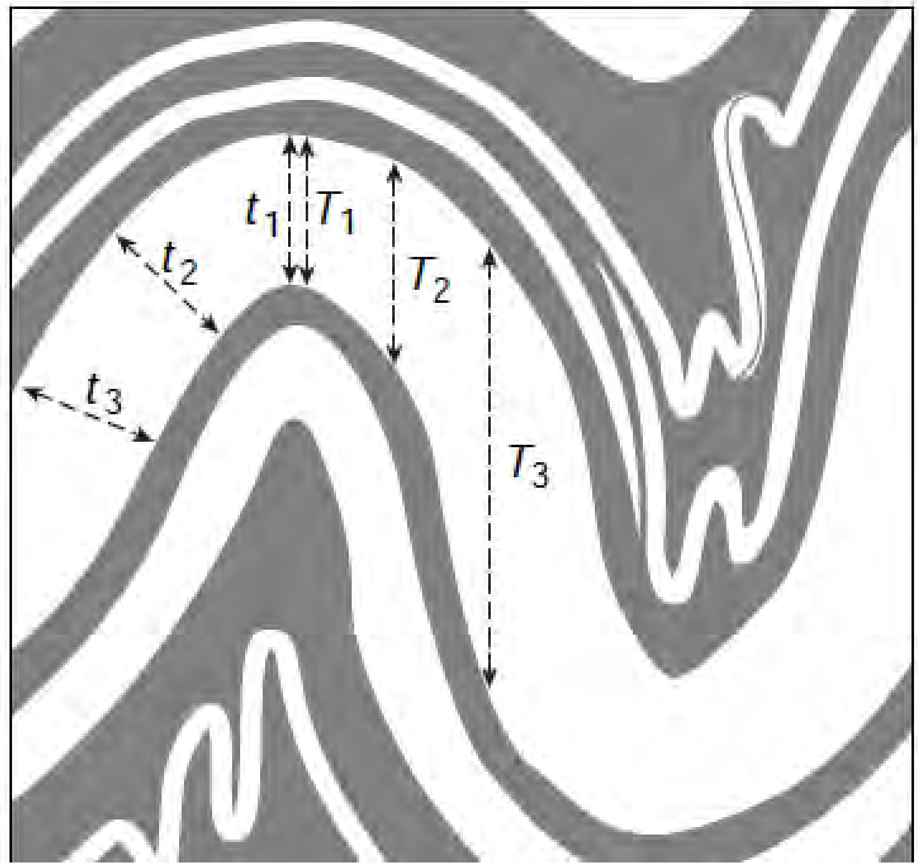
← Note that harmonic, disharmonic, and box folding varies as a function of layer thickness and detachments (above red lines) occur at the top of the thickest layer.

Fold shape Fig. 10.11a

Parallel fold

Parallel folds maintain constant layer thickness *across the fold (t1 = t2 = t3) but the layer thickness parallel to the axial surface varies (T1 < T2 < T3).*

*Note that parallelism must eventually break down in the cores of folds because of space limitation, which is illustrated by the small disharmonic folds



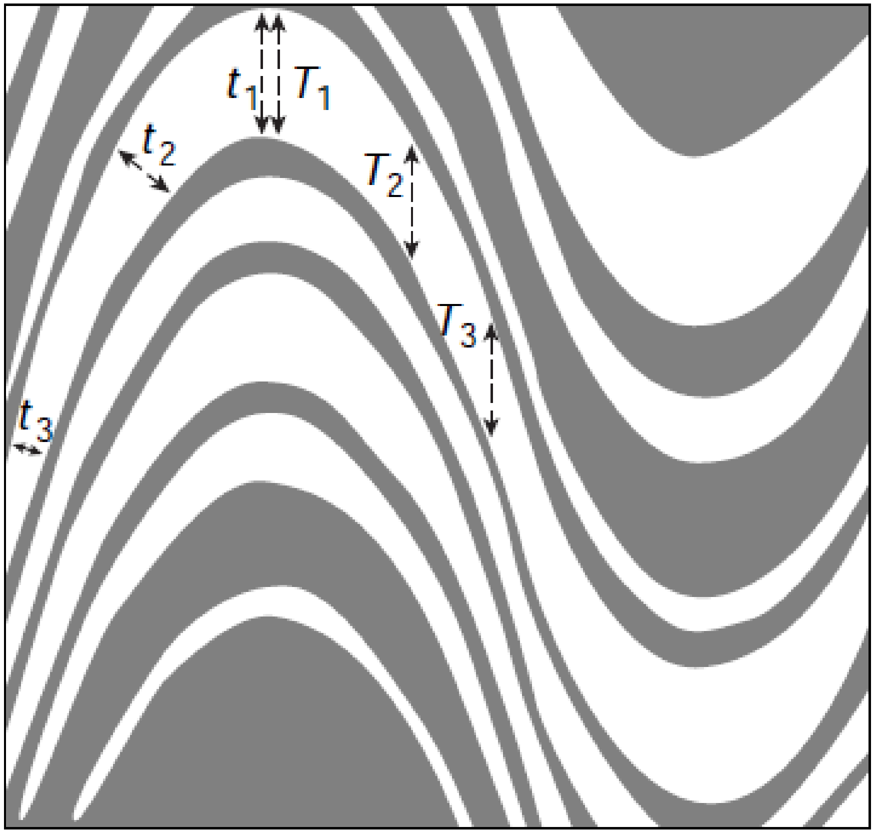
t is layer-perpendicular thickness;
T is axial trace-parallel thickness

Fold shape Fig. 10.11b

Similar fold

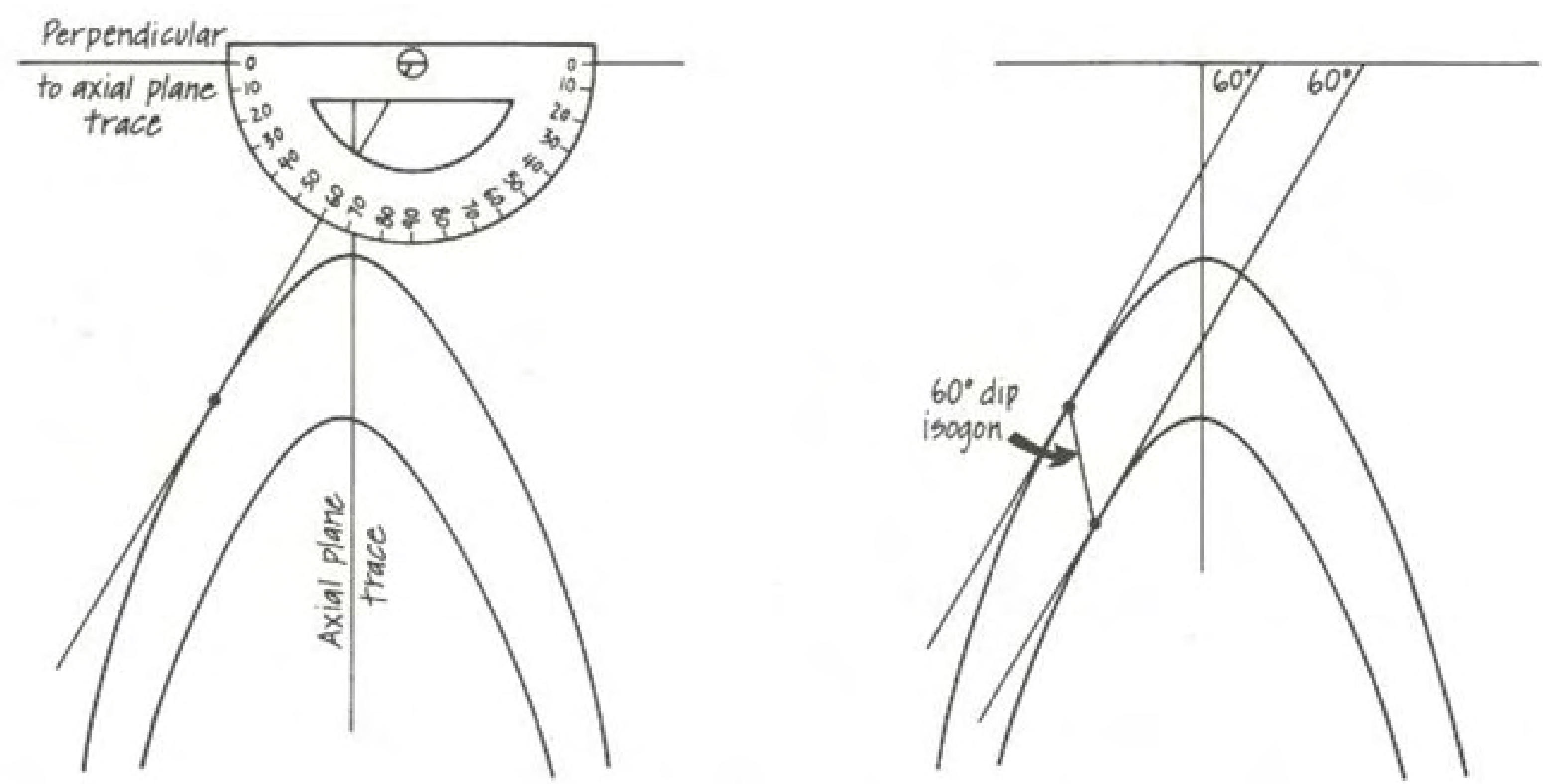
In similar folds, the layer thickness parallel to the axial surface remains constant*, so, T1 = T2 = T3, but the thickness across the folded surface varies (t1 > t2 > t3).*

Similar folds do not produce the space problem inherent in parallel folds.



t is layer-perpendicular thickness;
T is axial trace-parallel thickness

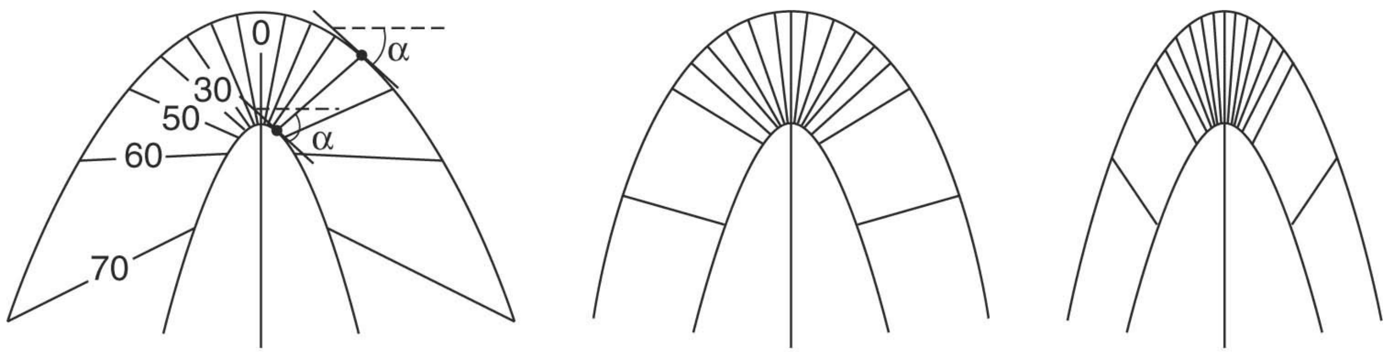
Fold classification based on dip isogons



The construction of a single dip isogon is shown, which connects the tangents to the upper and lower boundary of the folded layer with equal angle (α) relative to a reference frame;

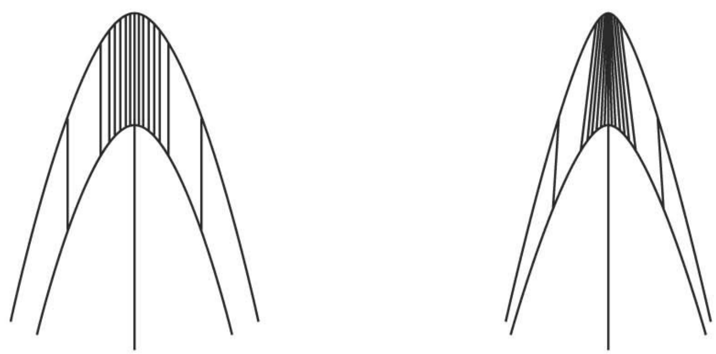
Fold classification based on dip isogons Fig. 10.12

Class 1 folds (a–c) have convergent dip isogon patterns



(a) Class 1A (b) Class 1B (parallel) (c) Class 1C

Class 2 folds (d) are parallel



(d) Class 2 (similar) (e) Class 3

Class 3 folds (e) have divergent dip isogon patterns

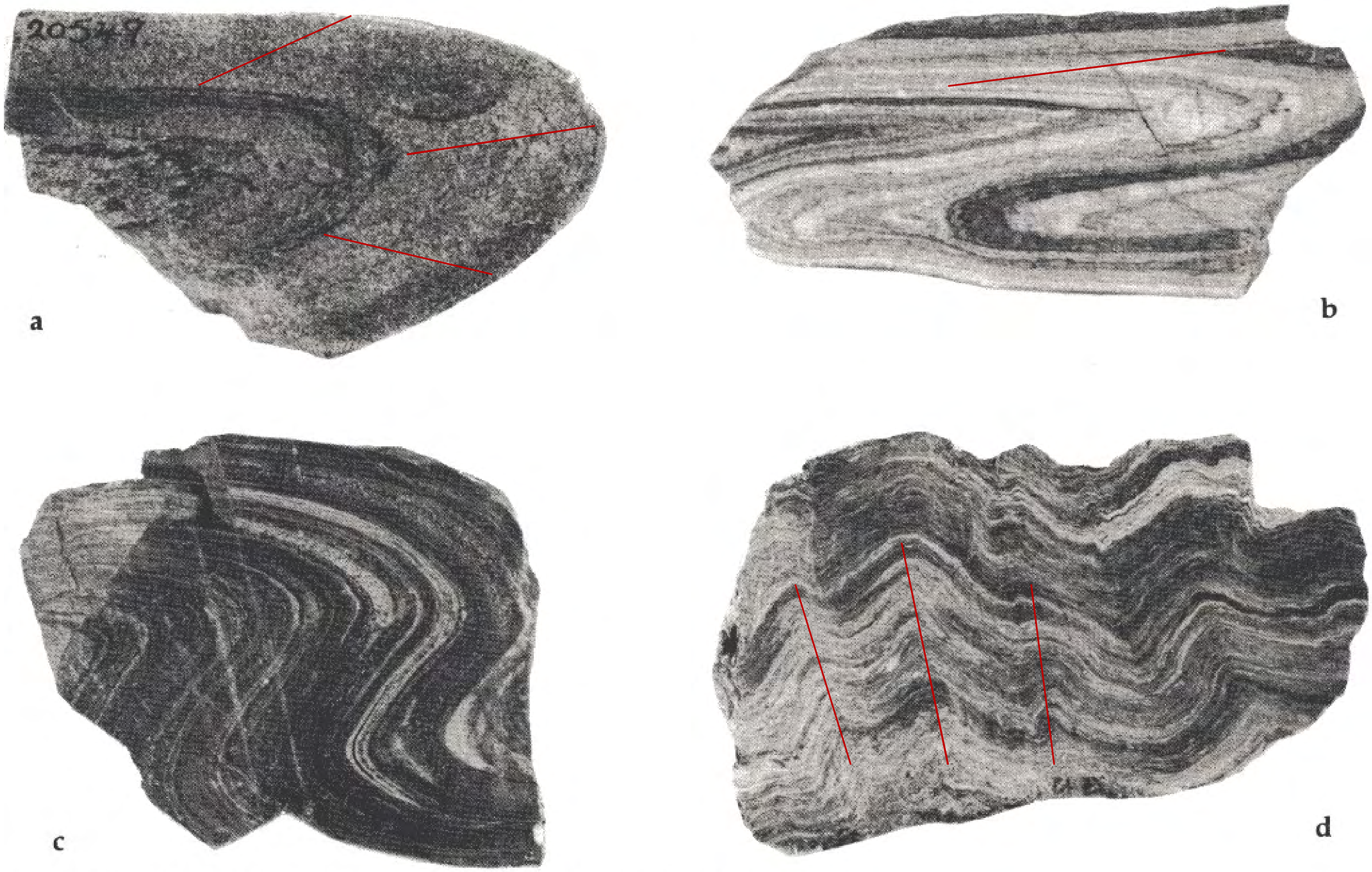
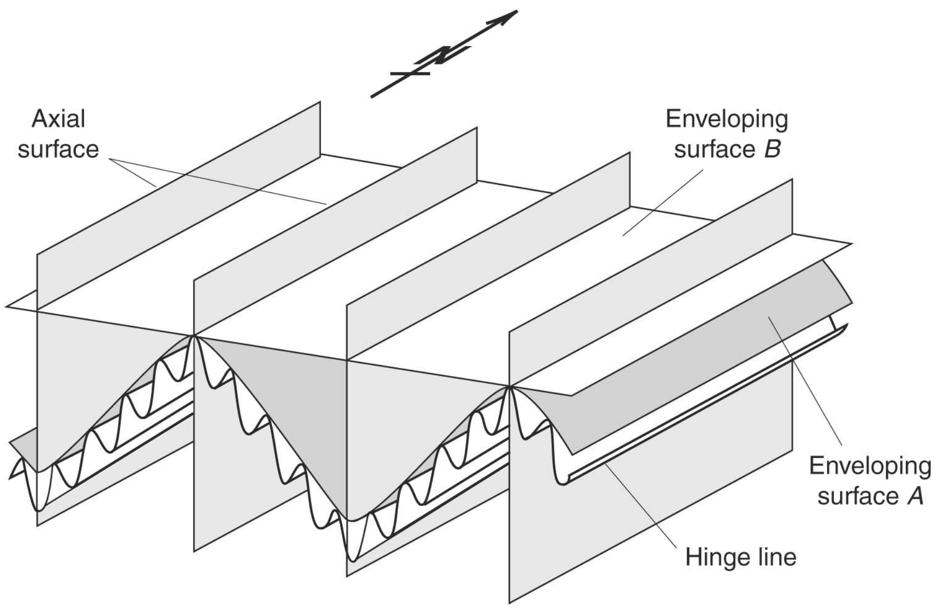
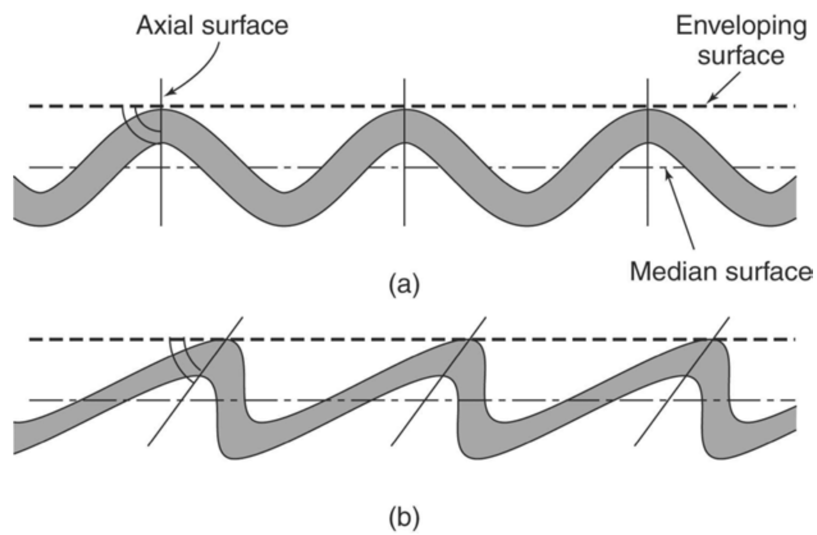


Fig. 6.17 Slabs of folds for use in Problem 6.3. From the collection of O.T. Tobisch.

Enveloping surface and fold (a)symmetry Fig. 10.13

A series of anticlines and synclines is a fold system





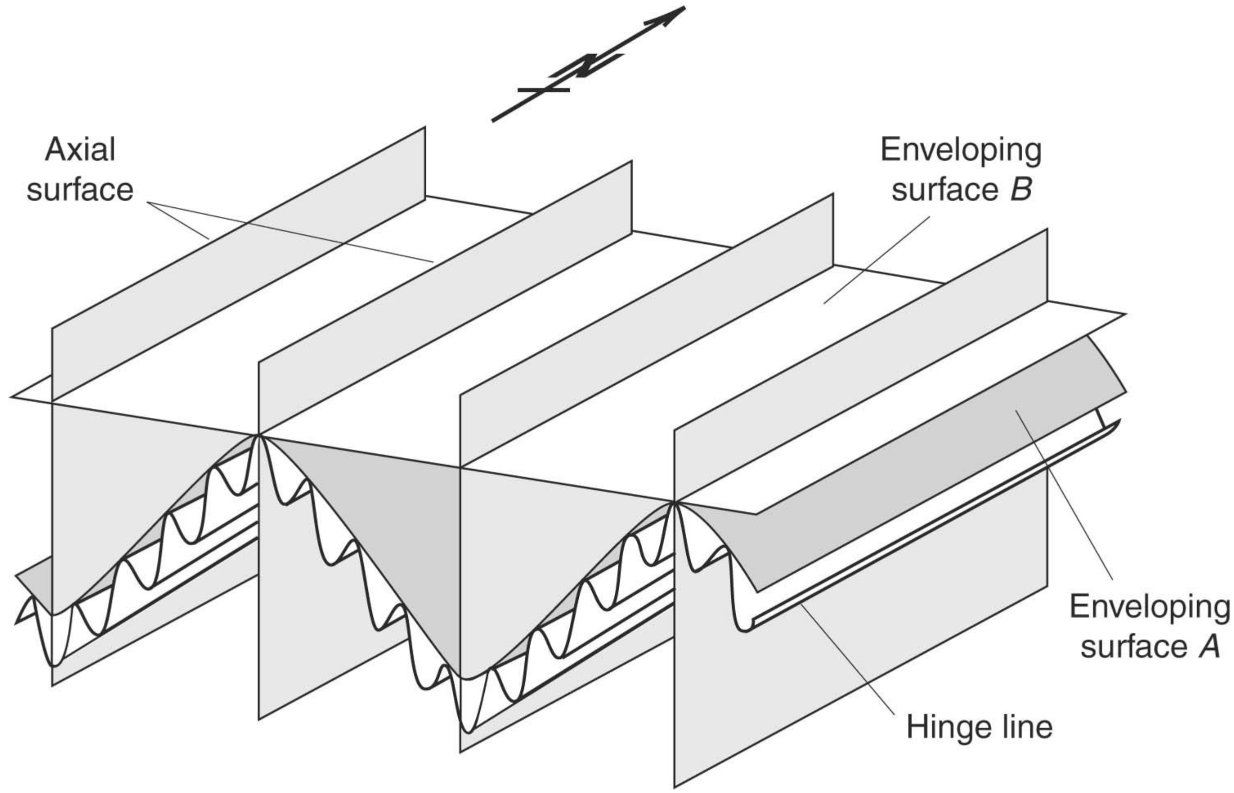
The fold enveloping surface.

a. Symmetric; orthorhombic; ~90^o
b. Asymmetric; monoclinic; < 90^o

Enveloping surface and fold (a)symmetry Fig. 10.13

The **enveloping surface** connects the antiform (or synform) hinges of consecutive folds (surface *A*).

If this imaginary surface appears to be folded itself, we may construct yet a higher-order enveloping surface (surface *B*).

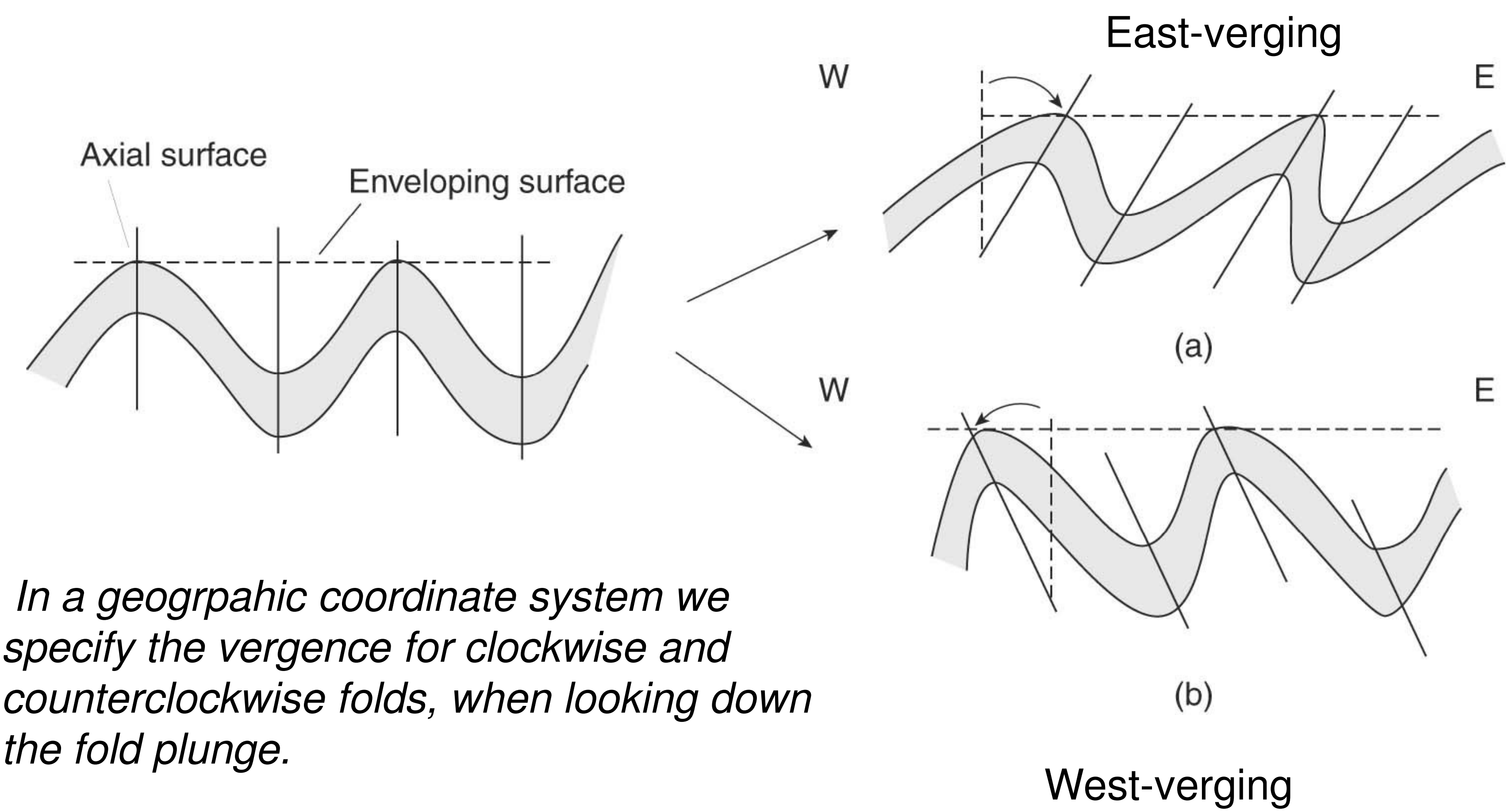


Note that the orientations (hinge line and axial surface) of the small folds and the large-scale folds are very similar.

Fold vergence

Fig. 10.15

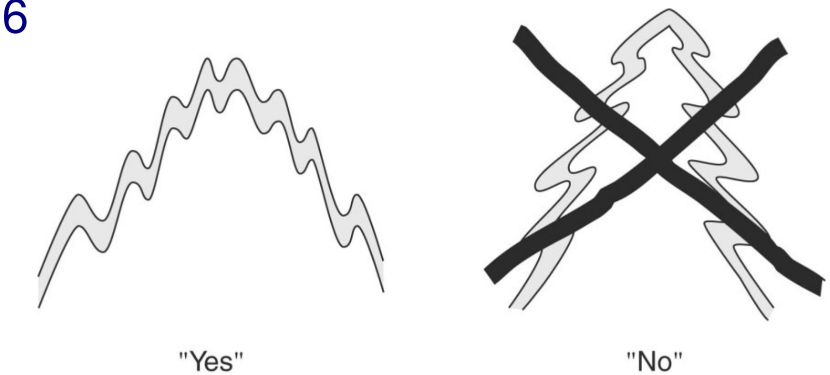
Is defined by (apparent) rotation of axial surface from a hypothetical symmetric fold into observed asymmetric fold, without changing orientation of enveloping surface.

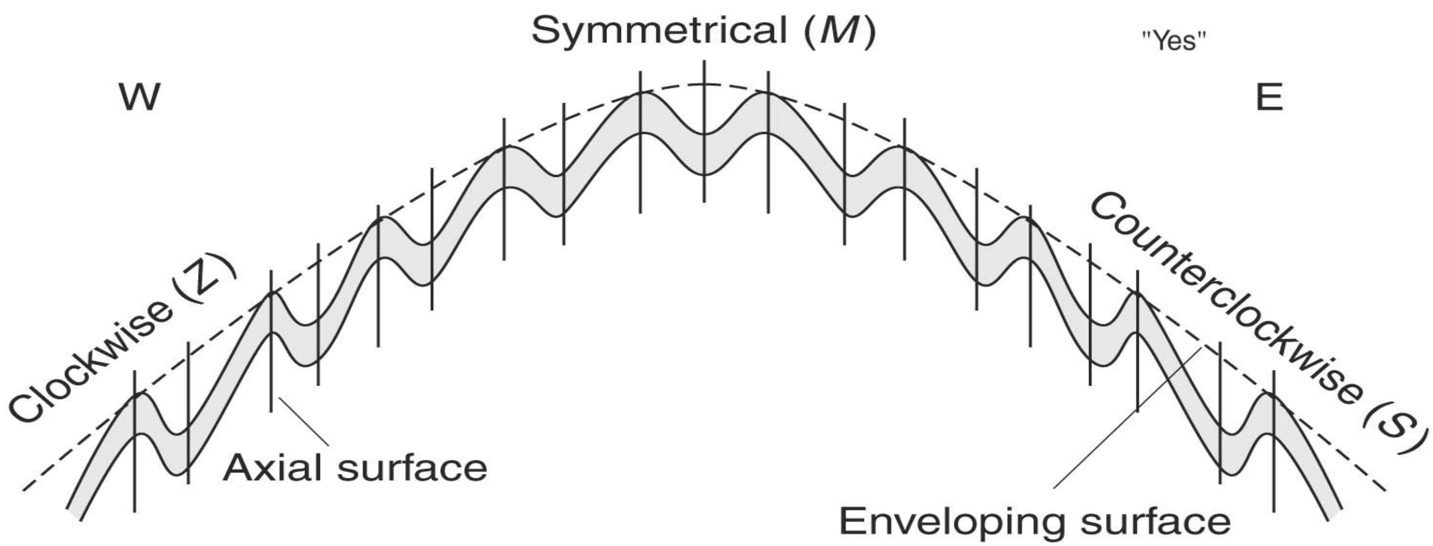


In a geogrpahic coordinate system we specify the vergence for clockwise and counterclockwise folds, when looking down the fold plunge.

Fold vergence – Antiform Fig. 10.16

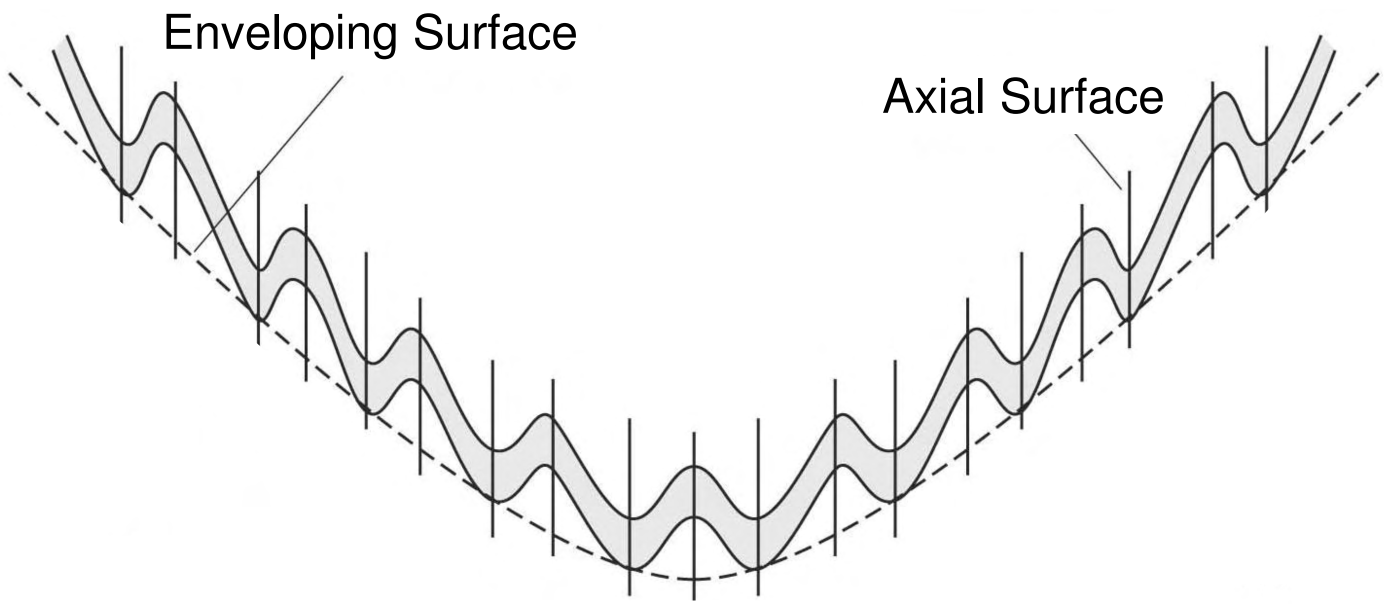
Parasitic folds across a large-scale antiform



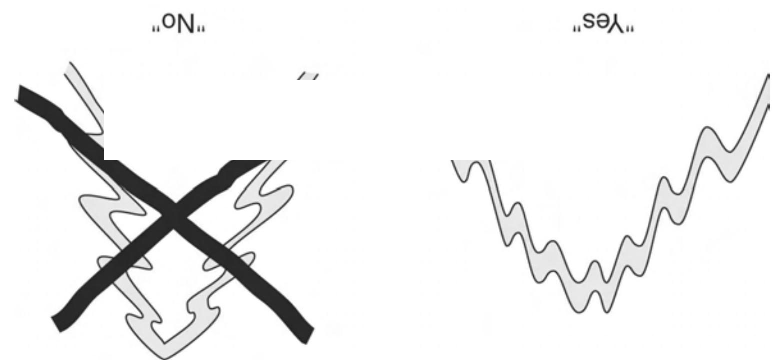


Looking down the fold axis, the parasitic fold changes from clockwise asymmetry (east-verging in the geographic coordinate system) to symmetric to counterclockwise asymmetry (west-verging) when going from W to E.

Fold vergence - Synform

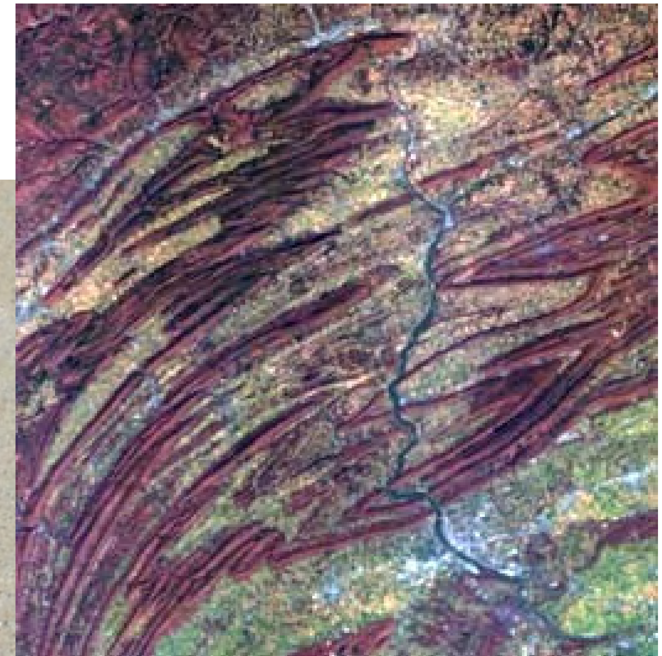


Parasitic folds across a large-scale synform



En-echelon folds

Hand specimen



Satellite view of central Appalachians

Fold Classification

1. F**acing direction** - upward or /downward?

2. *Orientation* of axis, hinge line,
   and axial surface,
   Is there symmetry and vergence?

3. Size with respect to amplitude and
   wavelength

4. Profile shape and interlimb angle,
   is it similar or parallel?

5. Is the 3D shape cylindrical or
   non-cylindrical and are there
   secondary features in the
   axial plane foliation or lineation?

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Vertical: 80°–90°	

TABLE 10.3	FOLD CLASSIFICATION BY INTERLIMB ANGLE
Isoclinal	0°–10°
Tight	10°–60°
Open	60°–120°
Gentle	120°–180°

DePaor, 2002

Fold Style

TABLE 10.4 | THE CHARACTERISTIC ELEMENTS OF FOLD STYLE

- In profile plane, is the fold classified as parallel or similar (or a further refinement)?
- What is the interlimb angle in profile?
- In three dimensions, is the fold cylindrical or noncylindrical?
- Is there an associated axial plane foliation and/or lineation present, and of what type are they?

Note that orientation and symmetry are not style criteria.

Super(im)posed folding: Fold Interference

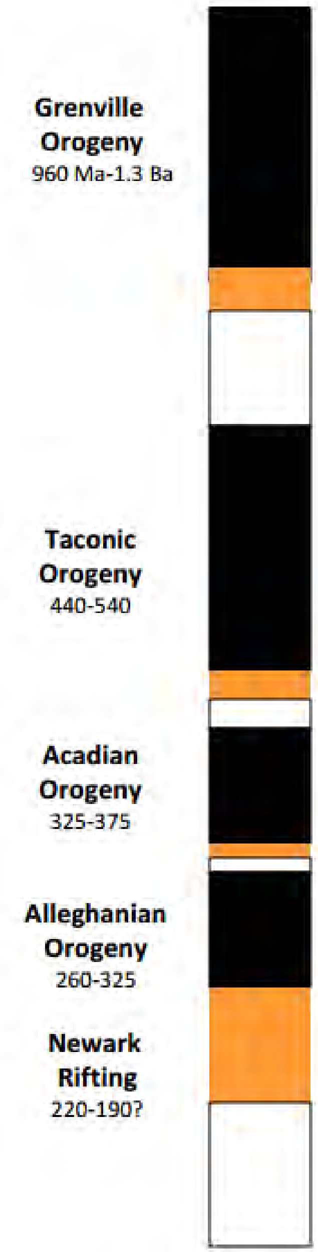
- Structural geologists use the term **fold generation** to refer to groups of folds that formed at approximately the same time interval and under similar kinematic conditions.

- A fold generation in an area can be referred to using a letter label *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** (such as the Siluro-Devonian “Acadian” phase in the Appalachians or the Cretaceous-Tertiary “Laramide” phase in the North American Cordillera, 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.

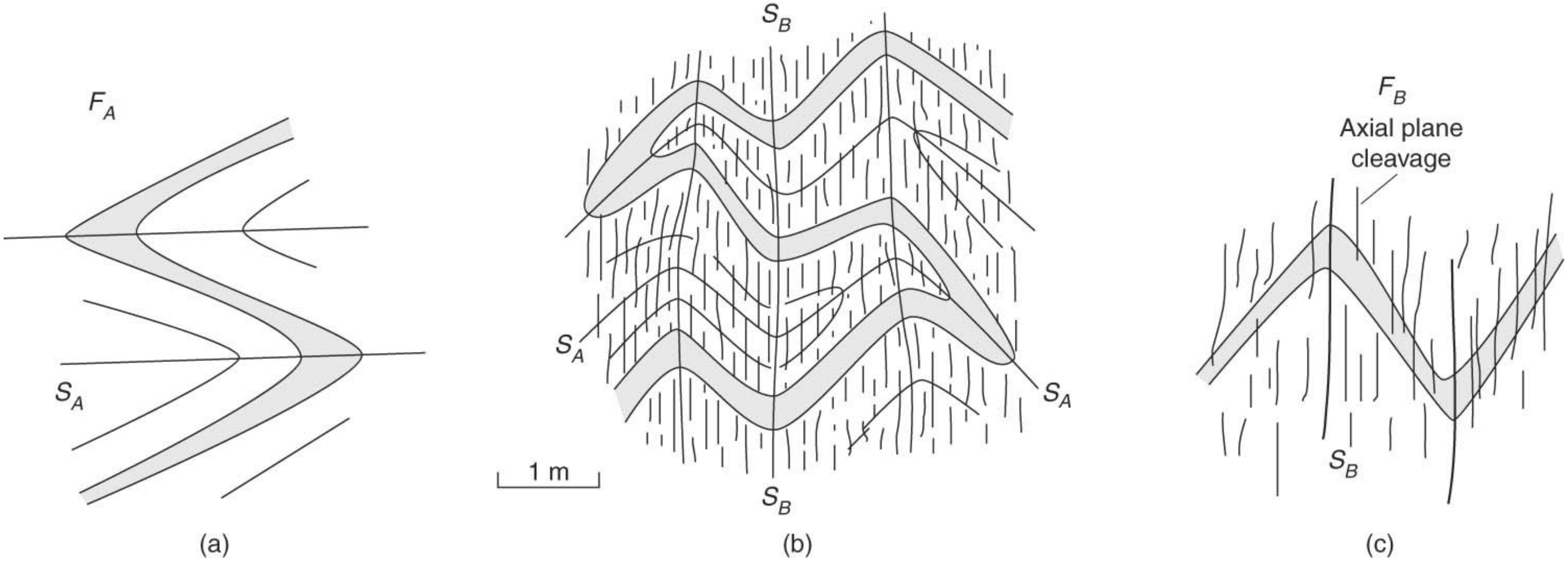
- The relative time principle of **superposed folding** is simple: folds of a later generation are superimposed on folds of an earlier generation.



Fold interference Fig. 10.23

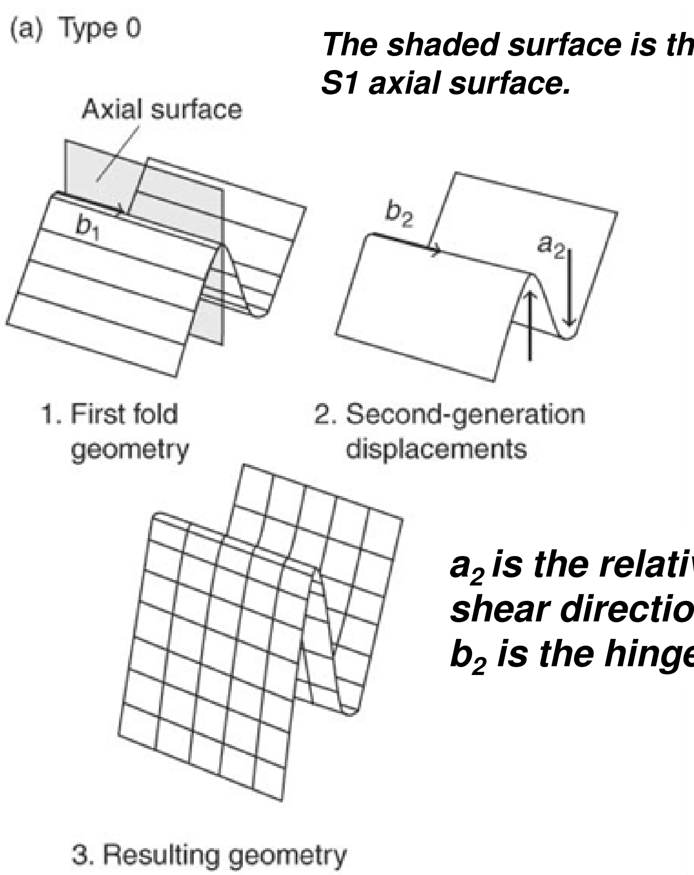
a superposed fold must be younger than the structure it folds.

F_A recumbent folds (a) are overprinted by F_B upright folds producing the fold interference pattern in (c).



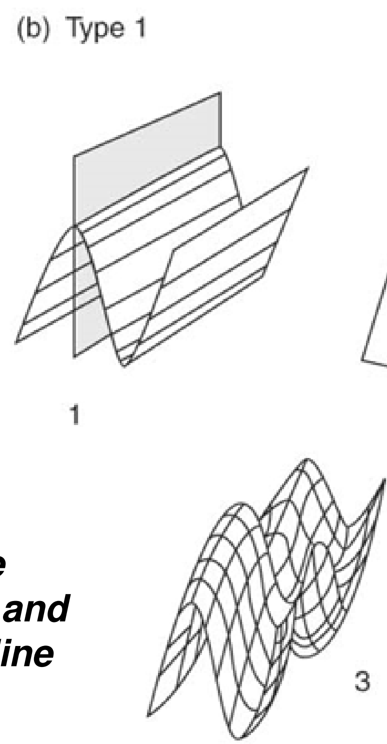
Four basic patterns of fold interference Fig. 10.24

- *The analysis assumes that F2 shear folds are superimposed on a preexisting F1 fold of variable orientation.*

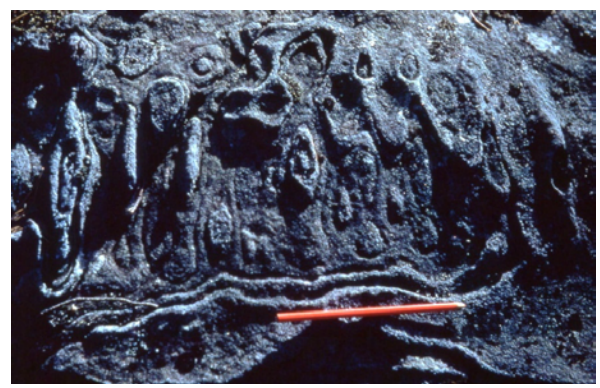


The shaded surface is the S1 axial surface.

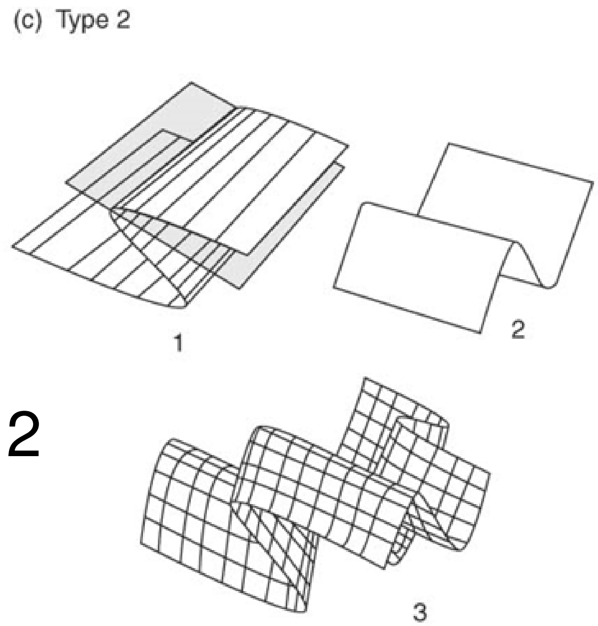
a_2 is the relative shear direction and b_2 is the hinge line



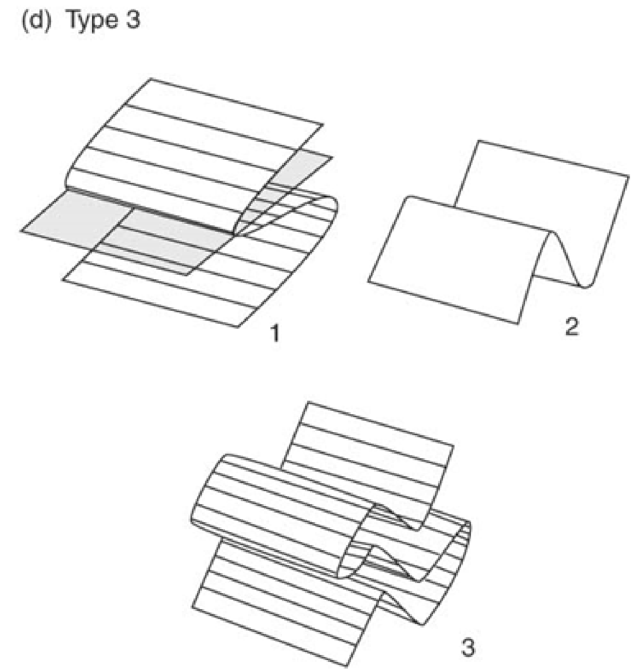
Type 1



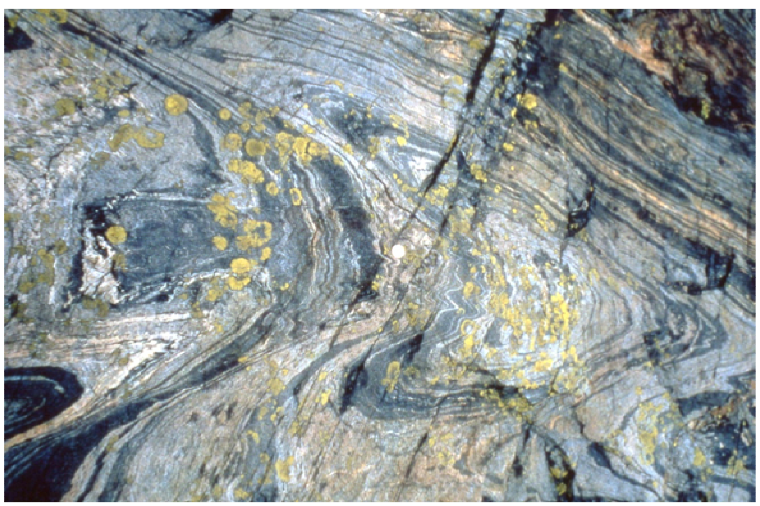
Four basic patterns of fold interference Fig. 10.24



Type 2

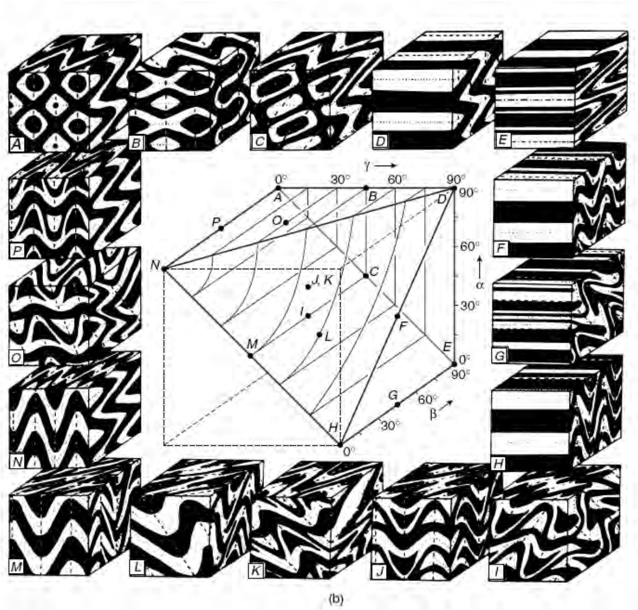


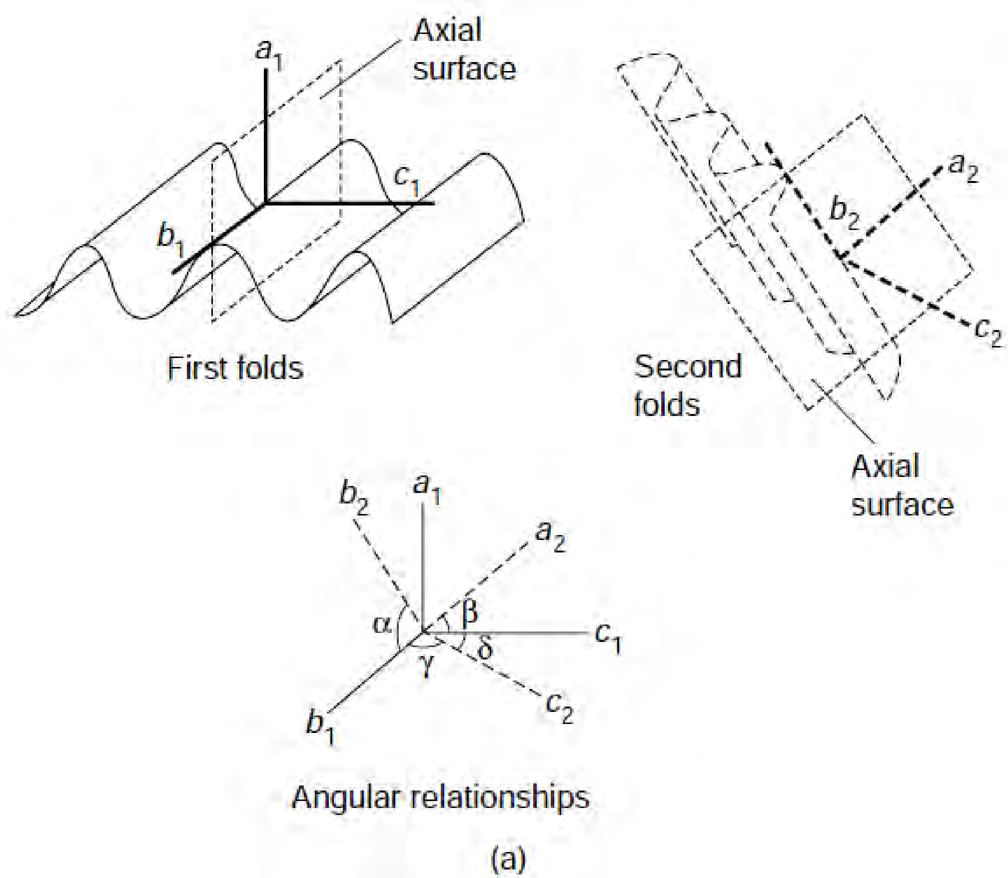
Type 3



Fold interference scheme Fig. 10.25

Geometric axes are used to describe the orientation of fold generations F1 and F2 that produce a wide range of intererence patterns when combined at carious angles:





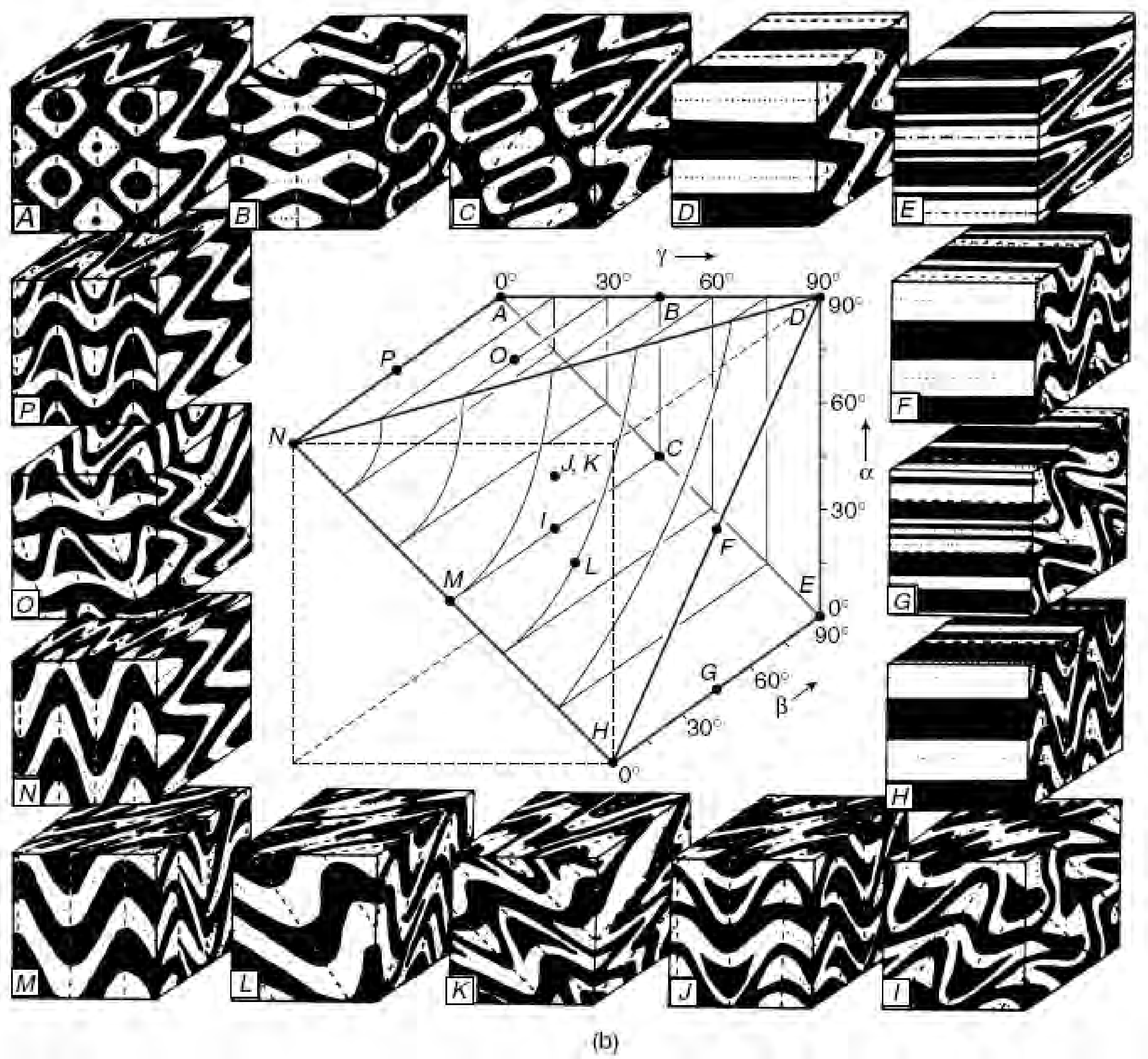
Fold interference scheme Fig. 10.25

In all patterns, layering was initially parallel to front face of cube.

F1 resembles case D;

F2 is similar to the folding in case D, but with different orientations.

Axial surface S1 is shown with dotted lines and axial surface S2 with dashed lines.



The Mechanics of Folding Sec.10.7 Passive Folding

Elevated temperatures can produce the right conditions for ***passive folding*** and it is common to find toothpaste-like structures in deformed metamorphic rocks.

Rocks that were deformed at or near their melting temperature have little or no competency contrast between layers and can form **migmatites,** which often contain wonderfully complex fold structures →

FIGURE 2.22 A migmatite from the North Cascades (Washington State, USA) showing complex folding and disruption.

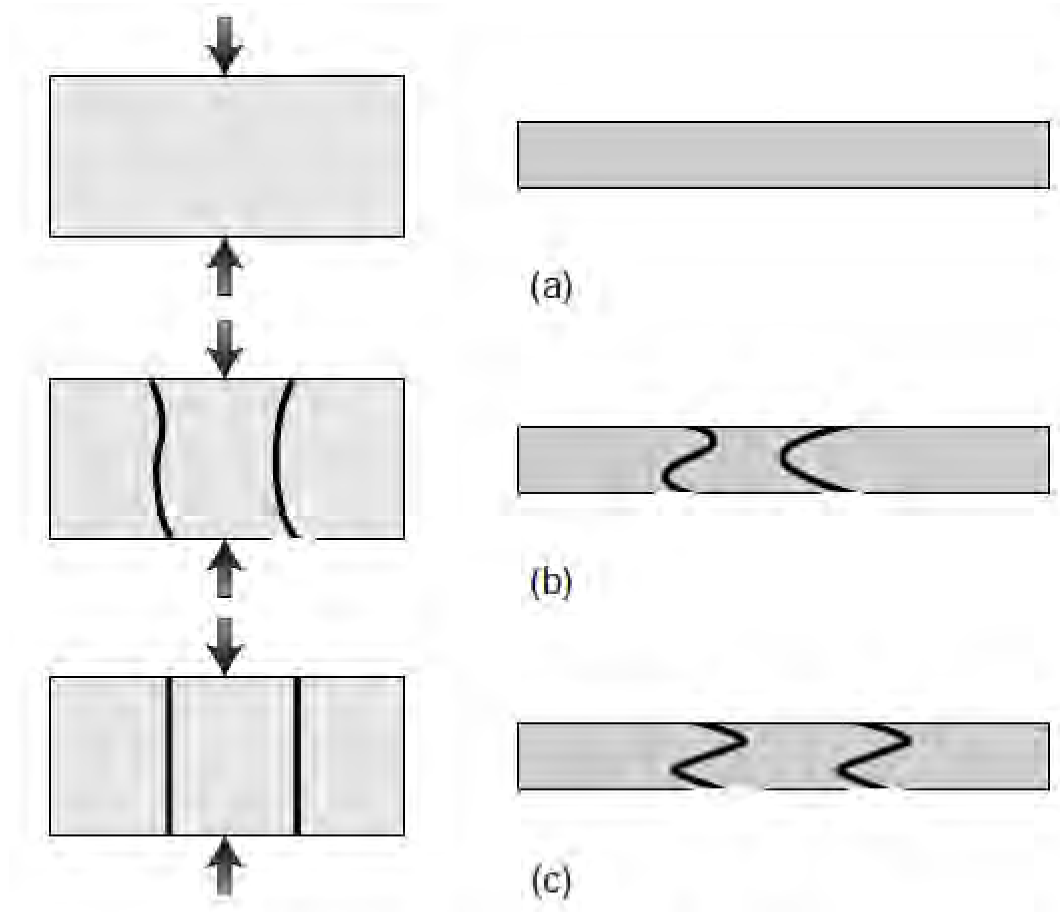
Similarly, passive folding occurs in glaciers that deform close to their melting temperature

The Mechanics of Folding Fig. 10.27 Passive Folding

Compression of a clay block of uniform color

with irregularly shaped layers of different colors

or with uniform colored layers separated by thin sheets of rubber



The Mechanics of Folding Sec.10.7 Active Folding

- During **active folding,** also called **flexural folding,** the layering has mechanical significance.

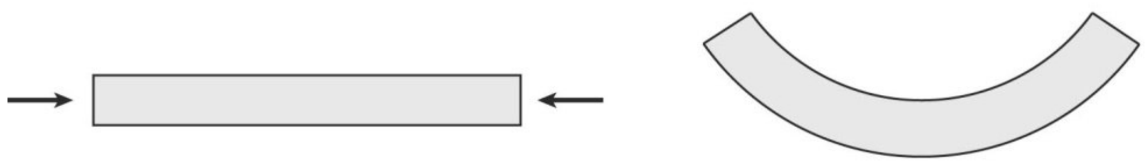
- ***There are two dynamic conditions for active folding: bending and buckling.***

In nature bending occurs during basin formation or flexural loading of a lithospheric plate, or during the development of monoclines over fault blocks.

In ***bending***, the applied force is oriented at an oblique angle to the layering

(a)

In ***buckling***, the force is oriented parallel to the mechanical anisotropy and is the most common

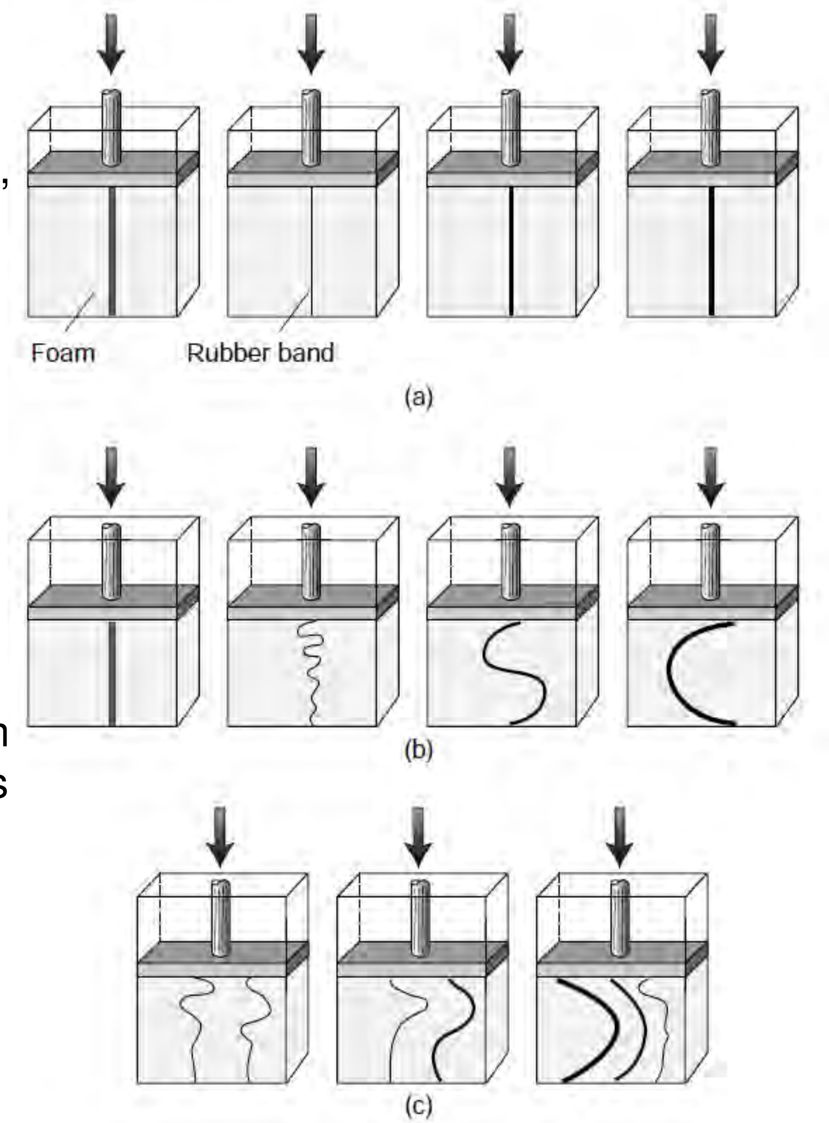


(b)

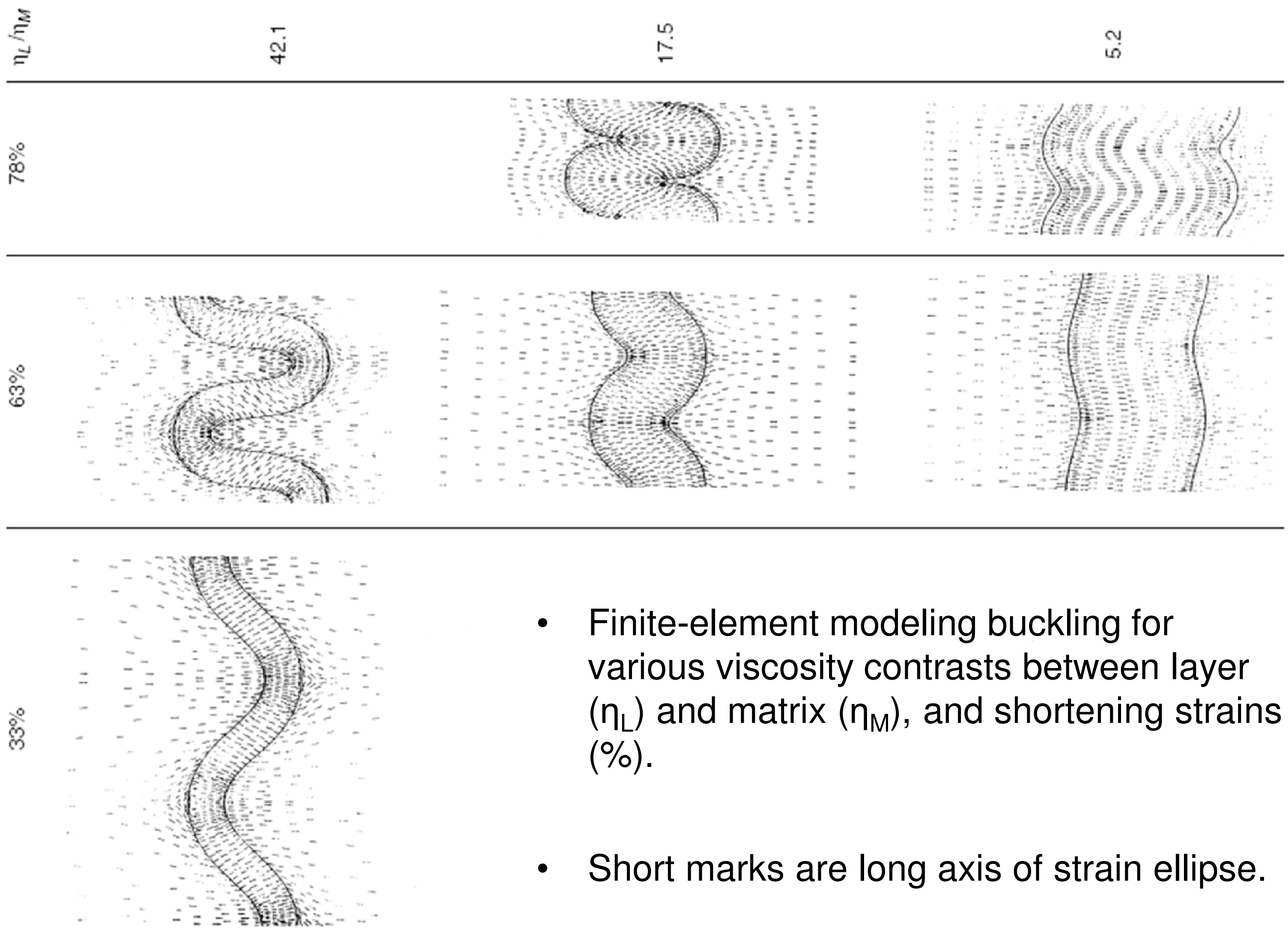
The Mechanics of Folding Sec.10.7 Buckle-fold experiments

Line drawings of deformation experiments with transparent boxes containing foam, and rubber bands.

- Four starting settings are shown that contain, from left to right, foam only (with marker line added), a thin, a medium, and a thick rubber band.
- When applying the same displacement (b), the setups respond differently.
- The foam-only box shows thickening of the marker line, but no folding.
- The boxes with rubber bands show folds with arc lengths varying as a function of thickness of each band.
- When using more than one band (c), the behavior depends on the combination of bands and their thicknesses, with the effect of the thicker bands being dominant.



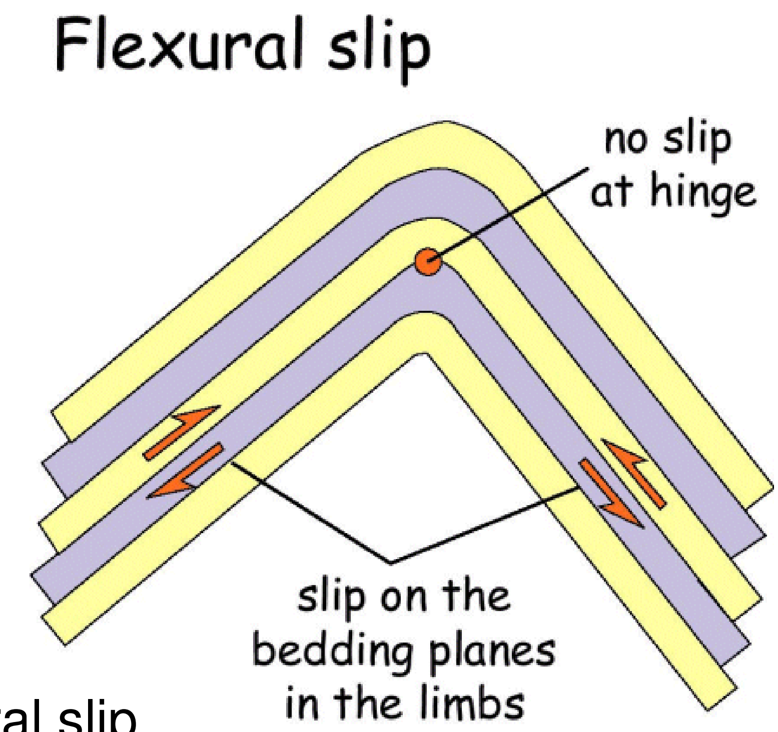
Viscosity contrast Fig. 10.31



- Finite-element modeling buckling for various viscosity contrasts between layer (η_L) and matrix (η_M), and shortening strains (%).
- Short marks are long axis of strain ellipse.

Flexural-slip fold model includes slip between layers Sec. 10.8.1

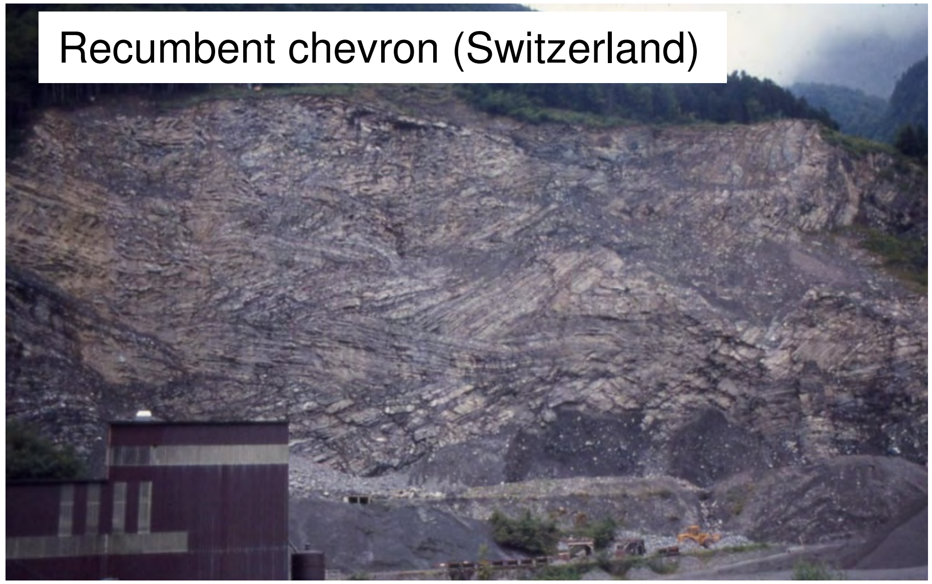
- The amount of slip between the layers increases away from the hinge zone and reaches a maximum at the inflection point.
- The amount of slip is proportional to limb dip: slip increases with increasing dip.

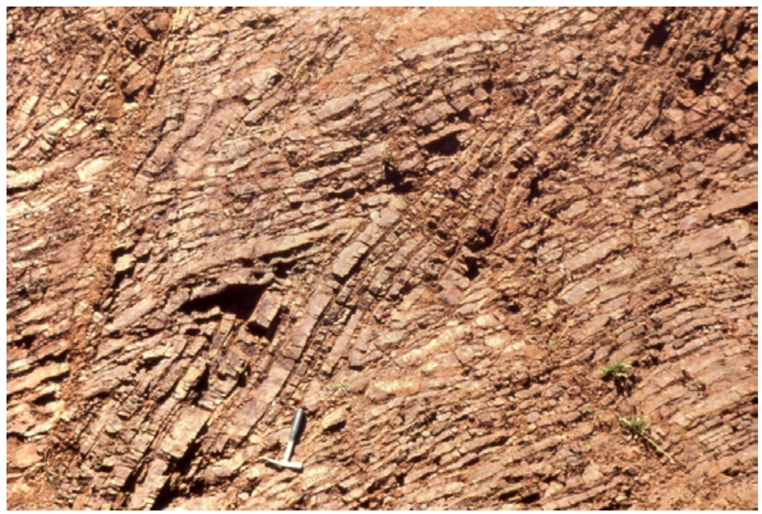


- A geometric consequence of the flexural slip model is that the fold is cylindrical and parallel (Class 1B); the bed thickness in flexural slip folds does not change.

Chevron and kink folds are examples of flexural slip folding in natural rocks that form because of a strong layer anisotropy.

Fold geometries: kink and chevron folds





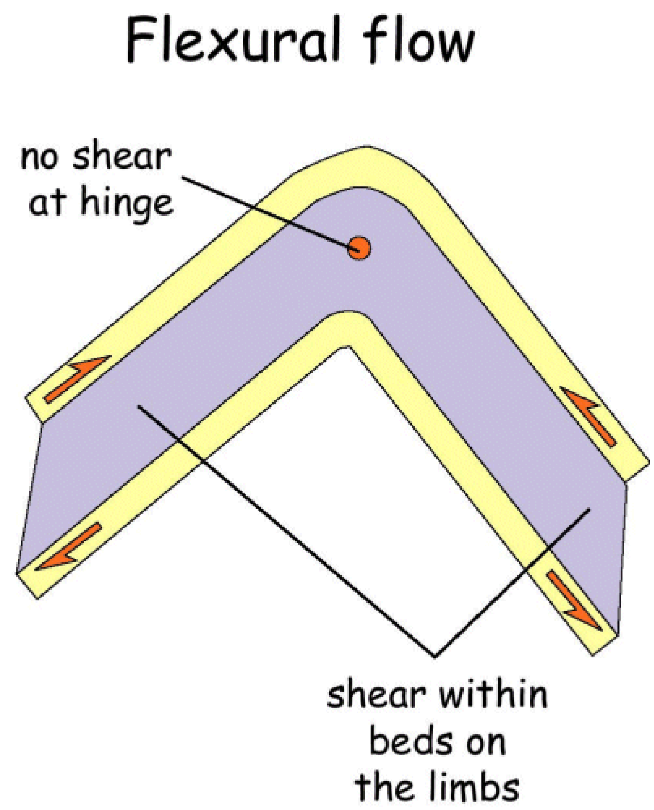
Chevron folds CA)

Flexural-flow fold model includes grain slip Sec. 10.8.1

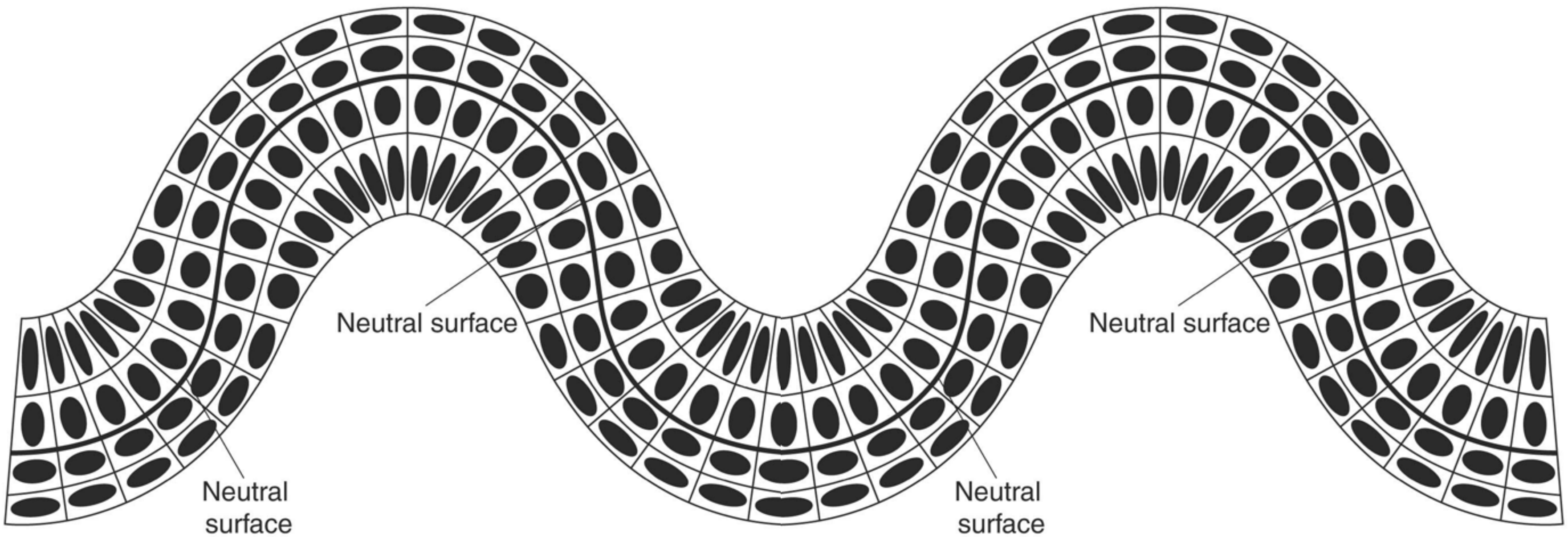
- Slip that occurs on individual grains within a layer, without the presence of visible slip surfaces, we call *flexural flow folding.*

- Although they differ in a few details, the geometric and kinematic consequences of both flexural slip and flexural flow folding are alike.

- A diagnostic feature of flexural slip folding that can be used in field analysis is that any original angular relationship in the slip surface before folding (say, flute casts in the bedding surfaces of turbidites) will maintain this angular relationship across the fold, because there is no strain on the top and bottom of the folded surface.



Neutral-surface fold model also results in parallel folds



A **neutral-surface fold** is a parallel fold having a zero-strain surface

Shear fold model Sec. 10.8.1

- Shear folds are passive features.

- While slip occurs on individual cards, the slip surface and the slip vector are not parallel to the folded surface, as they are with flexural folding.

- Most notably, shear folds have a distinct, *similar-fold (Class 2)* shape with the layer on each card remaining equal in length after shearing.

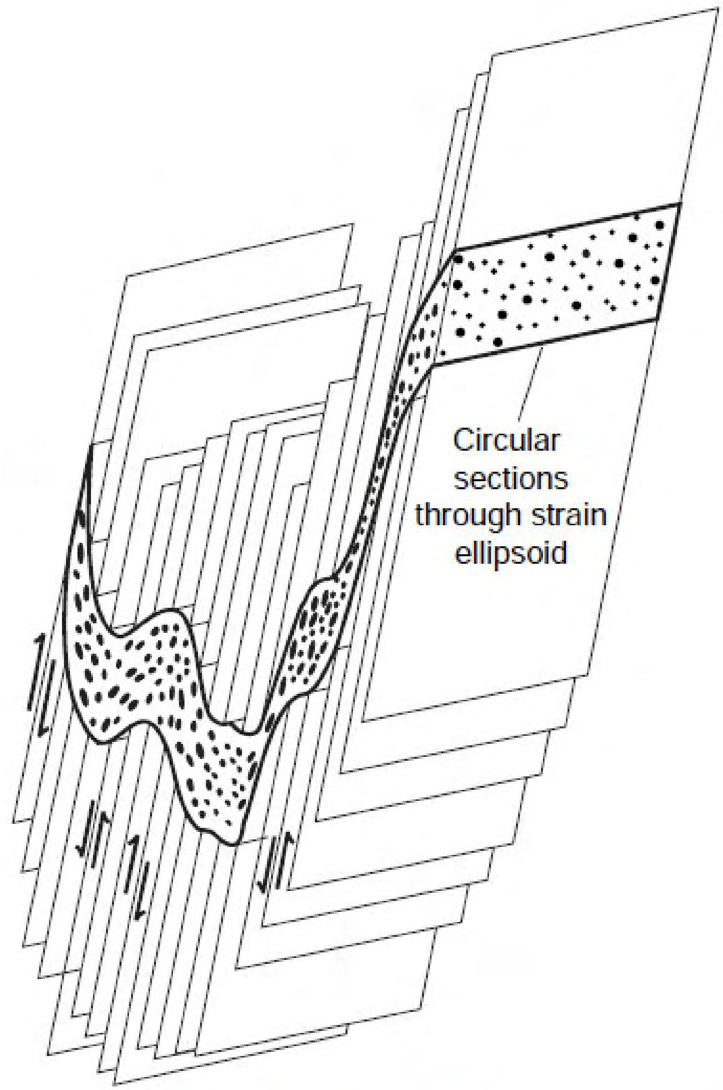
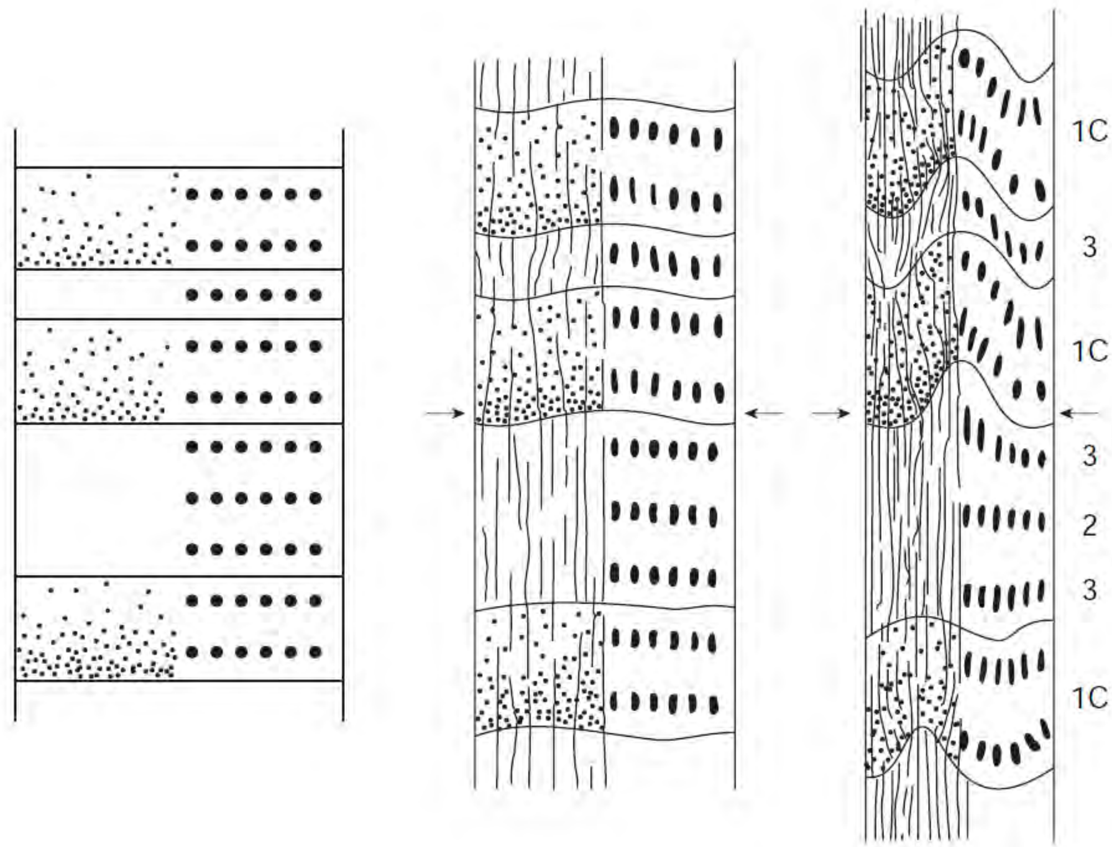


FIGURE 10.34 The strain pattern of shear folding.

Natural settings produce nested folds of different Classes

In all models, Class 3 folds are unaccounted for, which brings us to natural systems in which Class 3 folds form from the interaction between layers of different competency in a multilayered system.

- Folding of a multilayer consisting of sandstone(stippled) and shale layers.
- The incompetent shale layers accommodate the strong sandstone layers that form Class 1 folds
- This results in Class 3 and Class 2 folds in shale when the sandstone layers are closely and more widely spaced, respectively.



Fault-related Folds

Fault-related Folds

Fault-bend fold Fig. 18.18

Progressive stages during development of fault-bend fold.

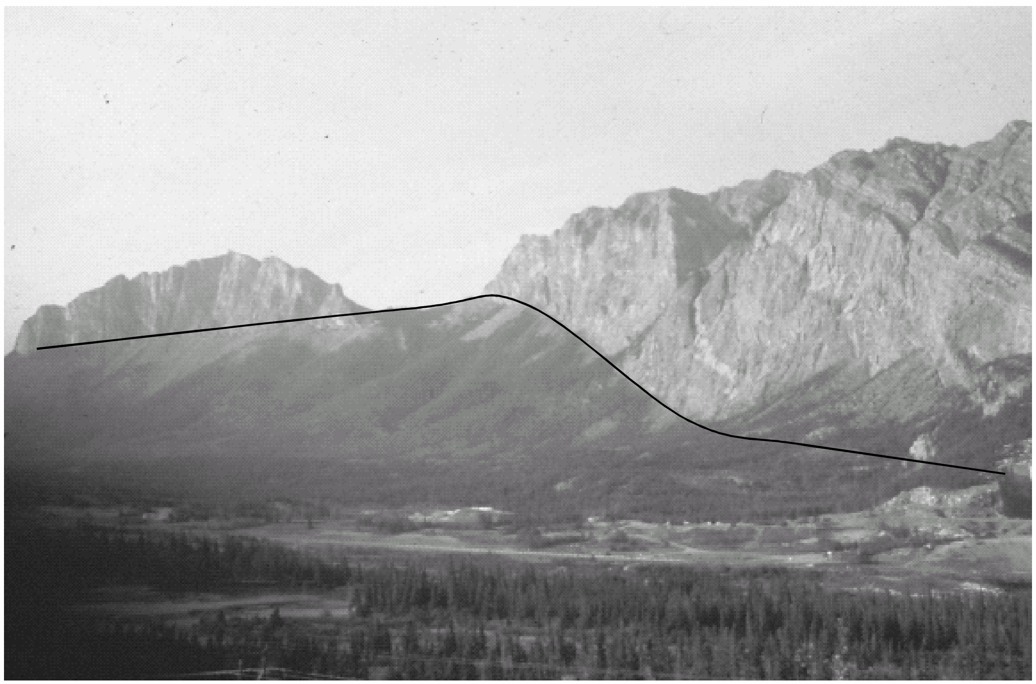
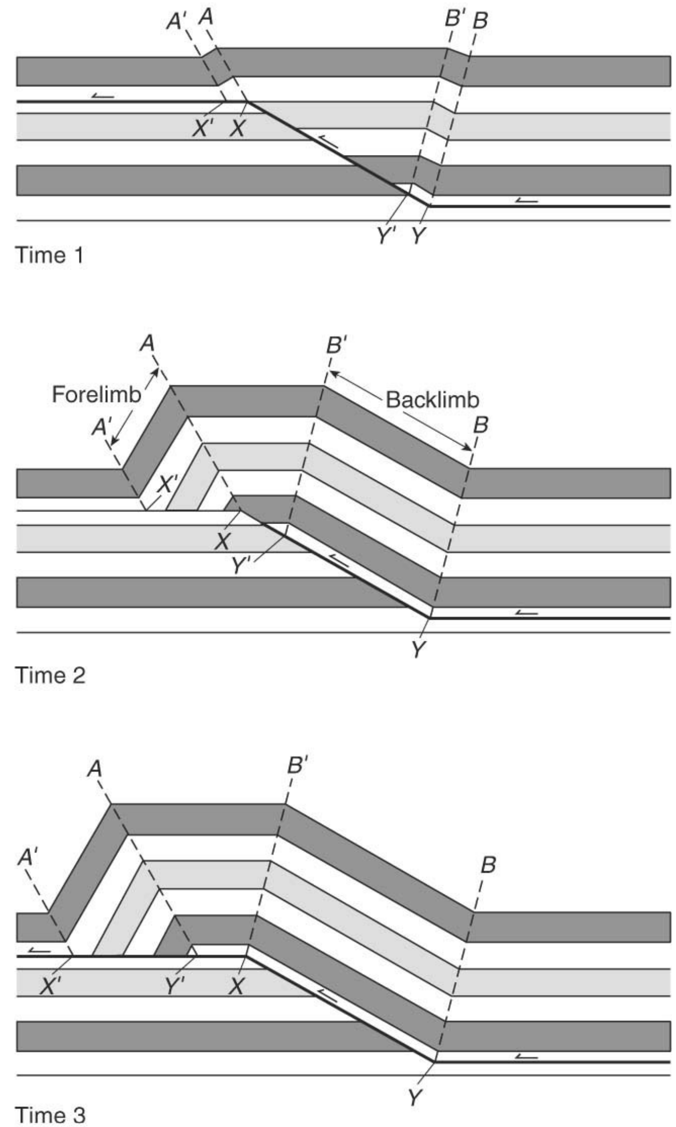


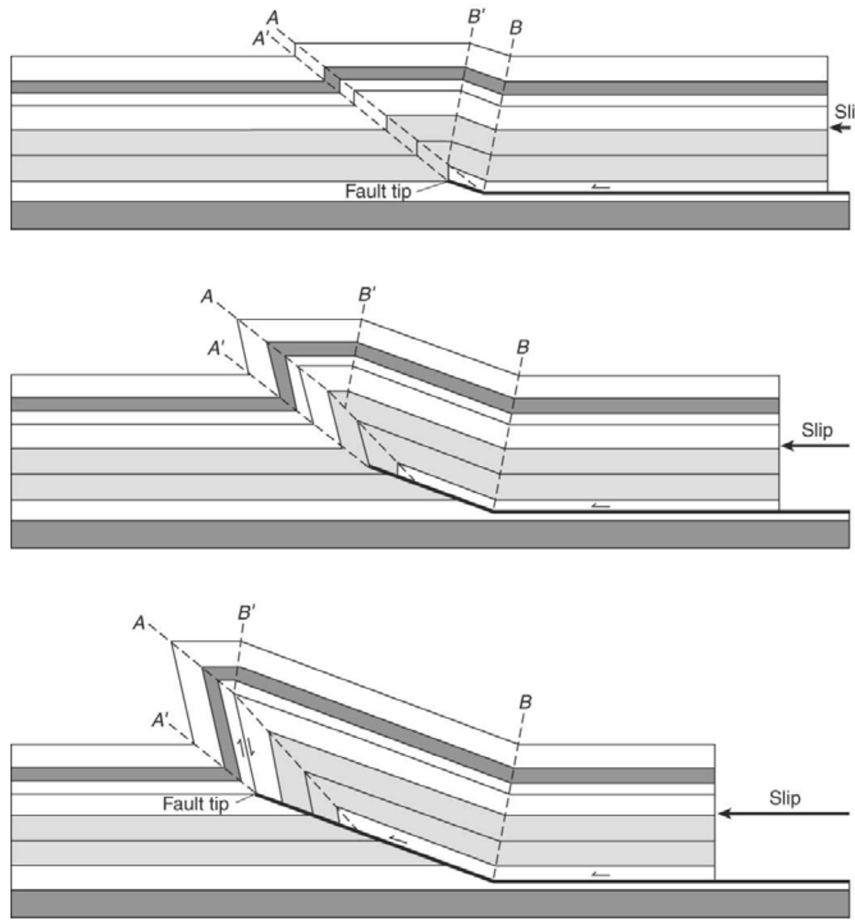
Photo of fault-bend fold above McConnell Thrust, Alberta. Paleozoic strata moved 5 km vertically and 40 km horizontally, and now lie above Cretaceous foreland basin deposits. (mirror image)



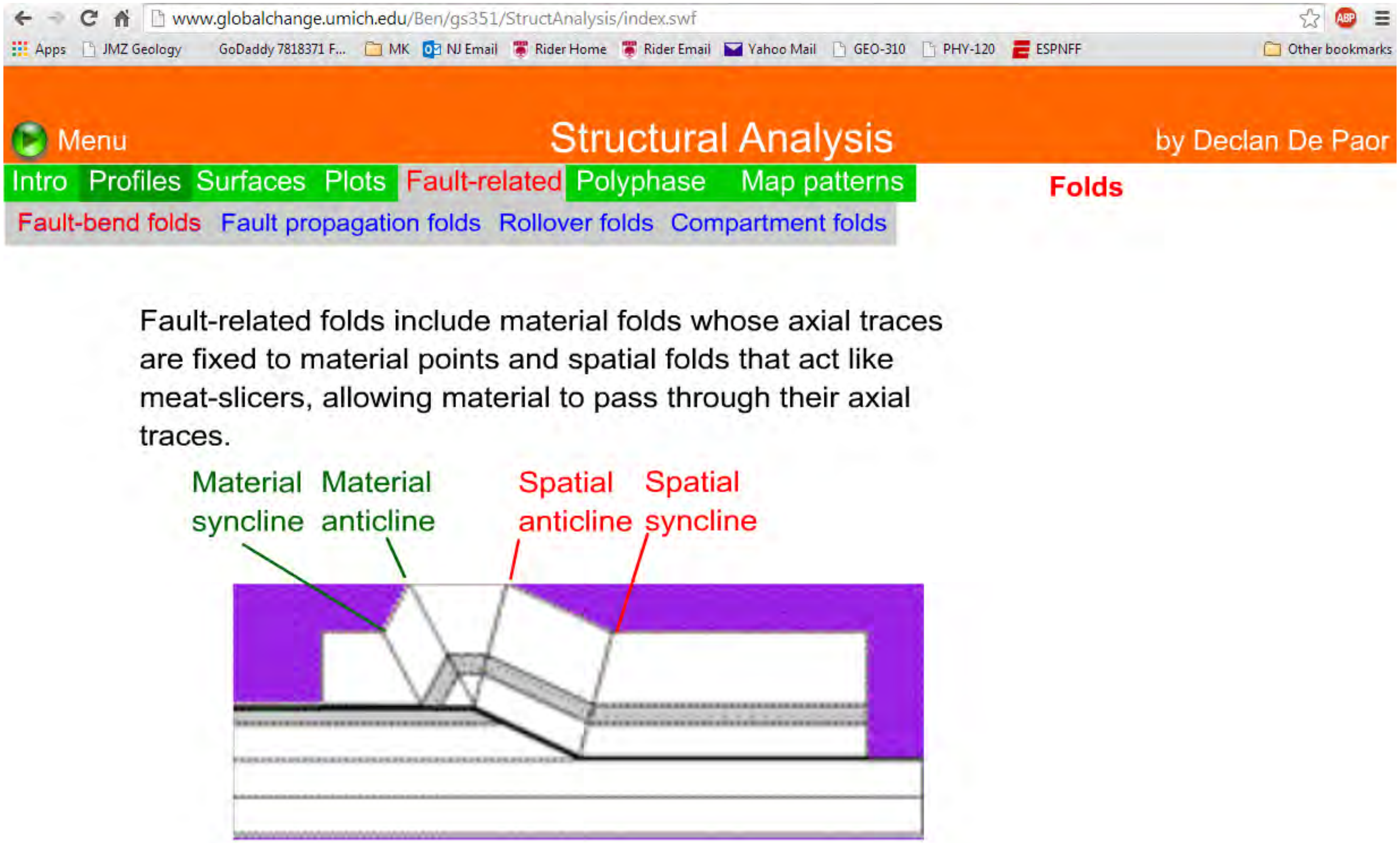
Fault-propagation fold Fig. 18.20

Exposure of a fold in the Lost River Range, Idaho, showing an asymmetric fold dying out updip in the core of a fold.

Progressive stages during development of fault-propagation fold.



Fault-related Folds



http://www.globalchange.umich.edu/Ben/gs351/StructAnalysis/index.swf

Fault-related Folding

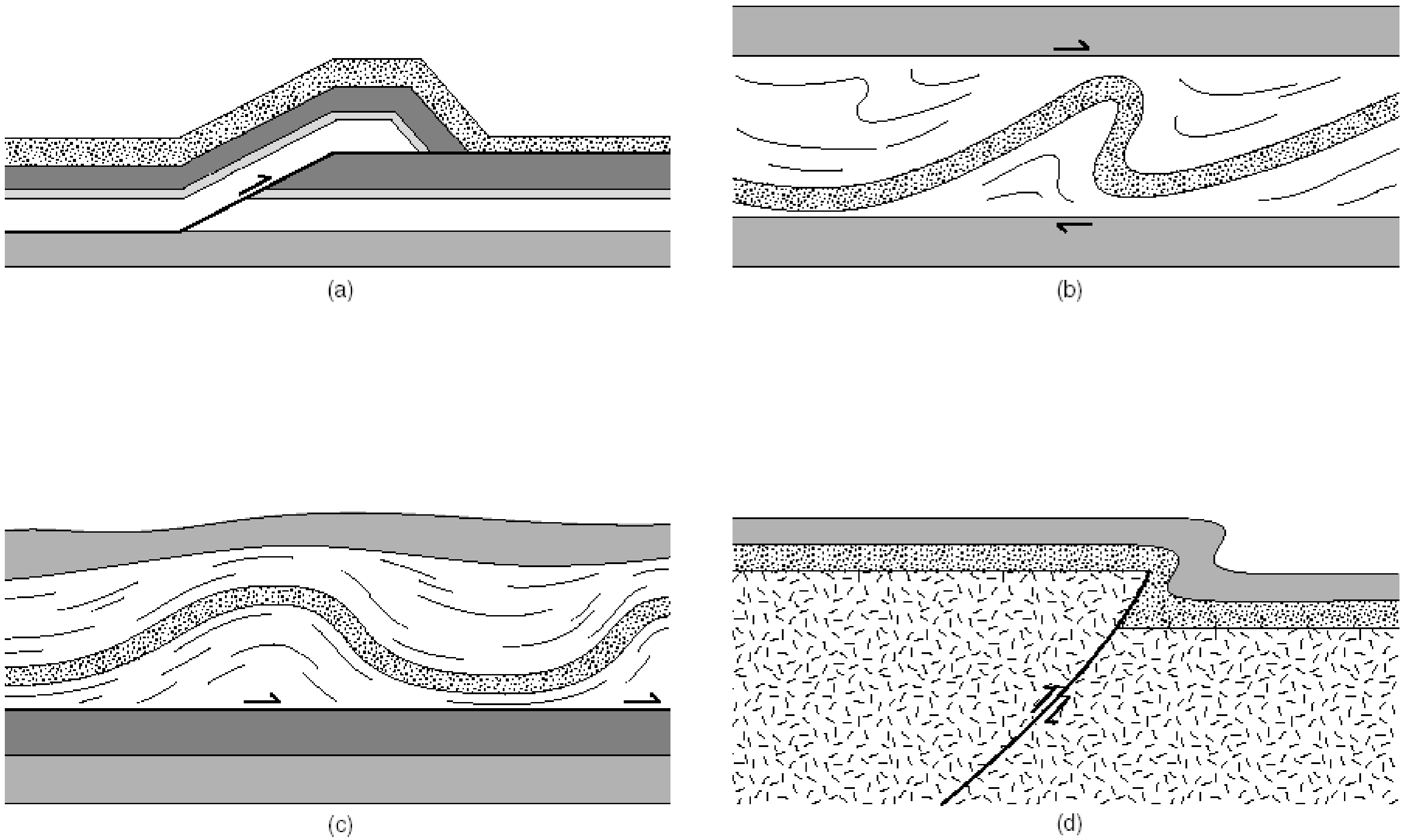
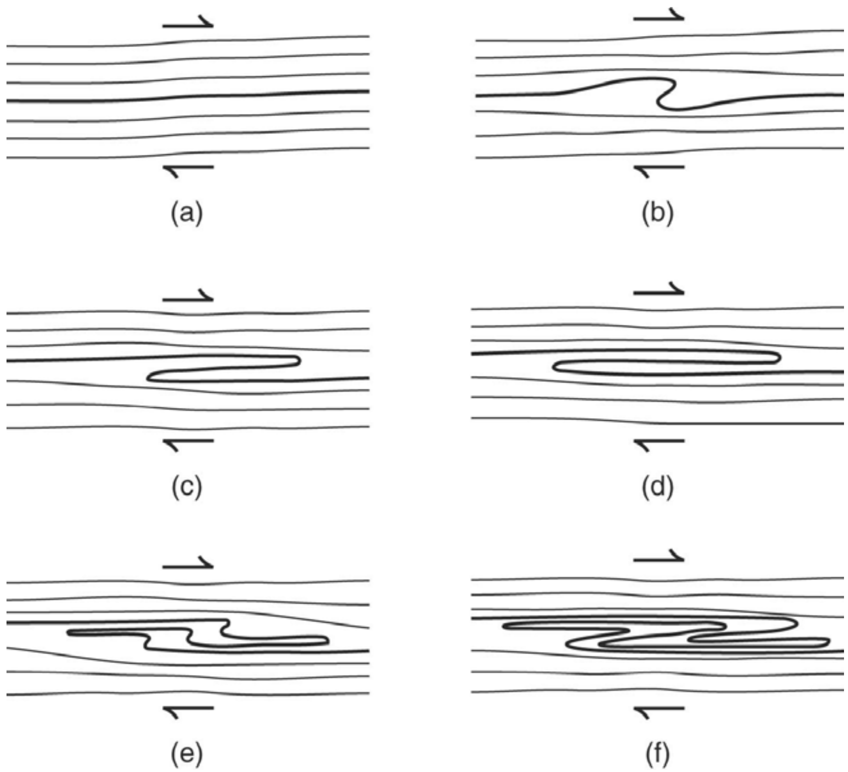
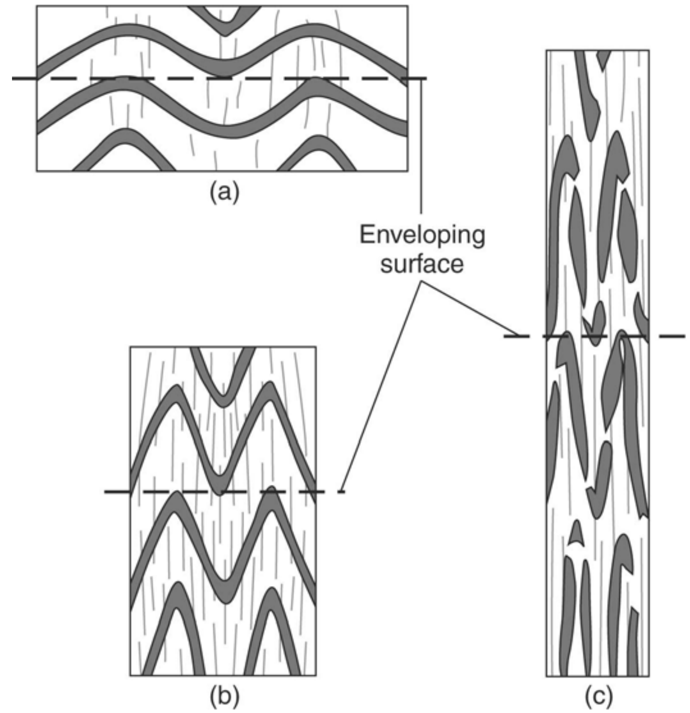


FIGURE 8.22 Fault-related folds. (a) Fault-bend fold on a thrust. (b) Folding in a fault zone. (c) Detachment fold. (d) Drape fold over faulted basement.

Transposition

Fold transposition





Asymmetric fold develops at a perturbation (a–d), which in turn gets refolded (e–f).