Folds and Folding

Earth Structure (2019)
(Processes in Structural Geology &Tectonics)

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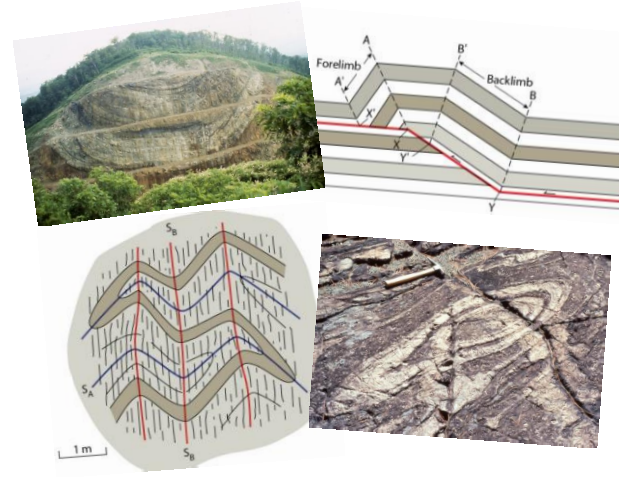
3/15/2019 10:06 AM

We Discuss …

Folds and Folding

- Fold Description
- Fold Classification
- Fold Systems
  - (A)symmetry and Vergence
- Fault-related Folds
  - Fault-propagation folds
  - Fault-bend folds
  - Detachment folds
- Elements of Fold Style
- Superposed Folding
- Fold Mechanics and Kinematics
  - Bending and Buckling
  - Basic fold math
  - Fold Strain
- Structure and Society



Elements of Fold Classification

fold shape in profile
- interlimb angle
- similar/parallel
- symmetry/vergence

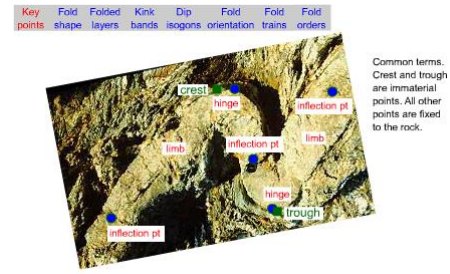
fold size
- amplitude
- wavelength

fold facing
- upward/downward

fold orientation
- axis/hinge line
- axial surface

fold in 3D
- cylindrical/non-cylindrical

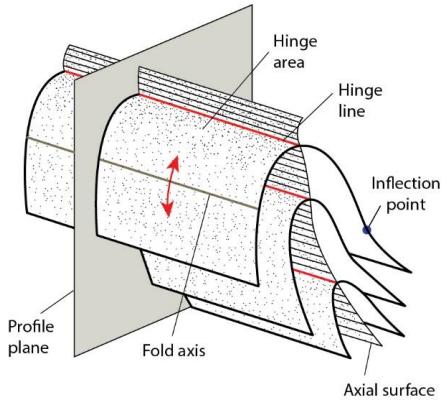
presence of secondary features
- foliation
- lineation



DePaor, 2002

Fold Terminology and Measures

L_w(or W) = Wavelength
L_a = Arc length
a = Amplitude



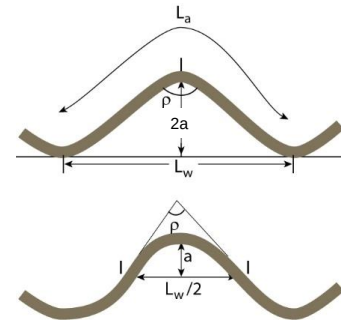
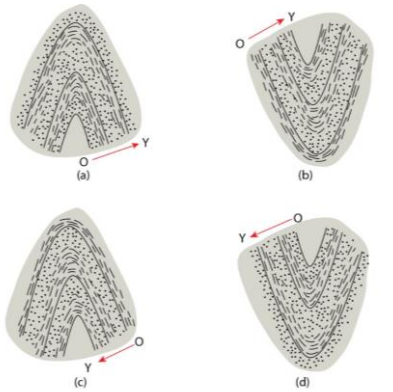
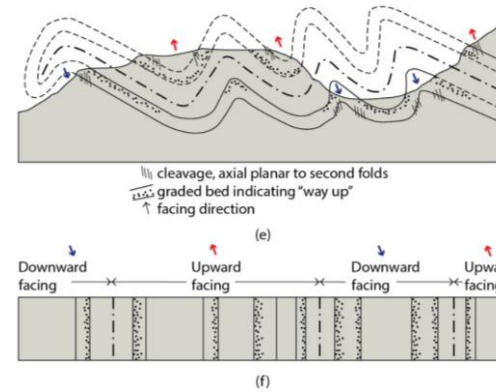


TABLE 10.3	FOLD CLASSIFICATION BY INTERLIMB ANGLE
Isoclinal	0°–10°
Tight	10°–60°
Open	60°–120°
Gentle	120°–180°

Anticline, Syncline and Fold Facing

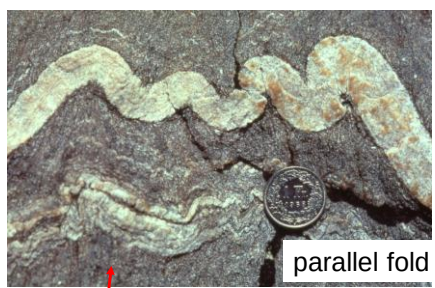


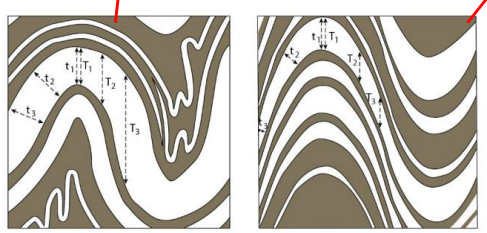


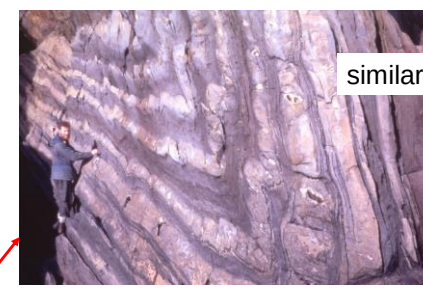
(a) **Anticline** (upward-facing antiform)
(b) **Syncline** (upward-facing synform)
(c) **Downward-facing anticline** (downward-facing antiform)
(d) **Downward-facing syncline** (downward-facing synform)

(e) profile view; (f) map view

Fold Shapes

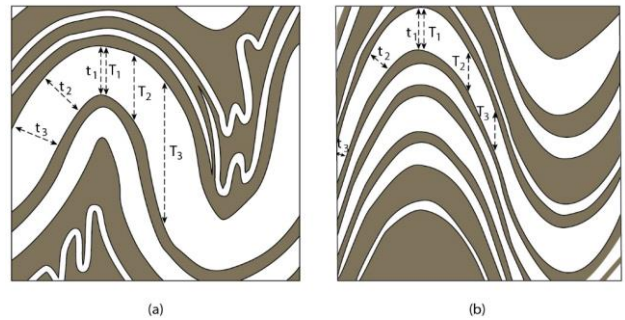

parallel fold




similar fold


ptygmatic fold

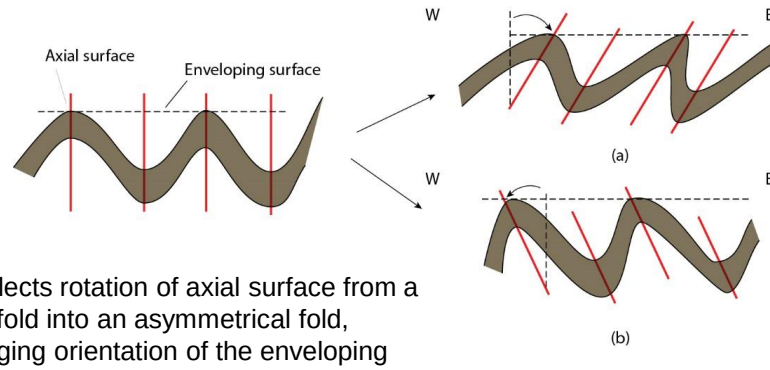
Fold Shape



Parallel fold Similar fold

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

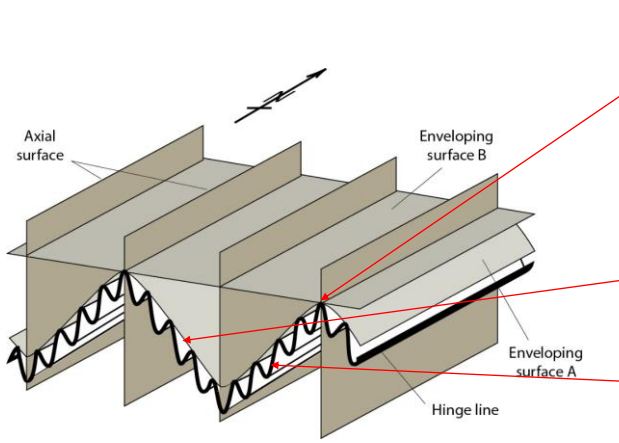
Fold Asymmetry and Fold Vergence



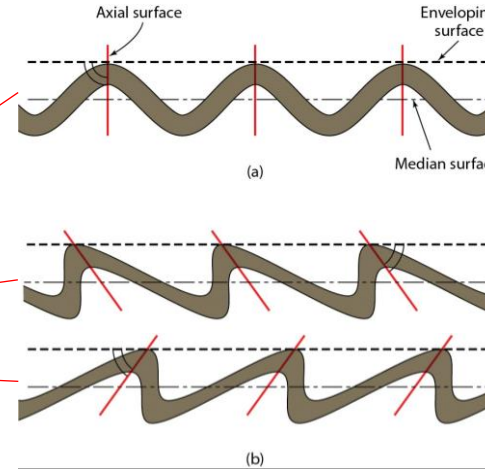
Vergence reflects rotation of axial surface from a symmetrical fold into an asymmetrical fold, without changing orientation of the enveloping surface:

(a) Clockwise (or, here, E) vergence
(b) Counterclockwise (or, here, W) vergence

Fold Systems: Enveloping surface and Fold (a)symmetry

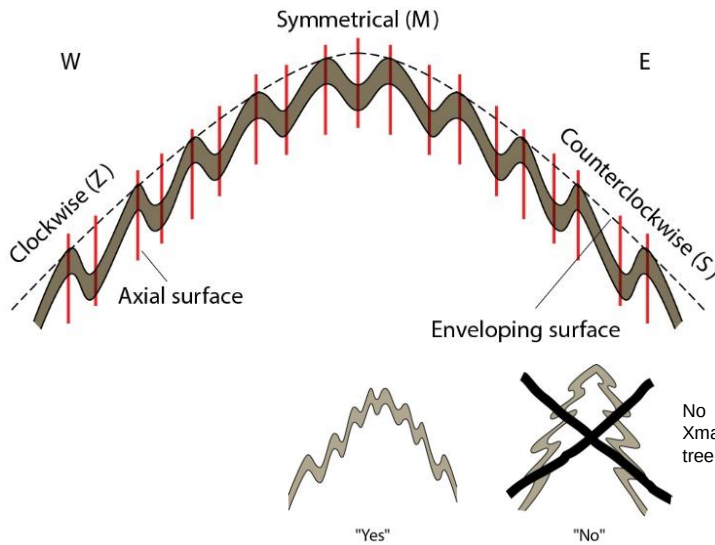


The fold enveloping surface

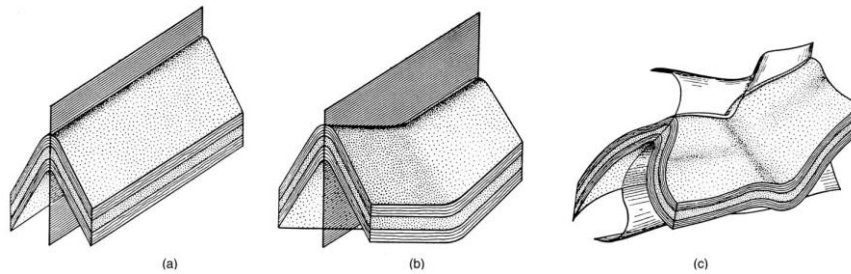


a. Symmetric; orthorhombic; ~90°
b. Asymmetric; monoclinic; < 90°

Fold Vergence - Anticlinorium

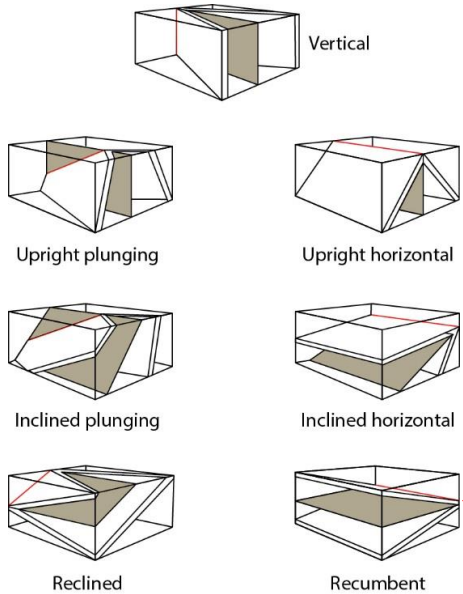


Folds in 3D: Cylindrical and Non-cylindrical Folds

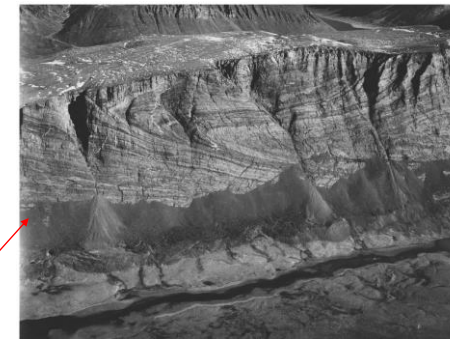


(a) Cylindrical fold
(b) Noncylindrical fold; planar axial surface
(c) Noncylindrical fold; curved axial surface

Fold Orientation



Fold classification based on orientation of hinge line and axial surface



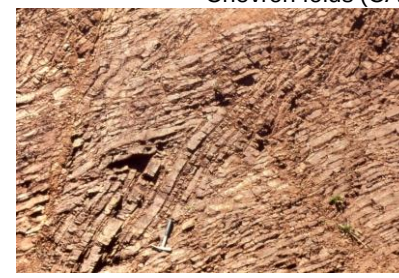
Recumbent fold in the Caledonides of northeast Greenland.

Other Fold Geometries: Kink folds and Chevron folds

Kink folds (Spain)

Recumbent chevron folds (Switzerland)

Chevron folds (CA)



Other Fold Geometries: En-echelon Folds

Hand specimen from N Spain

Regional view (central Appalachians)

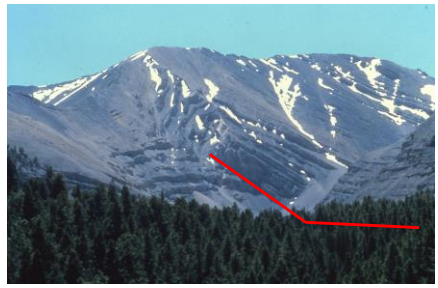
Other Fold Geometries: Monoclines

C Carrigan

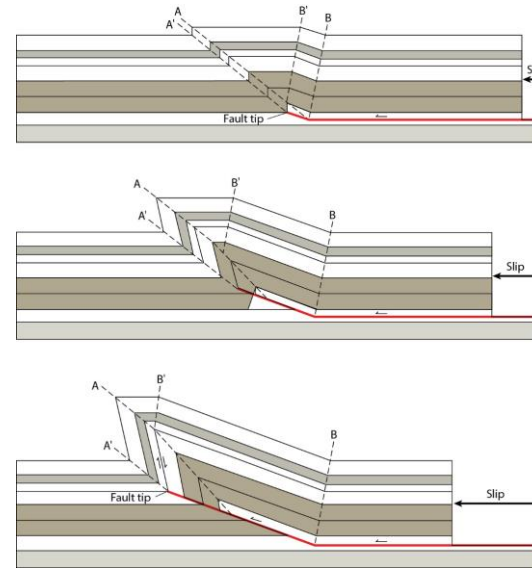
Monocline near Bighorn Mountains (WY). Folding occurred as Bighorns pushed upward; monocline on western margin of this range.
Uplift is part of Laramide deformation in western U.S., which includes the Black Hills (SD), Front Range of the Rockies, and others.

Fault-related Folding

Fault-propagation Folds



Fault-propagation fold in Lost River Range, Idaho, showing asymmetric fold dying out updip.

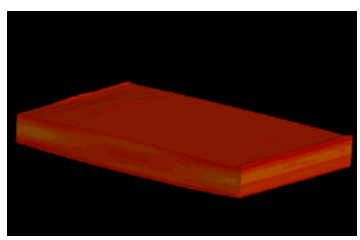


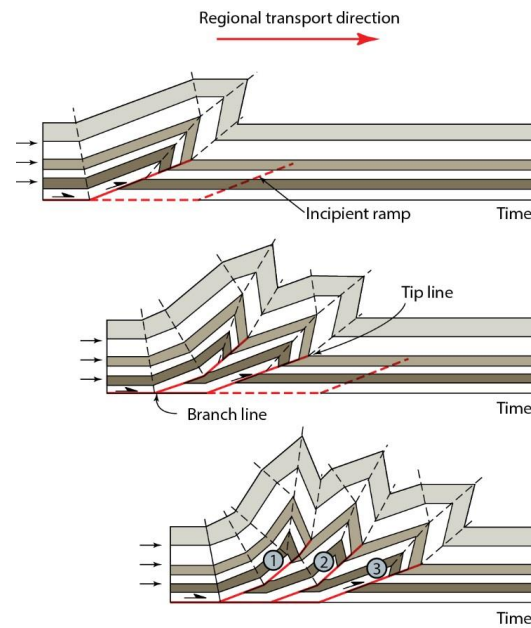
Progressive development of a fault-propagation fold.

Thrust Type: Imbricate Fan

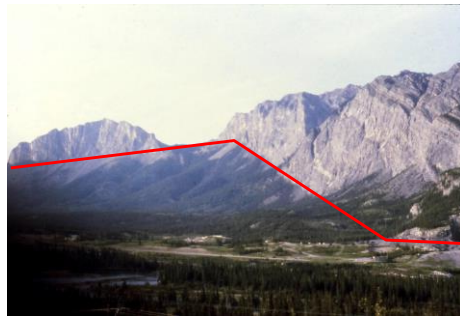
Relative small displacements.

Break-forward ("piggy-back") thrusting. Successively younger thrusts cut into footwall, and older faults and folds become deformed by younger structures.

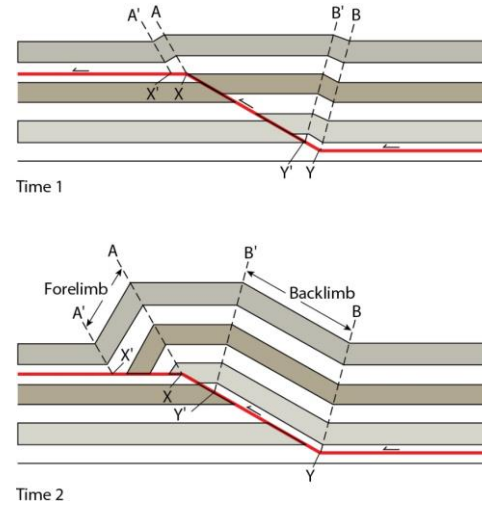




Fault-bend Folds



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

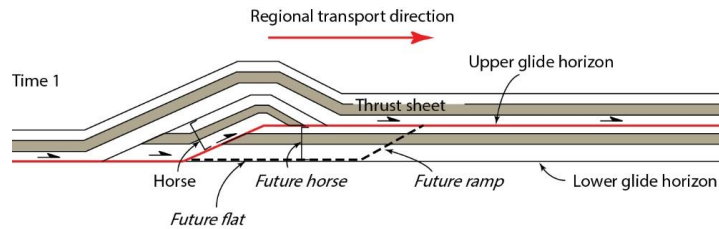


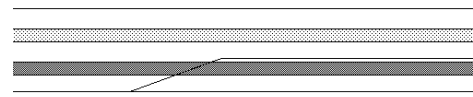
Progressive stages during development of fault-bend fold. Dashed lines are traces of axial surfaces.

Thrust Type: Duplex

Relatively large displacements.

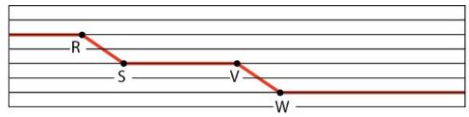
Flat-roofed duplex by progressive break-forward faulting. Roof thrust undergoes a sequence of folding and unfolding.





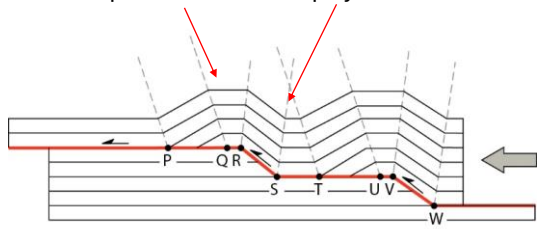
R. Allmendinger

Multiple-ramp Structures



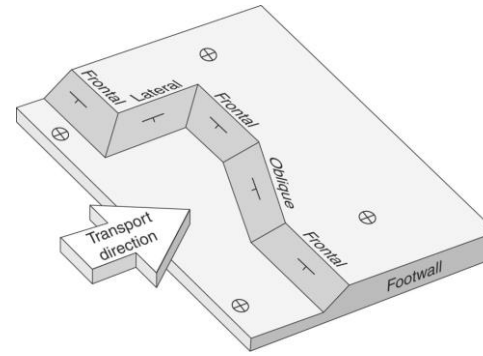
(a)

ramp anticline and ramp syncline



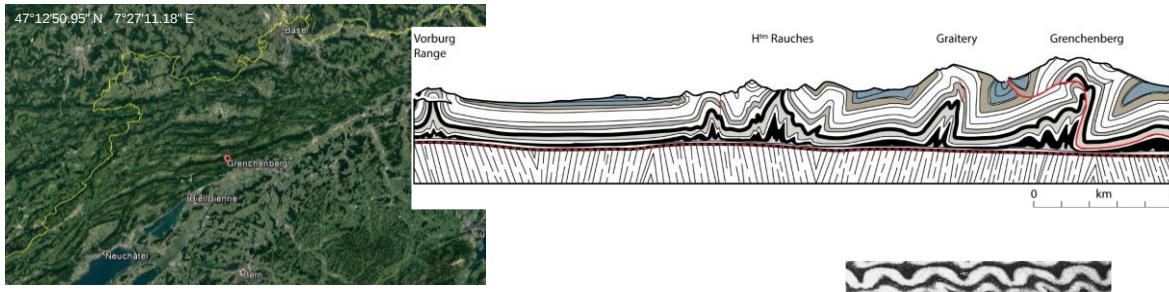
(b)

Note that number of hanging-wall ramps must match number of footwall ramps.

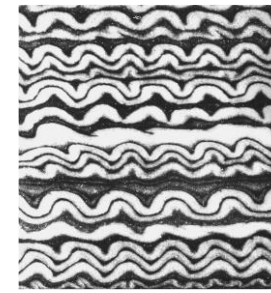


3D block diagram with types of fault ramps (hanging wall removed). “Tear faults” are vertically dipping lateral ramps.

Detachment Folds



Detachment folds above pre-Triassic basement (Jura Mnts, Switzerland).



Small-scale folds in anhydrite (Delaware Basin, TX), with detachments in organic-rich (dark) calcite layers.

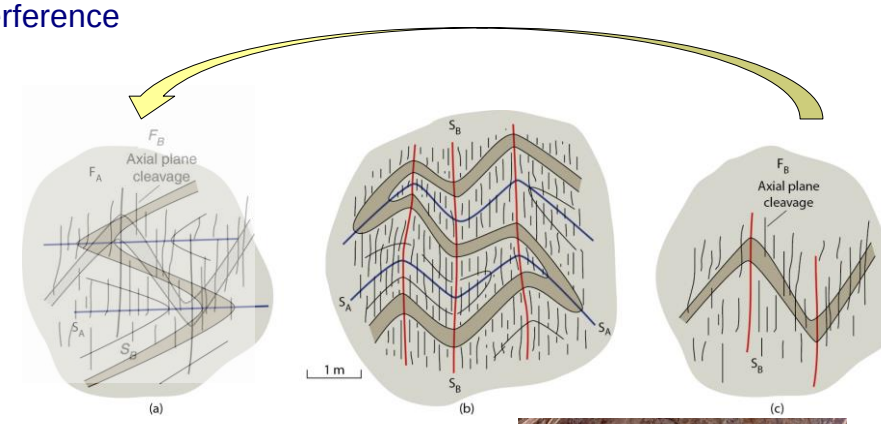
Super(im)posed Folding: Fold Interference Patterns

Type 1: “egg box”

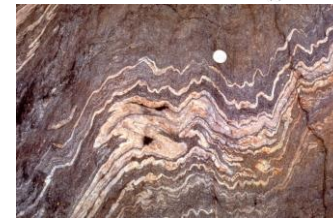
Type 3: “zig-zag”

Type 2: “mushroom”

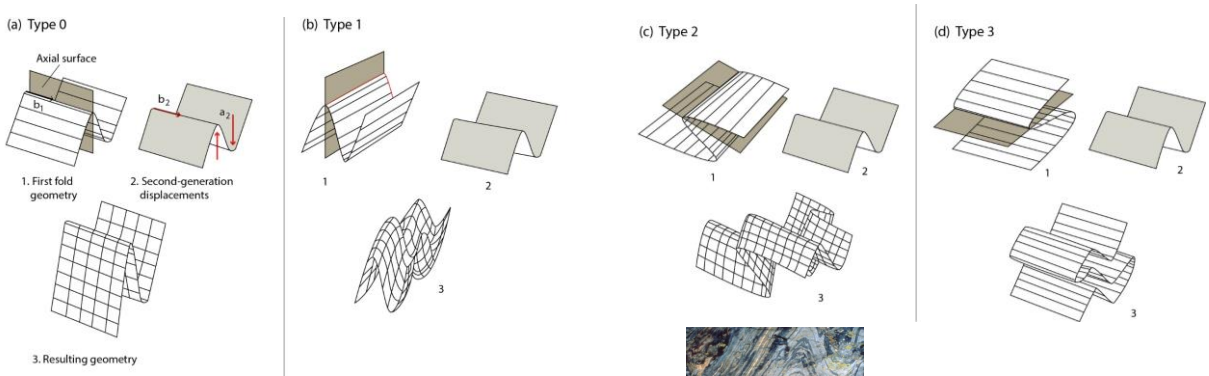
Fold Interference



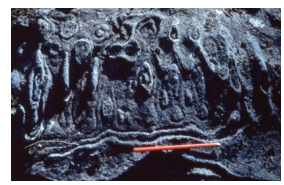
F_A recumbent folds (a) are overprinted by F_B upright folds (b), producing the fold interference pattern in (c).

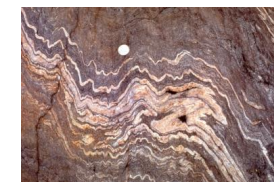


Basic Fold Interference Patterns



F2 folds (a_2 is relative shear direction and b_2 is hinge line) are superimposed on pre-existing F1 folds.





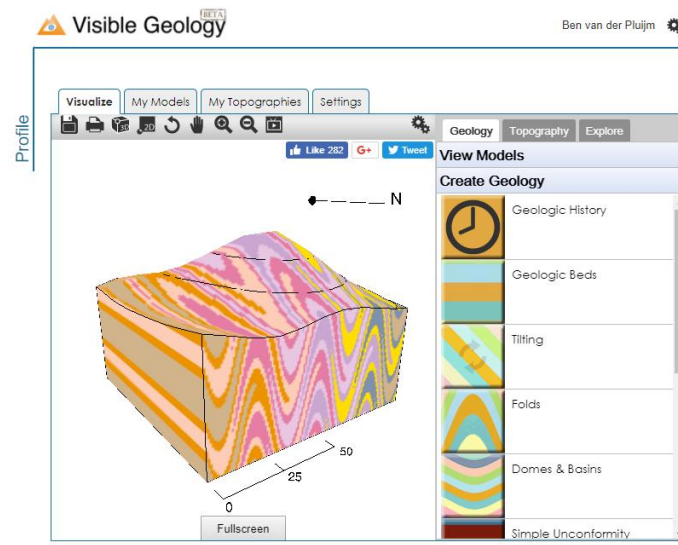
Homework: Fold Interference (Visible Geology)

This webapp allows you to create fold interference patterns and look at them from different angles, and add erosional surfaces and topography.

1. Create a layered block. Go to Geologic Beds and add beds until the block is filled.
2. Go to Folds, Add Folding Event, and create outcrop pattern (click on ⊗)
3. Add second Folding Event to visualize interference outcrop pattern (click on ⊗).

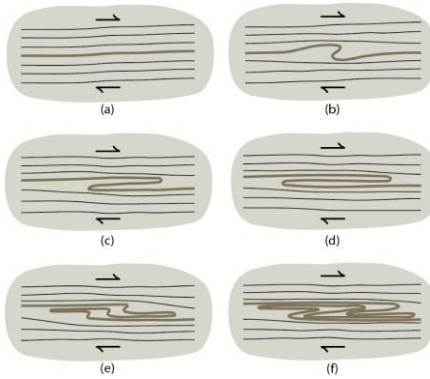
Fold, Fold again, Rotate, Erode, and Learn …

Submit screenshots of Type1,2,3 end-members we discussed (print or upload)



http://app.visiblegeology.com/

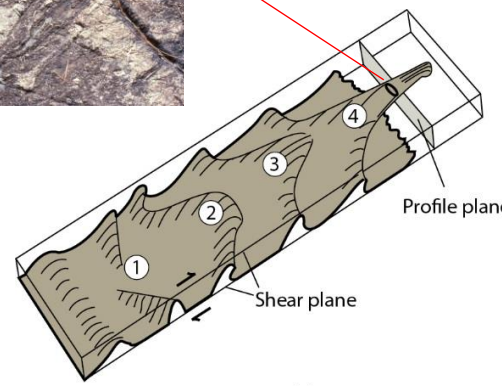
High Strain Zones: Fold Transposition

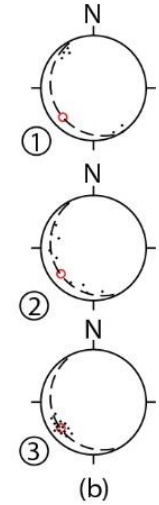


Asymmetric fold develops at perturbation (a–d), which then gets refolded (e–f).

High Strain Zones: Sheath Folds

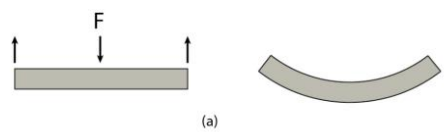
Grenville Front, Ontario, Canada



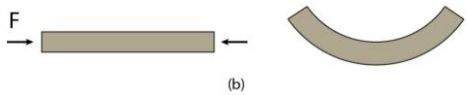


Folding: Mechanics and Kinematics

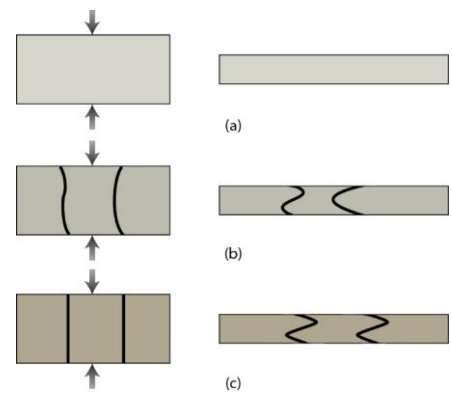
Folding: Bending vs Buckling



(a) Bending a layer (e.g., monocline).



(b) Buckling a layer.



Buckling:

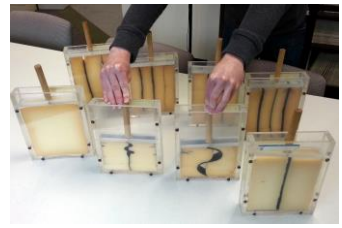
a) Compression of a foam block;
b) with irregularly shaped foam layers separated by thin sheets of rubber;
c) with uniform foam layers separated by thin sheets of rubber.

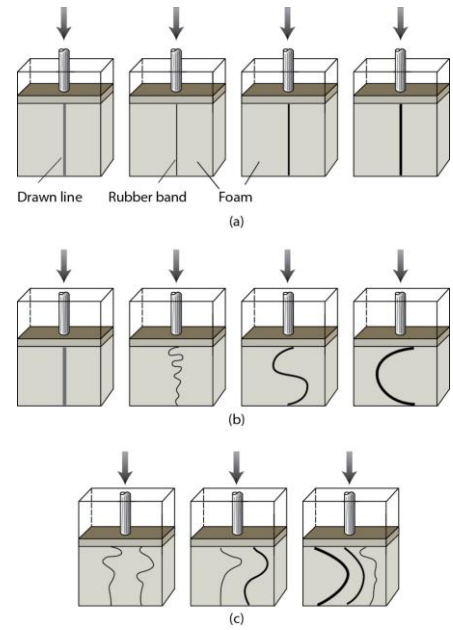
Trick in a Box: Experiments with Analogues

(a) Foam-only box shows thickening of marker line, but no folding.

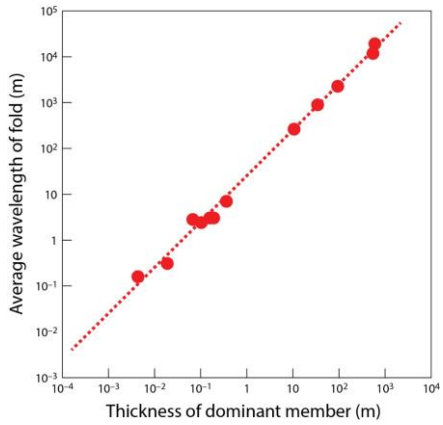
(b) Boxes with rubber bands show folds with arc lengths varying as a function of thickness of each band.

(c) When using more than one rubber band, behavior depends on combination of bands and their thicknesses, with thicker bands dominant.





Wavelength-Thickness Relationship



Log–log plot of wavelength (W) versus layer thickness (t) in folded sandstone layers (US Appalachians).

Sideling Hill, MD

Folding Math: Single Layer

Folding (Biot) equation

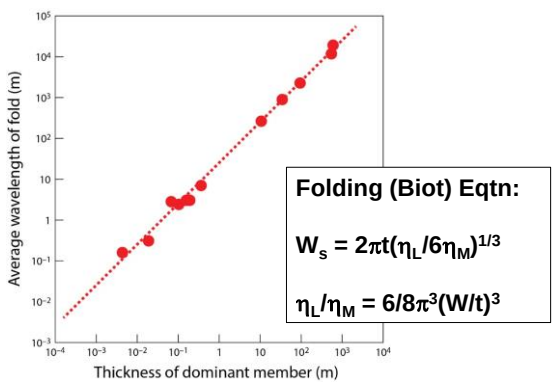
Linear (Newtonian) viscosity, the wavelength-thickness (W-t) relationship for a single layer with viscosity η_L in matrix with viscosity η_M:

$$W = 2\pi t(\eta_L/6\eta_M)^{1/3}$$

or, viscosity ratio is proportional to the cube of the L/t ratio:

$$\eta_L/\eta_M = 6/8\pi^3(W/t)^3$$

Thickness, Wavelength and Viscosity



Appalachian folds:

calculated viscosity ratio, $\eta_{sandstone}/\eta_{shale}$ (layer/matrix), is ~500.

Box Experiments:

calculated viscosity ratio, $\eta_{rubber}/\eta_{foam}$ is ~1000.

More Folding Math: Multi-Layer

Folding (Biot) equation

Linear (Newtonian) viscosity, the wavelength-thickness (W-t) relationship for a single layer with viscosity η_L in matrix with viscosity η_M:

$$\mathbf{W = 2\pi t(\eta_L/6\eta_M)^{1/3}}$$

or, viscosity ratio is proportional to the cube of the L/t ratio:

$$\mathbf{\eta_L/\eta_M = 6/8\pi^3(W/t)^3}$$

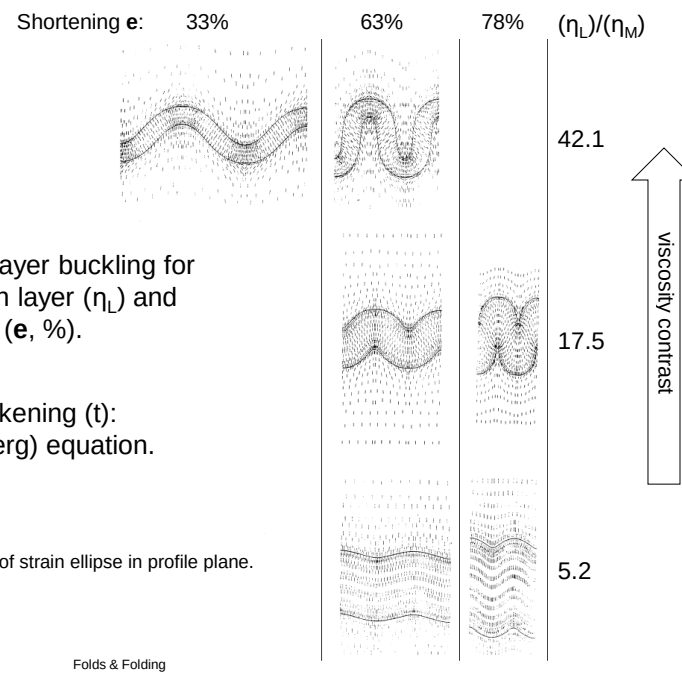
Interacting Multilayers

For N interacting multilayers:

$$\mathbf{W_{multi} = 2\pi t(N\eta_L/6\eta_M)^{1/3}}$$

Note: $W_{single}/W_{multi}=N^{2/3}$
so N multilayers ≠ N.t single layer

Effect of Viscosity Contrast



Finite-element modeling of single-layer buckling for various viscosity contrasts between layer (η_L) and matrix (η_M), and shortening strains (**e**, %).

Smaller contrast, greater layer thickening (t): strain-modified fold (or Biot-Ramberg) equation.

Short tick marks are orientation of long axis of strain ellipse in profile plane.

Extra: Folding Math and Strain

Folding (Biot) equation

Linear (Newtonian) viscosity, the wavelength-thickness (W-t) relationship for a **single layer** with viscosity η_L in matrix with viscosity η_M:

$$W_s = 2\pi t(\eta_L/6\eta_M)^{1/3}$$

or, viscosity ratio is proportional to the cube of the W/t ratio:

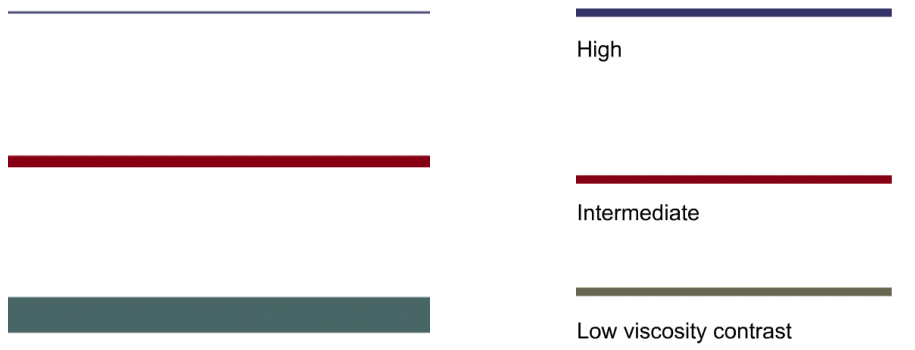
$$\eta_L/\eta_M = 6/8\pi^3(W/t)^3$$

Strain-modified folding (Biot-Ramberg) equation

Incorporating strain ratio, with R=X/Z:

$$W_s = 2\pi t\,[(\eta_L(R-1))/(6\eta_M.2R^2)]^{1/3}$$

Thickness and Viscosity



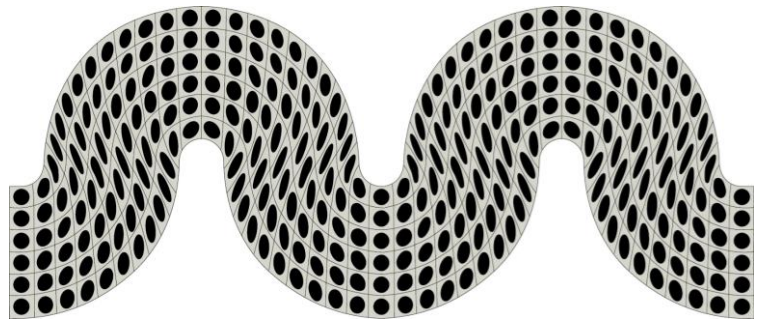
Fossen, 2016

$W_s = 2\pi t(\eta_L/6\eta_M)^{1/3}$

$W_s = 2\pi t\,[(\eta_L(R-1))/(6\eta_M.2R^2)]^{1/3}$

R = X/Z

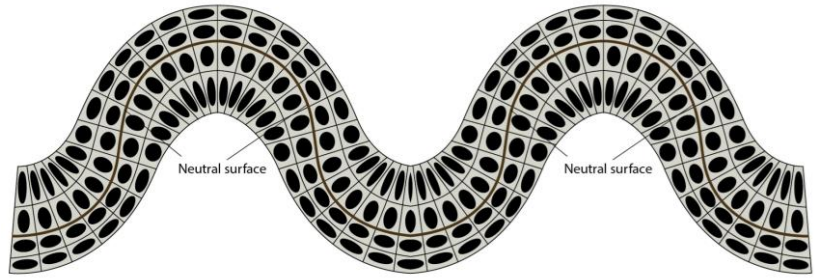
Folds and Strain: Flexural Folding



Strain pattern of flexural folding in fold profile plane (plane perpendicular to hinge line).

Formation of parallel folds.

Folds and Strain: Neutral-surface Folding



Strain pattern of neutral-surface folding in fold profile plane.

Formation of parallel folds.

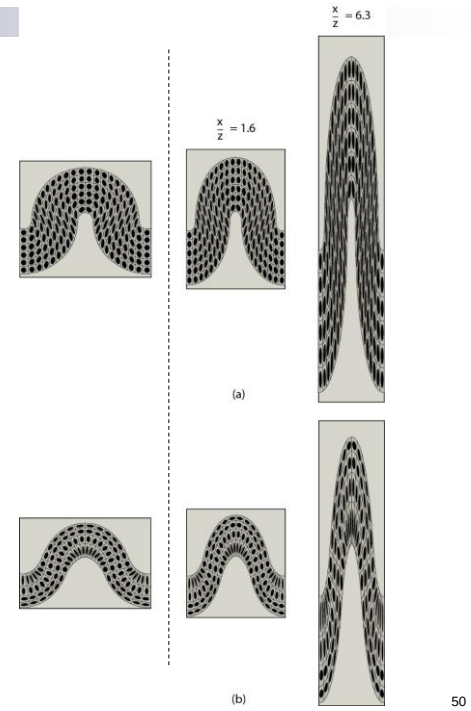
… but similar folds?

Superimposed Homogeneous Strain and Similar Folds

Effect of superimposed homogeneous strain on:
(a) flexural fold;
(b) neutral-surface fold.

Constant volume, plane strain with
X/Z = 1.6 (20% shortening), and
X/Z = 6.3 (60% shortening).

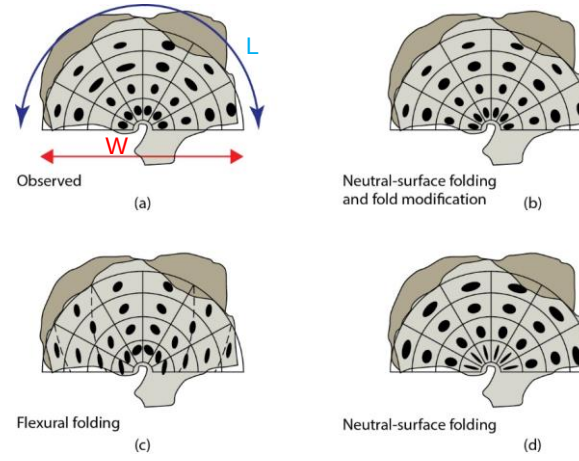
In both cases a parallel fold evolves into a **similar fold**.



Natural Example of Fold Strain

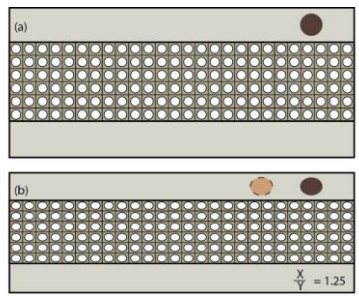
(a) Strain pattern in natural fold of limestone-pebble conglomerate;
(c) vs. strain predicted in flexural folding;
(d) and neutral-surface folding.

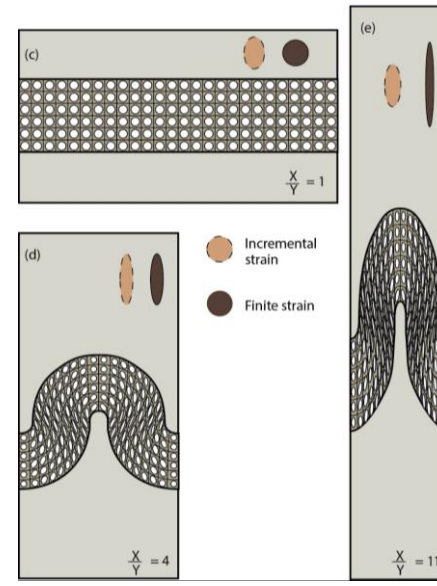
(b) With further modification, initial compaction and material transport away from inner arc region, a strain pattern like that observed in natural sample is re produced.



e = (W-L)/L
= -0.35 (= 35% shortening)

Representative Folding Scenario with Incremental and Finite Strains



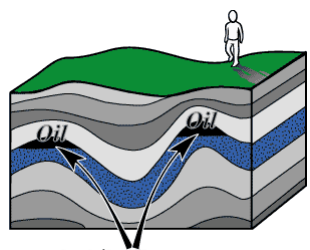


Deformation history:
(a) deposition
(b) 20% compaction (volume loss)
(c) layer-parallel shortening (layer thickening)
(d) buckling (flexural flow) creating parallel fold
(e) homogeneous shortening creating similar fold

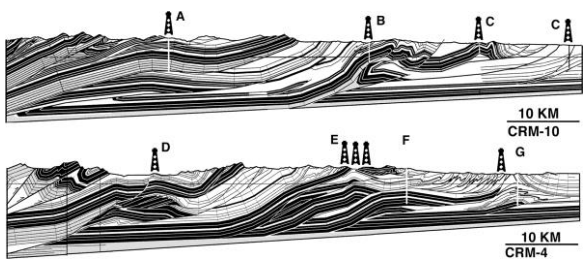
Strain at each step shown (~70% total shortening)

Structure and Society: Resources and Mountain Tourism

Oil and Gas

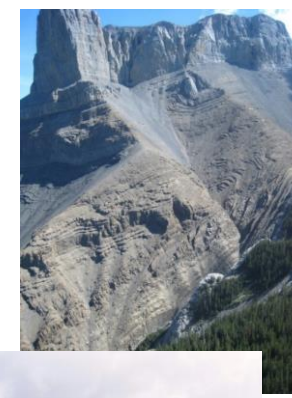


Anticline Traps



Roeder, 2010

Geo-tourism



Canadian Rockies