Folding II: Mechanisms and Kinematics

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1. **Fold Mechanisms**: Folding can considered from the standpoint of how stresses are applied to layers and how the layer rheology comes into play. Layer-parallel shortening results in buckling. Stresses applied across layers produces *bending*. If layer rheology does not control the folding process, it is *passive folding*.

   ![Fig. 11.15. Relation between fold mechanisms and how the forces are applied](image)

2. **Buckling**: Buckling is also called active folding. Stresses applied parallel to a layer results in initial *thickening*, then the development of sinusoidal folds with a specific *wavelength*.

   The buckling layers must have a *viscosity contrast* with the surrounding rock mass, with the layers being more competent: \( \mu_L > \mu_M \)

   ![Fig. 11.16. Buckling of a single layer results in initial thickening (b) followed by the development of sinusoidal folds (c)](image)

3. **Characteristics of Buckling Layers**: Buckling of single layers with homogeneous properties results in a *constant ratio of fold wavelength to thickness* \( (L/h) \). Thicker layers have greater wavelengths. The effect of the folding in the surrounding rock mass diminishes within about one wavelength of the layer.

   \[
   L/h = 2\pi (\mu_L / 6\mu_M)^{1/3} \quad \text{(ignores layer thickening).} \quad \text{In natural folds, usually } L/h < 10.
   \]

   ![Fig. 11.17. The wavelength of buckling layers scales with layer thickness](image)

4. **Characteristics of Buckling Layers**: The competent layers fold into Class 1B folds. If there are multilayers, the less competent layers will fold into Class 1A or 3 folds with sharp cusps pointing towards the more competent layers.

   ![Fig. 11.18. Folded multilayers produce Class 1B folds in the competent units (constant layer thickness) and Class 1A or 3 folds in less competent units](image)

5. **Characteristics of Buckling Layers**: Strain is heterogeneously distributed about a *neutral surface* through the layer center. The outer arc is extended and the inner arc is contracted. Extension of the outer arc may be overprinted by the initial layer-perpendicular thickening.

   ![Fig. 11.19. Distribution of strain within a buckled layer. Ellipses show the final shape of an originally circular shape](image)

6. **Characteristics of Buckling Layers**: Multiple layers act independently if widely spaced (higher wavelengths in thicker layers) but can act as *single layers of equivalent cumulative thickness* if sufficiently closely spaced.

   ![Fig. 11.20. Widely spaced layers buckle according to their thickness. Closely spaced layers act as if they are a single layer with equivalent cumulative thickness](image)
7. **Characteristics of Buckling Layers**: Thinner layers start to buckle first while thicker layers are still thickening. The thicker layers then buckle with a greater wavelength, refolding the thinner buckled layers and controlling the overall shape of the folding.

[Fig. 11.21. Thinner layers buckle first. When thicker layers start to buckle, the greater wavelength defines the overall shape of the folding] [Fig. 11.22: Folded multilayers]

8. **Passive Folding**: Passive folds form where there are no rheology contrasts between layers, which act as passive strain markers to the deformation (i.e., passive layers exert no mechanical influence on the folding). Shearing may result in Class 2 folds.

[Fig. 11.23. (a) Simple shear of passive layers results in Class 2 folding. (b) Layer-parallel shortening of passive layers] [Fig. 11.24: Passive folding produces harmonic folds within a mylonite zone in quartzite (no rheological contrast)]

9. **Bending**: Bending occurs when stresses are applied across layers, causing opposing torques. The mechanics of bending have been of great interest to engineers interested in bending plates and beams (e.g., Galileo in 1638).

[Figure. The bending beam problem considered by Galileo (1638)] [Figure. Bending moments on a bending beam]

10. **Bending**: Strain may be very heterogeneously distributed within bending layers, depending on the driving mechanism. Examples include:

   1. Differential compaction & boudinage
   2. Fault-bend folding
   3. Monoclinal warping above basement faults
   4. Bending over intruding salt diapirs or magma.

[Fig. 11.25. Various mechanisms of folding by bending of layers]

11. **Bending**: Example of bending of sedimentary rocks above a magma intrusion (lacrolith) at Mt. Hillers in the Henry Mountains, Utah.

[Figures. Henry Mountains related bending of sedimentary layers]

12. **Bending**: Monoclinal bending of sedimentary rocks above a basement fault along the San Rafael Swell, Goblin Valley, Utah.

[Figures. Monoclinal bending above faults in the San Rafael Swell, UT, and in the Rattlesnake Mountains, WY]

13. **Kinematic Models: Flexural Slip Folding**: Class 1B folds are commonly produced in multilayered assemblages where the layers can slide past each other along weak interfaces between them (cf. bedding plane slip).

Slickenlines may be visible on the bedding plane surfaces. Slip is a maximum at the inflection points and is zero at the fold hinges.
The convex side of the layer moves towards the hinge whereas the concave side moves away from the hinge (cf. folding a jelly sandwich).

[Fig. 11.27. (a) Folding of multilayers may occur through flexural slip, where each layer slides over the adjacent layers. (b) See next]

14. **Kinematic Models: Flexural Slip Folding:** Class 1B folds can also be produced by flexural flow or flexural shear. In this case, the shear is evenly distributed throughout the layers (i.e., plastic deformation). There is no net lengthening or shortening within layers.

[Fig. 11.27. (b) Flexural flow folding] 

15. **Kinematic Models: Flexural Slip Folding:** The amount of shear strain is related to the dip of the layers (assuming originally horizontal) and is zero at the fold hinge, increasing away from it equally at the top and bottom of the layer (i.e., no neutral surface).

16. **Kinematic Models: Flexural Slip Folding:** The sense of shearing is opposite on either side of the hinge (cf. folding a telephone book). Lines initially perpendicular to the layers do not remain perpendicular except at the hinge.

17. **Kinematic Models: Orthogonal Flexure:** Class 1B folds produced by orthogonal flexure produce a neutral surface with outer arc extension and inner arc contraction. Lines initially perpendicular to the layer remain perpendicular to the layer during folding. The outer arc lengthens and the inner arc shortens. This style is only possible for open folds. With ongoing folding, other mechanisms will occur (e.g., flexural slip or flow).

[Fig. 11.28. Identical Class 1B fold geometries produced by orthogonal flexure and by flexural flow folding. In orthogonal flexure, the neutral surface maintains its original line length. In flexural flow, there is no neutral surface]

18. **Kinking:** Well laminated anisotropic rocks (e.g., turbidite sequences; phyllosilicate rich layers) may fold by kinking. Kinks are cm-to-dm scale bands of sharp changes in layer orientation, producing folds of Class 2.

Kinks are similar to chevron folds but differ in that the kink bands form at an angle to the compression and may form conjugate bands.

[Fig. 11.29. Kinking of layers produces sharp hinges] [Fig. 11.30. Kink bands form at an angle to $\sigma_3$]

19. **Chevron Folds:** Chevron folds form by flexural slip. They are Class 2 folds that maintain layer thickness in the competent layers. Flexural flow occurs in the intervening layers to accommodate a space problem in the fold hinges. Extension occurs in the outer arc and contraction in the inner arc of the layer.

[Fig. 11.31. Chevron folds form by flexural slip folding] [Fig. 11.32. Veins indicate extension on the outer arc of the folded layers]
20. **Fold Interference Patterns**: More than one episode of folding deformation may result in refolded folds. The pattern of deformation then depends on the relative orientations of the axial surfaces as well as the relative wavelengths of each fold set. Visible patterns also depend on the orientation of the cross section relative to the folds.

[Fig. 11.34. Examples of different interference patterns based on the relative orientations of the fold axial planes during each folding episode]

21. **Fold Interference Patterns**:

[Fig. 11.35. Possible outcrop patterns where there is fold interference] [Fig. 11.36. Refolded fold in quartz schist]