

# Lab 8: Folds and their map patterns

Fall 2005

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Folds are one of the most common tectonic structures developed in deformed rocks. They form in rocks containing planar features such as sedimentary bedding, lithologic layering in metamorphic schists and gneisses, or planar features such as cleavage or schistosity produced during an earlier deformational event. They occur at all scales from the thin section to mountain ranges. At larger scales, complex folds may be difficult to understand while mapping in the field. Instead, we rely on the pattern that develops on the map. In addition to looking at the overall fold pattern of the units, we can gain information about the 3-D shape of the folds by analyzing other data such as strike and dips of the units, shapes and orientations of small-scale folds that are observed in the outcrop, and the orientation of fabrics (e.g. cleavages and lineations) that developed during folding.

### 1.1 Terminology and jargon

**Hinge line:** lines joining the points of maximum curvature on a fold. A physical property, so it has a location as well as an orientation.

**Hinge plane/surface:** the plane or surface containing the hinge lines of successive layers

**Crest (or trough) line:** line of highest (or lowest) elevation on a fold. Also a physical property.

**Crest (or trough) plane/surface:** the plane or surface containing the crest/trough lines.

**Limbs:** zones of minimum curvature, the close to planar part of the fold between the hinges.

**Fold axis:** a theoretical line which, if moved through space, would trace out a closely fitting surface to a fold (in particular, the fold axis generates a cylindrical fold, and real folds are only approximately cylindrical for small regions).

**Axial plane/surface:** plane or surface which connects the hinge lines on adjacent layers. Often approximated as bisecting the fold limbs.

**Axial surface trace:** intersection of axial plane and ground surface.

**Enveloping surface:** a plane or surface containing hinge lines of adjacent folds.

**Median surface:** a plane or surface containing inflection lines of adjacent folds.

**Fold train:** a series of folds.

**Symmetric folds:** folds in which (1) the median surface is planar, (2) the axial plane is perpendicular to the median surface and (3) the folds are bilaterally symmetrical about their axial planes.

**Asymmetric folds:** folds that are not symmetric. Limbs of asymmetric folds are of unequal length. Asymmetric folds are often classified as "Z-folds" or "S-folds" depending on the sense of overturn.

**Vergence:** direction of acute angle made by intersection of hinge surface and enveloping surface. Often used to infer a sense of shear, a direction of tectonic transport or the closure of large-scale folds.

**Cylindrical fold:** a fold whose hinge is a straight line; this is the kind of fold generated by moving a line (fold axis) through space parallel to itself.

**Non-cylindrical fold:** a fold whose hinge line is curved. Essentially all folds are non-cylindrical, but a non-cylindrical fold can usually be broken down into sub-regions which are cylindrical.

**Anticline:** a fold with older rocks in its core.

**Syncline:** a fold with younger rocks in its core.

**Antiform:** a fold whose limbs dip away from the hinge: that is, it opens downward (upside down U-shaped).

**Synform:** a fold whose limbs dip towards the hinge: i.e., it opens upward.

**Vertical fold:** a fold whose hinge line is vertical or nearly so.

**Reclined fold:** a fold whose axial surface is inclined and whose hinge plunges down the dip of the axial surface.

**Recumbent fold:** a fold whose axial surface is horizontal or nearly so.

**Overtured fold:** a fold where one limb is "upside-down". That is, older beds are found above younger beds.

**Dip Isogon:** theoretical line connecting points of equal inclination between two folded surfaces (fig. 6). One common scheme for classifying folds is based on whether isogons are 1) convergent isogons; 2) parallel; or 3) divergent and variations in **orthogonal thickness** and **axial trace thickness**.

**Parallel fold:** a fold in which the thickness measured orthogonally across the layer boundaries is constant throughout the fold.

**Concentric fold:** a subclass of parallel fold whose inner and outer surfaces are defined by circular arcs having a common center.

**Similar fold:** a fold characterized by (1) parallel dip isogons; (2) a decrease in orthogonal thickness from hinge to limb; (3) constant axial trace thickness.

**Interlimb angle:** the angle between limbs of a fold (fig. 7). This is also the basis for a classification scheme:

gentle 120° to 180°

open 70° to 120°

close 30° to 70°

tight 2° to 30°

isoclinal 0° to 2°

**Harmonic folds** In a folded multilayer, folds eventually die out parallel to the axial surface (unless they hit a free surface first). The **depth of folding** is the length down the axial surface that folds persist. **Harmonic** folds persist for a greater depth than many multiples of the fold half-wavelength, **disharmonic** folds die out within a distance on the order of the fold's wavelength.

**Parasitic folds** Folding often develops simultaneously at many scales such that smaller folds are found on the limbs of larger folds. These are termed parasitic folds, and it is common to distinguish between "first order folds" (map scale); "second-order folds" (tens or hundreds of meters) and third and higher order folds (meters to millimeters). Predictable changes in the asymmetry or vergence of parasitic folds are useful for determining the geometry of lower-order folds.

**Polyphase folding:** a term used when there are multiple episodes of folding.

## 1.2 Stereonets and folding

Prior to folding, the poles to a bedding plane plot as a single point or a concentration of points on a stereonet. Folding alters the distribution of the original poles. If the plane is folded about a straight fold axis (cylindrical folding), then the orientation of the poles will range from those on one limb to those on the other, and all the orientations will lie in an imaginary plane perpendicular to the fold axis.

Information from folded bedding is usually plotted in one of two ways. A Pi plot is a stereonet plot of poles to bedding. If the bedding was cylindrically folded, the poles will all plot roughly on a great circle perpendicular

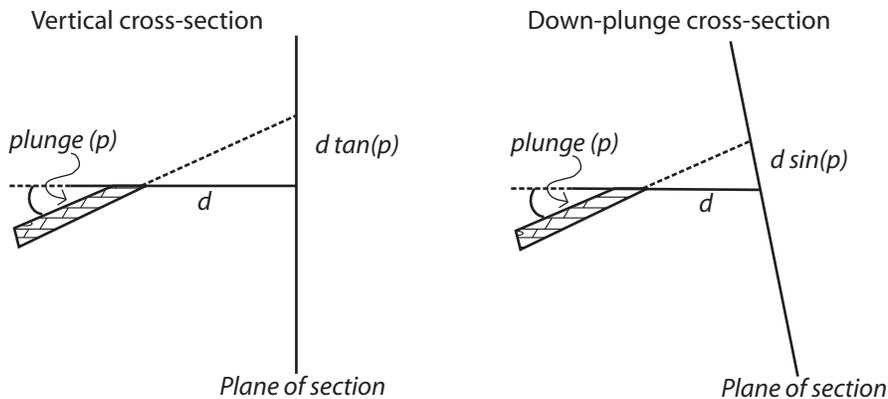
to the fold axis. The handout shows a variety of fold geometries and the corresponding stereonet plots. Look through these carefully until they make sense to you. Note the assumption in each of the plots that the collection of data is equally distributed along the length of the fold, and thus the density of points corresponds to the length of limb.

The tangent planes to cylindrically folded bedding intersect at the fold axis. A Beta plot can be made by plotting strike and dip measurements as great circles (rather than as poles to bedding) and finding the point where all the great circles intersect. The Beta and Pi methods do essentially the same thing, but the Pi plot is easier to work with.

The orientation of the axial plane to a cylindrical fold can be found with the orientations of two lines that are contained by the axial plane. One available line is the fold axis. By definition, the fold axis must lie in the axial plane. A second line is the trace of the axial plane across the ground. Draw trace on the map by connecting the points of maximum curvature for several folded beds and measure its general trend directly from the map. Find the axial surface by fitting a great circle through the points representing the fold axis and the surface trace of the axial plane. Another option is to draw a plane through the fold axis that bisects the fold limbs. This is not strictly correct, but it is a reasonable and often made approximation for drawing folds in cross section.

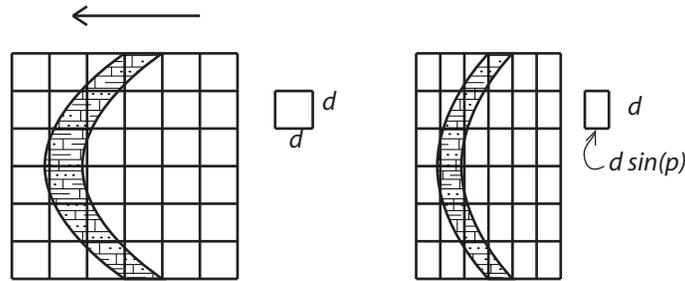
### 1.3 Down plunge projections

Up to this point, all of the cross sections we have looked at or constructed have been oriented vertically. In regions of folded rocks, it is often desirable to draw what is called a down plunge projection of the fold structure, a cross section drawn perpendicular to the plunge of a fold. Starting with a map outcrop of a fold, contacts are projected from their location on the map into the plane of the cross section. Depending on if you are doing a vertical cross section or a down plunge projection, the location of the contact on the plane of the cross section can be found at an elevation above the base line by multiplying the perpendicular map distance to the contact by the sine or tangent of the plunge.

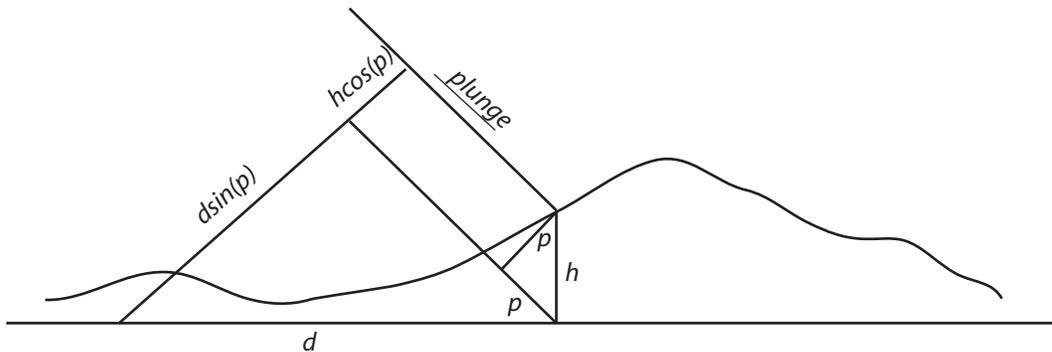


To draw a down plunge projection (or for that matter, any section of a plunging structure), start by drawing a square grid on the map parallel and perpendicular to the bearing of the plunge (which should be parallel and perpendicular to the line of the section as well). Condense the grid on the cross section, keeping the spacing constant in the direction perpendicular to plunge (parallel to line of section), but condensing the vertical scale by (grid spacing) \* (sine (plunge)). Then project points to appropriate elevations above the reference line of cross section using the grids as guides. Obviously, the closer the grid spacing, the more accuracy that you will have on your down plunge projection, but the longer it will take to draw your section. Balance these two factors accord-

ingly.



When topography is involved, drawing the down plunge projection becomes a little more complicated. However, it is still possible to draw a section fairly quickly. The elevation becomes a factor in where on the cross section a particular feature plots.



## 2 Exercises

1. Pick a fold on the table. Sketch the fold and identify, on your sketch: the hinge line, axial plane, the limbs. Identify the rock type. Are there linear fabric elements (eg. mineral lineations, stretching lineations, or intersection lineations?) present? Classify the fold according to the following schemes: (1) cylindricity; (2) symmetry; (3) tightness; (4) Ramsay's classification (using orthogonal thickness, axial trace thickness and the convergence of isogons).

2. Down plunge projection. The folds in figure 1 plunge  $30^\circ$  due west. a. Add fold hinge traces and a few strike and dip symbols (don't worry about the dip, just the direction) to the map. b. Construct a down plunge projection. c. Write a sentence or two on why its important to draw a fold perpendicular to the plunge rather than vertically.

3. Down plunge projection with topography. The fold in figure 2 plunges  $25^\circ$  due north. Construct an E-W profile of the fold perpendicular to the plunge with 340 m as the zero datum line. Use the formula given in the handout, but remember to convert all your measurements from the map and the elevations using the given scale. Interpolate elevations between contour lines.

4. Polyphase folding. Schematic map vies of several polyphase folds are shown in figure 3. For each of these 4 fold interference patterns, draw the traces of the F1 (first folding) and F2 (second folding) hinge surfaces. Also draw schematic cross sections along lines AA' and BB'. What is the approximate angular relation between the F1 and F2 fold axes?

5. Stereonet analysis. With the attitude data given in figure 4, construct a Beta diagram and a Pi diagram. What is the trend and plunge of the fold axis? (feel free to use a stereonet program for this, no need to do it by hand).

6. Stereonet analysis. With the attitude data given in figure 5, construct a contoured Pi diagram. Determine the following: a. trend and plunge of the fold axis b. approximate attitude of the axial plane c. approximate interlimb angle d. approximate fold style. Illustrate with a sketch.

7. Mapping folds and stereonet analysis. As seen in the map in figure 6, a series of sandstone and shales are unconformably overlain by a conglomerate unit. There are no faults in the area. Map symbols are:

-  Strike and dip of beds
-  Strike and dip at joints (arrow points down dip)
-  Vertical joint (strike is line without arrow)
-  Strike and dip of cleavage
-  Trend and plunge of minor folds
-  Trend and plunge of lineations

a. Make a "solid" geologic map from the given outcrop area, using extrapolative license. Remember the simplest interpretation is usually the right one. Pay attention to minor fold asymmetries as you complete the map. Lightly color the map and use a red pencil to draw in appropriate hinge surface traces, indicating if its an anticline, syncline, overturned anticline or overturned syncline. There is more than one sandstone and shale unit.

b. Analyze the fold structures by plotting on a single stereonet (using different symbols) i) poles to bedding ii) poles to slaty cleavage iii) minor fold axes Based on the plots, what is the style of folding? What is the orientation of the major fold axial surface in the center of the map? Calculate the angle between the axial surface and each limb of the major fold. Roughly sketch and characterize the folds?

c. On a separate stereonet plot, using different symbols, plot i) poles to joints in the sandstones and shales ii) poles to joints in the conglomerate Do the joints appear to be genetically related to the folds in the shales/sandstones? Are the joints in the conglomerates genetically related to the joints in the shales/sandstones? If so, why?