PART III Ductile Deformation

We Turn in this section to stuctures in rocks that form as a result of ductile deformation. The word *ductile* is used in the literature in several different ways, which creates considerable confusion and misunderstanding. Much of the problem can be traced to the fact that there are at least three different criteria by which ductile deformation can be recognized. It can be recognized by (1) the characteristic structures that are preserved in rocks; (2) the rheology of the deformation—that is, the form of the relationship among stress, strain rate, pressure, and temperature; or (3) the microscopic mechanisms that operate to produee the deformation.

Our use of the term is based on the first set of eriteria, which is consistent with our emphasis on describing rocks using nongenetic terminology. We use the term ductile deformation to refer to a permanent, coherent, solid-state deformation in which there is no loss of cohesion on the scale of crystal grains or larger and no evideuce of brittle fracturing. Thus there is evidence for distributed smoothly varying deformation with no evidence for discontinuities such as open cracks or pores along grain boundaries or within grains, discrete shear planes on the scale of crystal grains or larger, or angular grain fragments that indicate brittle fracturing. Our definition specifically excludes cataclastic flow, which many would consider a ductile deformation but whieh we consider to be characteristic of the brittle–ductile transition. It also in principle excludes soft-sediment deformation, which is not a coherent deformatiou at the grain scale.

Many writers refer instead to plastic or crystal plastic deformation. These terms imply a mechanism of deformation that may not be appropiate. For example, it is not clear that they would appropriately describe deformation accomplished by solution–diffusion phenomena. The term *plastic* carries implications of a specific type of rheological behavior that does not include, for example, dependence of the strain rate on the first power of the stress (see Part IV).

The value of a descriptive and nongenetic term is that the criteria for using the term can be agreed upon on rhe basis of observable structures and characteristics so differences in interpretation do not affect the use of the word. Nevertheless, we expect that the identification of appropriate descriptive features should be useful for inferring the rheology and mechanism of the deformation. Thus in Part IV, we discuss those characteristics of rheology and mechanism that are associated with the structures of ductile deformation. In particular, we find that ductile deformation, in the sense in which we use the term, is associated with the dependence of strain rate on stress raised to a power generally between 1 and 5, thar it is a thermally activated process that occurs at elevated temperatures roughly above half the absolute melting point of the material, and that the rheology of ductile deformation is only weakly dependent on the confining pressure. In terms of mechanism, ductile deformation is accomplished by the motion of defects called dislocations through crystal lattices and/or by diffusion. Thus in praetice, observational evidence for any of these conditions or phenomena may provide additional justification for applying the term *ductile deformation*.

In the end, we must admit that there is no completely satisfactory and unambiguous term to use. Moreover, the processes by which rocks deform range from brittle to ductile, and imposing arbitrary boundaries on such a gradation is always to some extent unsatisfactory.

Terminology aside, the most important eoncept of this part of the book, is that many structures oceur in rocks that could form only by flow of the rocks in the solid state. Solid-state flow at first may seem to be an oxymoron: Liquids flow, but do solids? In fact they do. Much of our modern use of metals, for example, depends on solid-state flow. Bars, rods, and sheets of steel, as well as copper and aluminum wire, are all produced by rolling out blocks of metal or drawing it through dies, essentially forcing it ro flow in the solid state into rhe desired configuration. Glaciers also flow slowly yet inexorably downhill by processes that include solid-state flow. Metals and glacier ice, like rocks, are polycrystalline materials; they are made up of an aggregate of crystals. By analogy, it may not seem so surprising, then that rocks also can undergo large amounts of solid-state flow when subjected to the appropriate conditions.

Our aim in Part III is to documenr the evidence for the solid-state flow of rocks; provide a means for objectively describing the characteristics of the resulting structures; and introduce the concept of strain, by which we can measure ductile deformation and begin to understand how the different types of structures form.

First we describe folds in rocks (Chapter 11) and various kinematic models that can account for their formation (Chapter 12). We then describe foliations and lineations (Chapter 13) and models for their formation (Chapter 14). With these fundamental structures providing evidence for pervasive ductile deformation in rocks, we next investigate how we can describe that deformation quantitatively through the eoncept of strain (Chapter 15) and how that concept helps us evaluate and interpret different models for the formation of folds, foliations, and lineations (Chapter 16). To conclude Part III, we describe methods for actually measuring strain in rocks and discuss examples of its application to the study of natural structures (Chapter 17).

CHAPTER

11 The Description of Folds

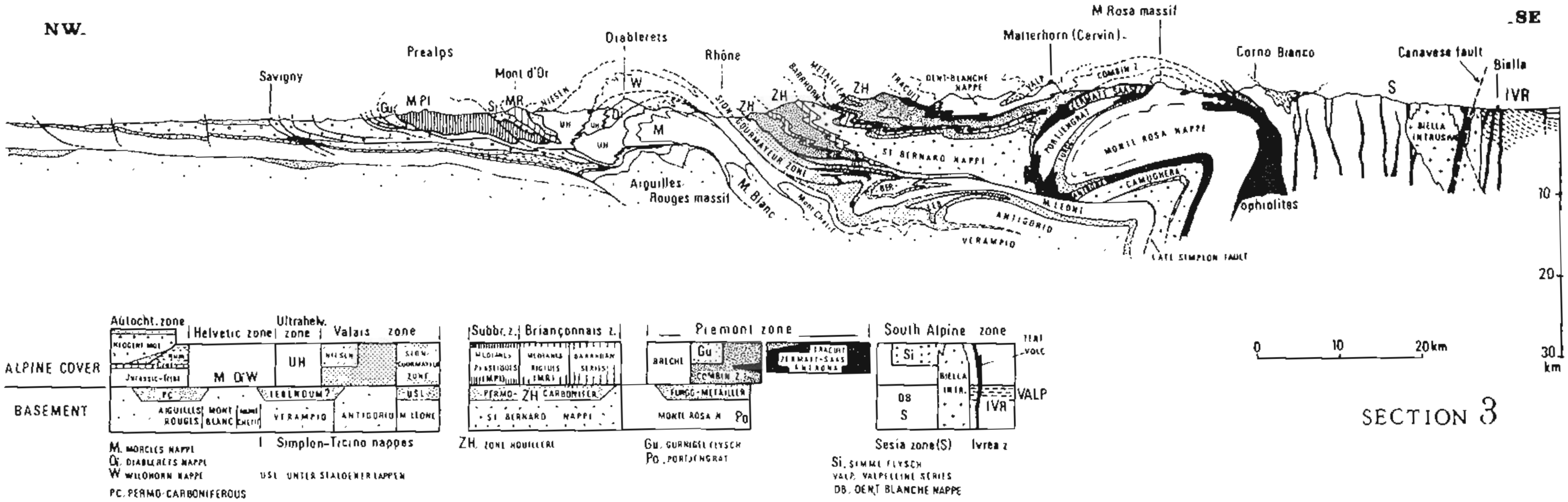
Folds are wavelike undulations that develop during deformation of rock layers, such as sedimentary strata. They are the most obvions and common structnres that demonstrate the existence of dnctile deformation in the Earth (see Section 1.3). In fact, as long ago as 1669, the Danish naturalist Nicholas Steno described folds and attributed them to Earth movements. Folds occur on all scales, ranging from huge features that dominate the regional strncture of orogenic core zones (Figure 11.1*A*) and form entire mountain sides (Figure 11.1*B*), through mesoscopic folds on the scale of an outcrop (Figure 11.1C), to folds visible only under a microscope.

Orogenic belts are all characterized by a number of fold systems. The flanks of orogenic belts are generally marked by large fold and thrust belts in unmetamorphosed to lightly metamorphosed sedimentary rocks, which are underlain by major décollemenrs (see Chapter 6). These belts, exemplified by the Appalachian Valley and Ridge province (Figure 11.2*A;* see Figures 6.12*A* and 6.13*A*), the Canadian Rockies (Figures 6.12*B* and 6.13*B*), the Himalaya front, and the Jura mountains north of the Alps (Figure 11.2*B;* see Figure 7.11 and 6.21) commonly contain folds that are continuous for tens of kilometers and that in cross section are eharacterized by layers of relatively constant thickness.

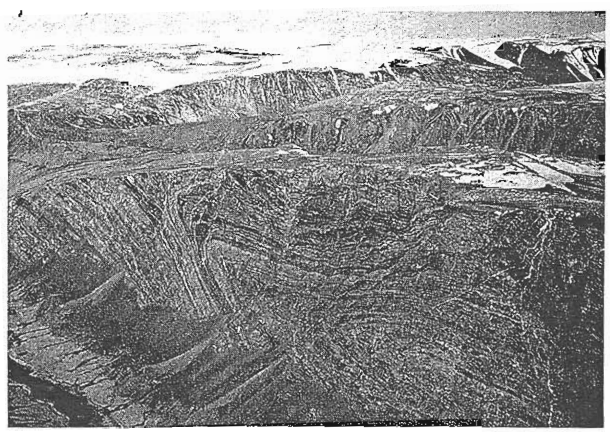
In the central regions, or core zones, of orogenic belrs, the exposed rocks were generally deformed at greater depth, where the temperature is higher than in the outer fold and thrust belts. The deformation there is associated with pervasive metamorphism and recrystallization of the rocks, and the folding is more intense, resulting in folds with a different appearance from those in the fold and thrust belts (Figure 11.1*B*, C). Cross sections of the core zones of the Alps (Figure 11.1*A*) and of the New England Appalachians (see Figure 12.35) indicate rhe large-scale character of such fold systems. Shapes of folds similar to those in metamorphic rocks (Figure 11.1*B*, C) also typify deformed salt deposits (see Figure 12.34*B*) and glaciers, which deform at much lower temperatures than the high-grade metamorphic silicare rocks. Such structures apparently imply a high degree of mobility of the roeks and their component minerals during deformation.

Although most folds we observe are in bedding or former bedding surfaces, folds also affecr other types of layers, including dikes, veins, metamorphic or igneous compositional layering, and foliations, which are planar structures defined; for example, by the preferred orientation of platy minerals in the rock (see Chapter 13).

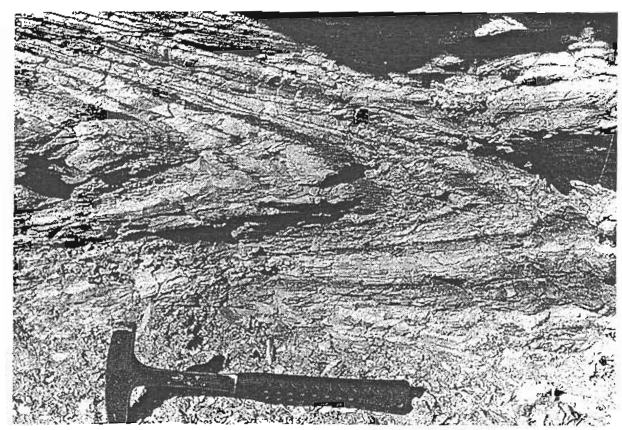
Folds are usually studied strictly to reveal their geometry. The shape, orientation, and extent of folds can be of critical importance in finding economically valuable deposits and in predicting continuations of known deposits. Oil and gas are commonly trapped in



A.

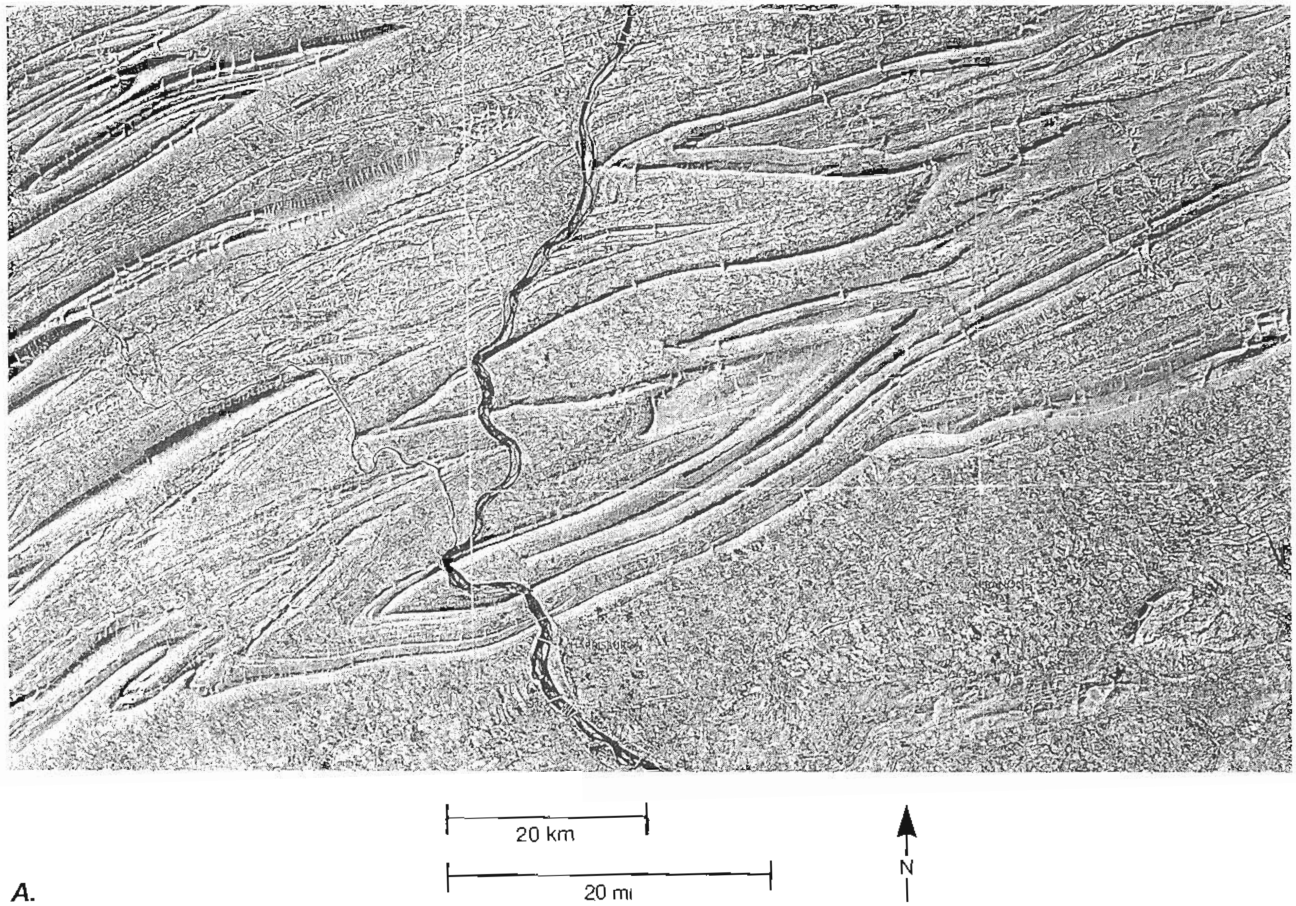


B.

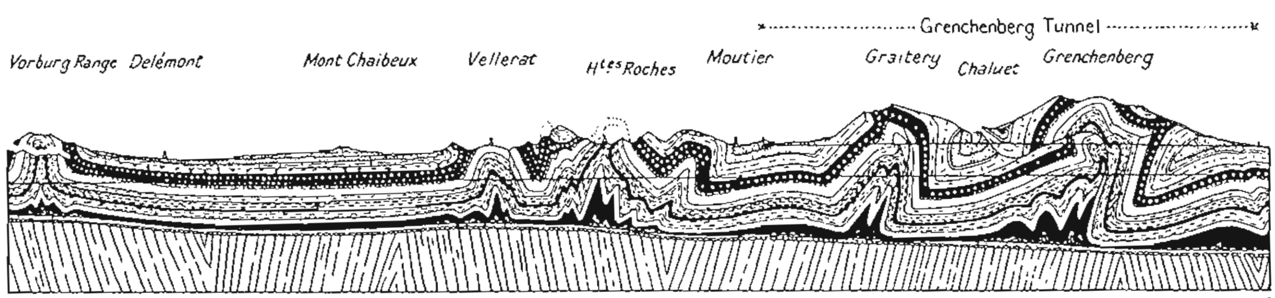


C.

Figure 11.1 Seales of folding in duetile metamorphic rocks. *A.* Cross section of metamorphosed rocks in central region of western Alps. *B.* This fold in metamorphic gneiss (Grandjeans-Fjord, east Greenland) is typical of folding in the meramorphic cores of orogenic belts. Height of the cliff is 800 m. *C.* Fold in banded marbles in the Snake Range detachment, western Nevada.



A.



B.

Figure 11.2 Folds in sedimentary rocks of fold and thrust belts. *A.* Folds in sedimentary rocks of Appalachians. Ridges are formed by erosion-resistant sandstones and conglomerates. Note the fold train of doubly plunging anticlines and synclines in the northwest. *B.* Cross section of the Jura Mouutains north of the Alps, showing the folds in the sedimentary layers (largely limestones) and the décollement, or sole fault, below the fold. Folds are class 1B to class 1C.

the up-bowed parts of folds. Ore deposits may be concentrated in certain parts of folds, such as hinge zones, which are the most sharply curved areas, or they may be located in particular layers that have been folded.

Beyond their economic importance, however, folds provide a record of tectonic processes in the Earth. The great variety of fold shapes in rocks must reflect both the physical conditions (such as stress, temperature, and pressure) and the mechanical properties of the rock that existed when the folds developed. If we could understand the significance of fold geometry, then we would have a valuable key to understanding conditions of deformation in the Earth.

The description of folds should be free of genetic implications, because genetic terms require interpretation of the origin, which may not be well understood. Ultimately, however, we wish to associate fold geometry with the mechanism of formation so that accurate description can lead to useful interpretation. Thus the geometric description in this chapter serves as the basis for the discussion, in subsequent chapters, of the kinematics (Chapter 12, Sections 16.1 and 17.3) and the mechanics (Sections 20.2 and 20.3) of fold formation. The terminology for describing folds has evolved and accumulated over the past century or so of geologic investigation, and it is extensive and not always consistent. We introduce the most useful terms in this chapter and present an objective system of describing fold geometry in terms of elements of fold style.

11.1 Geometric Parts of Folds

The simplest part of a fold that displays the characteristic fold geometry is a single folded surface such as a bedding surface, which is the interface between two layers of rock. A folded layer can be viewed as the volume contained between two such surfaces. Most folds consist of a stack of layers folded together, and they can be described as a nested set of folded surfaces. We discuss the parts of folds by looking first at folded surfaces, then at folded layers and multilayers.

Parts of a Single Folded Surface

Figure 11.3 shows several features of folds in a single surface. A single fold is bounded on each side by an inflection line where the surface changes its sense of curvature—for example, from convex up to concave up. (Fold I in the figure is bounded by inflection lines i_1 and i_2.) If the fold surface is planar in the region of the inflection, then by definition we take the inflection line to be the midline of the planar segment. A fold train is a series of folds characterized by alternating senses of curvature. Folds that are convex upward (folds I and III) are antiforms, and folds that are concave upward (fold II) are synforms. A fold system is a set of folds of regional extent characterized by a comparable geometry and presumably a common origin.

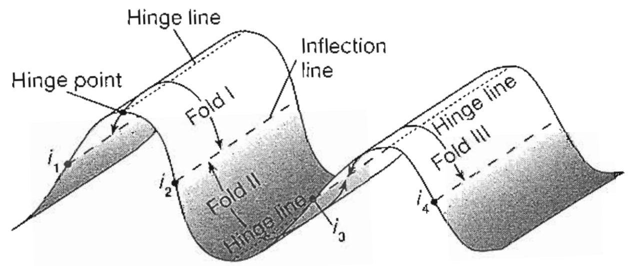


Figure 11.3 Features of a fold train in a single surface. Folds I and III are convex up; fold II is concave up. Folds I and III are unshaded; fold II and the incomplete parts of folds at either end are shaded. Inflection lines (dashed) delimit individual folds; points i_1, i_2, i_3, and i_4 are the inflection points. Dotted lines are the hinge lines of each fold.

The curvature of any surface is a measure of the change of orientation per unit distance along that surface. A circular arc has constant curvature, and a flat plane has no curvature. In general, the curvature measured along the folded surface from one inflection line to the next is not constant, and the hinge line, or more simply the hinge, is the line in the folded surface along which the curvature is a maximum (Figures 11.3 and 11.4*A*, *B*). A single fold may have more than one hinge (Figure 11.4*B*). If the maximum curvature is constant along an arc of finite length, then we take the midpoint of the arc to be the location of the hinge point (Figure 11.4*C*). The curvature may also vary in magnitude *along* any given hinge, and the hinge need not be a straight line (see, for instance, Figure 11.5*A*).

A fold with a single hinge closes where the limbs converge at the hinge zone (Figure 11.4*A*). On an outcrop pattern of such a fold, the closure is also sometimes called the nose of the fold. For a double-hinge fold, the closure is in the region of minimum curvature between the two hinges (Figure 11.4*B*).

The hinge zone is the most highly curved portion of a fold near the hinge line (Figure 11.4*A*); the limbs (sometimes called the flanks) are regions with lowest curvature and include the inflection lines. Technically, the hinge zone can be defined as that portion of the folded surface having a greater curvature than the reference circle that is tangent to both limbs at the inflection points of the fold (Figure 11.4*A*). In the unusual case of a fold with constant curvature, the areas near the hinge and those near the inflection lines are still referred to loosely as the hinge zone and limbs, respectively.

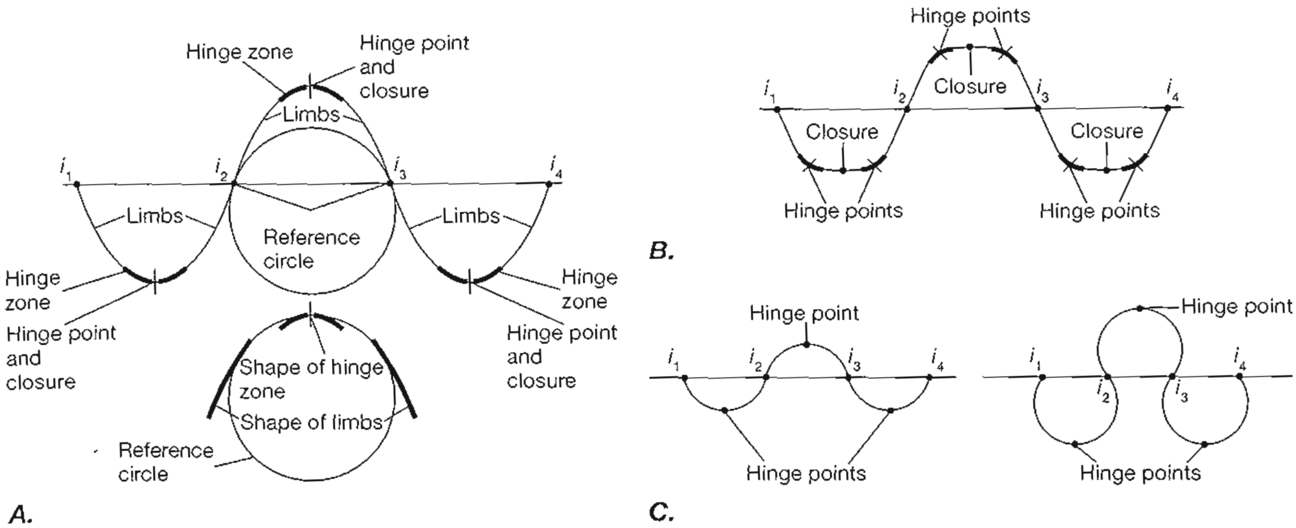


Figure 11.4 Definition of a hinge point, closure, hinge zone, and limb of a fold. *A.* The hinge points are points of maximum curvature. The closure point is the hinge point on a single-hinge fold. The *hinge zone* and *limb* are defined with reference to a circle that is tangent to both sides of the fold at two adjacent inflection points. The part of the fold that has a curvature greater than that of the reference circle is the hinge zone; the parts between the hinge zone and the inflection points that have a curvature less than that of the reference circle are the limbs. *B.* Individual folds may have two hinges. The closure point is the point of minimum curvature between the two hinges. C. Fold trains in which each fold has constant curvature and thus is the arc of a circle (perfect circular folds). Hinge points are the midpoints of each of the arcs.

The crest line and trough line on a fold are the lines of highest and lowest elevation, respectively, on the folded surface (Figure 11.5). These lines may, but do not necessarily, coincide with the hinge (Figure 11.5*B*), and they need not be straight lines (Figure 11.5*A*). Culminations and depressions are areas where crest or trough lines go through maximum and minimum elevations, respectively.

We generally portray the form of a fold by its profile, which is the trace of the folded surface on a plane normal to the hinge line (Figure 11.6*A*). The profile is the form of the fold seen when it is viewed looking parallel to its hinge. The curvature of most folds is greatest along their profiles. The hinge, inflection lines, and crest and trough lines appear on the profile, of course, as points.

A cylindrical fold is one for which a line of constant orientation, called the fold axis, can be moved along the folded surface without losing contact with it at any point (Figure 11.6*A*). Thus it is a line of fixed orientation that makes an angle of 0° with every orientation of the folded surface. Folds that do not possess this property are called noncylindrical folds. A conical fold is one whose surface is everywhere at a constant nonzero angle to a line of fixed orientation, which is also called the fold axis (see Figure 11.7*A*). A fold axis is thus an

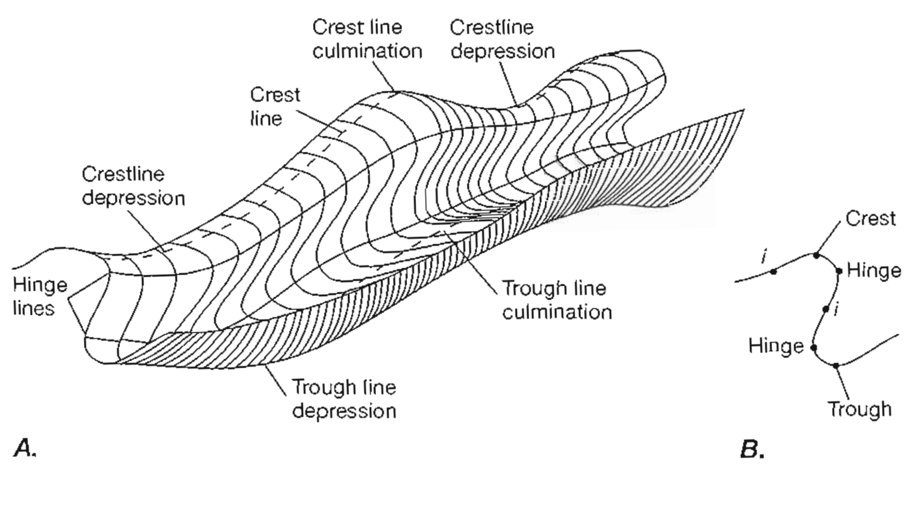


Figure 11.5 Crest and trough of a fold. *A.* Three-dimensional view of fold. *B.* Cross section normal to the hinge.

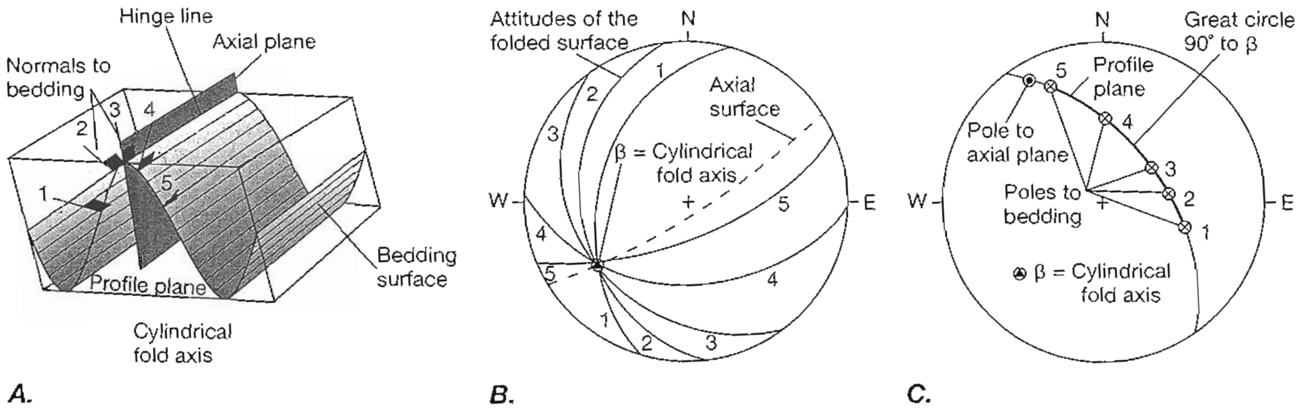


Figure 11.6 Geometry of a cylindrical fold in three dimensions and on a spherical projection. *A.* Diagram of a cylindrically folded surface, showing the fold axis, the profile plane, and the perpendiculars to the folded surface, which are parallel to the profile plane. *B.* Schmidt net (equal area) plot of several orientations of the cylindrically folded surface in part *A*, all of which intersect at the fold axis. *C.* Schmidt net (equal area) plot of the poles to the surface orientations plotted in part *B*. All the poles must lie along a great circle perpendicular to the fold axis. The great circle also defines the orientation of the profile plane.

imaginary geometric property of certain kinds of folds. Folds that are neither cylindrical nor conical in geometry do not, strictly speaking, possess a fold axis.

Although natural folds are never geometrically perfect, many have approximately cylindrical geometry, at least locally, and so can be described by the orientation of an approximate fold axis. Even irregular folds generally can be divided into local segments each of which is approximately cylindrical so the fold axis can be defined locally. The irregularity of the fold can be described by the variation, from place to place, in the orientation of the fold axis.

At the hinge of a cylindrical fold, the fold axis coincides with the hinge line, and for this reason the two terms are used interchangeably. It is useful to maintain the distinction, however, because the term *hinge line* refers to a linear feature having a specific orientation at a *specific location* on the folded surface, whereas the term *fold axis* refers to a line having only *a specific orientation* that characterizes the fold geometry, at least locally. Moreover, noncylindrical folds have a hinge but (with the exception of conical folds) no fold axis.

The geometry of a cylindrical fold and its fold axis has a particularly simple representation on a stereographic projection, which can be extremely useful in the analysis of folding in a region. A line of constant orientation plots as a point on a stereographic projection. A plane plots as a great circle. If the line lies in the plane, then on the projection, the point must lie somewhere on the great circle. The fold axis is by definition a common orientation to all attitudes of a cylindrically folded surface. Thus on a stereographic projection the point representing the attitude of the fold axis must lie on each of the great circles representing attitudes of the folded surface. Thus these great circles must all intersect at the fold axis orientation (Figure 11.6*A*, *B*). Moreover, any line perpendicular to the folded surface must also be perpendicular to the fold axis. On a stereographic projection, all lines perpendicular to a reference line must lie along the great circle normal to the reference line. Thus the locus of lines plotted normal to the folded surface (called the poles to the surface) must be along the great circle normal to the fold axis (Figure 11.6*C*). This great circle also defines the orientation of the profile plane (Figure 11.6*A*).

These geometric relationships, and the fact that many folds are at least locally almost cylindrical, enable a field geologist to deduce the orientation of a fold axis from measurements of two or more different attitudes of a folded surface. Plotting these attitudes as either great circles (Figure 11.6*B*) or their poles (Figure 11.6*C*) makes it possible to determine the orientation of the fold axis; this technique is especially useful in areas where, owing to the scale of the folds or to limited exposure, the fold axis is not directly observable.

For a conical fold (Figure 11.7*A*), the great circles representing orientations of the folded surface do not intersect in a point, and they do not exhibit an easily recognized relationship to the fold axis (Figure 11.7*B*). The poles to the folded surface however must lie along a small circle at a constant angle from the fold axis (Figure 11.7*C*).

Parts of Folded Layers and Multilayers

The geometry of a folded layer or a stack of folded layers is equivalent to that of a nested set of two or more folded surfaces. A single multilayer fold is delim-

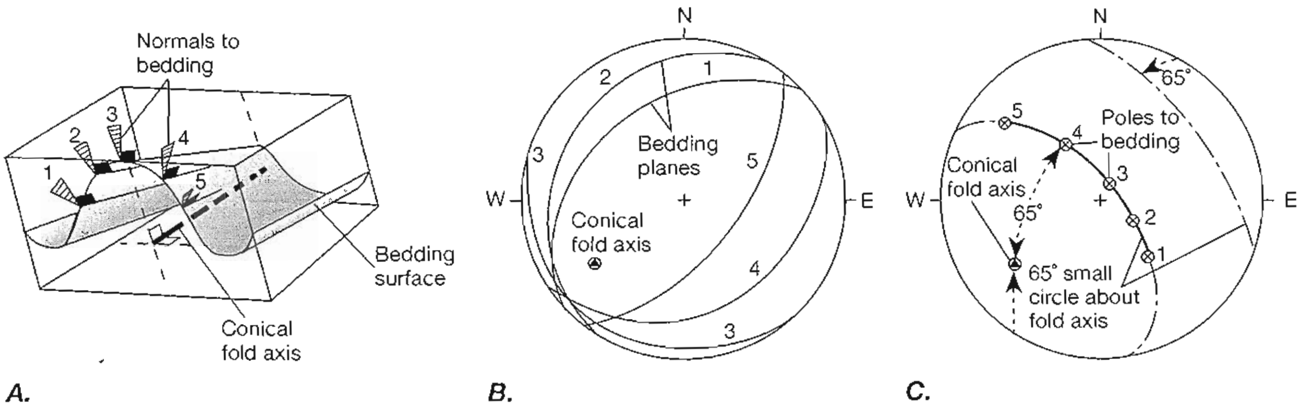


Figure 11.7 Geometry of a conical fold in three dimensions and on a spherical projection. *A.* Diagram of a conically folded surface. The fold axis is a line of constant orientation that is at a constant nonzero angle to the folded surface—in this case, 25°. The front face of the block is perpendicular to the fold axis, not the hinge line, and therefore is not the profile plane. The perpendiculars to the bedding surface (1 through 5) are in this case all 25° from the plane normal to the fold axis and 65° from the fold axis itself. *B.* Schmidt net (equal area) plot of various attitudes of a conically folded surface. *C.* Schmidt net plot of the poles to the folded surface and the fold axis shown in part *A.* The poles lie on a small circle around the fold axis.

ited by two **inflection** surfaces that join the inflection lines on adjacent folded surfaces in the nested stack (Figure 11.8).

The surface joining all hinge lines in a particular nested set of folds is variously called the **hinge surface**, the **axial surface**, and (if the surface is planar) the **axial plane**. In field studies, we usually recognize folds by their outcrop pattern on a topographic surface. The intersection of the axial surface with a surface of exposure is a linear feature called the **axial surface trace**, which in general is very different from both the hinge line and the fold axis and must not be confused with either (Figure 11.9). The axial surface trace is never parallel to the hinge line unless the hinge is parallel to the surface of exposure.

If the folded layers are sedimentary beds, and if we can determine their relative ages, then we can distinguish anticlines from synclines. **Anticlines** (derived from the Greek *anti,* which means "against," and *klinein,* which means "to slope") are folds in which the older layers are on the concave side of a bedding surface and the younger layers are on the convex side. Synclines

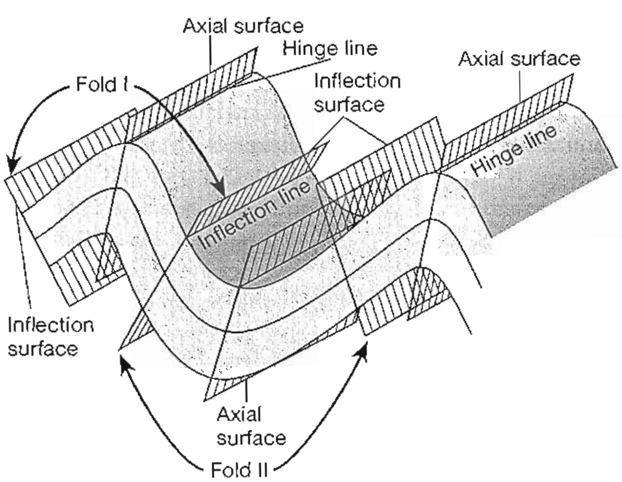


Figure 11.8 Folds in multilayers. A train of folds, showing the inflection surfaces, each of which contains the inflection lines of all the folded surfaces on one limb of a nested set of folds, and the hinge or axial surfaces, each of which contains all the hinge lines in a single nested set of folds.

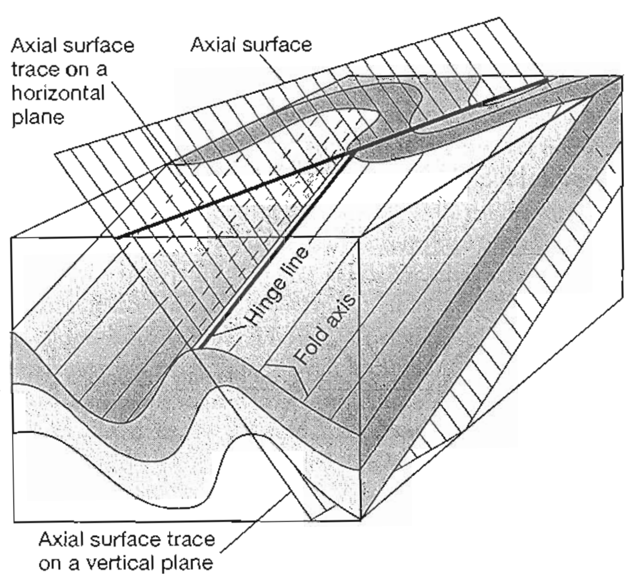
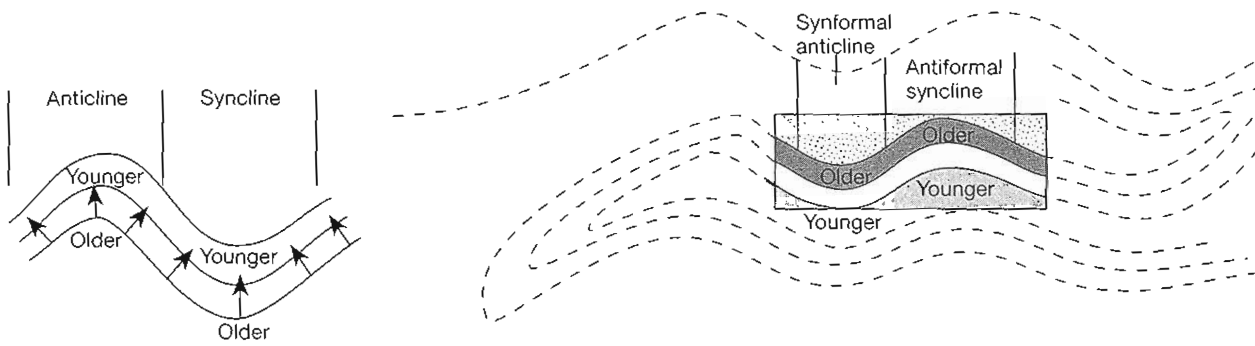


Figure 11.9 Block diagram of folds, showing the distinction among the axial surface trace on a vertical and a horizontal surface, the hinge line, and the fold axis.



A. Upright beds *B.* Overturned beds

Figure 11.10 Distinction between an anticline and a syncline in a fold cross section. Arrows point from oldest to youngest beds—thar is, in the stratigraphic up direction. The dashed structure in part *B* suggests one way in whieh large secrions of strata could be overturned.

(the Greek *syn*, means "with, to") are folds in which rhe younger layers are on the coneave side of a bedding surface and the older layers are on the convex side.

Most anticliues are convex up (antiforms) and most synclines are concave up (synforms) (Figure 11.10*A*), although this geometry is not universal. In areas of complex deformation where the entire stratigraphy has been overturned, anticlines may be synformal and synclines antiformal (Figure 11.10*B*).

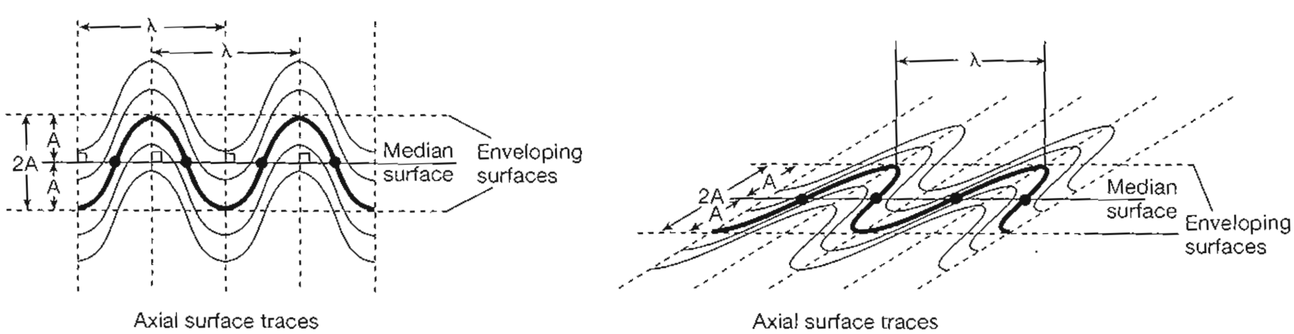
11.2 Fold Scale and Attitude

The Scale of Folds

Scale is a measure of the size of a fold in a layer or stack of layers. There are two components of the scale: the amplitude *A* and the wavelength λ (Figure 11.11). We define them with reference to the enveloping surfaces and the median surface. The enveloping surfaces are the two surfaces that bound the fold train developed in a single folded surface. The median surface includes all the inflection lines of a fold train in a single surface. The amplitude of any fold is the distance from the median surface to either of the envelopiug surfaces, measured parallel to the axial surface. The wavelength is the distance, measured parallel to the median surface, between one poiut on a fold and the geometrically similar point on a neighboring fold—from one antiformal hinge to the next, for example, or from one synformal hinge to the next.

The Attitude of Folds

The orientation in three-dimensional space of a fold or traïn of folds is an important factor in any geologic study of folded rocks. Accordingly, an extensive nomenclature has been based on the attitude of folds. We express the attitude of a fold by the trend and plunge of the hinge line or fold axis and the strike and dip of the axial surface. A fold is upright if the dip of the axial surface is close to vertical; it is steeply, moderately, or gently inclined as the dip angle progressively decreases; aud it is recumbent if the axial surface is close to horizontal. Depending on the plunge of the hinge, a fold



A. *B.*

Figure 11.11 The scale of folding is defined by the wavelengrh λ and the amplirude *A* for (*A*) symmetric folds aud (*B*) asymmetric folds.

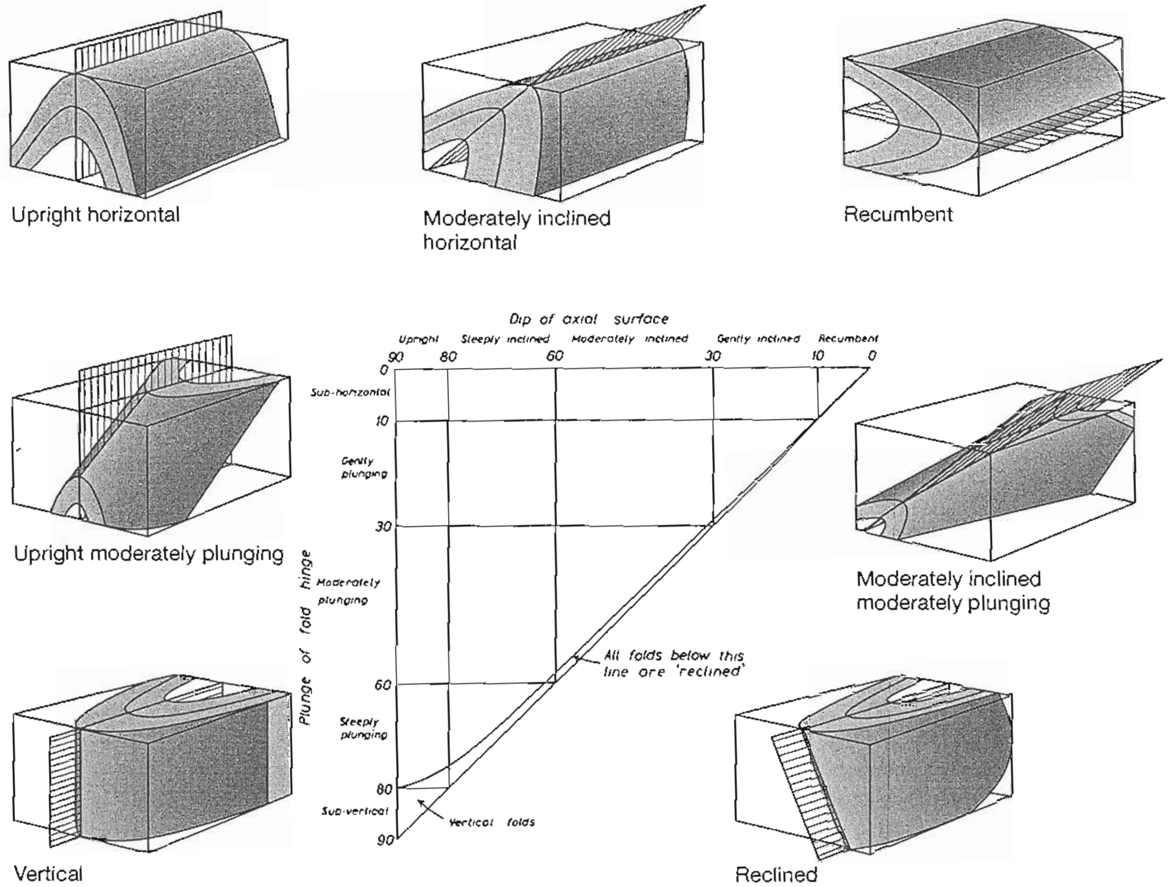


Figure 11.12 The terminology for describing fold attitude as defined by the plunge of the hinge (vertical axis) and the dip of the axial surface (horizontal axis). The center graph showing the ranges of angles associated with each term, and the surrounding diagrams of folds in varying attitudes, corresponding to the categories in the graph.

is horizontal; subhorizontal; gently, moderately, or steeply plunging; subvertical; or vertical. A reclined fold is one whose hinge plunges down the dip of the axial surface. Thus a fold could be upright horizontal; moderately inclined; moderately plunging; recumbent; and so forth. Figure 11.12 (the central triangular diagram) displays graphically the conventional definitions of these terms, and the surrounding diagrams give examples of the various categories.

No folds are indefinite in length; all eventually die out along the hinge by decreasing in amplitude or terminating against a fault. Where upright or inclined horizontal folds die out, the hinge line must plunge. If a fold hinge plunges at both ends and the hinge line is at least a few times as long as the half-wavelength, it is a doubly plunging fold (see folds in the northwest part of Figure 11.2*A*). As the length of the hinge becomes comparable to the half-wavelength of the fold, the fold is called a dome or a basin, depending on whether it is antiformal or synformal.

Several other common terms specify relative orientations of the limbs of folds. A homocline (derived from the Greek *homo,* which means "same," and *klinein,* which means "to slope") is characterized by a surface such as bedding thar has a nonhorizonral attitude, uniform over a regional scale with no major fold hinges (Figure 11.13*A*). A monocline (the Greek *mono* means "single, only") is a fold pair characterized by two long horizontal limbs connected by a relatively short inclined limb (Figure 11.13*B*). A structural terrace is a fold pair with two long planar inclined limbs connected by a relatively short horizontal limb (Figure 11.13*C*). An inclined or recumbent fold in which oue limb is overtnrned—that is, rotated more than 90° from its origiual horizontal position (Figure 11.13*D*)—is sometimes called an overturned fold. Note that the term *overturned* refers to only one limb of the fold, uot to the whole fold. Thus an overturned anticline (Figure 11.13*D*) is not the same as an upside down, or synformal, anticline (Figure 11.10*C*).

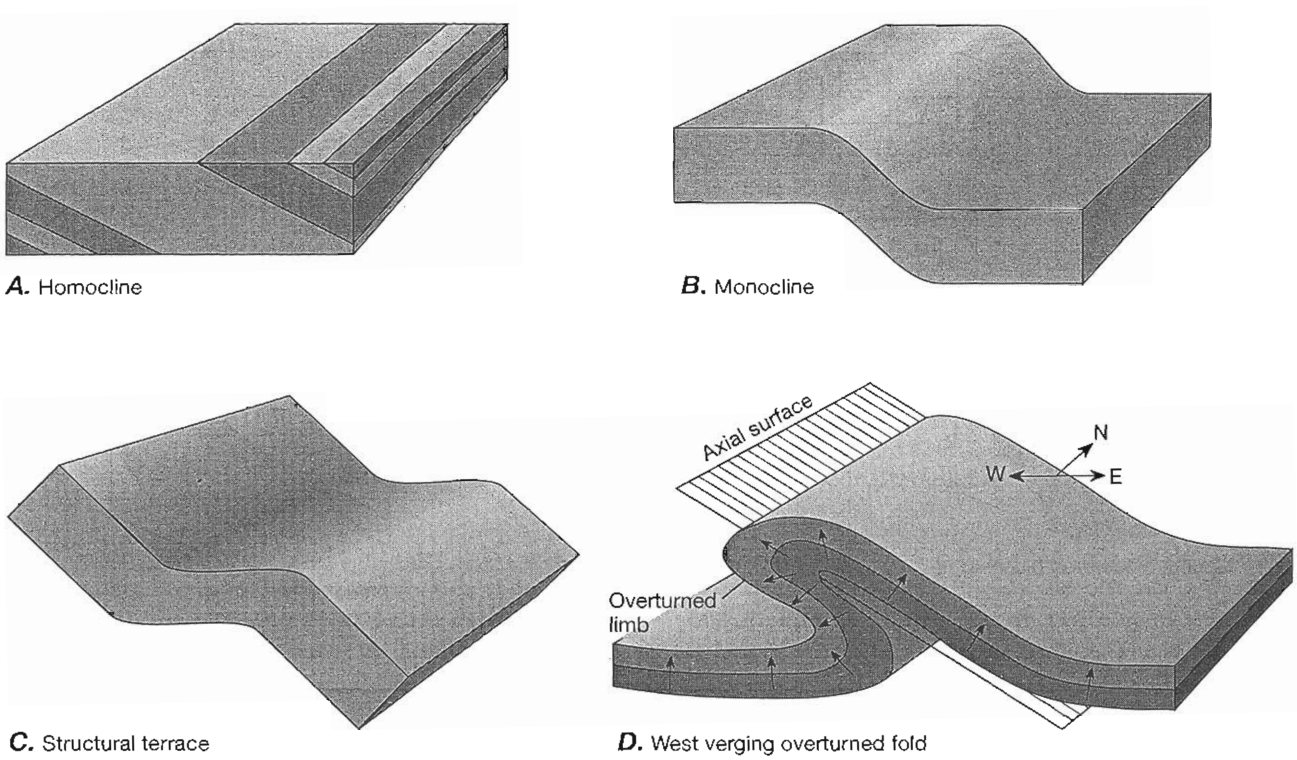


Figure 11.13 Structural terms describing the orientation of fold limbs. In part *D*, the arrows show the stratigraphic up direction on the sedimentary beds.

11.3 The Elements of Fold Style

The **style** of a fold is the set of characteristics that describe its form. It is analogous, for example, to the architectural style of a building. Over years of working with folds, geologists have identified certain features as particularly useful in describing folds and understanding how they develop. We refer to these features, which are summarized in Table 11.1, as the elements of fold style. In this section, we briefly define and discuss these elements. In Section 11.5, we apply these definitions to describe the most common fold styles that appear in deformed rocks.

Table 11.1 Elements of Fold Style

1. Cylindricity
2. Symmetry
3. Style of a folded surface
    - Aspect ratio
    - Tightness
    - Bluntness
4. Style of a folded layer (Ramsay's classification)
    - Relative curvature: dip isogon pattern
    - Orthogonal thickness
    - Axial trace thickness
5. Style of a folded multilayer
    - Harmony
    - Axial surface geometry

We must first define two angles that describe the amount that a surface has been folded (Figure 11.14). The folding angle ϕ is the angle between the normals to the folded surface constructed at the two inflection points of a fold. It is the angle through which one limb has been rotated relative to the other by the folding. The more commonly used interlimb angle ι is the angle between the tangents to the two fold limbs constructed at the inflection points. It measures the dihedral angle between the two limbs and is the supplement of the folding angle (that is, $\iota = 180 - \phi$).

Cylindricity

The degree to which a fold approximates the geometry of a cylindrical fold (Section 11.1) is a feature that characterizes different styles of folding. The cylindricity is represented qualitatively on a stereonet by how closely the poles to planes around a fold fit a great circle distribution (Figure 11.6C). The distance along the hinge for which the cylindrical geometry is maintained, measured as a proportion of the half-wavelength, is also a significant characteristic of the cylindricity. A multilayer fold can be described as cylindrical if the attitudes from all surfaces in the multilayer conform to the geometry of a cylindrical fold (Figure 11.6C). The term cylindroidal is sometimes used to describe a fold that closely approximates an ideal cylindrical geometry.

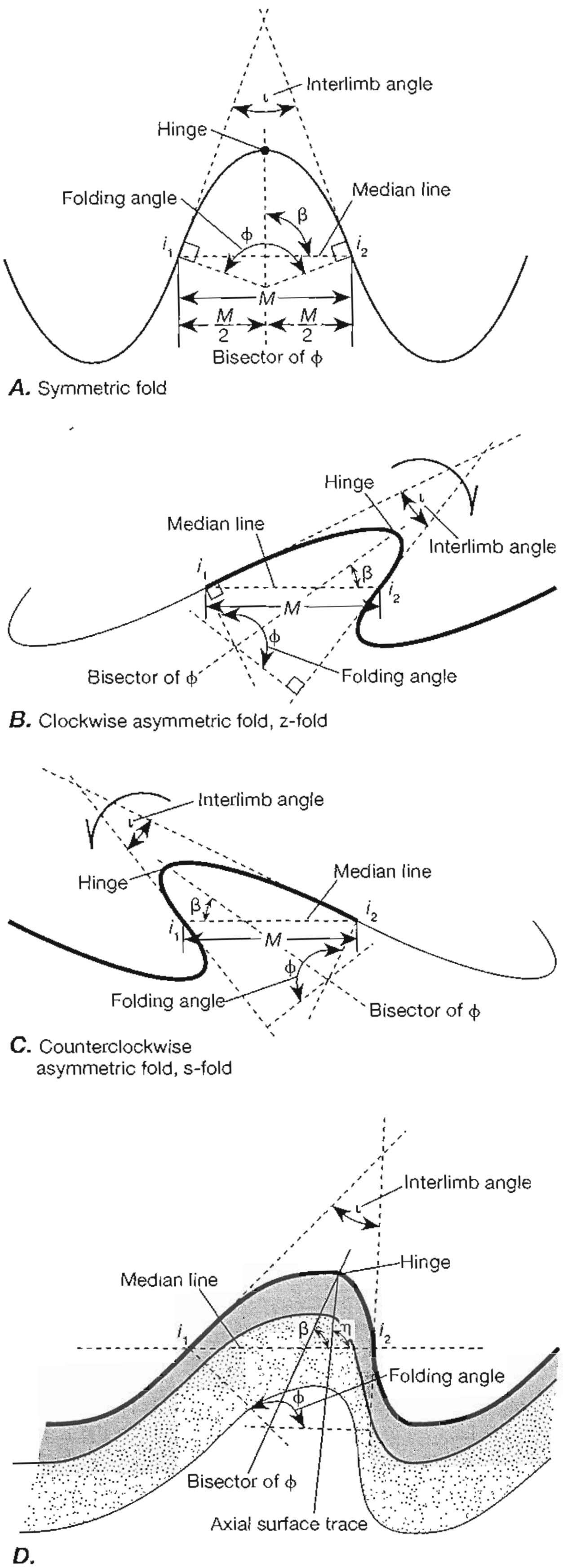


Figure 11.14 (*Left*) The folding angle, the interlimb angle, and the symmetry of folds. In part *A*, the fold profile from the hinge to i_1 is the mirror image of the profile from the hinge to i_2. The bisector of the folding angle and the interlimb angle is the mirror plane, and it is the perpendicular bisector of the median line $i_1 i_2$. β equals 90° in part *A*, but it is not equal to 90° in parts *B* and *C*. In part *D*, an asymmetric multilayer fold is characterized by the inclination β of the folding angle bisector as well as by the inclination η of the axial surface with respect to the median surface.

Symmetry

A folded surface forms a symmetric fold if in profile, the shape on one side of the hinge is a mirror image of the shape on the other side, and if adjacent limbs are identical in length (Figure 11.14*A* and 11.11*A*). For folded layers and multilayers, the axial plane is the mirror plane of symmetry. It is the perpendicular bisector of the median surface between the inflection points, and it bisects both the folding angle ϕ and the interlimb angle ι.

Asymmetric folds in profile have no mirror plane of symmetry, and the limbs are of unequal length (Figures 11.11*B* and 11.14*B*, *C*). The degree of asymmetry is determined for a folded surface by the angle of inclination β between the bisector of the folding angle ϕ (or the interlimb angle ι) and the median surface (Figure 11.14*B*, *C*). For a multilayer fold, the axial plane is not generally parallel to the bisector of the interlimb angle, and the angle of inclination η between the axial surface and the median surface is another independent characteristic of the asymmetry (Figure 11.14*D*).

The sense of asymmetry of a fold changes depending on whether we view the fold from one direction along the hinge or from the other. By convention, we specify the sense of asymmetry on a plunging fold when looking *down the plunge* of the hinge line. An asymmetric fold is a clockwise fold, or z-fold, if the short limb has rotated clockwise with respect to the long limbs, and the short limb with its two adjacent long limbs therefore defines a z-shape (Figure 11.14*B*). An asymmetric fold is a counterclockwise fold, or s-fold, if the short limb has rotated counterclockwise with respect to the long limbs, and the short limb with its two adjacent long limbs therefore defines an s-shape (Figure 11.14*C*).

If the fold hinge is horizontal, the geographic direction of viewing must be part of the description of the asymmetry; for example, the fold is counterclockwise (or an s-fold) looking north. For an inclined fold with a horizontal to gently plunging hinge, however, the sense of asymmetry is more conveniently specified by the vergence (from the German word *Vergenz,* which means "overturn"). The vergence is the direction of "leaning" of the axial surface or the up-dip direcrion on the axial surface of an asymmetric fold. In Figure 11.13*D*, for example, the vergence of the fold is to rhe west.

Small symmetric folds, especially if they are within the core of a larger fold, are sometimes called m-folds.

The Style of a Folded Surface

We describe the geometry of a folded surface by specifying three style elements: aspect ratio, tightness, and bluntness. To define these characteristics, it is first convenient to construct a quadrilateral around the fold in question such that the sides are tangent to the limbs of the fold at the inflection points, the base is the line M between the inflection points, and the top is tangent to the fold and normal to the bisector of the folding angle ϕ. For symmetric folds, the quadrilateral is a trapezoid, as shown in Figure 11.15*A* and *B* for folds with a folding angle $\phi = 130°$ and 230°, respectively.

The aspect ratio P is the ratio of the amplitude A of a fold, measured along the axial surface, to the distance M, measured between the adjacent inflection points that bound the fold (Figure 11.15). In other words, P is the ratio of the height of the quadrilateral to its base. For a periodic fold train, in which successive folds have the same wavelength λ (Figure 11.11), M is the half-wavelength ($\lambda/2$). Folds of increasing aspect ratio have a wide, broad, equant, short, or tall aspect, as defined in Table 11.2.

The tightness of folding is defined by the folding angle ϕ or the interlimb angle ι (Figure 11.15). As the degree of folding increases, the folding angle increases and the interlimb angle decreases. Folds are gentle, open, elose, tight, isoclinal, fan, or involute folds, as defined in Table 11.3. Isoclinal folds, which have essentially parallel limbs, fall on the boundary between acute folds ($\phi/2 < 90°$) and obtuse folds ($\phi/2 > 90°$).

The bluntness b measures the relative curvature of the fold at its closure (Figure 11.15). It is defined by

$$b = \begin{cases} r_c/r_0 & \text{for } r_c \leq r_0 \\ 2 - r_0/r_c & \text{for } r_c \geq r_0 \end{cases}$$

where r_c is the radius of curvature at the fold closure, and r_0 is the radius of the circle that is tangent to the limbs at the inflection points. Folds are sharp, angular, subangular, subrounded, rounded, or blunt (Table 11.4 and Figure 11.16). A bluntness of $b = 0$ describes folds that have perfectly sharp hinges ($r_c = 0$); $b = 1$ describes perfectly circular folds, which, for both acute and obtuse folds, consist of a single circular arc; $b = 2$ describes a double-hinged fold with a flat closure ($r_c = \infty$). One can picture the folds having $b = 2$ by looking at the right-hand end of the series of folds in the shaded trapezoids in Figure 11.16*A* and *B* and imagining the radius of closure curvature to increase indefinitely. Thus all folds must have a bluntness between 0 and 2. For double-hinged folds, a complete description must include the bluntness of the hinges in addition to the bluntness of the closure.

We show the range of fold styles defined by the aspect ratio and the bluntness for two constant folding angles, $\phi = 130°$ (Figure 11.16*A*) and 230° (Figure 11.16*B*). The folds along the horizontal line of shaded trapezoids in each diagram show the styles that can occur within a single shape of trapezoid. They are distinguished only by different values of the bluntness. The folds along any vertical line show how fold style changes for different aspect ratios at constant bluntness. The folds along the inclined line labeled perfect folds are

Table 11.2 Aspect Ratio

Descriptive Term	Aspect Ratio P	
	$P = A/M$	Log P
Wide	$0.1 \leq P < 0.25$	$-1 \leq \log P < -0.6$
Broad	$0.25 \leq P < 0.63$	$-0.6 \leq \log P < -0.2$
Equant	$0.5 \leq P \leq 2$	$-0.2 \leq \log P < 0.2$
Short	$1.58 \leq P < 4$	$0.2 \leq \log P < 0.6$
Tall	$4 \leq P < 10$	$0.6 \leq \log P < 1$

Source: After Twiss (1988).

Table 11.3 Tightness of Folding

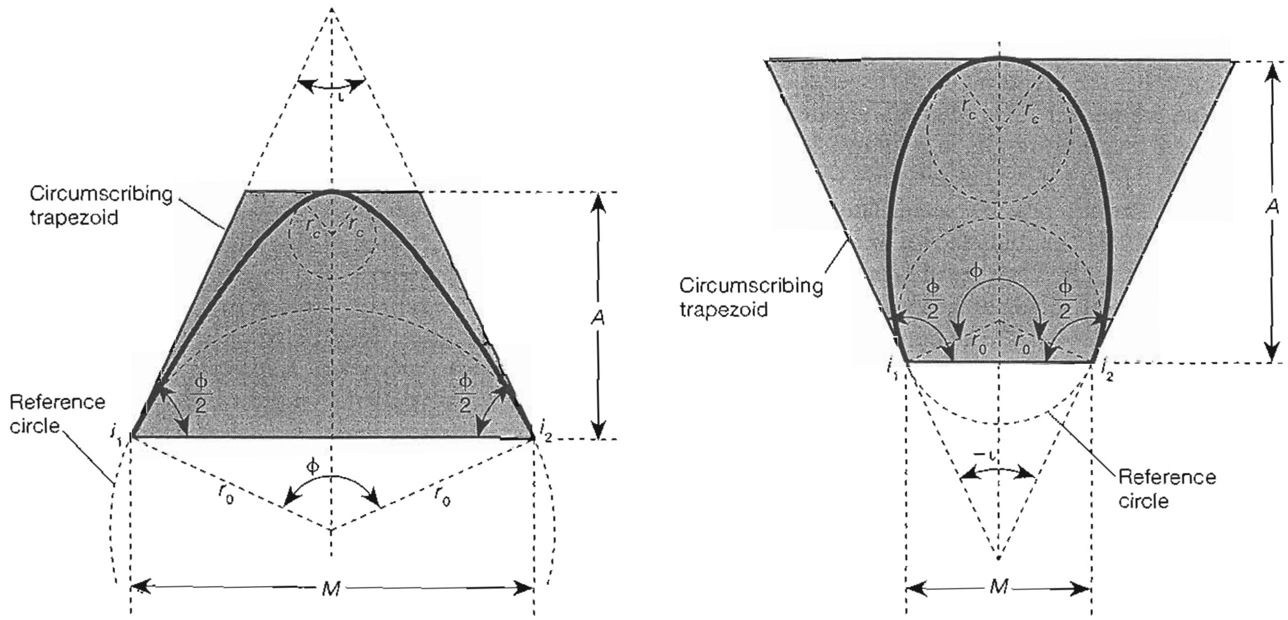
Descriptive Term	Folding Angle ϕ, deg	Interlimb Angle ι, deg
Acute		
Gentle	$0 < \phi < 60$	$180 > \iota > 120$
Open	$60 \leq \phi < 110$	$120 \geq \iota > 70$
Close	$110 \leq \phi < 150$	$70 \geq \iota > 30$
Tight	$150 \leq \phi < 180$	$30 \geq \iota > 0$
Isocliual	$\phi = 180$	$\iota = 0$
Obtuse		
Fan	$180 < \phi < 250$	$0 > \iota > -70$
Involute	$250 \leq \phi < 360$	$-70 \geq \iota \geq -180$

Source: Modified after Fleuty (1964).

Table 11.4 Bluntness of Folds

Deseriptive Term	Blunrness
Sharp	$0.0 \leq b < 0.1$
Angular	$0.1 \leq b < 0.2$
Subangular	$0.2 \leq b < 0.4$
Subrounded	$0.4 \leq b < 0.8$
Rounded	$0.8 \leq b \leq 1$
Blunt	$1 < b \leq 2$

Source: After Twiss (1988).



A. Acute fold: $P = 0.6$; $\phi = 130°$; $b = 0.18$

B. Obtuse fold: $P = 1.7$; $\phi = 230°$; $b = 0.7$

Figure 11.15 The style of a folded surface is characterized by the quadrilateral formed by the tangents to the limbs at the inflection points, by the line $i_1 i_2$, and by the normal to the folding-angle bisector that is tangent to the fold near the closure. The curvature of the folded surface within the quadrilateral further defines the style. The aspect ratio $P = A/M$. The bluntness b is defined in terms of the relative values of the closure radius r_c and the reference radius r_0.

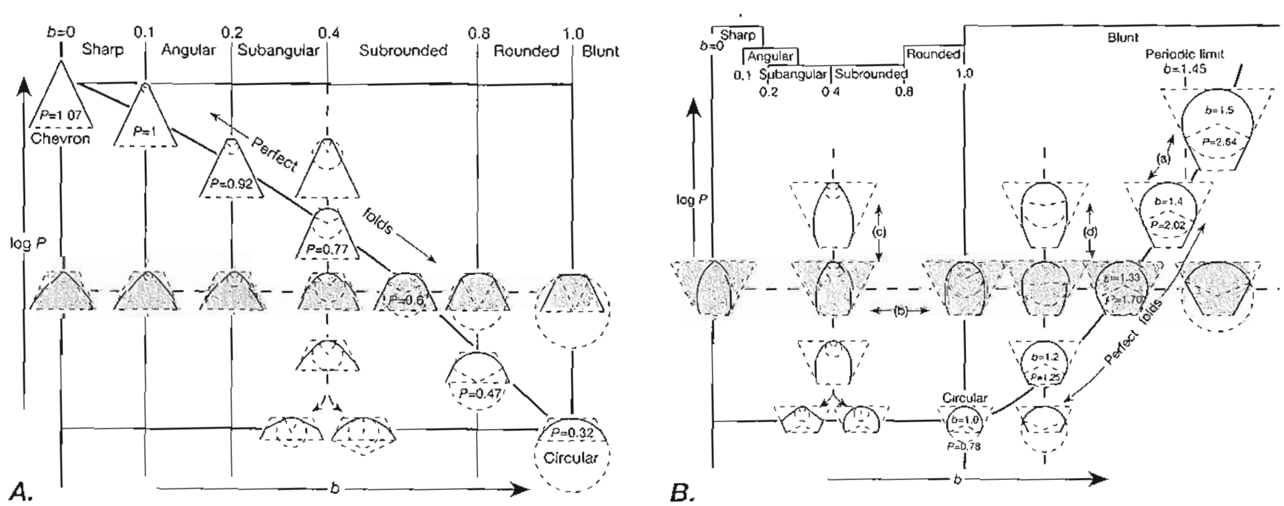


Figure 11.16 Variation of possible fold styles on planes of constant ϕ through fold style space. Axes are not to scale. Bluntness categories are indicated across the top of each diagram. The reference radins for all folds in each diagram is the radius of the perfect circular fold at the lower end of the line of perfect folds. Shaded trapezoids show bluntness categories for the shaded trapezoids in Figure 11.17. Perfeet folds have perfectly straight limbs tangent to hinge zones that are perfectly eircular ares. *A.* Aeute folds for $\phi = 130°$. Perfect folds plot along the diagonal from the perfect chevron fold in the upper lefr to the perfect circular fold in the lower right. All single-hinged folds plot within the shaded area. Outside this area, folds are multiple-hinged. *B.* Obtuse folds for $\phi = 230°$. Perfect folds plot along the diagonal curve from the perfect circular fold in the lower eenter through the limit for periodic folds at the vertical dashed line in the upper right. All single-hinged folds plot within the shaded area. Outside that area, folds are multiple-hinged.

idealized folds having perfectly planar limbs that are tangent to perfectly circular hinge zones. Note that increasing either the bluntness or the aspect ratio beyond the value for perfect folds (that is, outside the shaded area of the diagram) results in a fold with two hinges.

Figure 11.17, a plot of aspect ratio versus tightness, shows the various possible quadrilateral shapes that define fold style. The folds shown in the quadrilaterals are all perfect folds. The shaded area indicates the possible range for all single-hinged folds. Perfect chevron folds, for which $b = 0$, are an upper bound limiting the geometry of all folds. Perfect circular folds, for which $b = 1$, are a lower bound for all possible single-hinged folds. Any obtuse, single-hinged, perfect fold that is part of a periodic fold train must have a closure radius less than or equal to the half-wavelength of the fold ($r_c \leq M$). These folds therefore provide an upper bound for single-hinged periodic folds.

The heavy dashed lines and the solid trapezoids show where Figure 11.16*A* and *B*, and the shaded trapezoids in those figures, projects onto this plot. The shaded trapezoids in Figure 11.17 expand in the third dimension into the row of shaded trapezoids shown in Figure 11.16*A* at a value of $P = 0.6$, and in Figure 11.16*B* at a value of $P = 1.7$.

This brief outline of the three-parameter method for classifying the style of a folded surface gives some idea of the wide variety of fold shapes that can be simply described. With a fuller investigation of the three-dimensional geometry of "fold style space," we can show, for example, that all perfect folds plot on a single surface in the space that defines the boundary between all possible single- and double-hinged folds. Note that we have restricted our discussion to symmetric folds. Asymmetric folds can also be included in this scheme, although they are considerably more complex.

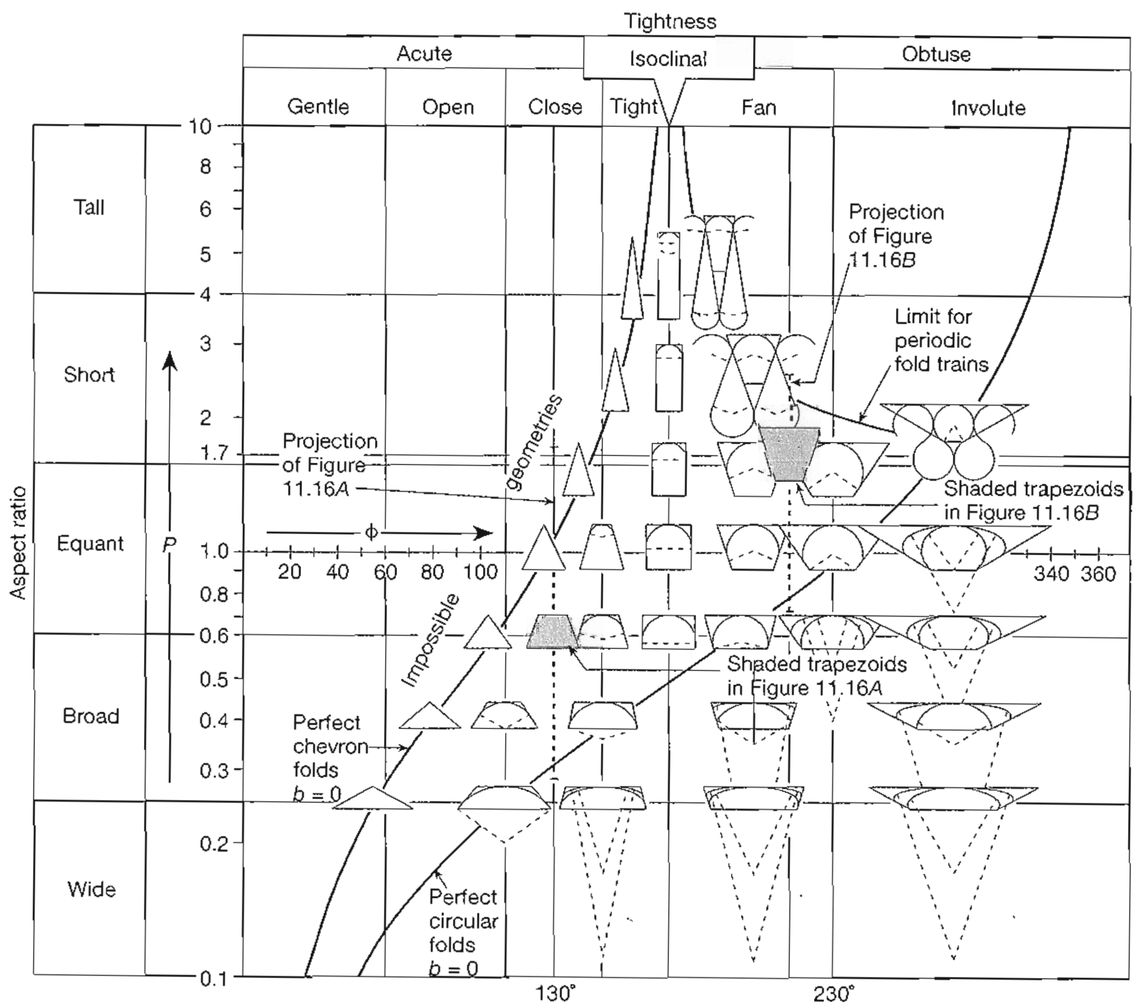


Figure 11.17 Plot of the logarithm of aspect ratio vs. tightness showing a selection of quadrilaterals and a few representative perfect and double-hinged folds. Also shown are areas of impossible geometries, areas of double-hinged folds, and lines for circular folds and periodic obtuse fold trains. Figure 11.16*A*, *B* projects onto this diagram along the heavy vertical lines.

The Style of a Folded Layer: Ramsay's Classification

The style of a folded layer is determined by comparing the fold styles of the two surfaces of the layer. The comparison is conveniently made by using three geometric parameters that are defined relative to a given pair of parallel lines tangent, respectively, to the inner (concave) and outer (convex) surfaces of the layer on the fold profile (Figure 11.18). The inclination of the fold surface at the point of tangency is given by α, the angle between the tangent line and the line normal to the axial surface trace. The three geometric parameters are as follows: (1) the **dip isogon**, which is the line across the layer connecting two points of equal dip on opposite surfaces of the layer; (2) the **orthogonal thickness** t_α, which is the perpendicular distance between the two parallel tangents; and (3) the **axial trace thickness** T_α, which is the distance between the two tangents, measured parallel to the axial surface trace. The two measures of layer thickness t_α and T_α are related by $t_\alpha = T_\alpha \cos \alpha$.

The elements of style for a folded layer are defined according to how these geometric parameters vary across the fold from the hinge to the limbs, or with increasing values of the surface inclination α.

1. The **relative curvature** or the variation in dip isogon. The relative curvature of the convex and concave surfaces is revealed by constructing a set of dip isogons at regular intervals from the hinge to the limb, each of which connects points of identical inclination α on the inner (concave) and outer (convex) surfaces (Figure 11.19). If the dip isogons converge toward the inner side of the fold, the curvature of the inner surface is greater than that of the outer surface; if they diverge toward the inner surface, the opposite is true.

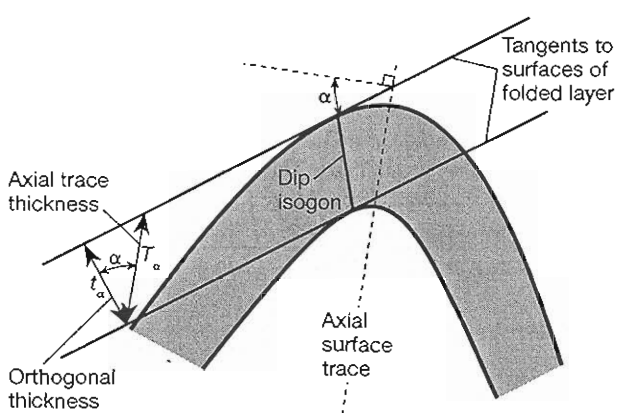


Figure 11.18 Definition of the layer inclination α, the dip isogon, the orthogonal thickness t_α, and the axial trace thickness T_α used to define the style of folded layers.

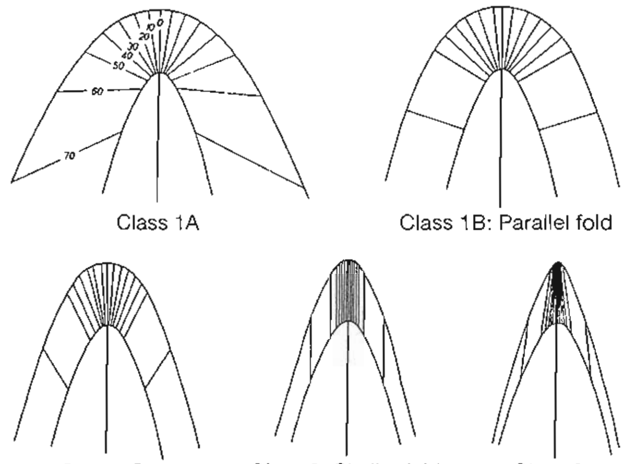


Figure 11.19 Ramsay's classification of folded layers (see Table 11.5).

For most folded layers, the relative curvature is consistent and defines three styles of folds. Dip isogons that converge toward the inner side of the fold characterize class 1 folds (Figure 11.19*A*, *B*, *C*). Parallel dip isogons, which also are parallel to the axial surface, characterize class 2 folds (Figure 11.19*D*). Folds of this style are referred to as **similar folds**, because adjacent fold surfaces ideally are identical (similar) in form. Dip isogons that diverge toward the concave side of the fold characterize class 3 folds (Figure 11.19*E*). The relative curvature is most obvious in the hinge zone, which generally makes it possible to classify folds by visual inspection.

2. Variation in the **orthogonal thickness**. The variation in the orthogonal thickness from hinge to limb is characteristic of different styles of folds and is the basis for the subdivision of class 1 folds (Figures 11.19*A*, *B*, *C* and 11.20*A*).

   For class **1A** folds, the orthogonal thickness increases from hinge to limb (Figure 11.19*A*). For class 1B folds, the orthogonal thickness is constant from hinge to limb (Figure 11.19*B*); These folds are referred to as **parallel folds** because t_α is constant all around the fold. Concentric folds are parallel folds whose inner and outer surfaces both have a bluntness of $b = 1$. Thus, they are folds defined by two circular arcs having a common center. For class **1C** folds, the orthogonal thickness decreases from hinge to limb (Figure 11.19C). The orthogonal thickness also decreases from hinge to limb for class 2 and class 3 folds (Figure 11.20*A*).

3. Variation in the **axial trace thickness**. The three classes of fold style also differ in the way the axial trace thickness varies. From hinge to limb—that is, with increasing α—the axial trace thickness increases in class 1 folds, is constant in class 2 folds, and decreases in class 3 folds (Figure 11.20*B*).

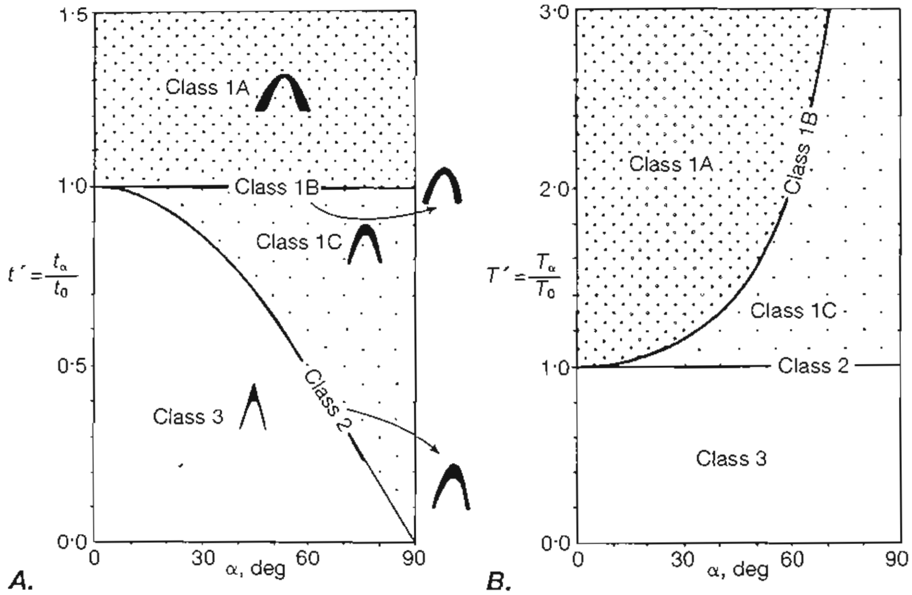


Figure 11.20 The classification of folded layers according to the thickness variation of the layer with increasing α (that is, from hinge to limb). *A.* Fold classes distinguished by the normalized orthogonal thickness $t' = t_\alpha/t_0$, where t_0 is the orthogonal thickness at the hinge where $\alpha = 0$. *B.* Fold classes distinguished by the normalized axial trace thickness $T' = T_\alpha/T_0$, where T_0 is the axial trace thickness at the hinge where $\alpha = 0$.

Table 11.5 summarizes the characteristics of the different fold classes in terms of the dip isogon geometry and the variation in orthogonal thickness and axial trace thickness. The characteristics of thickness shown in Figure 11.20 demonstrate that fold classes 1B and 2 are idealized geometries that form the boundaries between the other classes of folds. Thus some combinations of the geometries that fall in classes 1A and 1C closely approach class 1B style. Similarly, some combinations of fold geometries in classes 1C and 3 closely approach class 2 style. Not all possible folds are included in this classification, but most of the commonly observed geometries are included, and the characteristics of other styles can be presented on graphs such as in Figure 11.20.

The Style of a Folded Multilayer

A multilayer fold is composed of a stack of layers folded together. Its fold style can be defined in terms of the harmony of the folding and the axial surface geometry.

1. Harmony of Folding. In profile, all multilayer folds must die out in both directions along the axial surface trace (Figure 11.21) unless the folded sequence includes a free surface such as the Earth's surface. The depth of folding D is the distance along the axial surface trace over which the folding persists. The harmony H is a scale-independent measure of the rate at which the fold dies out along the axial surface trace and is equal to the ratio of the depth of folding D to the half-wavelength $\lambda/2$.

$$H = 2D/\lambda$$

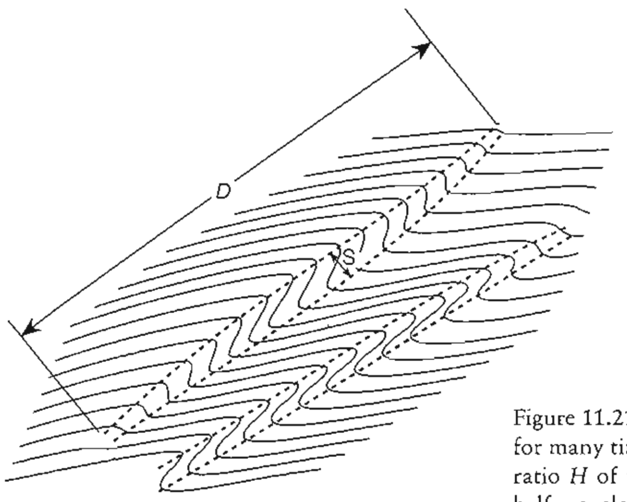
A harmonic fold is continuous along its axial trace for many multiples of the half-wavelength (Figure 11.21*A*). A disharmonic fold dies out within a couple of half-wavelengths or less (Figure 11.21*B*).

In general, because multilayer folds die out along the axial surface trace, dip isogons must form closed contours between two adjacent hinges (Figure 11.22*A*). As the fold amplitude increases, reaches a maximum, and then decreases along the axial surface

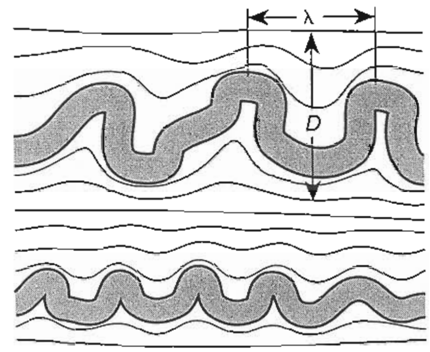
Table 11.5 Style of a Folded Layer

Class	Dip Isogon Geometry (from convex to concave surface)	Orthogonal Thickness (from hinge to limb)	Axial Trace Thickness (from hinge to limb)
1	Convergent		Increases
1A	Convergenr	Increases	Increases
1B	Convergenr	Constant	Increases
1C	Convergent	Decreases	Increases
2	Parallel	Decreases	Constanr
3	Divergent	Decreases	Decreases

Source: Afrer Ramsay (1967).



A.



B.

Figure 11.21 Harmony of folded multilayers. *A*. Harmonic folds affect layers for many times the half-wavelength along the axial surface. They have a large ratio *H* of the depth of folding *D* to half the wavelength λ: $H = 2D/\lambda$. The half-wavelength may conveniently be approximated by the spacing of adjacent axial surfaces *S*. This fold style is approximately a multilayer class 2 fold. *B*. Disharmonic folds die out within a distance on the order of a wavelength along the axial surface and thus have a small ratio of depth to half-wavelength. Nearby layers fold independently of one another.

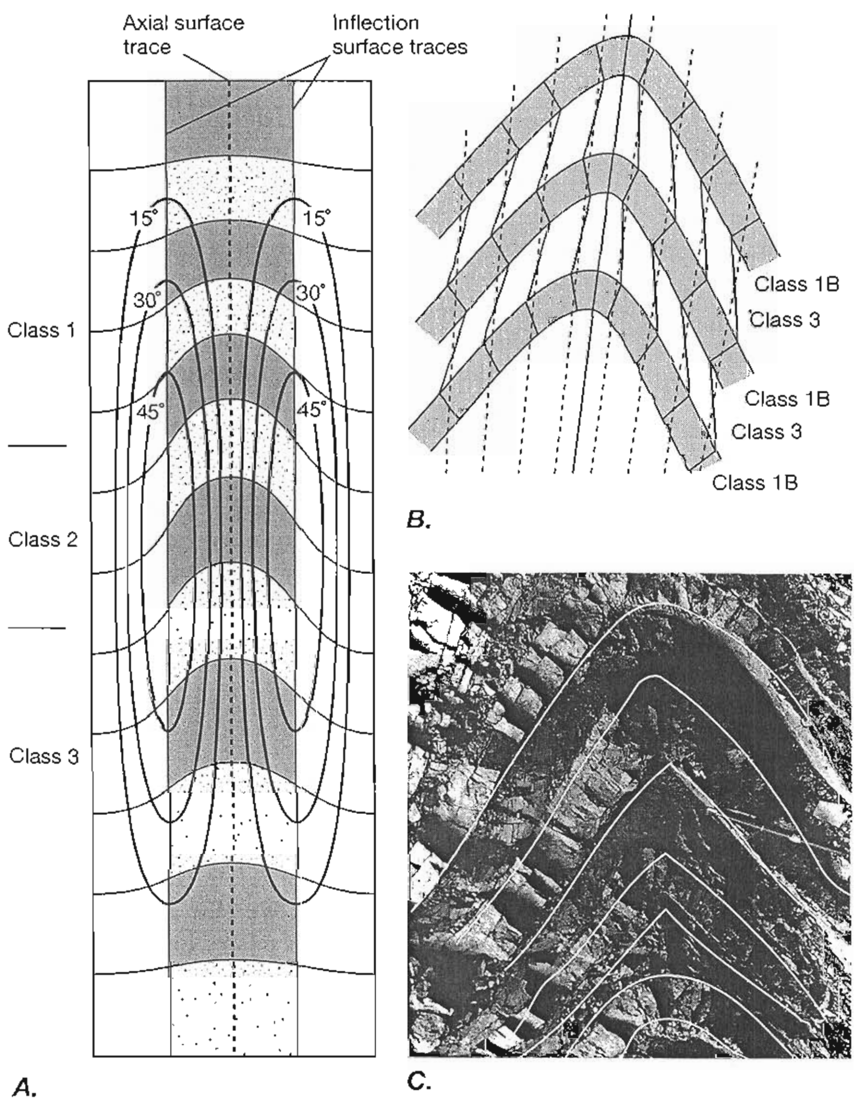


Figure 11.22 Profiles of multilayer folds, showing dip isogon patterns in successive layers. *A*. The dip isogon pattern in a multilayer fold that dies out in both directions along the axial surface trace. In the shaded fold, isogons show regions of convergenee (class 1), parallelism (class 2), and divergence (elass 3). *B*. Diagram of a fold in which the dip isogons are alternately converging (elass 1b folds) and diverging (class 3 folds) in suecessive layers. The average isogon pattern is approximately parallel to the axial surface, giving an approximately class 2 geometry. C. Folds in an interlayered chert–shale sequence that approximates the geometry shown in part *B* (lines drafted on photo emphasize bed contacts).

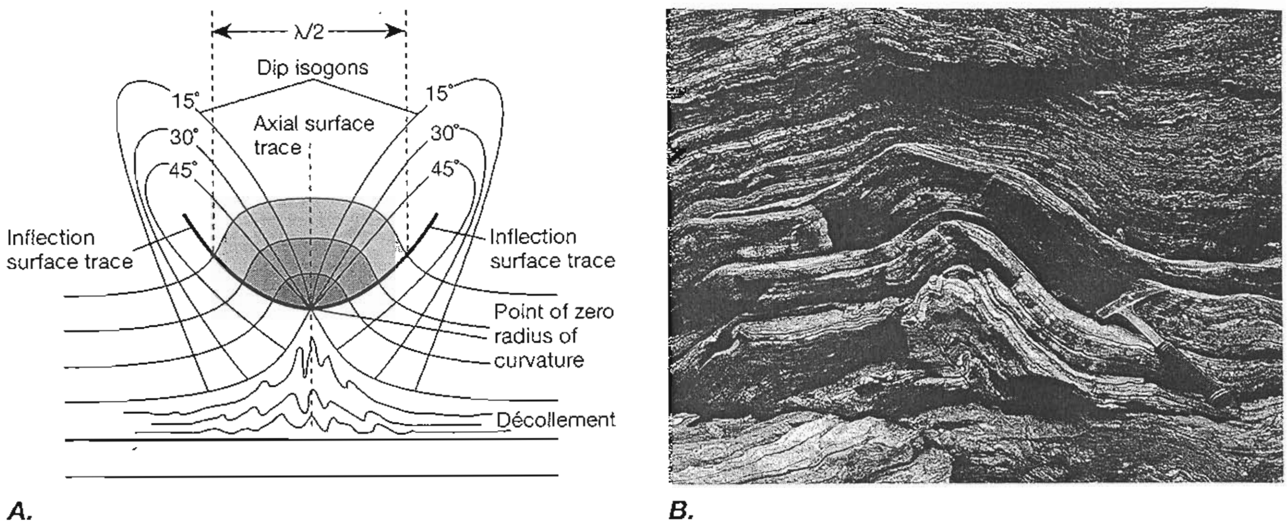


Figure 11.23 Disharmonic nature of class 1B folding resulting in a surface of disharmony or décollemenr. *A*. Diagram of a class 1B fold showing the surface of disharmony, the décollement. The half-wavelength is measured on the surface that has the maximum amplirude. Dip isogons converge strongly on the point of zero radius of curvature. *B*. A class 1B fold formed in a banded gneiss during deformation well after peak metamorphism.

trace, the dip isogons converge, are roughly parallel, and then diverge. Thus all three of Ramsay's fold styles must occur in every multilayer fold. Although the strict definitions of the fold class nomenclature are more difficult to apply to multilayer fold classification, the dip isogon pattern still reveals important characteristics of the folds.

For harmonic folds, the average convergence or divergence of the dip isogons is very small, so the folds approximate a class 2 (similar) geometry. Dip isogons consttucted for each layer, however, may vary smoothly from layer to layer (Figure 11.22*A*) or changc radically, in some cases alternating from convergent to divergent in succeeding layers (Figure 11.22*B*, *C*). In the latter cases, the harmony is determined by the trend of thc dip isogons averaged over several adjacent layers.

For disharmonic folds (Figure 11.21*B*), the dip isogons converge or diverge very strongly along the axial surface trace. For multilayer folds that approximate class 1B (parallel) folds, for example, the radius of curvature decreases toward the concave side of the fold, and the dip isogons converge strongly (Figure 11.23*A*). Where thc radius of curvature approaches zero, the fold must die out rapidly along the axial surfacc at a décollement or a sole fault (Figure 11.23). In fold and thrust belts this décollement commonly corresponds to the basal thrust fault into which thrusts converge (Figure 11.2*B*; sec also Chapter 6).

2. Axial Surface Geometry. Throughout our discussion so far, we have assumed that the axial surface is planar. Many folds, in fact, display parallel or subparallel axial surfaces that are planar or only slightly curved. It is not unusual, however, for folds to have a nonplanar axial surface; such folds are called convolute folds. In some cases the axial surface itself describes a cylindrical fold (see Figures 12.31 and 12.32), whereas in others it is more irregular. The convolution generally is the result of deformation of earlier folds by one or more subsequent generations of folding. We discuss the geometry of such superposed folding in Section 12.7.

Some folds of a single generation develop with axial surfaces that have widely disparate orientations or that split into two or more surfaces. Such folds are usually called polyclinal folds (derived from the Greek *poly*, which means "many" and *klinein*, which means "slopc").

11.4 The Order of Folds

Folds characteristically develop simultaneously at different scales, so large folds include smaller-scale folds in their limbs and hinge zones. We generally distingnish among these different scales of related folds in terms of their order, the largest-scale folds being first-order folds, and successively smaller scale folds bcing of higher order (Figure 11.24). Firsr-order folds are generally regional-scale features. Folds observed on the outcrop scale are commonly second- or highet-otder folds. Higher-order

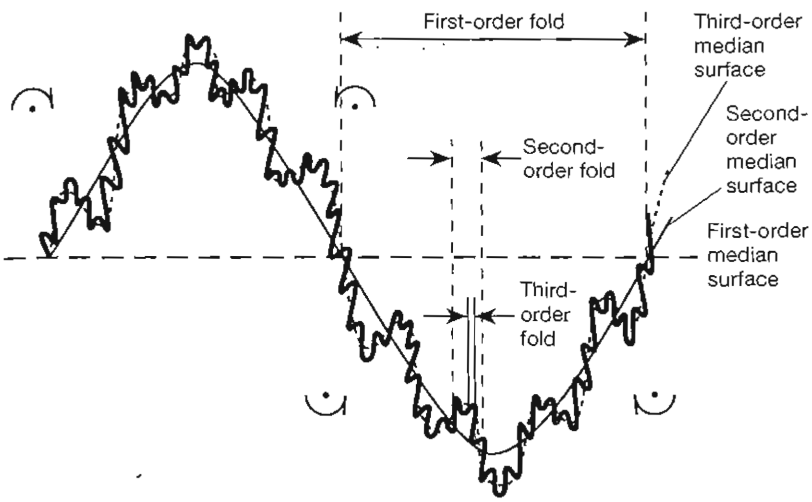


Figure 11.24 Illustration of different orders of folding. A fold train showing three orders of folds. The median surface of third-order folds defines the second-order folds, and the median surface of the second-order folds defines the first-order folds. The asymmetry of the second-order folds changes across rhe axial surfaces of the first-order folds, and the asymmetry of rhe third-order folds changes across the axial surfaces of the second-order folds. Because of the different limb lengths of the seeond-order folds, the predominanr asymmetry of the third-order folds is differenr on opposite sides of first-order axial surfaces.

folds are sometimes called parasitic folds. The median surface of a set of high-order folds defines the folds of the next lower order. Thus the median surface of a train of third-order folds defines the second-order fold train, and the median surface of second-order folds describes the first-order fold shape (Figure 11.24; see Figure 12.18).

The asymmetry of higher-order folds changes across the axial sutface of the next lower-order fold, as seen in Figure 11.24, and this feature is a very convenient field mapping tool for identifying the presence and location of low-order folds. The style and attitude of higher-order folds are generally very close to those of lower-order. This correspondence, known as **Pumpelly's rule**, is also a valuable aid in deducing the geometry of large structutcs.[1]

11.5 Common Styles and Structural Associations of Folding

Some combinations of style elements occur together so often in deformed rocks that thesc fold styles have been given names. Moreover, certain styles of folds are characteristic of particular tectonic scttings. In this section we describe some of the more common of these associations.

Parallel Folds

This style of fold is strictly defined as class 1B for either single or multilaycr folds. In standard usage, however, the term applies to class 1A and class 1C folds whose geometry is very close to that of class 1B (Figure 11.20). Folds of this style characterize the geometry of fold and thrust belts, which lie on the matgins of orogenic belts (Figure 11.2).

Rocks of these deformed belts are mostly unmetamorphosed to lightly metamorphosed layered sediments. Generally, the folds are approximately cylindrical over distances along the hinge that are large compared with the wavelength. Hinges are horizontal to gently plunging, and in the outer regions ncar the foreland they tend to have upright axial surfaces, widc aspect, and gcntle to open limbs. In the inner part of the belt closer to the hinterland, the aspect ratio tcnds to increase, limbs are tight or isoclinal (Figure 11.17), and the axial surfaces become inclined ot recumbent (Figure 11.12), with vergence towatd the foreland. Hingcs are rounded in some cases and angular in others.

At a depth comparable with their dominant wavelength, tbe parallel folds of these belts die out at a sole fault, or décollement, as required for the geometry of class 1B multilayer folds (Figures 11.2*B* and 11.23). This décollement tends to rise to progressively higher stratigraphic levels toward the foreland in a series of steps or ramps that alternately parallel and cross-cut the bedding. Some of these folds, called fault-ramp folds, devclop as the thrust sheet slides up thesc ramps (Figures 6.6 and 6.11).

The structure of fold and thrust bclts in map vicw is exemplified by that of the Appalachian Valley and Ridgc province (Figures 11.2*A* and 6.12*A*). The folds are continuous for up to tens or hundreds of kilometcrs. They typically die out as plunging structures, and the shortening accommodated by a fold that dies out is taken up eithcr by adjacent folds or by thrust faults. The higher-amplitude folds are toward the interior of the range, and both the amplitude and the abundance of folds decreases toward thc foreland. In the Appalachian Plateau, for example, the folding angle of thc dominant folds is typically only a few degrees.

[1] The rule is named for Raphael Pumpelly, the geologist for the U.S. Geological Survey who first proposed this relationship, which he recognized from mapping in the metamorphic rocks of the Green Mountains, western Massachusetts, in 1894.

Similar Folds

As strictly defined, similar folds have the geometry of class 2 single and multilayer folds. In common usage, however, the term is applied to fold styles that are very close to the class 2 style but that range from class 1C to class 3 (Figure 11.20). These folds are typical of the regionally metamorphosed central core zones of orogenic belts (Figure 11.1). They vary in attitude, and many are recumbent, although upright and reclined folds are not unusual. The folds are approximately cylindrical, although the distance along the hinge for which the cylindrical geometry is consistent is highly variable. Asymmetric folds are typical. The folds tend to have large aspect ratios, close to isoclinal limbs (see Figure 11.17), and angular to subangular hinges (see Figure 11.16*A*). Fold axial surfaces commonly are convolute and themselves describe fold systems. An axial surface foliation is often associated with the folds.

Folds of this style that are large-scale, recumbent, and isoclinal are called fold nappes (Figure 11.1*A* and *B*).[2] In some cases, the overturned limbs of these folds become sheared out so that the fold is further displaced by faulting, thus becoming a thrust nappe (an example is the Morcles nappe shown in Figure 11.1*A*).

Folds in salt domes and glaciers tend also to be similar folds. In both settings, the folds are generally harmonic and tight to isoclinal, with subangular to angular hinges. Folds in salt domes are steeply reclined with their axes parallel to the margins of the structure, whereas in glaciers the folds tend to be gently plunging, recumbent features.

Other Styles of Folds

Chevron and kink folds are cylindrical, harmonic, multilayer class 2 folds that have angular to sharp hinges, equant aspect, and gentle to close limbs. Chevron folds are symmetric (Figure 11.25*A*, *C*) and kink folds are asymmetric (Figure 11.25*B*). Both fold styles commonly develop in rocks that have a strong planar mechanical anisotropy such as phyllites and schists, which are characterized by a strong preferred orientation of abundant platy minerals, and finely laminated rocks such as interbedded sandstones or cherts with shales. In the latter case, the multilayer class 2 geometry is provided by alternations between class 1 and class 3 folds in the

[2] The term *nappe* is a French word meaning "cover sheet" or "tablecloth" and refers to any allochthonous sheetlike body of rock that has moved on a shallowly dipping surface. A nappe may originate as a recumbent isoclinal fold or as a thrust fault.

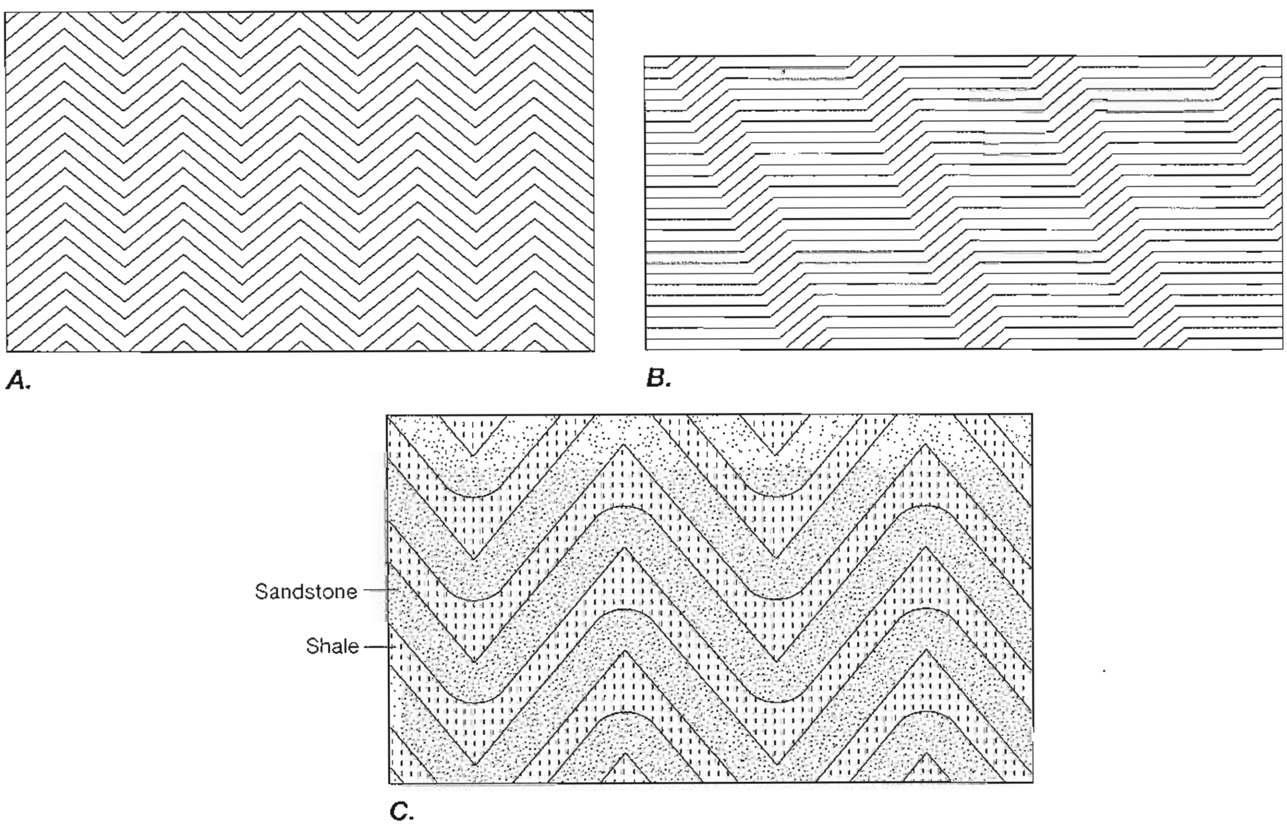


Figure 11.25 *A*. Chevron folds, *B*. kink folds, *C*. chevron folds in a sequence of alternating layers such as sandstone and shale.

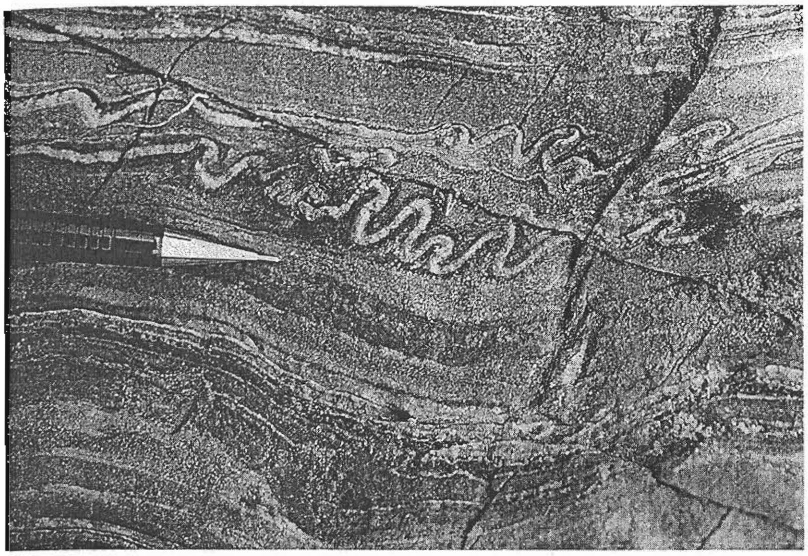


Figure 11.26 Ptygmatically folded layers in a banded marble, Bishop Creek roof pendent, Sierra Nevada, California.

sandstones and shales, respectively (Figures 11.25C and 11.22C).

Ptygmatic folds (the Greek word *ptygma* means "fold") are disharmonic folds that develop in individual layers. The folds tend to be equant in aspect with close to fanning limbs, rounded to subrounded hinges, and class 1B or 1C layer geometry. They typically develop in layers, dikes, or veins in metamorphic rocks (Figure 11.26) and in sandstone layers or dikes in some sedimentary sequences.

Additional Readings

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