University of Anbar

College of Science

Department of Applied Geology

Advanced Structural Geology

Title of the lecture

Folds and Folding

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Folds and Folding

Introduction

In simple terms, a fold is a structural feature that is formed when planar surfaces are bent or curved. If such surfaces (like bedding, cleavage, inclusions) are not available you will not see a fold even though the rock was deformed. Folding is a manifestation of ductile deformation because it can develop without fracturing, and the deformation is (heterogeneously) distributed over the entire structure. Looking at a fold from a kinematic perspective, you realize that strain in this structure cannot be the same everywhere. We recognize distinct segments in a fold, such as the hinge area and the limbs, the inner and the outer arc, each of which reflect different strain histories, regardless of scale. The geometry of folds tells us something about, for example, the degree and orientation of strain, which in turn provides critical information about the deformation history of a region.

Anatomy of a folded surface

The schematic illustration in Figure 1 shows the basic geometric elements of a fold. 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**. You may think of a **limb** as the less curved portion of a fold. In a limb there is a point where the sense of curvature changes, called the **inflection point**. Folds with a straight hinge line (Figure 2a) are called **cylindrical folds** when the folded surface can wrap partway around a cylinder. If this is not the case and the hinge line curves, the folds are called **noncylindrical** (Figure 2b). In reality the lateral extent of cylindrical folds is restricted to the outcrop scale or even less, because over greater distances the hinge line of folds typically curves. Nevertheless, you will find that we may conveniently treat natural folds as cylindrical by dividing them into segments with straight hinge lines.
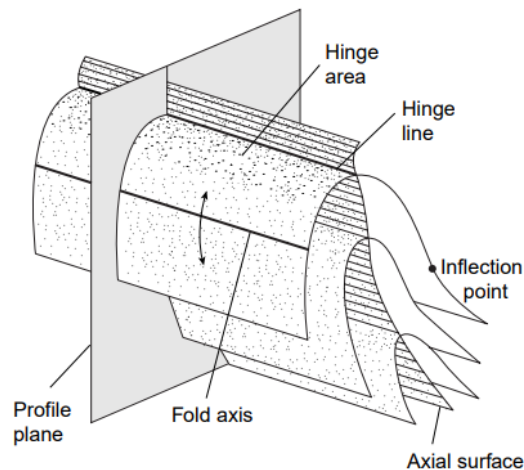

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Figure 1 The terminology of a fold.
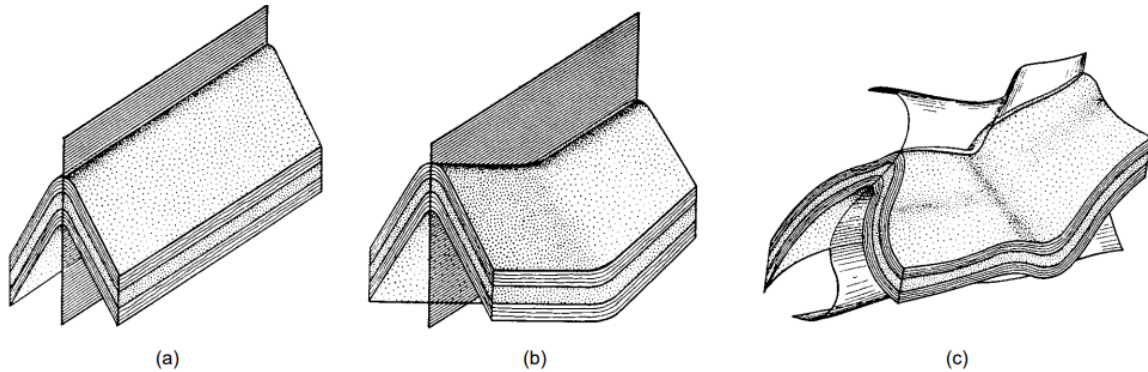

(a) (b) (c)

Figure 2 A cylindrical fold (a) is characterized by a straight hinge line and a noncylindrical fold (b) by a curved hinge line. The axial surface may be planar, as in (a) and (b), or curved (c).

A cylindrical surface consists of an infinite number of lines that are parallel to a generator line. This generator line is called the **fold axis**, which, when moved parallel to itself through space, outlines the folded surface. In the case of cylindrical folds, the fold axis is of course parallel to the hinge line. The topographically highest and lowest points of a fold are called the **crest** and **trough**, respectively, and these do not necessarily coincide with hinge lines. The surface containing the hinge lines from consecutive folded surfaces in a fold is the **axial surface** (Figures 1 and 2). The term **axial plane** is loosely used by some, but the surface is not necessarily planar as seen in Figure 2c (recall the distinction between surface and plane). Moreover, the axial surface does not necessarily divide the fold into equal halves that are mirror images of one another. The reference plane used to describe fold shape is called the **fold profile plane**, which is perpendicular to the hinge line (Figure 1). Note that the profile plane is not the same as a cross section through the fold, which is any vertical plane through a body, much like the sides of a slice of layered cake. If the hinge line is not horizontal, then the profile plane is not parallel to the cross-sectional plane, which has implication for the fold geometry description. The angle between fold limbs as measured in the profile plane is called the interlimb angle (Figure 3).
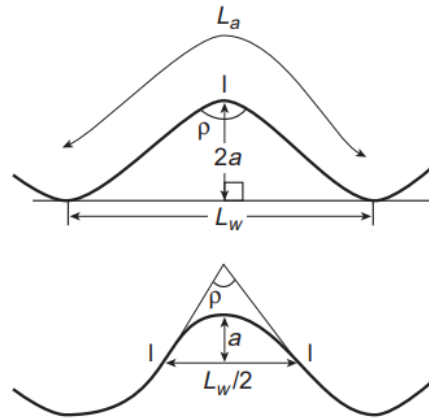
Figure 3 The interlimb angle (ρ), the wavelength (L_w), the amplitude (a), and the arc length (L_a) of a fold system in profile.

Intuitively you realize that the interlimb angle offers a qualitative estimate of the intensity of folding; the smaller the interlimb angle, the greater the intensity of folding. Finally, we recognize the **amplitude**, **wavelength**, and **arc length** of a fold in profile. These terms are used in the same manner as they are in wave physics. The wavelength is defined as the distance between two hinges of the same orientation, while the arc length is this distance measured over the folded surface; the amplitude is half the height of the structure measured from crest to trough (Figure 3). These and other terms associated with folds are summarized below.

- 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

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- 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

When successive layers in a folded stack have approximately the same wavelength and amplitude, the folds are called **harmonic**. If some layers have different wavelengths and/or amplitudes, the folds are **disharmonic**. In extreme circumstances, a series of folded layers may be totally decoupled from unfolded layers above or below. When this happens, a **detachment** horizon exists between folded and unfolded layers.

Fold Facing: Antiform, Synform, Anticline, and Syncline

Draw a fold on a piece of paper. Chances are that you place the hinge area at the top of the structure, outlining something like a sharp mountain. This particular fold geometry is called an **antiform**. The opposite geometry, when the hinge zone is at the bottom (outlining a valley), is called a **synform**. The explanation for the modifier's "anti" and "syn" is that the limbs dip away from or toward the center of the fold, respectively. You will find that many geologists use the terms anticline and syncline as synonyms for antiform and synform, but this is incorrect. The terms anticline and syncline imply that the stratigraphic young direction in the folded beds is known. This is an important distinction for regional analysis, so let's look at this in some detail. Imagine a sequence of beds that is laid down in a basin over a period of many millions of years. Obviously, the youngest bed lies at the top while the oldest bed is at the bottom of the pile (this is Steno's **Law of Superposition**). When we fold this sequence into a series of antiforms and synforms, we see that the oldest bed lies in the core of the antiform and the youngest bed lies in the core of the synform (Figure 4a and b). Under these circumstances we call them anticlines and synclines, respectively. In an **anticline** the beds young away from the core; in a **syncline** the beds young toward the core. In both cases the young direction points (or faces) upward, so we call these structures **upward-facing folds**. Now turn the original sequence upside down: the oldest bed now lies at the top and the youngest bed at the bottom (Figure 4c and d). While we generate the same geometry of antiforms and synforms, the young direction is opposite to what we had before. In this antiform, the beds young toward the core, while in the synform the beds young away from the core. Both cases are **downward-facing folds**, and an antiform with this young characteristic is therefore called a **downward-facing antiform**; analogously, we recognize a **downward-facing synform**. Remember that when you find downward-facing folds in the field, you immediately know that some secondary process has inverted the normal stratigraphic sequence; that is, we cannot violate the Law of Superposition. Downward-facing folds are not as uncommon as one might guess. They are typically found in areas containing an early "generation" of regional folds with horizontal axial surfaces, which are quite common in collisional mountain belts. Subsequent folding of these early structures generates a series of upward- and downward-facing folds, as shown in Figure 4e.

Fold classification

The classification of folds is based on four components:

1. Fold shape in three dimensions, primarily distinguishing between cylindrical folds and noncylindrical folds (Figure 2).
2. Fold facing, separating upward-facing folds and downward-facing folds (Figure 4).
3. Fold orientation.
4. Fold shape in the profile plane.

The first two components, three-dimensional fold shape and fold facing, have already been introduced (Figures 2 and 3, respectively). In this section, we concentrate on the other two components of fold classification: fold orientation and fold shape.
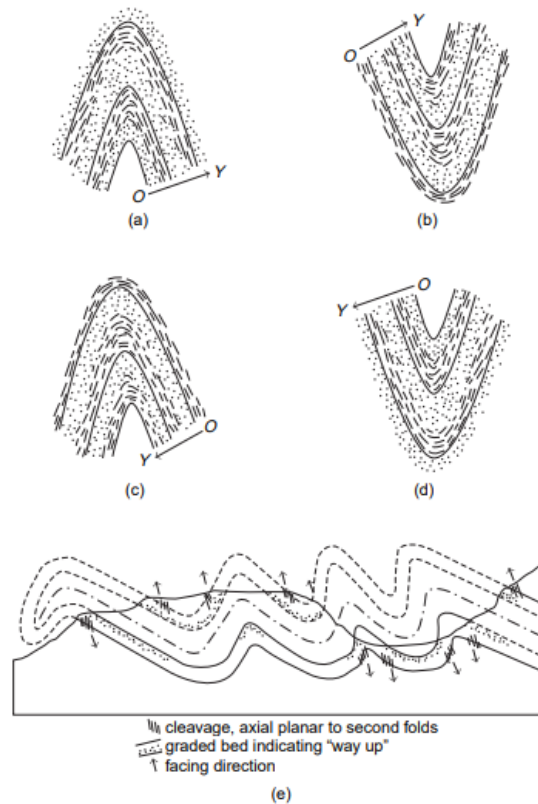

Figure 4 Antiforms, synforms, and fold facing. An upward-facing antiform (a) is also called an anticline and an upward-facing synform (b) is called a syncline. Downward-facing antiforms (c) and downward-facing synforms reflect an early history that placed the beds upside down prior to folding. These forms may occur in a region containing two generations of folding (e).

Fold Orientation

The first measurement we take is the orientation of the hinge line. On the scale of an outcrop the hinge line is typically fairly straight, and we determine its plunge (say, 20°) and direction of plunge (say, 190°). We now say that the fold is shallowly plunging to the South. Secondly, we measure the orientation of the axial surface. We measure a dip direction/dip of 270°/70° for the axial surface, which completes our description of the fold: a shallowly south-plunging, upright fold. Remember that the hinge line always lies in the axial surface. A practical convention we use the angular ranges shown below.

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°	

 In the European Alps, for example, large-scale recumbent folds are often associated with thrust faulting, and they are called **nappes**. A term that is used for a steeply plunging, inclined fold is a **reclined fold**. In all cases remember that your field measurements will be no more accurate than ±2° (compass accuracy), but that the feature you measure will probably vary over an even greater angle of ±5°–10°.

Fold Shape in Profile

Fold shape in profile describes the interlimb angle and any changes in bed thickness. The interlimb angle of a fold is the angle between the limbs. We assume that the limbs are relatively planar or we use the tangent at the inflection points (Figure 3). The values corresponding to the various terms are listed below.

Isoclinal	0°–10°
Tight	10°–60°
Open	60°–120°
Gentle	120°–180°

The second characteristic of fold shape in profile is any change in bed thickness across the structure. If you look at Figure 5a, you will notice that the bed thickness does not change appreciably as we go from one limb of the fold to the other. In contrast, the fold in Figure 5b has thin limbs and a relatively thick hinge area.
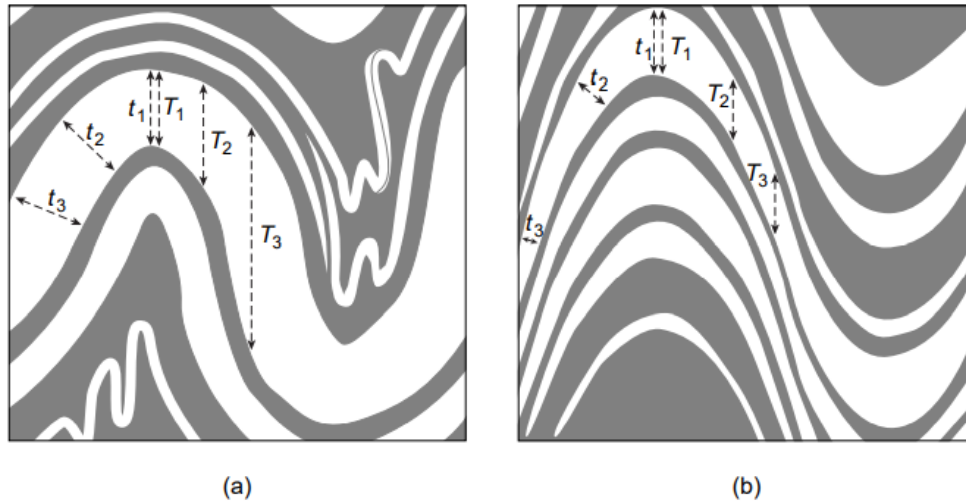

(a)   (b)

Figure 5 Parallel folds (a) maintain a constant layer thickness across the folded surface, meaning, $t_1 = t_2 = t_3$, but the layer thickness parallel to the axial surface varies ($T_1 < T_2 < T_3$). In similar folds (b), the layer thickness parallel to the axial surface remains constant, so, $T_1 = T_2 = T_3$, but the thickness across the folded surface varies ($t_1 > t_2 > t_3$).

We quantify these observations by using a method called dip-isogon analysis. Dip isogons connect points on the upper and lower boundary of a folded layer where the layers have the same dip relative to a reference frame (Figure 6). Three classes are recognized: convergent dip isogons (Class 1), parallel dip isogons (Class 2), and divergent dip isogons (Class 3). The terms "convergence" and "divergence" are used with respect to the core of the fold; when the dip isogons intersect in a point in the core of the fold, the fold is called convergent, and vice versa. The two geometries shown in Figure 5 are special cases. Dip isogons that are perpendicular to bedding throughout the fold define a **parallel fold**, whereas dip isogons that are parallel to each other characterize a **similar fold**. This terminology (especially the use of "parallel") may be confusing, but remember that parallel and similar describe the geometric relationship between the top and bottom surfaces of a folded layer. In the field, loosely using the terms similar (representing Class 2 and 3) and parallel (representing Class 1A, 1B, and 1C) is usually sufficient to describe the fold shape in profile. So, we added two more components to our description of a fold. Now as a test, sketch a shallowly plunging, upright, tight, similar, downward-facing synform in the margin of the text. The only parameter we have excluded in our classification is **fold size**. To specify this, we can use terms like microfold (microscopic size; up to millimeter scale), mesofold (hand specimen to small outcrop size; centimeter to meter scale),

and macrofold (mountain size and larger; hundreds to thousands of meters). Although the lengthy description above is certainly not pretty, it ends up being very informative and complete.
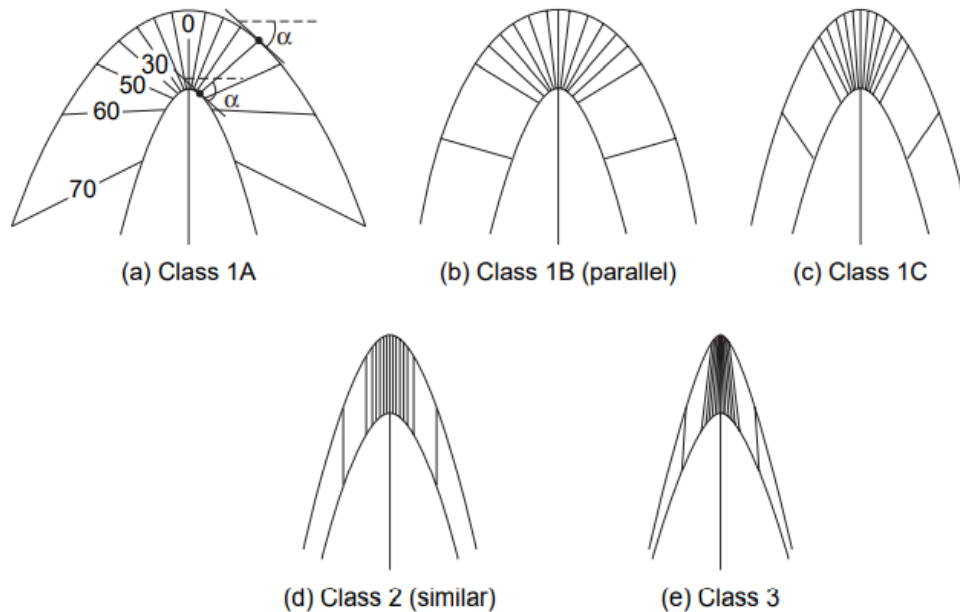

Figure 6 Fold classification based on dip isogon analysis. In Class 1A (a) the construction of a single dip isogon is shown, which connects the tangents to the upper and lower boundary of the folded layer with equal angle (α) relative to a reference frame; dip isogons at $10°$ intervals are shown for each class. Class 1 folds (a–c) have convergent dip isogon patterns; dip isogons in Class 2 folds (d) are parallel; Class 3 folds (e) have divergent dip isogon patterns. In this classification, parallel (b) and similar (d) folds are labeled as Class 1B and Class 2, respectively.

Mechanism of folding

Folds are the most commonly occurring structure in the earth's crust. This fold is the one of the best markers to know the deformation of particular rock mass or landform in geological past. They Occurs in micro, meso and macro scale. Their geometry and style of folding gives idea about type of deformation. They are also important by economically for oil traps, searching ore and mineral exploration. Why folds are generated and how they evolve in the rock mass such. To know about the folds, we need to do field observation. From this study we can know the folding history which helpful to understand the mechanism. Mechanism is the process by which different types of folds are generated.

Folding mechanisms

There are many types of folding mechanisms.

1. **Bending**

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Bending involves forces applied and acting at high angles to layers that may or may not have competence contrasts. A layer subjected to bending is like a notebook supported at the ends and loaded in the middle. The notebook bends downward when the load is placed in the middle Figure 7.
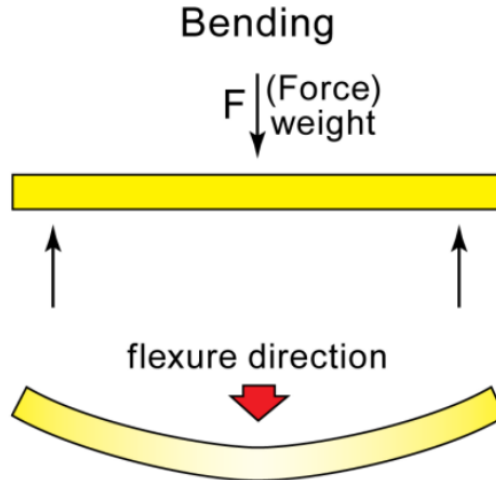

Figure 7. Folding mechanism by bending.

2. Buckling

Buckling is a well-known active mechanism for the development of rounded folds in a competent layer (i.e., a layer with low rate of ductile flow) enclosed in an incompetent (with high rate of ductile flow) medium of sufficient viscosity contrast. Gently pushing the two extremities of a paper sheet on a table towards each other reproduces this folding mechanism. When the force is small the sheet remains flat. As the force is slowly increased, it suddenly becomes curved. This rapid change from a flat to a curved (buckled) form at a particular force is due to the development of a mechanical instability figure 8.
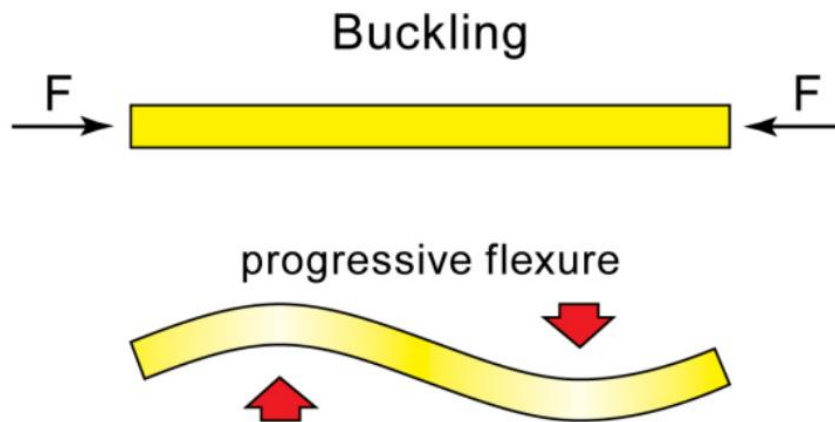

Figure 8 Folding mechanism by buckling

Flexural-slip and flexural flow:

A multilayer can be a pile of competent layers separated by surfaces of discontinuity or alternating layers of highly contrasting competence. The mechanical consequence is that the competent layers on either side of the surface of discontinuity or of a weak layer may easily slide relative to each other. This shear "decoupling" of layers allows a fold to accommodate a greater flexure than if the stack deforms as a single layer.

3. **Flexural-slip mechanism**

describes discrete faulting, usually coincident with bedding planes and accompanying folding. A classical simulation is to bend a book or pile of paper sheets; increasing bending about the fold axis is accommodated by increasing slip between the pages of the book or sheets of the pile. The thickness of individual sheets does not change, meaning that each sheet makes a parallel fold (i.e. layer surfaces remain parallel). Slip is an important part of folding because layer-parallel stresses increase with increasing rotation of the limbs figure 9.
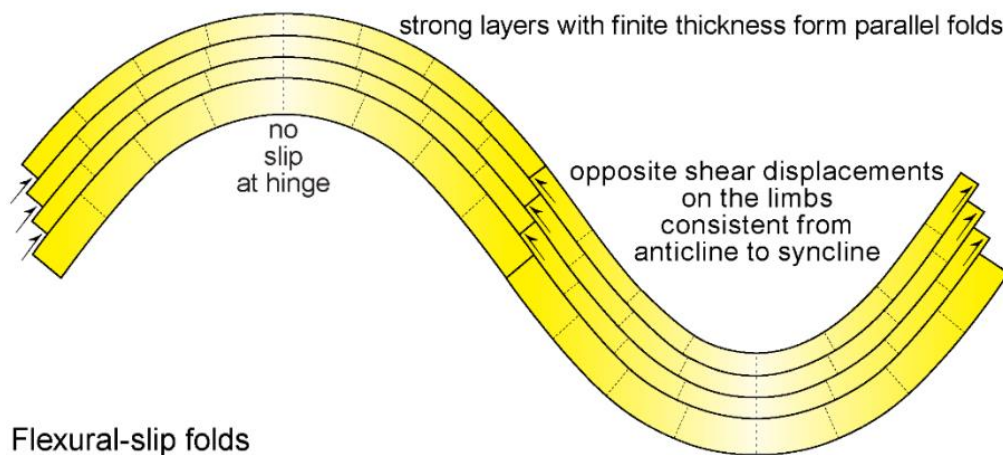

Figure 9 Folding mechanism by flexural slip

4. **Flexural flow mechanism**

describes bedding-parallel shear homogeneously distributed within the ductile layer being folded between stiffer layers. Like for flexural slip, bedding-parallel shear in limbs is opposite across the axial plane. The strain pattern due to hingeward shear tends to develop thickened hinges between thinned limbs, i.e., flexural-flow folds are mostly similar. Flexural-flow is sometimes applied to the weak layers that take up bedding-parallel motion within larger parallel folds. In this case, the stiff, active layers tend to keep their thickness throughout the deformation to produce and control the overall shape of concentric and/or parallel folds while the incompetent layers undergo flexural flow. In order to maintain similarity from bed to bed, ductile material moves out of the limbs into the hinges figure 10.
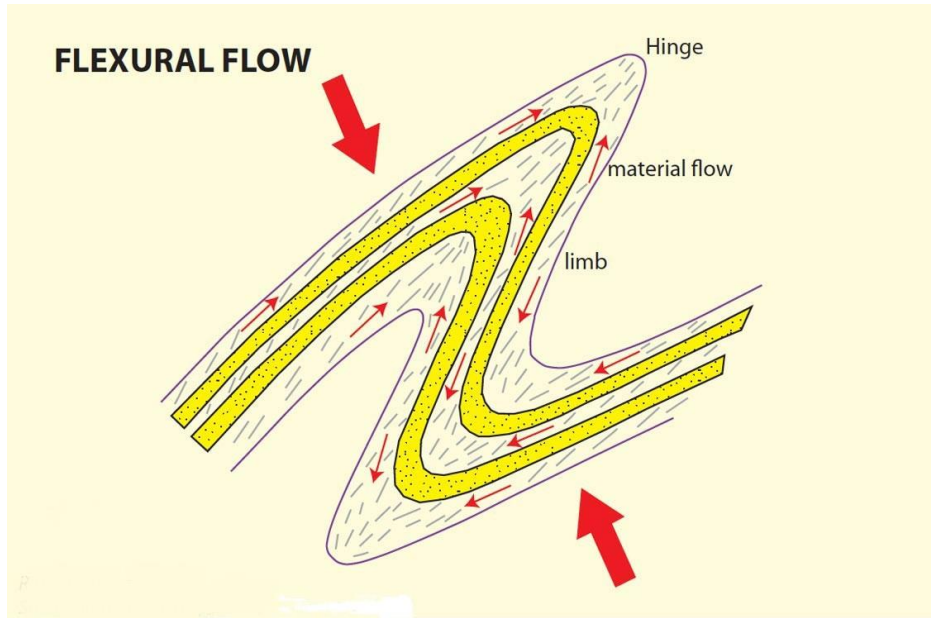
Figure 10 Folding mechanism by flexural flow

References

Ben A. van der Pluijm, and Stephen Marshak. (2004) EARTH STRUCTURE AN INTRODUCTION TO STRUCTURAL GEOLOGY AND TECTONICS. Second edition.