Notes XI
Folds

Fall 2005

1 Reading

Begin by re-examining the lab on folds, especially the handout. Two chapters are devoted to folds in TM. The first (ch. 11) is rather dreary stuff about the description and classification of folds. The second is a far better investment of your time and energy.

2 Jargon

As usual, a laundry list of key terms.

Fold hinge, fold axis; hinge surface, axial surface; cylindrical / non-cylindrical fold.
Types of folds: concentric, parallel, similar.
Detachment folds, chevron folds, fault propagation folds, diapir or deroulement folds.
Harmonic / disharmonic folds, ptygmatic folds.
Neutral surface.
Axial planar foliation.

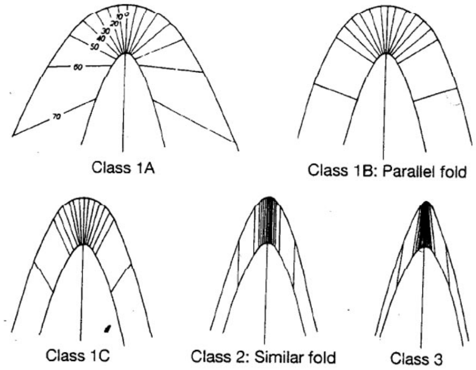
3 Terminology and classification

Field measurements of folds: standard list of measurements and observations include: cylindricity of fold, style of folding of multilayers (harmonic or disharmonic), thickness of folded layers, strike/dip of beds around fold; orientation (trend/plunge) of hinge line; orientation of axial surface (hinge surface); asymmetry of folds (S or Z?); presence of axial planar foliation, intersection lineations, stretching lineations; secondary structures on limbs or in hinge (eg. evidence of flexural slip between layers; evidence of dilatancy – like fractures – in hinge).

Careful measurement and documentation of even small minor folds in the field is crucial because (1) minor fold geometries are often related to geometry of large map-scale folds that control the distribution of rock units; (2) deformation style of folds reflects conditions of deformation (i.e. ductile vs. brittle); (3) folding can occur as a result of shortening or tectonic transport so constraining the geometry and style of folding is crucial for unravelling tectonic history of an area.

3.1 Classification

Field measurement and description of folds forms the basis for a classification of folds. Note that fold classification schemes can be based on geometry (purely descriptive classification) vs. mechanics (a classification that infers a model of formation). Geometric classification schemes can get pretty abstruse but a good classification scheme reflects differences in process and conditions of formation. Detailed fold classification schemes are described in pp. 220–235 of TM. Broadly speaking though, two (or three) common fold styles are especially worthy of note: **parallel** and **similar** folds.



3.1.1 Parallel folds

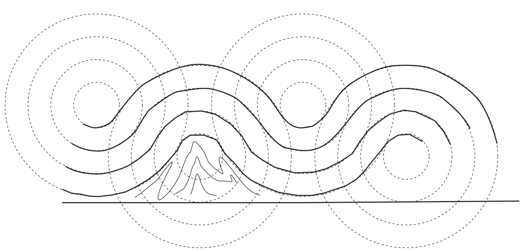
Parallel folds (Class IB in Ramsay's scheme) are folds where the orthogonal thickness of the layer is constant about the fold. **Concentric** folds are a special case of parallel folds where the outer and inner layers define arcs that have a common center of curvature. These kinds of folds are common in upper crustal tectonic settings, where most deformation occurs by proceses that only permit limited ductile flow of rock.

3.1.2 Similar folds

Similar folds (Ramsay's class II) are characterised by parallel dip isogons, but more to the point, by relative thinning of fold limbs and thickening of hinge zones. These folds are common in metamorphic terranes, i.e. where most deformation occurs by mechanisms permitting extensive ductile flow of rock.

4 Geometric considerations for folds

Especially for concentric folds, geometry creates constraints for the continuation of the folds at depth as well as local space problems.



The **Busk construction** method is a way to extapolate fold geometries. Busk folds are arcs of circles centered on common points. Therefore, this construction method produces concentric fold geometries. However, Busk construction requires that folds eventually "die out" on an essentially unfolded surface. Comparing the length of folded layers at the top of the construction (l3) to the bottom surface, it is clear that the lengths are rather unequal, and that the bottom of the folds (surface l0) is a **detachment** surface. These kinds of folds are therefore called **detachment folds** (figure 11.2 in TM shows a real world example of detachment folds – note that these folds depart from ideal concentric geometry).

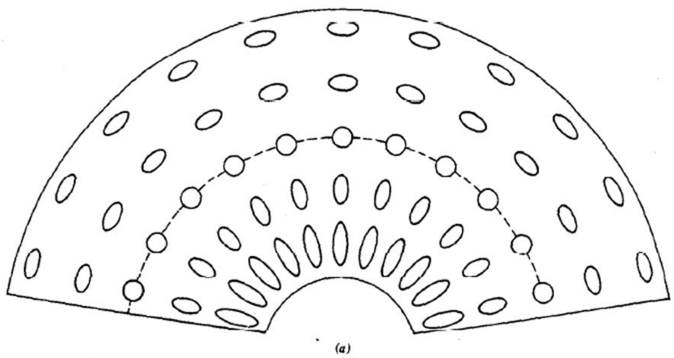
Another requirement is that some amount of material has to flow ductilely into the bottom of the anticlines in order to solve a "space problem" : if the folds are truly concentric this geometry has to break down as the radii of curvature get smaller and smaller. If the folds form above weak rocks (which might explain why the folds detach where they do), this material has to flow into the core of the fold. In some cases, this material flows according to pressure gradients and the pressurization of the ductile layer can produce piercement diapirs in the core of the structure (fig. 6.9 page 102, for a general idea of what this might look like).

5 Models of fold formation

The common models of fold formation present a series of end-member possibilities. The models are not mutually exclusive, and the combination of various fold mechanisms may explain observed geometries better than any single mechanisms. Despite much work on these problems, you might feel that some models fail to be completely compelling. You would not be alone.

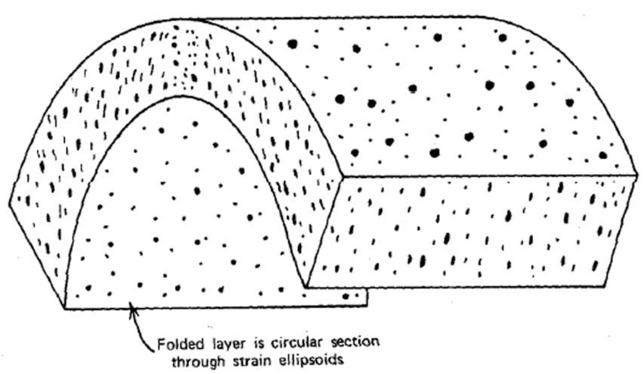
5.1 Buckling

Buckling is what happens when you push on the ends of fairly rigid layer (put a piece of paper on a flat surface and push the edges towards one another: this is buckling). Buckling of a layer will produce parallel fold geometries, since the thickness of the layer is unaffected. The important thing to realize is that the model predicts a characteristic pattern of strain, and so is testable by going out into the field and checking to see whether that pattern actually obtains.



Characteristic features of buckle folds:
(1) the upper part of the layer folded anticlinally will be in extension, the lower half in compression. You can define a **neutral surface** that separates areas of compression and extension. On this surface, material points experience no strain.
(2) Deformation occurs only by bending about the fold axis. Ideally, there is no extension parallel to the fold axis. That is, this is an example of **plane strain**.
(3) Compressive and extensional strain increase with distance from the neutral surface.

5.2 Flexural slip

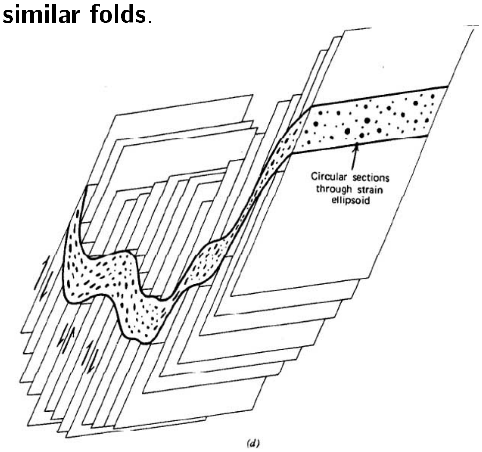


This is "phonebook folding" or "deck of cards" folding. The idea is that folds are produced by shear on surfaces parallel to the layer being folded. This model produces parallel folds.
Important features:
1) Deformation occurs by bending about the fold axis and shear on the slip surfaces in directions normal to the fold axis. It is also plane strain. Fold axis is parallel to the intermediate principal strain axis.
2) Layer maintains its thickness, but there is **no** neutral surface.
3) Folded layer is a circular section through strain ellipses.

4) Profile of fold shows a divergent fan of strain ellipses.
5) A passive linear marker on the fold surface will maintain its orientation wrt to the fold axis. After folding, a stereonet plot of the lineation will have it define a small circle about the fold axis.

5.3 Passive flow folding

The layer being folded is assumed to exert no mechanical effect on the folding process. It is just a passive marker. Folds form by differential flow along closely spaced surfaces oblique to the layer being folded. This will produce **similar folds**.



Characteristic features:
1) Also plane strain. Deformation by simple shear on shear planes. The shear planes are circular sections through the strain ellipsoid.
2) The direction of shearing can be quite variable. The only requirement is that shear plane is not parallel to the layer. However, the maximum fold amplitude obtains when shear direction is normal to the fold axis.
3) In the plane parallel to the axial plane of the fold, no changes in layer thickness will be observed. However, viewing the fold normal to the shear plane and parallel to the presumed shear direction, you will see great variation between the thickness of hinges and limbs. This variation requires no flow of material from limbs to hinges.
4) Shear sense on the shear planes changes from limb to limb on the same fold. Strain ellipses, and principal planes of strain make a divergent fan.
5) There is no neutral layer, and strains are constant at all points within a layer.
6) These folds can be harmonic over large lengths, as opposed to concentric folds, where geometry requires them to be detached.
7) A passive linear marker is distorted and rotates towards the slip direction. Since the slip direction is never parallel to the hinge of the fold produced, initially linear markers will never be oriented parallel to the fold hinge.
8) There is no relationship between layer thickness and wavelength of folds.

5.3.1 Why this model is inadequate.

OK. You can make folds by passive slip or passive flow. But is it really what happens? Recall that what we need is a model to explain the kinds of folds commonly observed in metamorphic terranes. In these areas, folds are typically characterized by 1) similar fold geometry, in particular thinning at limbs and (relative) thickening at hinges; 2) stretching lineations parallel to fold hinges; 3) commonly disharmonic folding; 4) common apparent relationship between layer thickness and competency and wavelength and style of folding. Passive flow folding can do (1) but utterly fails at (2), (3) and (4).

More importantly, is there any evidence for the existence of slip surfaces? Similar folds are commonly associated with **axial planar foliation**, so on the face of it, a potential slip surface exists. But offsets (i.e. evidence for slip) across the cleavage or foliation planes are not common, and where present are more likely the effects of pressure solution. If related to shear on these surfaces, we might expect to see a stretching lineation oriented at high angle to the fold axis. More commonly, stretching lineations are parallel to the fold axis. Finally, axial planar surfaces are principal planes of strain. There should be no shear on them at all.

5.4 Combination of fold mechanisms

Our 3 simple models suffer from some problems.

1. They produce either ideal parallel or ideal similar folds. In Ramsay classification, that means class IB and class II folds. But in nature, class IC and class III folds are common

2. They predict folds forming under conditions of **plane strain** and **simple shear**. That is, they assume what is pretty much the simplest strain regime. This is unlikely to be correct.

3. All the above mechanisms predict that the intermediate strain axis λ_2 lies parallel to the fold axis. That is, everywhere we look, we should see stretching lineations perpendicular to the fold axis. Far more common, especially in high grade zones, is for the stretching lineation to be parallel to the fold hinge.

4. One of the most common secondary structures associated with folds is the presence of an axial planar foliation or axial planar cleavage. This is developed in rocks of a wide variety of rock types, fold geometries and metamorphic grades: from disjunctive fracture cleavages at low grade to high grade fabrics formed from crystal-plastic deformation. Only passive flow folds (indirectly) accounts for the role of foliation development during deformation – but in this case, the interpretation that the axial planar foliation is a slip surface is questionable.

Ideal, theoretical models also ignore what seems to be a fundamental property of folds: folds form in **layered** sequences, with **competency contrasts** between the layers. In fact, competency contrasts appear to be *necessary* for folds to form (this is certainly true for metamorphic rocks.

5.4.1 Wavelength of folds: a function of layer thickness

Theoretical and experimental work on folding of viscous materials produces results that accord with that last observation: that fold wavelength is a function of layer thickness, as well as **competency contrast**. For a relatively strong layer bounded above and below by weak material, the dominant wavelength of folds is predicted to be

$$\lambda_i = 2\pi h \sqrt[3]{1/6 \frac{\eta_1}{\eta_2}}$$

where h is the thickness of the layer, and η is the viscosity of each layer. Note how the wavelength is a directly related to both layer thickness and viscosity contrast.

5.4.2 Wavelength of folds: multiple layers

For a stack of multiple layers – say alternating layers of viscosities η_1 and η_2, the number of layers changes the details of the relationship described in the equation above:

$$\lambda_i = 2\pi h \sqrt[3]{\frac{1}{6n^2} \frac{\eta_1}{\eta_2}}$$

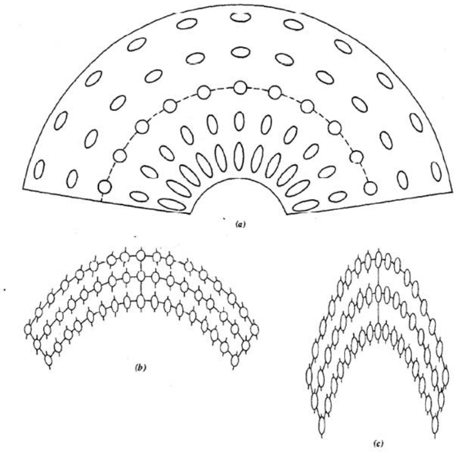
where n is the number of layers. That is to say, there is a dependence on the number of layers. But the relative viscosities and layer thickness still exert a first order control.

Complications arise when you have a number of competent layers, with different characteristic wavelengths (that is, the wavelength that they would fold at if a layer of such a thickness and viscosity were to fold alone), being folded together. It turns out that if the layers are sufficiently far apart, each will behave independently of the others, each folding at its own characteristic wavelength, and so this would produce **disharmonic folding**. "Sufficiently far" in this case means something like 1/4 to 1/2 the characteristic wavelength of that layer.

If the layers are closer together, though, there is interference between them. The thinner layer will often show two wavelengths of folding: the larger wavelength controlled by an adjacent, thicker layer and its own characteristic wavelength superimposed upon it.

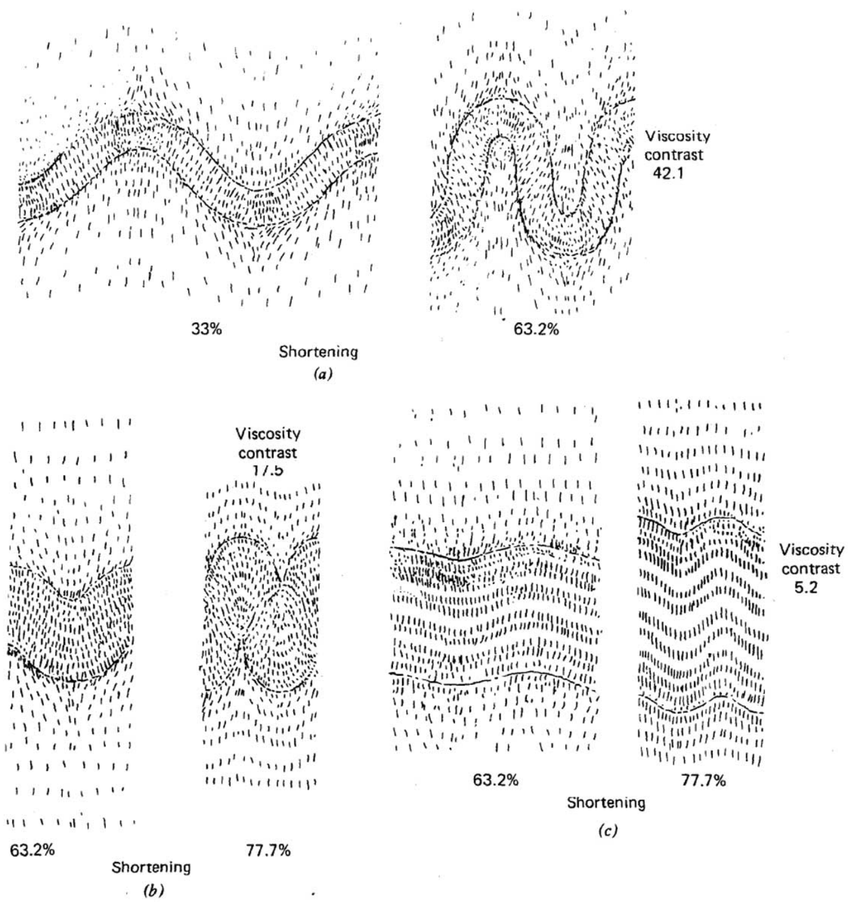
5.4.3 Polygenetic models: the quest for more realistic fold geometries

More realistic fold geometries can be produced by combining various mechanisms with each other, or with an additional amount of homogeneous shortening. The figure below shows the distribution of strain in a slab folded so that it has a neutral surface (a); then subject to additional homogeneous shortening of 20% (b) and 50 % (c). (See discussion and figures, pp. 243–245, figs. 12.12 and 12.13).



5.5 Numerical models

The following figure shows some results from numerical simulation of fold formation. This is an early simulation of the deformation of a single, viscous layer enclosed in a homogenous, viscous medium. Thin lines are drawn perpendicular to the principal axis of shortening at each point. Three cases are shown, for different viscosity contrasts. Note that as viscosity contrast decreases, the importance of folding (versus homogeneous pure shear shortening) decreases. Note also the deflection of principal axes of strain near the boundary between the two layers.



6 Other kinds of folds: kink folds, chevron folds, diapirs

Kink folds are asymmetric folds with straight limbs and sharp hinges. They occur as a short limb connecting two long limbs. Kink geometries are often adopted for idealizing fold geometries when constructing cross sections of fold and thrust belts. But beyond just an idealization, they actually exist! Various models of kink band formation include:

1. Migration of the kink band boundary into undeformed material
2. Kink band boundaries don't migrate, but instead mark the boundaries of a small shear zone within which layers rotate and shear past one another.

Chevron folds are symmetric folds with completely straight limbs and very tight fold hinges. One model for chevron fold formation has them being the result of interference of growing kink bands. Alternatively, chevron folds can form by flexural slip folding. If the layers are of some finite thickness, voids will form in the hinge zones. These voids are places that you might expect to be a locus of veining and fluid migration.

Diapirs are antiformal domes that appear to have been intruded vertically into their host rock. Salt and pressurized shales are common materials involved in diapiric emplacement. On larger scales, domal culminations of high grade gneisses are common features of the internal parts of mountain belts. Commonly, diapir emplacement is thought to require density inversion, a view motivated by the observation that salt is typically less dense than compacted, lithified sediments[1] and by early modeling of diapiric and domal culminations using materials with viscous rheology. Leaving aside considerations of buoyancy for the time being, material within a diapir is necessarily weak, and therefore

[1] In fact, even though many people still labour under this assumption, modern modelling and investigation of salt tectonics environments has conclusively shown that density inversion is not needed for diapirism, nor is plausibly inferrable in many cases

flows according to pressure gradients. For various reasons, pressures on the flanks of diapirs are higher than in the center of the diapir, so material moves laterally into the diapir, and then up into the diapir. Diapir-like flow of weak material is also noted filling the cores of anticlines in detachment fold settings.

7 Review questions

1. Draw a flexural slip and a passive flow fold. Draw the expected sense of shear along the folded layers
2. Consider a layer with a pre-existing lineation that acts as a passive marker. What happens to the lineation when the layer is folded according to the three main models of fold formation. The key will be to determine whether the folding will cause rotation of the passive marker. That is: is the layer with the lineation a circular section of the strain ellipsoid (no rotation), or not?
3. In an perfect, upright flexural slip fold, what happens to the fold with depth and why?