CHAPTER

13

Foliations and Lineations in Deformed Rocks

A foliation[1] is a homogeneously distributed planar structure in a rock.[2] Examples of foliations include sedimentary bedding; the planar alignment of sedimentary clasts; the planar structure defined by the parallel alignment of platy minerals in a schist, a slate, a shale, or a volcanic rock; the parallel alignment of flattened mineral grains and conglomerate pebbles; and compositional banding defined by the concentration of particular minerals into layers, which is common in gneisses, ultramafic rocks, and some volcanic rocks.

A lineation is a homogeneously distributed linear structure. Lineations are surficial if they are present along discrete surfaces, penetrative if they occur throughout the volume of a rock. Examples of surficial lineations include sedimentary groove casts in a bedding surface and the parallel alignments of mineral fibers that develop along some fault surfaces. Examples of penetrative lineations include the hinges of pervasive small crenulations in a foliation, the preferred alignment of elongate mineral grains such as amphiboles or quartz, and the linear alignment of elongate clusters of grains of a particular mineral such as quartz or mica.

Foliations and lineations are primary if they originate by primary sedimentary or igneous processes. Primary sedimenrary processes such as sediment transport and deposition produce, for example, linear tool marks, the preferred orientation of sedimentary clasts, and bedding. Primary igneous processes such as flow and crystallization result in the preferred orientation of bubbles and pumice fragments or in compositional streaks and bands. Foliations and lineations are secondary if they originate by secondary processes such as tectonic deformation or metamorphism. We sometimes use terms such as *sedimentary foliation, igneous lineation,* and *tectonite foliation* to specify the inferred origin of a foliation. Because the origin of a structure is an interpretation, however, it is an inappropriate basis for classification, and we define *foliation* and *lineation* in strictly descriptive terms.

In this chapter we discuss foliations and lineations that are characteristic of tectonites, which are rocks whose structure is a product of deformation and which are commonly, but not necessarily, metamorphosed. Most such foliations and lineations are secondary in origin, although some may be inherited primary features. S-tectonites and L-tectonites are rocks dominated by planar and linear preferred orientation, respectively, of mineral grains.

Generally we consider a structure to be homogeneonsly distributed, or penetrative, if the spacing or the

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[1] Derived from the Latin *folium,* which means "leaf." The definition of the term *foliation* is not universally agreed on. Some authors use it in a more specific sense than we have adopted.

[2] A feature that is homogeneously distributed in a body has the same characteristics in any arbitrary volume of the body.

scale of the structure in a rock is very small compared to the size of the rock volume under consideration. To qualify as a foliation or lineation, a structure must be penetrative within a volume that has a dimension on the order of tens of centimeters. Planar features that have an average spacing on the order of meters are not foliations but structures such as fractures, faults, or shear zones. The spacing of many foliations, for example in slates, is so small as to be unresolvable in hand sample. If a lineation occurs on a penetrative planar structure such as a foliation, then the lineation also is penetrative.

Several other terms are used to describe penetrative planar features in rocks. The term S-surface is generally synonymous with *foliation* (the S comes from the German *schiefer* which means "schist"). It refers to any penetrative planar feature of a rock and therefore includes sedimentary bedding, schistosity, and axial surfaces of folds, which may be simply geometric constructs rather than actual physical features in the rock. Bedding is commonly designated S_0, and other penetrative planar features such as foliations and axial surfaces are labeled S_1, S_2, . . . , where the subscripts generally indicate the sequence in which the different features developed. We have, in fact, already used this notation in our discussion of superposed folding (Section 12.8).

Rock cleavage, or simply cleavage, is the tendency of a rock to break or cleave along surfaces of a specific orientation. All cleavages are foliations, and the two terms are often used to describe the same structure. *Foliation* is a more general term than *cleavage,* however, because it includes planar geometric features that might not result in a cleavage. Planar alignment of slightly flattened grains (for example, of quartz in a quartzite, olivine in a peridotite, or compositional banding in a gneiss) would define a foliation but could provide so small a mechanical anisotropy that it would not result in a cleavage.

The terms layer and banding describe planar tabular features in rocks that are characterized by differences in composition, or possibly in texture, from adjacent rock. The terms are commonly used in descriptions of plutonic igneous rocks and high-grade metamorphic gneisses.

We outline a morphological classification for foliations in tectonites in Figure 13.1 and Sections 13.1 to 13.4. The classification is based on the shape and/or arrangement of components of the rock. This approach is preferable to the use of numerous older terms that are poorly defined, are imprecise, or have a genetic connotation (see Section 13.6).

Many foliations have a structure characterized by laminar to lenticular domains, which are restricted volumes that are uniform with regard to a particular structure and that differ in that regard from adjacent volumes. Foliation domains are distinguished by differences in preferred orientation of mineral grains, in structure, or in composition. Foliations defined by domains that have a spacing of 10 μm or more are spaced foliations (Figure 13.1; see also Figures 13.2 to 13.10). Foliations that exhibit a finer domainal structure, or no domainal structure at all, are continuous foliations (Figure 13.1; see also Figures 13.11 and 13.12).

Foliation and cleavage	Spaced	Compositional	Diffuse
			Banded
		Disjunctive	Stylolitic
			Anastomosing
			Rough
			Smooth
		Crenulation	Zonal
			Discrete
	Continuous	Fine	Microcrenulation
			Microdisjunctive
			Microcontinuous
		Coarse	

Figure 13.1 Morphological classification scheme for foliations.

Spaced foliations are categorized on the basis of four features: (1) domain shape, (2) domain spacing, (3) distinguishing characteristics of individual domains, such as mineral composition or the preferred orientation of mineral grains, and (4) the proportion of the rock occupied by the different types of domains. We recognize three categories of spaced foliation: compositional, disjunctive, and crenulation foliations (Figure 13.1).

A morphological classification of lineations in tectonites is outlined in Figure 13.18 and in Sections 13.7 and 13.8. We divide tectonite lineations into two major categories: Structural lineations are defined by geometric structures, mineral lineations by mineral grains or aggregates (Figure 13.18). Both types of lineations may be either surficial or penetrative.

13.1 Compositional Foliations

Compositional foliations (Figure 13.2) are marked by layers, or laminae, of different mineralogical composition. A planar alignment of platy or needle-shaped crystals may also be present, but the rock has at most a weak tendency to cleave parallel to the foliation. We subdivide these structures on the basis of mineralogical variation and the spacing and relative thicknesses of the compositional layers. Diffuse foliations are characterized by widely spaced weak concentrations of a mineral

A.

B.

Figure 13.2 Compositional foliations. *A.* Sparse compositional foliation in a dunite, Klamath Mts., Oregon. The rock is composed mainly of olivine. Concentrations of pyroxene crystals in sparse layers define the foliation. Scale bar is 6 in. *B.* Banded compositional foliation in a high-grade metamorphic gneiss, Wopmay Orogen, NW Canada.

in a rock of predominantly one lithology. They are common in ultramafic rocks such as dunites in which diffuse layer concentrations of pyroxene crystals define a weak compositional layering (Figure 13.2*A*). Diffuse foliations also occur in deformed granites in which concentrations of mafic minerals define the foliation. Banded foliations are composed of relatively closely spaced compositional layers that are mineralogically distinct and of comparable abundance. They are common in high-grade metamorphic gneisses (Figure 13.2*B*).

13.2 Disjunctive Foliations

Disjunctive foliations (Figures 13.3 through 13.8; the Latin word *disjunctus* means "disjoined or detached") are characterized by thin domains, called cleavage domains or seams, marked by concentrations of oxides and strongly aligned platy minerals. The cleavage domains are separated by tabular to lenticular domains called microlithons in which platy minerals may be less abundant or more randomly oriented (Figures 13.3 and

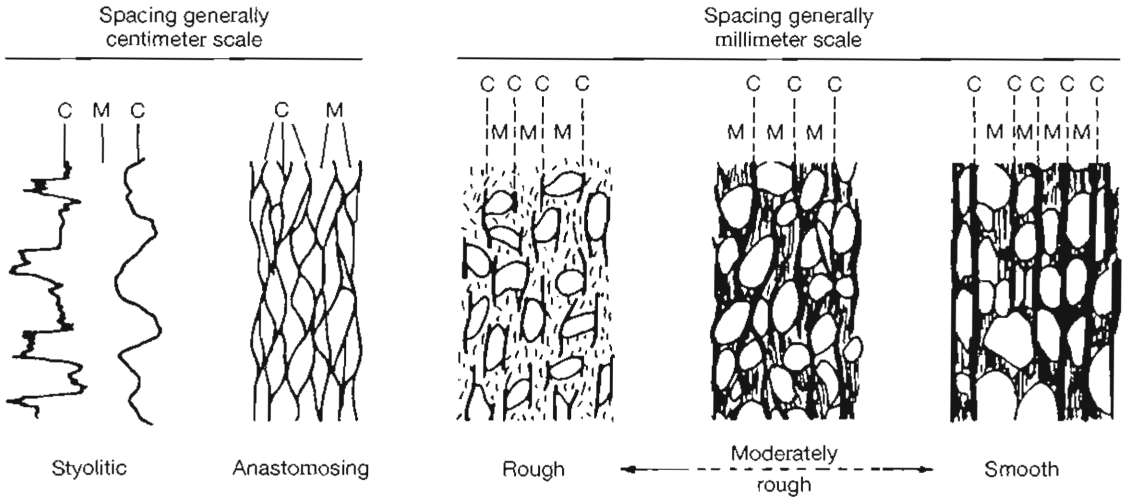


Figure 13.3 Sketches showing characteristics of the various types of disjunctive foliation. C marks cleavage domains; M marks microlithons. Note the change from the centimeter to millimeter scales.

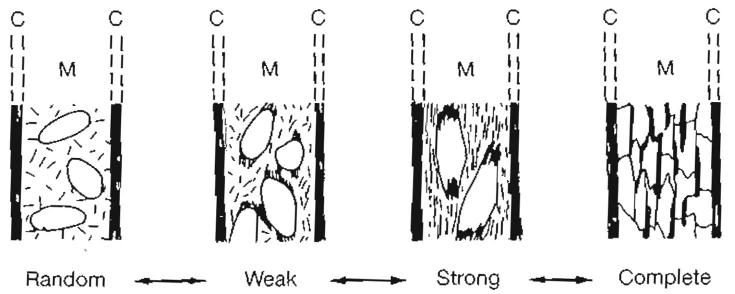


Figure 13.4 Preferred orientation within a microlithon bounded on either side by cleavage domains. C marks cleavage domains; M marks microlithons. In random fabric, the large grains have no preferred orientation, and the fine platy minerals in the matrix are also not oriented. Weak fabric is characterized by a slight elongation of coarse mineral grains and weak preferred orientation of their long axes, weak development of mica "beards" at the ends of the coarse mineral grains, and a weak preferred orientation of the platy minerals in the matrix. Strong fabric is characterized by distinct elongation of the coarse mineral grains and strong alignment of their long axes, well-developed and oriented mica "beards," and strong alignment of the platy minerals in the matrix. In completely oriented fabric, detrital grain shapes are not preserved; mineral grains are elongated and show a strong preferred orientation. The fabric is transitional to a continuous foliation.

13.4). Disjunctive foliations commonly form in previously unfoliated rocks such as limestones or mudstones, although in some foliated rocks they may also develop cross-cutting the earlier foliation.

We divide disjunctive foliations into four groups—stylolitic, anastomosing, rough, and smooth—on the basis of the smoothness or regularity of the cleavage domains (Figure 13.3). This order corresponds to a general increase in smoothness of cleavage domains and to a decrease in spacing, as well as to a tendency toward stronger preferred mineral orientations within the microlithons. The fabric of the microlithons ranges from random to complete, which provides the basis for further subdivision (Figure 13.4).

Stylolitic foliation (in Greek, *stylos* means "stalk" and *lithos* means "rock") exhibits long, continuous, but very irregular cleavage domains that commonly have a distinct toothlike geometry in cross section (Figures 13.3*A* and 13.5*A*). This type of foliation is typical in limestones in which the cleavage domains characteristically are thin, dark, clay-rich seams. In some limestones, fossil fragments are truncated by a stylolite (Figure 13.5*B*). The spacing of the cleavage domains ranges from 1 to 5 cm or more. There is generally no preferred orientation visible in the microlithons.

Anastomosing foliation is distinguished by long, continuous, wavy cleavage domains that form an irreg-

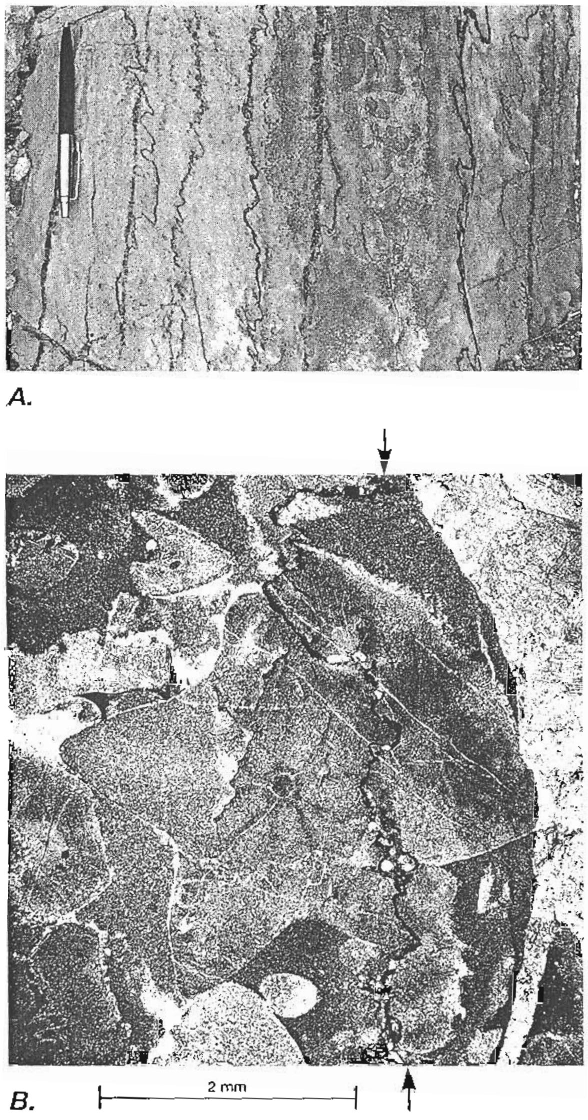


Figure 13.5 Stylolitic foliation. *A*. Stylolitic foliation in limestone layers. Stylolites are the dark irregular lines in the rocks. *B*. Stylolite (see arrows) truncating a pentacrinoid fossil in a limestone. The stylolite is the roughly vertical, irregular black seam. The fossil is shaped like a five-pointed star, but two of the points on the right side are truncated by the stylolite and have been largely removed by solution.

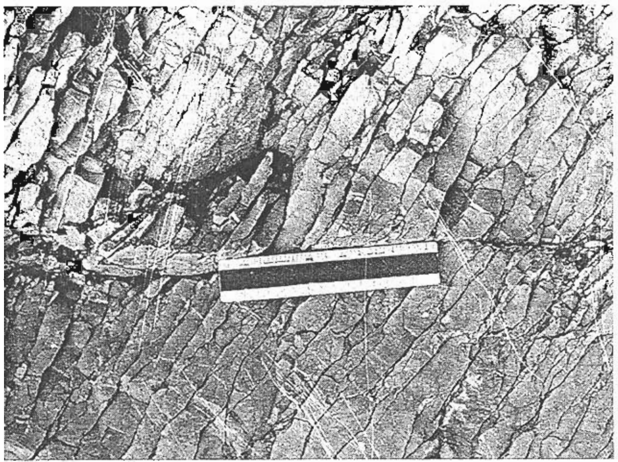


Figure 13.6 Anastomosing foliation in a limestone. Bedding is parallel to the ruler.

ular network outlining lenticular microlithons (Figures 13.3*B* and 13.6). Such foliations are common in limestones and in phyllites and schists. The spacing of the cleavage domains tends to be smaller than for stylolitic foliation, averaging perhaps 0.5 to 1 cm. The cleavage domains contain concentrations of platy minerals with a strong preferred orientation parallel to domain boundaries. The fabric within the microlithons is usually random to weak.

Rough foliation typically develops in rocks containing abundant sand-size mineral grains. The cleavage domains are short, discontinuous concentrations of highly oriented platy minerals that bound or envelope the coarse grains (Figures 13.3C and 13.7). The spacing of the cleavage domains is generally 1 mm or less. Microlithons exhibit a wide range of preferred orientations from random to strongly oriented (Figure 13.4).

Smooth foliation represents the planar end of the spectrum from irregular to planar cleavage domains (Figures 13.3*D*, *E*). Cleavage domains are long, continuous, and smooth and have concentrations of highly oriented platy minerals. The spacing of the cleavage domain is generally less than a millimeter. Fabric development within the microlithons commonly ranges from random to completely oriented (Figure 13.4). With decreasing domain spacing, this type of foliation is transitional with microdomainal, fine, continuous foliations characteristic of some slates (Figure 13.8), as described in Section 13.4.

13.3 Crenulation Foliations

Crenulation foliations are formed by harmonic wrinkles or chevron folds that develop in a preexisting foliation. The new foliation cuts across the old foliation and is

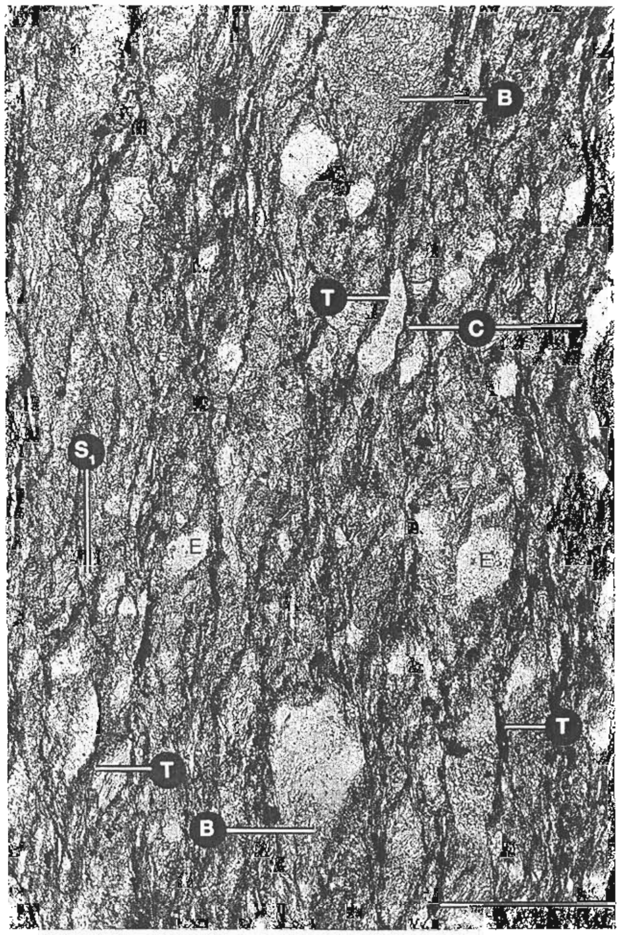


Figure 13.7 Rough foliation (S_1) in a deformed wacke. Dark seams are the cleavage domains composed of insoluble residues. At C, remnant detrital sand grains are truncated against cleavage domains. At T, thin plate-like quartz grains result from solution of the grains along cleavage domains (see Section 14.3). B marks "mica beard" overgrowths on detrital grains. Scale bar is 1 mm.

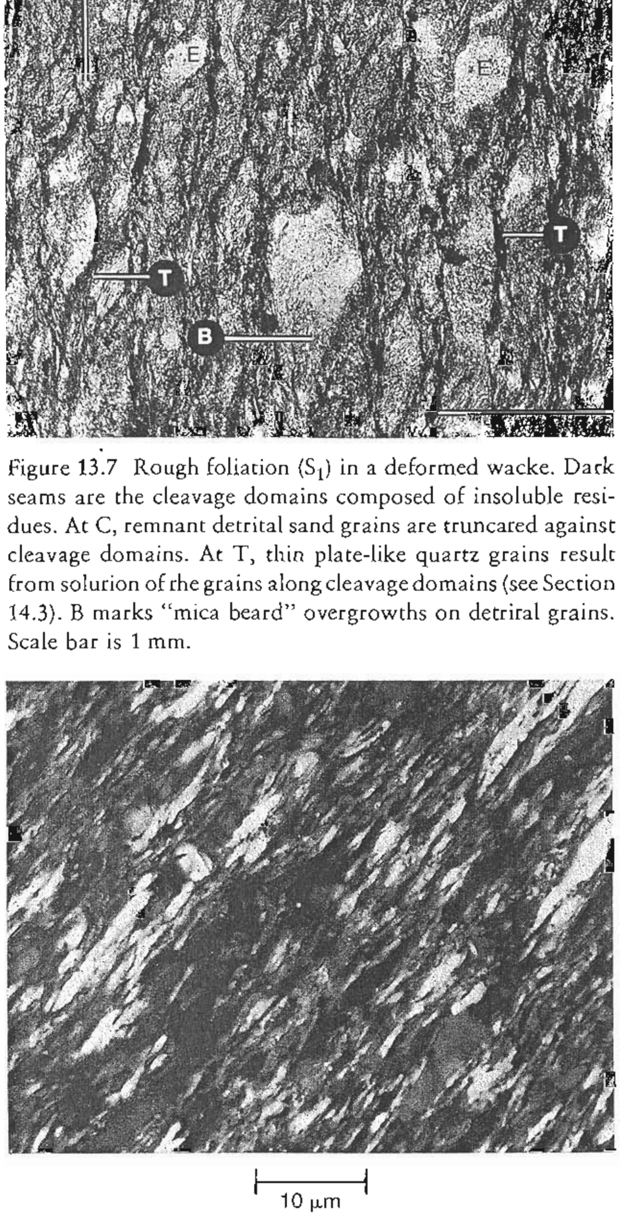


Figure 13.8 Smooth foliation in a slate.

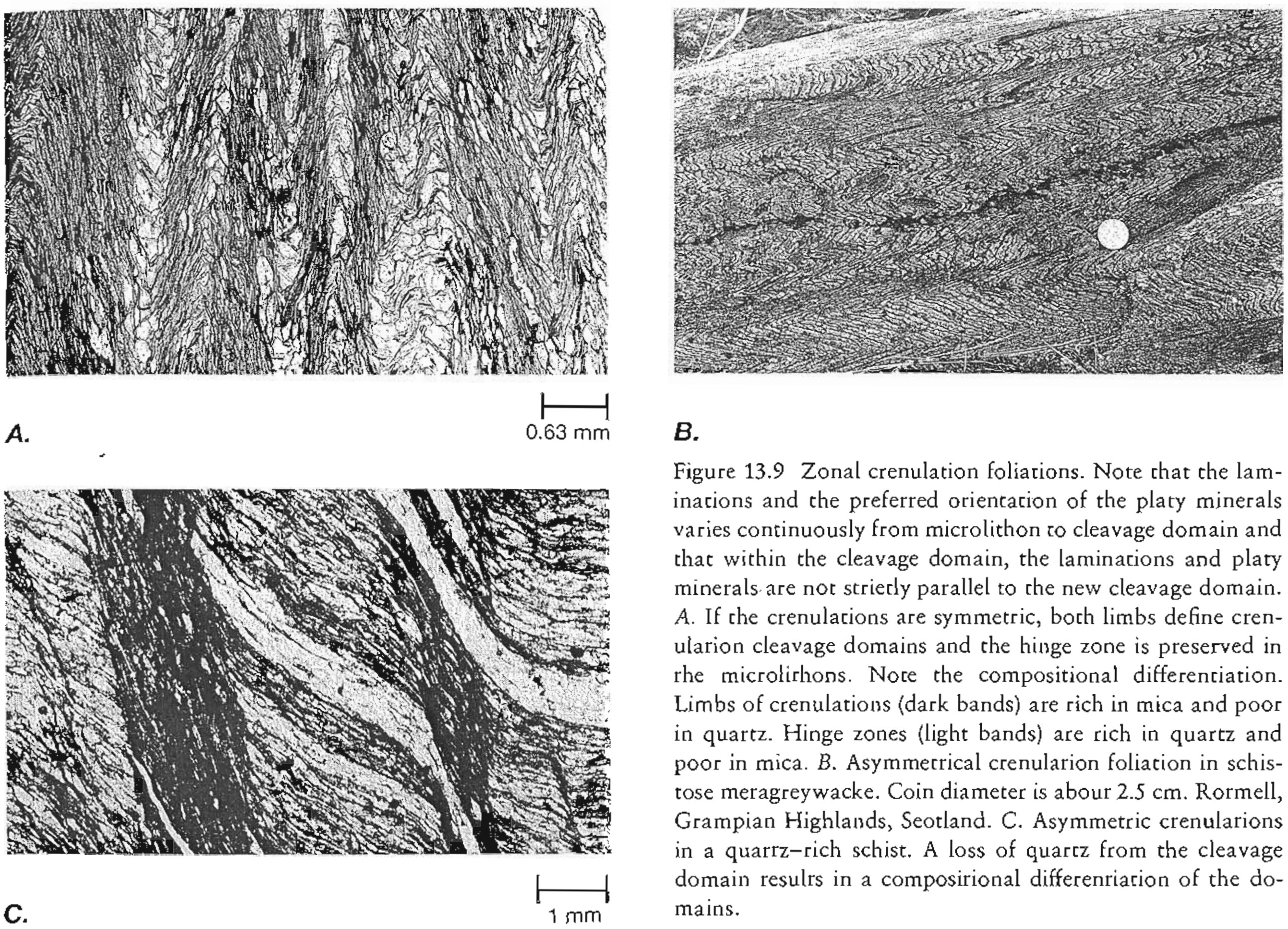


Figure 13.9 Zonal crenulation foliations. Note that the laminations and the preferred orientation of the platy minerals varies continuously from microlithon to cleavage domain and that within the cleavage domain, the laminations and platy minerals are not strictly parallel to the new cleavage domain. *A.* If the crenulations are symmetric, both limbs define crenulation cleavage domains and the hinge zone is preserved in the microlithons. Note the compositional differentiation. Limbs of crenulations (dark bands) are rich in mica and poor in quartz. Hinge zones (light bands) are rich in quartz and poor in mica. *B.* Asymmetrical crenulation foliation in schistose metagreywacke. Coin diameter is about 2.5 cm. Rormell, Grampian Highlands, Scotland. *C.* Asymmetric crenulations in a quartz–rich schist. A loss of quartz from the cleavage domain results in a compositional differentiation of the domains.

defined by both limbs of symmetric crenulations (Figure 13.9*A*) or by one of the limbs of asymmetric crenulations (Figure 13.9*B*, *C*). The old foliation is preserved in the microlithons either as the hinges of symmetric crenulations (Figure 13.9*A*) or as one of the limbs of asymmetric crenulations (Figure 13.9*B*, *C*). The microlithon width is comparable to the half-wavelength or wavelength of the crenulations.

The orientation pattern of platy minerals in the cleavage domain is the basis for the further subdivision of crenulations. In a zonal crenulation foliation, the platy minerals in the new cleavage domain are oriented at a small angle to the domain and form a continuous variation of orientations from the platy minerals in the microlithons (Figure 13.9). The microlithon boundaries are gradational. In many cases, there is a compositional difference between cleavage domains and microlithons characterized by a higher proportion of platy minerals in the cleavage domains then in the microlithons.

In a discrete crenulation foliation, the orientation of platy minerals in the new cleavage domains is parallel to the domains and sharply discordant with the orientations of platy minerals in the microlithons (Figure 13.10). The crenulations are preserved in the microli-

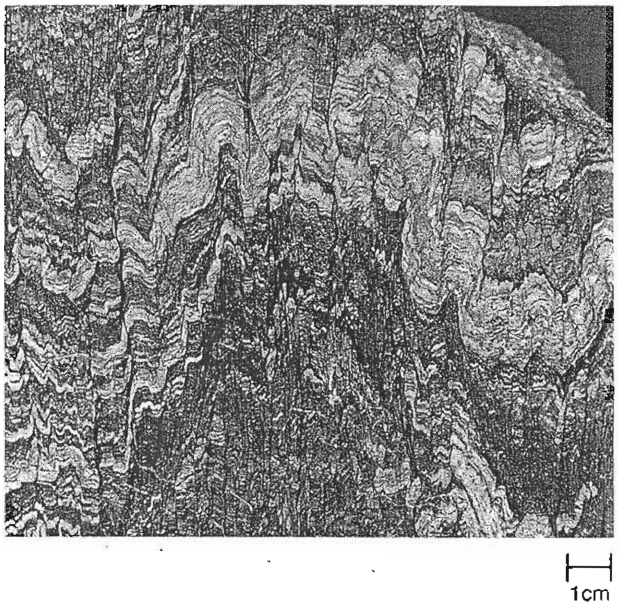


Figure 13.10 Discrete crenulation cleavage in a slate. Note the sharp discontinuity in orientation that marks the boundary between cleavage domain and microlithon. The orientation of the platy minerals in the cleavage domain is parallel to the domain boundary.

thons. The cleavage domains are generally narrow and may or may not correspond to limbs of crenulations in the microlithons. Differences in mineralogy between the two domains are similar to those of zonal foliations.

All variations between these two "extremes" of crenulation foliation can be observed. In fact, it is not uncommon to find both morphologies in the same sample.

13.4 Continuous Foliations

Continuous foliations are defined either by domains with a spacing less than 10 μm (Figure 13.11*A*, *B*) or by a nondomainal structure (Figure 13.12). They are divisible by grain size into fine and coarse continuous foliations (Figure 13.1), as exemplified by slates and schists, respectively. Fine continuous foliations may be either microdomainal or microcontinuous. The microdomainal fine foliations may be microcrenulation (Figure 13.11*A*) or microdisjunctive (Figure 13.11*B*), and they have the same characteristics as their macroscopic counterparts except that the microdomain spacing is less than 10 μm. A microcontinuous fine foliation is characterized by the parallel alignment of all platy or inequant grains in a rock, and it lacks any domainal structure. The terms *microdomainal* and *microcontinuous* are impractical to use as field classification terms, because in fine-grained rocks only an electron microscope can reveal the distinction between the structures.

Coarse continuous foliations are characterized by the complete orientation of homogeneously distributed platy minerals (Fig. 13.12*A*) or by the alignment of

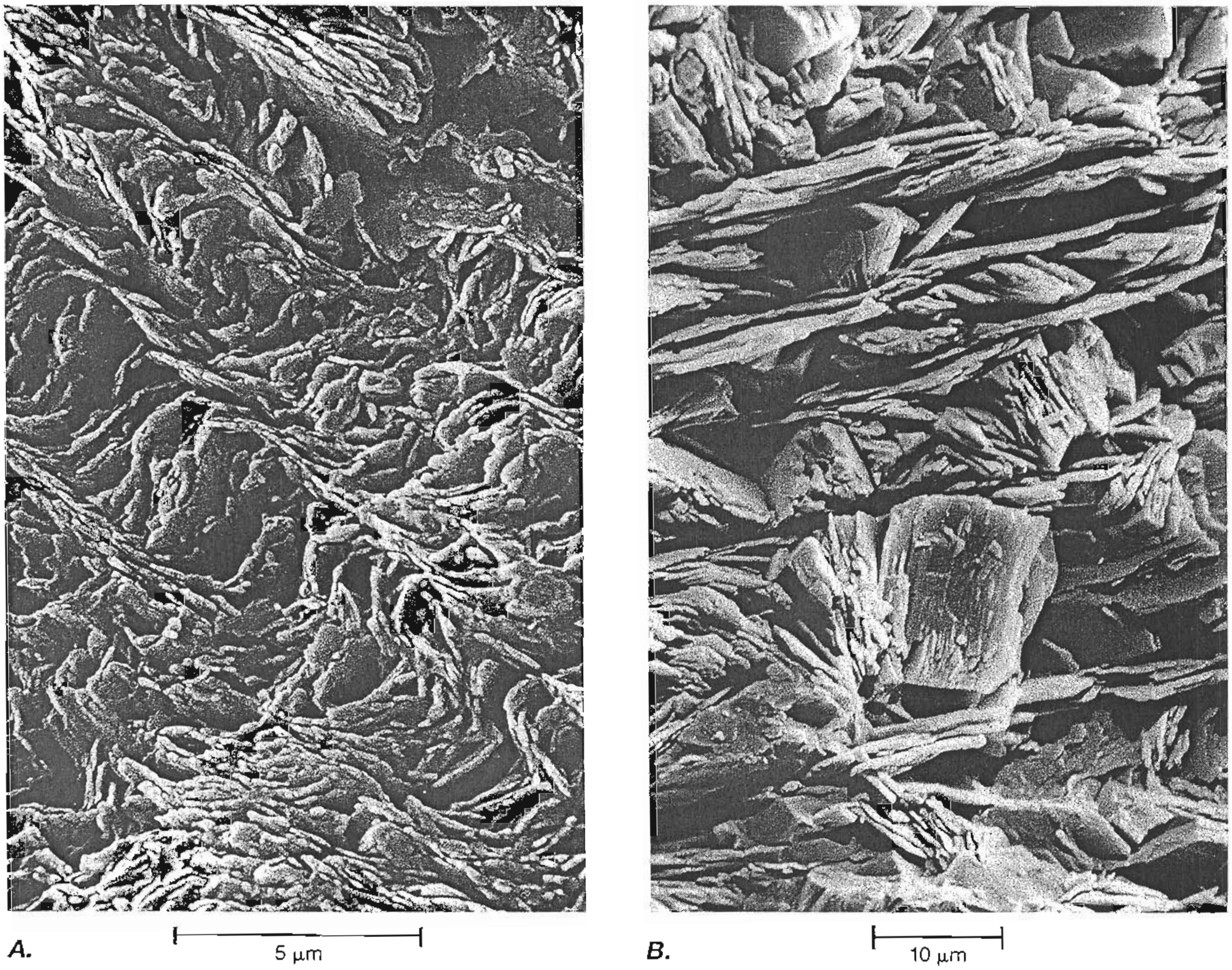


Figure 13.11 Scanning electron micrographs of continuous fine foliations. *A*. Microdomainal continuous fine foliation in a slate with a microcrenulation structure. *B*. A microdisjunctive continuous fine foliation in a slate.

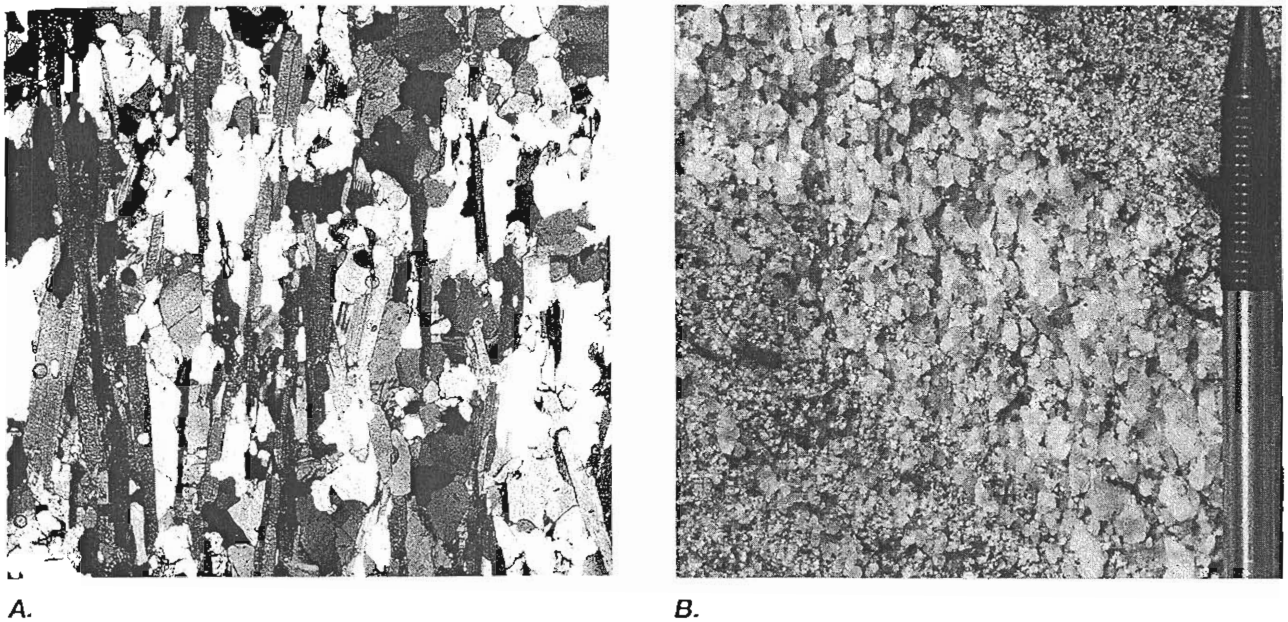


Figure 13.12 Coarse continuous foliation showing a strictly continuous structure. *A.* A schist with the foliation defined by mica. *B.* A grain-shape foliation parallel to the pencil in a very coarse-grained marble layer.

flattened mineral grains (Fig. 13.12*B*). They have no domainal structure, which would be easily revealed by the coarse grain size.

13.5 The Relationship of Foliations to Other Structures

Secondary foliations so commonly occur parallel or subparallel to the axial surfaces of folds that the association is almost axiomatic. Such foliations are called axial surface foliations or axial plane cleavages. The orientation of such foliations characteristically changes progressively from one side of the fold to the other, or fans across the fold, and is actually parallel to the axial surface only at the hinge surface. Foliation fans are convergent or divergent, depending on whether the foliation orientations converge toward one another (Figure 13.13*A*, layers I and III) or diverge from one another (Figure 13.13*A*, layer II) in passing from the convex to the concave side of a fold.

It is important to distinguish foliation fans from fans of dip isogons on folds. The terminology and the geometry are the same for both, and diagrams of the two features look similar. The foliation fan, however, is an actual physical structure that can be observed in the rock (Figures 13.13*B*) whereas the dip isogon fan is a geometric construction (Figures 11.18 and 11.19). In general, the two features are not parallel.

The extent of fanning of an axial surface foliation is typically associated with the composition of the rock in which the foliation is developed. Foliations tend to be most strongly convergent across folds in rocks that contain only small proportions of platy minerals, such as sandstones, and they are least convergent or divergent in rocks rich in platy minerals, such as schists and slates. The orientation of the foliation commonly changes significantly at a lithologic contact (Figure 13.13*A, B*). We call this feature a refracted foliation or refracted cleavage by analogy with the bending, or refraction, of a light ray as it passes obliquely across an interface between two media. The analogy has no significance, however, beyond the similarities of geometry.

The relationship of foliations subparallel to the axial plane of folds is so consistent that it can be used in field mapping to help determine the geometry of the folding. In an area that has been subjected to only one generation of folding, it can also be a valuable indicator of whether sedimentary beds are overturned or right side up, because a given surface of axial foliation can cut a particular folded surface only once (Figure 13.14*A*). Thus the relative orientations of bedding and foliation (Figure 13.14*B*) permit us to determine the general location and direction of the fold closures, as shown in Figure 13.14*A* (see also 13.13*A, B*). An interpretation of Figure 13.14*B* that has the fold closing to the left at the top of the photo and to the right at the bottom would be incorrect, because it would require the foliation plane to cut a single bedding surface more than once.

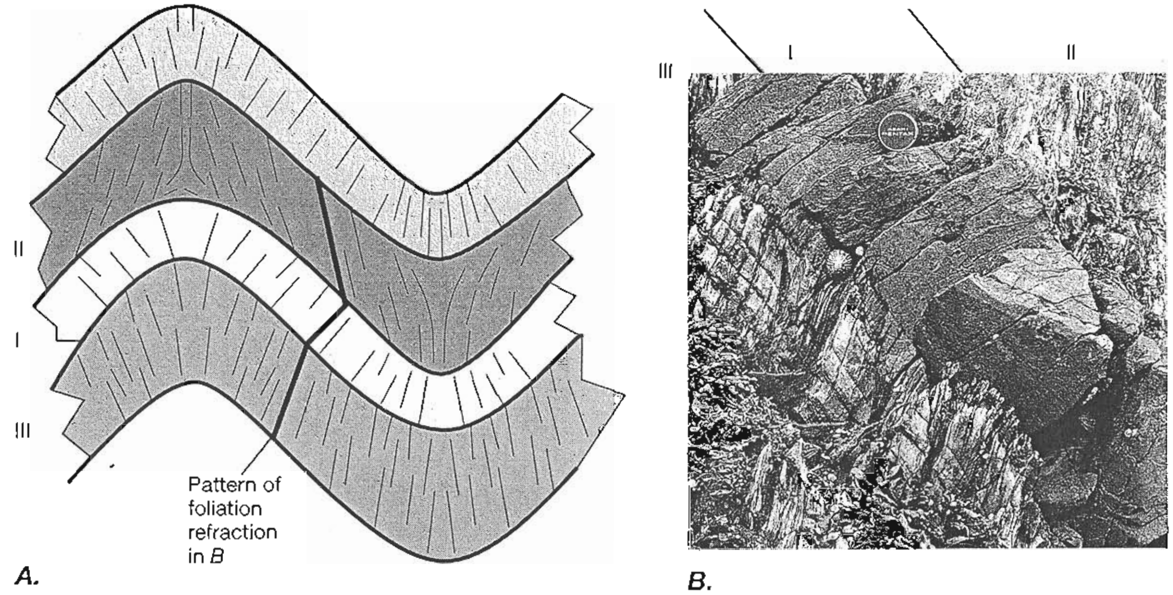


Figure 13.13 Convergent and divergent foliation fans on folds, and the refraction of foliation across lithologic contacts. *A.* The typical pattern of foliations in a folded sequence of sandstone, shale or slate, and siltstone. The foliation pattern is convergent in the sandy (I) and silty (III) layers and divergent in the slate (II). Foliation orientation is "refracted" at the contacts between the layers. The heavy line across the middle limb emphasizes the foliation orientations shown in part *B*. *B.* A sandstone (I), shale (II), siltstone (III) sequence showing the "refraction" of the foliation at the contacts. The photo illustrates the orientations of the beds shown in the middle limb of the diagram in part *A*. Silurian beds, Port Allen, Southern Uplands, Scotland.

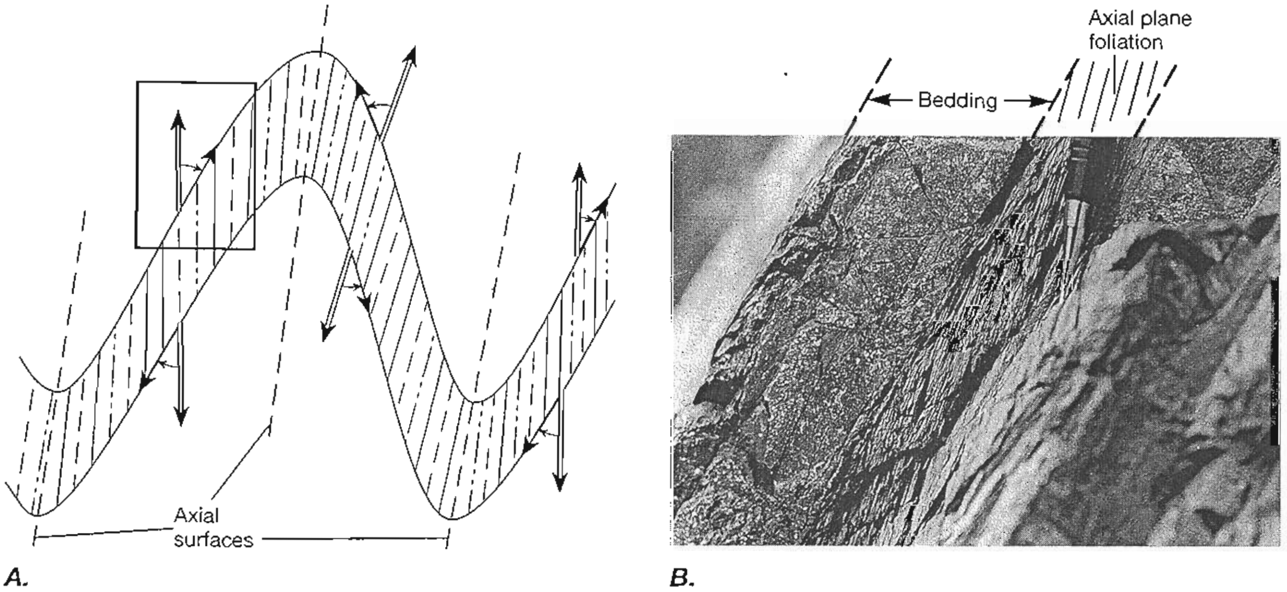
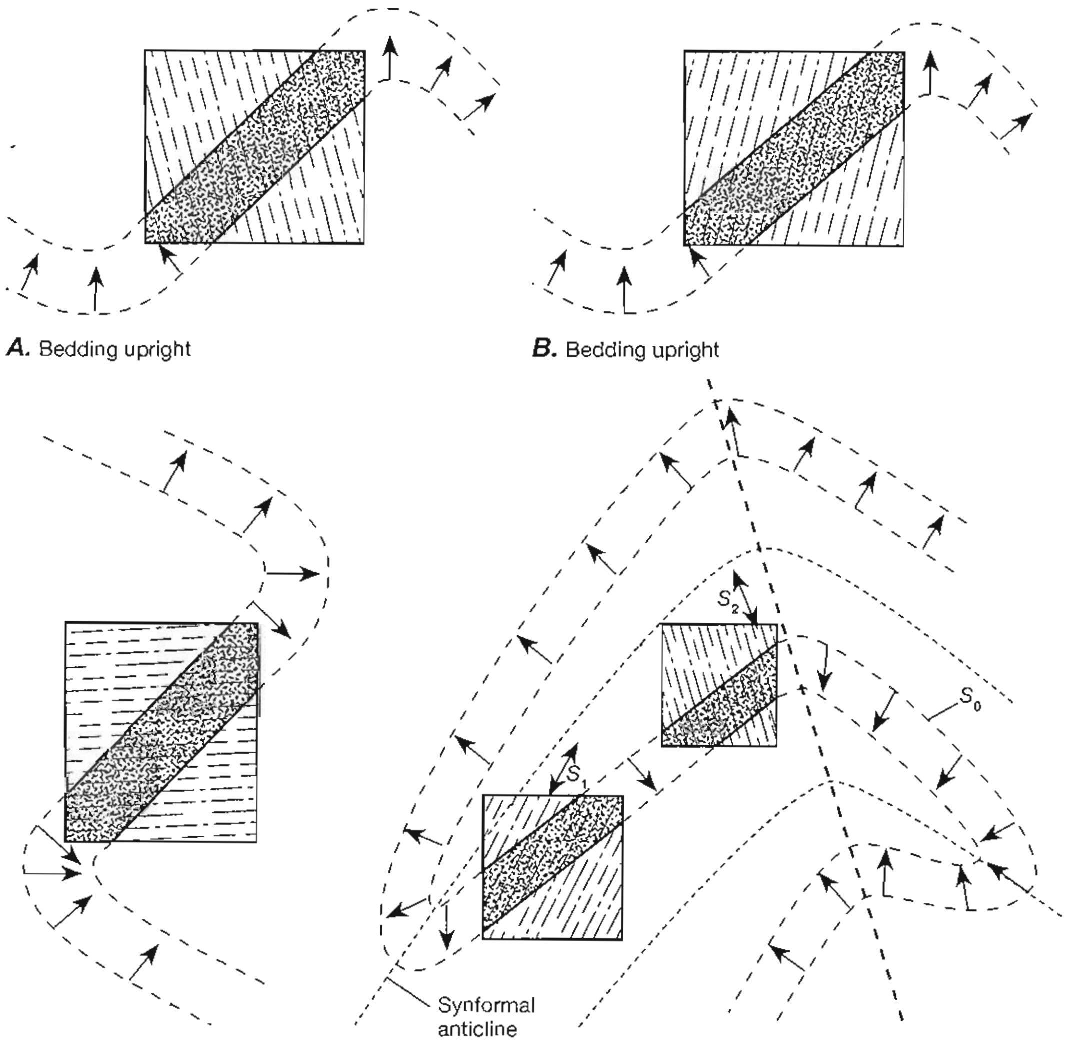


Figure 13.14 The use of bedding-foliation relationships to deduce the location of fold closures and axial surfaces. A foliation plane cannot cut a given bedding surface more than once. *A.* Folded bedding with an axial foliation. Hollow arrows point along the foliation. Solid arrows point along bedding planes. The sense of rotation of the hollow arrow through the acute angle from the foliation toward the bedding (solid arrow) changes across an axial surface. The box outlines the foliation–bedding relationship shown in part *B*, and the fold indicates the correct inference for the direction of fold closure. *B.* Bedding–foliation relationship in interbedded sandstone and shale. The foliation is obvious in the shale layer. The bedding–foliation relationship in the photograph indicates that the fold closes upward to the right and downward to the left, as shown in part *A*. Marathon thrust belt, Texas.

A useful rule of thumb by which to remember this relationship is to imagine an arrow drawn along the foliation surface (Figure 13.14*A*) and then rotated through the acute angle from the foliation to the bedding. The sense of rotation is the same as the sense of asymmetry that a higher-order fold would have at the same location (see Figure 11.24): clockwise (z) on the left side of an antiformal fold, and counterclockwise (s) on the right side (Figure 13.14*A*). The sense of rotation changes across an axial surface. Thus it can be used to map the locations of axial surfaces and to infer the direction of closure of the lower-order (larger) fold, even when the exposure does not permit direct observation of these features.

Inferring the location of the fold closures in this manner enables us to deduce whether the bed is overturned or not, provided we know that only one generation of folds has affected the rocks (Figure 13.15*A*–



A. Bedding upright

B. Bedding upright

C. Bedding overturned

D. Complex folding with overturned beds

Figure 13.15 Use of bedding-foliation relationships to deduce the stratigraphic up direction in simply folded layers. The boxes outline the part of the structure that is assumed to be observable in the field. The dashed continuation of the structure shows the unobservable portion. The arrows in the folded layer indicate the stratigraphic up direction. *A.* Upright bedding is indicated if bedding and foliation dip in opposite directions. *B.* Upright bedding is indicated if bedding and foliation dip in the same direction and bedding has the shallower dip (see also Figure 13.14*B*). *C.* Overturned bedding is indicated if bedding and foliation dip in the same direction and bedding has the steeper dip. *D.* For complex folding, the relationships between bedding and foliation do not give reliable results for the stratigraphic up direction. In this example, note that the foliation could be S_1, parallel to the first-generation axial surface (lower box), or S_2, parallel to the second-generation axial surface (upper box), and in both cases the bedding is overturned. Comparison of the upper box with part *A* and of the lower box with part *B* shows that the technique does not work in this case.

C). Another rule of thumb is helpful: If bedding and foliation dip in opposite directions, the bedding must be upright (Figure 13.15*A*). If bedding and foliation dip in the same direction, the bedding is upright if it has a shallower dip than the foliation (Figure 13.15*B*) and is overturned if it has a steeper dip than the foliation (Figure 13.15*C*).

This method for determining the "stratigraphic up" direction does not work if multiple generations of folding have affected the rocks. In this case the folding is complex, and different foliations may develop in association with the different fold generations. In places on a synformal anticline (for example, the boxes in Figure 13.15*D*), neither the S_1 nor the S_2 foliation provides the correct indication that the bedding is overturned (see Figure 13.15*A*, *B*). Thus the method must be applied with caution. When deformation is complex, we must rely on geopetal structures such as those described in Section 2.2.

Rocks that display multiple generations of deformation commonly have two foliations, which may be the same type or different types, and which may or may not be equally well developed. The earlier foliation commonly becomes folded with a second foliation developed subparallel to the axial surface of the second-generation folds. This relationship is most obvious in the hinge zone of the second-generation folds. On the limbs, the two foliations may be parallel and completely indistinguishable such that the rock appears to contain only one foliation. If multiple foliations are present, it is important to recognize and distinguish them while mapping, because they provide information about different parts of the deformation history and must be separated in the analysis of the structure of the area.

In ductile shear zones the rocks may contain two foliations (labeled S and C in Figure 13.16), both of which develop during a single deformation. Such rocks are called **S-C tectonites.** The **S-foliation** is a continuous coarse foliation defined by the preferred orientation of mica grains and commonly by elongate quartz grains; its dominant orientation is oblique to the ductile shear zone. The **C-foliation** (the C comes from the French *cisaillement,* which means "shear") is a set of shear bands in the rock that develop subparallel to the boundaries of the shear zone. The C-foliation surfaces may have fibrous crystals (slickenfibers, see Section 13.11) lying

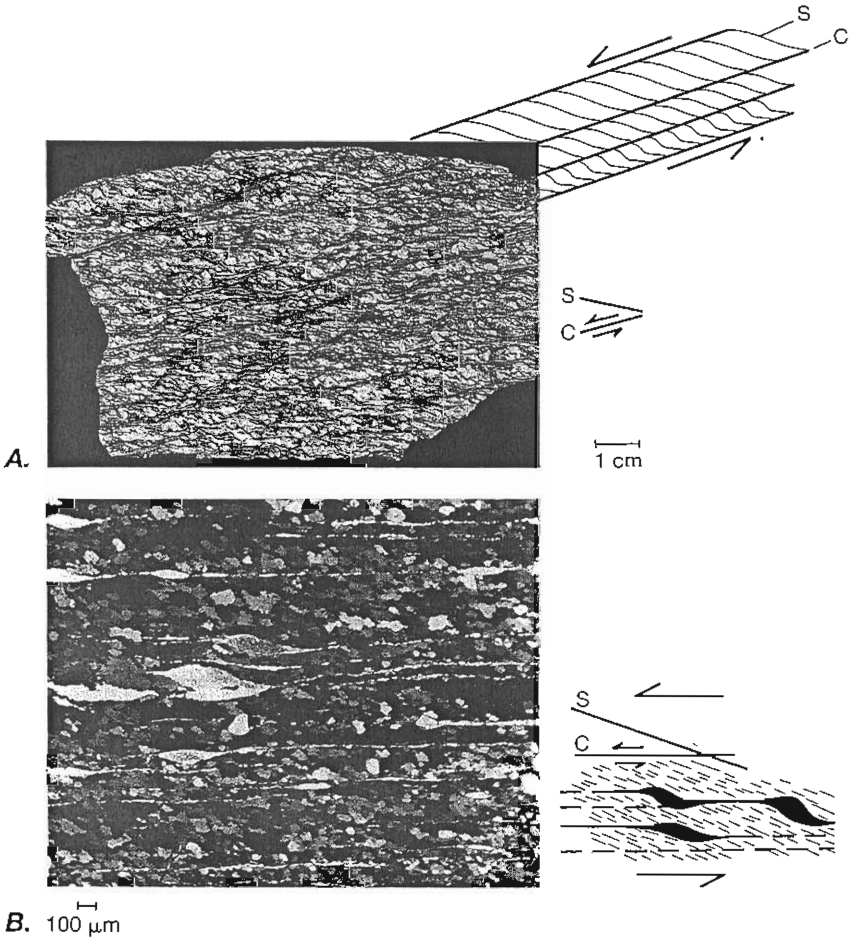


Figure 13.16 Foliations in an S-C tectonite. *A.* Type I S-C tectonite in a ductile shear zone in a granodiorite. The S-foliation is continuous coarse mica foliation that curves toward an orientation parallel to the C-foliation, which in turn is parallel to the shear zone boundaries. This sense of curvature is the same as the general shear sense and indicates a sinistral shear. The idealized geometry is shown in the adjacent diagram. *B.* Type II S-C tectonite in a quartz-rich mylonite. The S-foliation is defined by the grain-shape foliation of the quartz and by the preferred orientation of large mica porphyroclasts ("mica fish"). The C-foliation is the shear plane defined by the trails of fine micas commonly connected to the tips of the porphyroclasts. The sense of curvature from the mica porphyroclasts to the mica trails is the same as the sense of shear on C, and it indicates sinistral shear. The idealized relationships are illustrated in the adjacent diagram, in which the micas are shown in black.

on and subparallel to them, indicating that they were shear surfaces during the deformation. If platy minerals are relatively abundant, a type I S-C tectonite develops in which the C-foliation cross-cuts an S-foliation that has a sigmoidal shape between adjacent C-surfaces (Figure 13.16*A*). If platy minerals are relatively sparse, as in some micaceous quartzites, a type II S-C tectonite develops (Figure 13.16*B*). The S-foliation is defined by the preferred orientation of the large mica grains (called mica porphyroclasts, or "fish") and by a grain-shape foliation in the quartz. The C-foliation is defined by thin seams of very fine-grained mica connected to the ends of the mica "fish." In both cases, micas in the S-foliation curve toward parallelism with C, and the sense of curvature defines the shear sense on the shear zone: Counterclockwise indicates sinistral shear, clockwise indicates dextral shear (see Figure 4.17C). With large amounts of shearing, the S- and C-foliations may become essentially parallel and indistinguishable, and a new foliation, labeled C′, may develop that has characteristics similar to those of the C-foliation but is oriented at a low angle to the shear zone boundaries.

Although the S-C morphology is similar to some examples of crenulation foliation (Figure 13.9*C*, for example), it is important to recognize that the S and C surfaces form during the same deformation, whereas crenulation foliations result from the superposition of two separate deformations.

A transposition foliation results from the superposition of a tectonite foliation on an earlier compositional layering, such as bedding or a compositional foliation. With progressive deformation, the compositional layering becomes isoclinally folded and dismembered (Figure 13.17). The earlier layering is transformed into a discontinuous banding parallel to the new foliation and the folds are no longer recognizable except possibly for scattered rootless folds, which are isolated isoclinal fold hinges that have axial surfaces parallel to the foliation and are not connected to any other hinges.

13.6 Special Types of Foliations and Nomenclature

Many terms for various types of foliations exist in the geologic literature. Some terms are strictly descriptive and are therefore useful in referring to specific morphologic features. Others have genetic connotations that may be misleading. We strongly recommend abandoning the use of genetic terms for descriptive purposes because many are not well defined, and their use may lead to incorrect assumptions about the origin of structures. Interpretation, of course, has a valid place in any scientific investigation, but the descriptive use of inter-

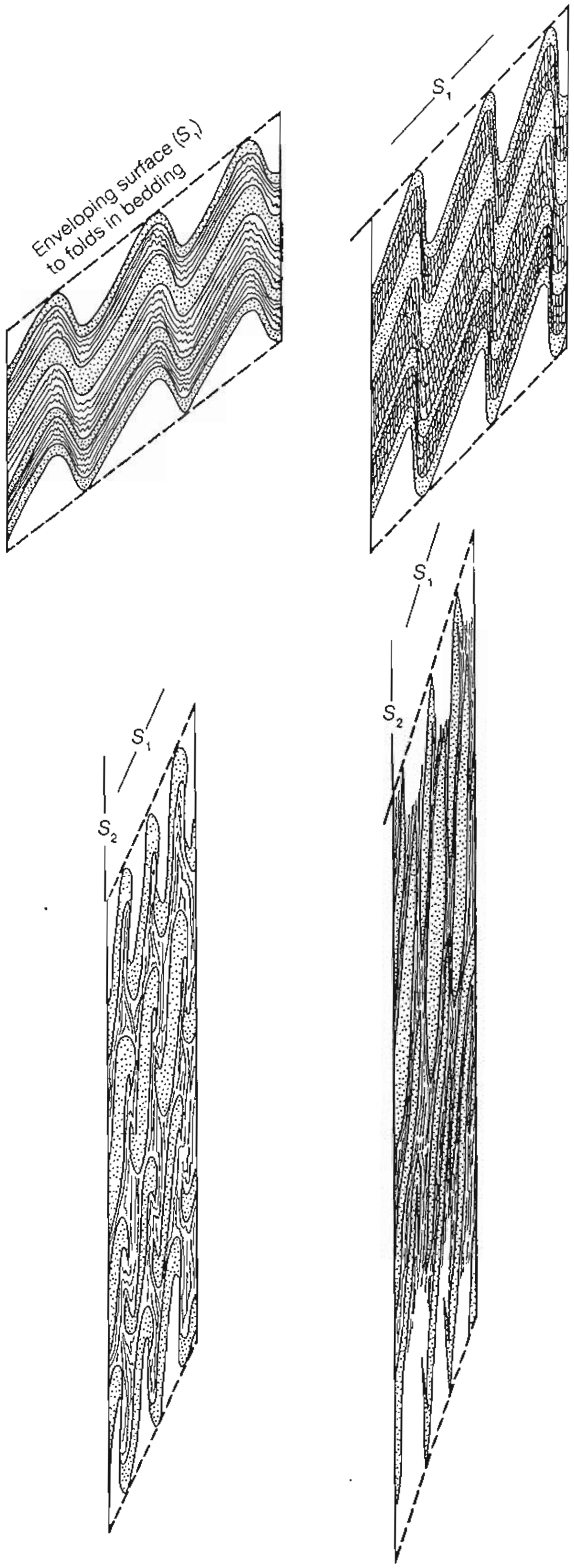


Figure 13.17 A possible sequence in the development of a transposition foliation. S_1 is the enveloping surface to the folds in bedding. S_2 is the transposition foliation.

pretive terms inevitably leads to confusion. In this section we review some common terms and indicate what we believe to be the equivalents in the morphological classification presented in Sections 13.1 through 13.5.

Four terms—*slaty cleavage, phyllitic cleavage, schistosity,* and *gneissic foliation*—are not so specific as categories in the morphological classification given earlier, but they remain useful terms for general and field description. The first three of these describe a continuum in grain size for foliations in rocks containing abundant platy minerals. The last pertains to rocks in which platy minerals are not abundant.

Slaty cleavage refers to fine continuous foliations characteristic of slates. Slates are very fine-grained, low grade metamorphic rocks that contain abundant sheet silicates (generally clays, chlorites, and micas). They may also contain subordinate amounts of silty and carbonaceous material. The foliation may be either continuous or micro-spaced, but in the latter case, the micro-domain spacing certainly cannot be recognized in the field. The foliation provides a very strong cleavage to the rock, along which the rock breaks easily and tends to weather preferentially. Rocks with slaty cleavage traditionally have been a valuable source of materials such as roofing slates and blackboards.

Phyllitic cleavage resembles slaty cleavage except that the grain size of the rock is slightly coarser. It characterizes phyllites, which are low (greenschist) grade, fine-grained, metamorphic rocks that contain abundant micas and/or chlorite. In hand sample, the surface of the foliation has a sheen, and individual sheet silicate flakes may be just resolvable with a good hand lens. The foliation is generally intermediate between a fine and a coarse continuous foliation, although some phyllitic cleavages may be smooth disjunctive foliations. The foliation strongly affects the rock's weathering pattern.

Schistosity refers to the foliation found in coarse-grained, mica-rich, medium-to-high-grade metamorphic rocks. Chlorite, biotite, or muscovite defines the foliation, and the mineral grains are coarse enough to be visible with the unaided eye. This foliation may appear as an anastomosing to smooth disjunctive foliation or as a coarse continuous foliation. It provides a strong cleavage to the rock.

Gneissic foliations are foliations that develop in gneisses, which are coarse-grained, high-grade metamorphic rocks in which platy minerals are sparse or absent. The term includes compositional foliations as well as coarse continuous foliations defined by the alignment of sparse platy minerals, by flattened mineral grains, or by needle-shaped mineral grains. The foliation generally provides at best a weak cleavage.

The following terms all have a genetic connotation and will not be used in this book. We include them for the sake of completeness and, we hope, for strictly historical interest and reference in understanding the older literature.

Flow cleavage is a loosely defined term that seems to have been applied to continuous axial surface foliations interpreted to have been the result of a large amount of ductile deformation in the rocks. It was commonly, and erroneously, interpreted to represent the orientation of flow (shear) planes in the rock during ductile deformation.

Fracture cleavage refers to a variety of disjunctive foliations or discrete crenulation foliations. The term has most often been applied to disjunctive foliations in which the microlithon has little or no fabric and the cleavage domains are thin and can have the superficial aspect of a penetrative set of fractures, especially on weathered surfaces. The term is misleading because the fractures that are observed are in general secondary structures that form along previously developed foliation planes.

Shear cleavage, solution cleavage, and strain–slip cleavage are terms that have been used to describe a variety of spaced foliations. Solution cleavage refers to disjunctive foliations, especially at the more irregular end of the scale. Shear cleavage and strain–slip cleavage both refer to crenulation foliations. None of these terms is well defined, and none should be used descriptively. If solution or shearing has been independently demonstrated, the use of *solution cleavage* or *shear cleavage* as an interpretive term is acceptable.

13.7 Structural Lineations

Figure 13.18 shows a morphological classification of lineations in deformed rocks. We discuss the two main subdivisions, structural lineations and mineral lineations, in this and the following section.

Structural lineations are defined by the preferred orientation of a linear structure contained within a rock. They include discrete lineations, which are formed by the deformation of discrete objects such as ooids, pebbles, fossils, and alteration spots, and constructed lineations, which are formed from planar features constructed or deformed during the deformations and include the intersection of two foliations, crenulation hinge lines, boudin lines, structural slickenlines, and mullions.

Discrete Lineations

Ductile deformation of the rock may distort discrete objects in the rock into well-aligned elongate shapes. Discrete lineations of this nature include stretched peb-

Lineations in tectonites (surficial or penetrative)	Structural	Discrete	Pebbles Ooids Fossils Alteration spots
		Constructed	Hinge lines Intersections Boudin lines Mullions Structural slickenlines
	Mineral	Polycrystalline	Rods Mineral clusters Mineral slickenlines Nonfibrous overgrowths
		Mineral grain	Acicular habit grains Elongated grains Mineral fibers Fibrous vein filling Slickenfibers Fibrous overgrowths

Figure 13.18 Morphological classification scheme for lineations.

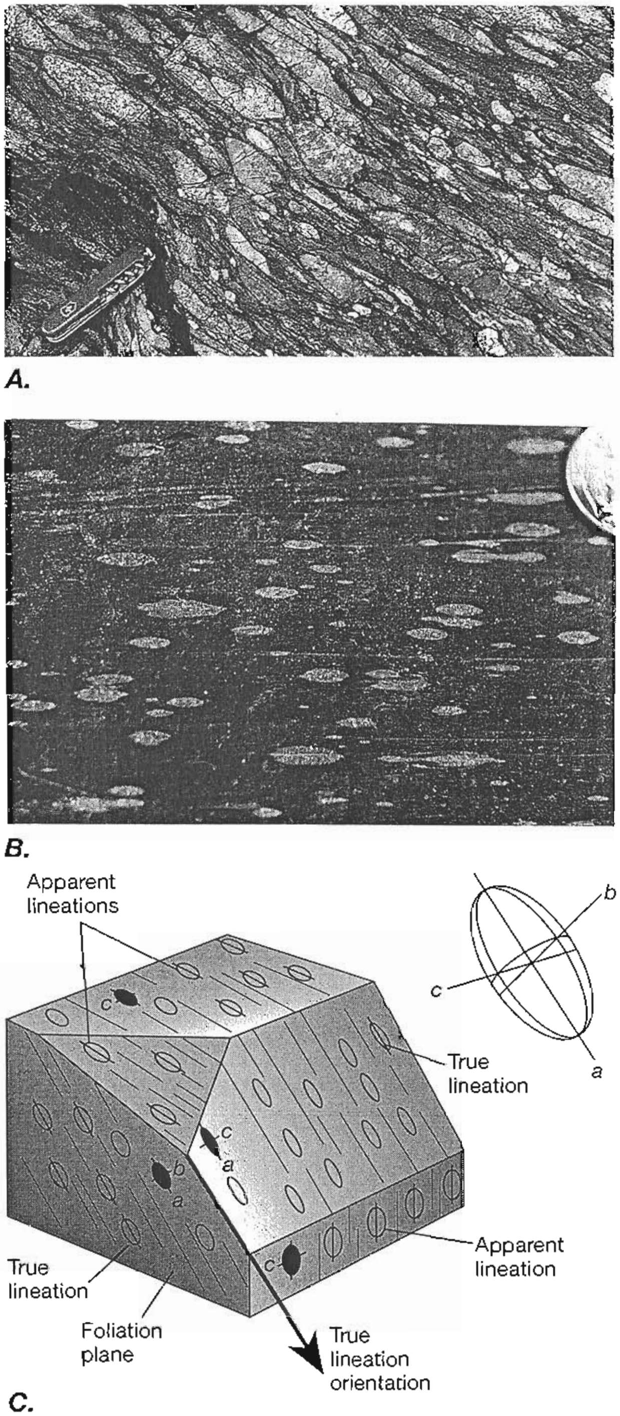
ble conglomerates (Figure 13.19*A*), deformed oolitic limestone, and slates with alteration spots (Figure 13.19*B*). In these cases, objects that were roughly spherical before deformation are deformed into ellipsoidal shapes whose long and intermediate axes (*a* and *b*, respectively, in Figure 13.19C) may define a foliation, and whose long axes define a lineation. The true orientation of the lineation is apparent only on planes that contain the *a* axis of the ellipsoid. Although other sections through an ellipsoid are generally elliptical in shape, the long axis of such an ellipse is not the true lineation.

Alteration spots, also called reduction spots, are volumes in rock distinguished mainly by color differences caused by chemical alteration of some of the rock's components (Figure 13.19*B*). They may be initially spherical features that develop in the sediment shortly after deposition; they are most common in slates.

Constructed Lineations

A variety of lineations fall into the category of constructed lineations, and they have in common the characteristic that the structures originated during deformation of the rock.

The intersection of two planar elements such as two foliations, one of which may be bedding, defines an intersection lineation. If one foliation is defined by platy minerals or flattened mineral grains, the lineation appears on the intersecting foliation as the parallel alignment of the edges of platy mineral grains or of the long axes of the flattened mineral grains (for example, the


A.

B.

C.

Figure 13.19 Discrete lineations. *A*. A stretched pebble conglomerate showing quartzite pebbles flattened parallel to the foliation and elongated to define a lineation. *B*. Alteration spots in a slate. The foliation is perpendicular to the plane of the photo, and the maximum and minimum axes of the ellipsoids are exposed (*a* and *c*; see also part C). C. True and apparent lineations associated with ellipsoidal structures. The true lineation orientation is shown on any plane containing the *a* axis (longest axis) of the ellipsoid. Planes of other orientations show elliptical sections through the ellipsoidal structures that do not define the true orientation of the lineation.

intersection of S_1 with the S_0 surface in Figure 13.20*A*). If one foliation is bedding or a spaced foliation in which the cleavage domains and the microlithons differ in mineralogy, the intersection lineation may appear on the intersecting foliation as streaks of different composition (for example, the intersection of S_0 with the S_1 surface in Figure 13.20*A*). Two intersecting foliations can produce a lineation called a pencil cleavage (Figure 13.20*B*), so named because the tendency of the rock to cleave along both foliation surfaces produces elongate rhombic prisms or "pencils."

Fold hinge lineations are defined by the preferred orientation of microfold or crenulation hinges developed in foliations. The crenulations may, but need not, be associated with a crenulation foliation. On a regional scale, the orientation of hinges of outcrop-sized folds may be treated as a regionally penetrative lineation.

Boudins (the French word *boudin* means "blood sausage") are linear segments of a layer that has been pulled apart along periodically spaced lines of separation called boudin lines (Figure 13.21*A*). The boudins may be completely separated from one another, or they may be connected by an attenuated neck in the layer, in which case the boudin line may also be called a neck line. Boudins are most easy to recognize in an exposure that is at a high angle to the boudin line (Figure 13.21*B*, *C*). The process of forming boudins is called boudinage.

Boudins display a wide variety of shapes. Pinch-and-swell structures are rather gentle oscillations in the thickness of a bed. The necks between boudins may be smoothly curved, or they may look more like fractures. In some cases the necks appear broken, and the space between the broken ends may be filled in with a sec-

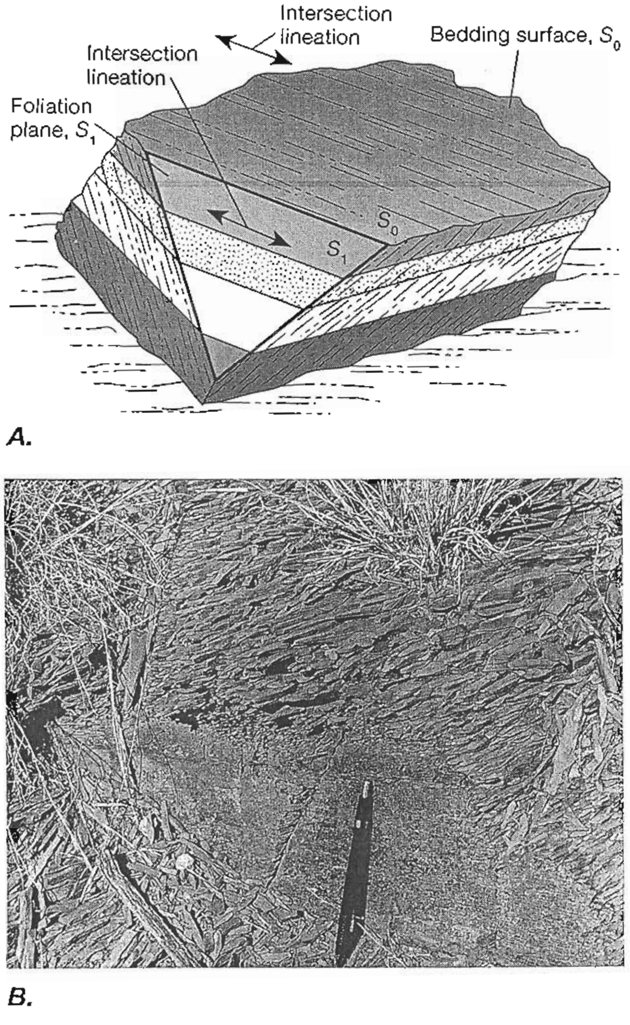


Figure 13.20 Intersection lineations. *A*. The intersection of a foliation and a bedding surface. The trace of the secondary foliation S_1 on the bedding S_0 and the trace of S_0 on S_1 are essentially the same lineation. *B*. Pencil cleavage in argillite, an intersection lineation defined by the intersection of two foliations, one of which may be bedding. Cleavage of the rock along both foliations produces elongate prisms, or pencils, of rock.

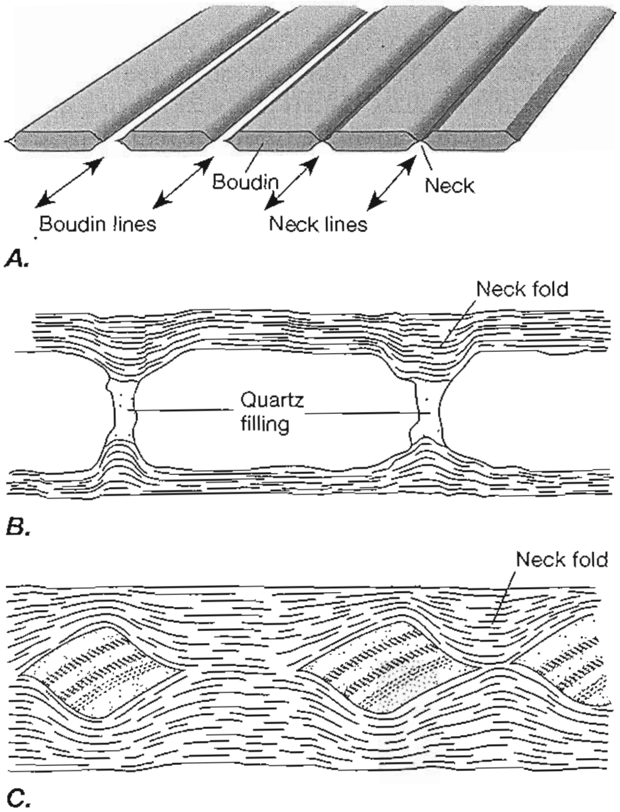


Figure 13.21 Boudins. *A*. Diagram of a boudinaged layer, showing the relationship between the boudins, the necks, and the boudin and neck lines. When viewed in a two-dimensional section normal to the boudin line, boudins often look like a chain of link sausages. *B*. Boudins separated by fractured necks with concentrations of quartz filling the gap between. *C*. Boudins offset along their boudin lines and rotated.

ondary mineral, commonly quartz or calcite (Figure 13.21*B*). In some boudins there is little or no thinning of the layer. Instead it may shear along a surface oblique to the layering. Subsequent separation and rotation of the segments form a string of boudins shaped, in cross section, like rhombs or parallelograms (Figure 13.21*C*).

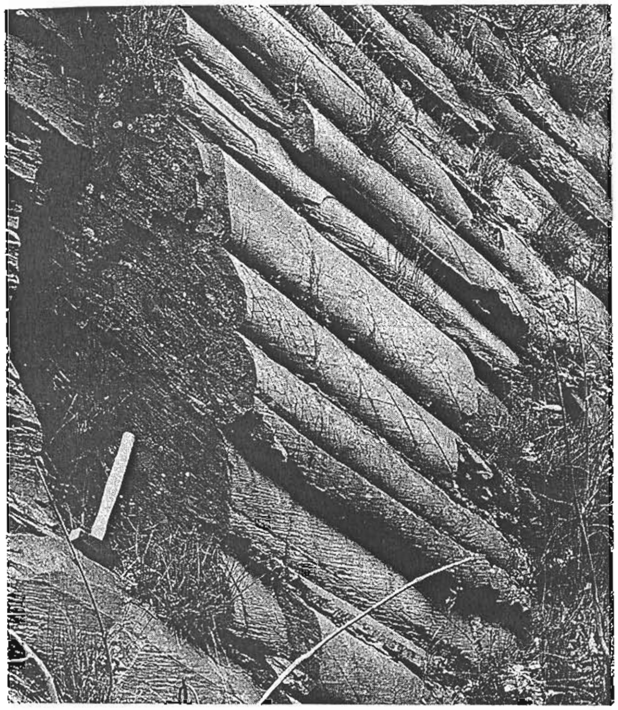
Where finely laminated layers are present on either side of the boudinaged layer, laminations near the necks commonly describe disharmonic folds, called neck folds, that conform to the interface between the layers (Figure 13.21*B, C*) and die out a short distance away from the interface. Any fine laminations in the boudinaged layer itself also bend and thin into the neck area.

Most boudin lines define a pronounced lineation. Some, however, display much scatter in orientation, and others may occur in two intersecting sets, with tablet-shaped boudins called tablet boudinage, or chocolate tablet structure, because of their resemblance to the tablets of a chocolate bar.

Structural slickenlines (Figure 4.8*A, B*) are grooves and ridges that appear on slickensides, the polished surfaces that develop along faults.[3]

Mullions are linear fluted structures developed within a rock or at lithologic interfaces. The name derives from the resemblance of the geologic structure to the vertical fluted architectural structures, called mullions, that separate windows in Gothic cathedrals. They are characterized in cross section by convex surfaces with intervening cusps (Figure 13.22*A*) or by alternating convex and concave surfaces (Figure 13.22*B*). Characteristically, they have a cross-sectional dimension of a few to several tens of centimeters and an indefinite linear dimension.

The surfaces of fold mullions are defined by parting along the cylindrically folded surfaces of layers of foliations. At a boundary between two thick layers of very different competence, such as a sandstone and a shale,


A.

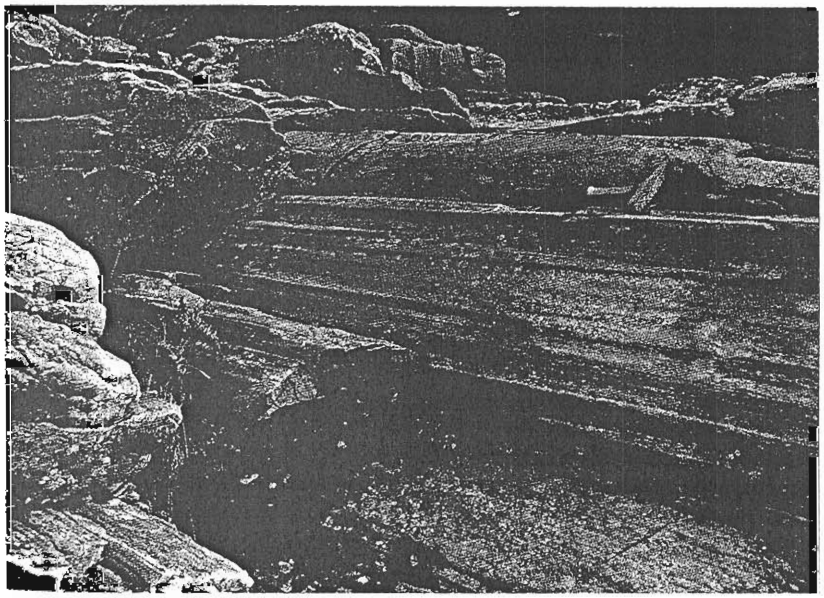

B.

Figure 13.22 Mullions. *A*. Fold mullions in a sandstone at the contact with a shale (now eroded away). The mullion surface is restricted to the bedding surface; it does not form a closed cylindrical surface. *B*. Irregular mullions showing the irregular cross section and the strongly cylindrical structure of the lineation. The mullion surfaces may be coated with a thin film of mica.

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[3] Slickensides are surfaces, although a number of authors use the term to refer to the lineations in the surface. Three types of lineations develop on slickensides: structural slickenlines, mineral slickenlines, and slickenfibers. The first is described here; the other two are described in the next section. The mechanisms by which these lineations are produced are discussed in Chapter 14.

the mullions appear in the more competent member as cylindrical surfaces convex toward the incompetent rock, joined by cusps that point into the competent rock (Figure 13.22*A*). This type of mullion is restricted to the bedding surface.

Irregular mullions are long fluted structures showing an irregular cross section that conforms in general neither with bedding nor with foliation (Figure 13.22*B*). The surfaces of the mullions may be covered with a thin film of mica, and the surface of one mullion fits exactly against that of its neighbors. Some structures of this nature are fault mullions and result from irregularities in the fracture surface (Figure 4.8*B*). Other irregular mullions, such as in the one shown in Figure 13.22*B*, are not well understood.

13.8 Mineral Lineations

Mineral lineations consist of a preferred orientation of either individual elongate mineral grains or elongate polycrystalline aggregates (Figure 13.18). Mineral grain lineations are formed by the parallel alignment of individual acicular (from the Latin word *aciculus,* which means "needle-like") mineral grains such as amphibole, by grains of minerals that have been stretched into an elongate shape, or by mineral fibers that have grown in a preferred orientation. Polycrystalline mineral lineations are formed by the preferred orientation of elongate clusters of grains of a particular mineral measuring at least a few grains in diameter. A preferred orientation of a crystallographic axis of the mineral is commonly associated with both types of lineation, although it need not be parallel to the orientation of the lineation. Mineral lineations may occur as surficial lineations on lithologic contacts, foliation surfaces, or fault surfaces and as penetrative lineations in the rock.

Polycrystalline Mineral Lineations

A variety of structures fall into the general category of polycrystalline mineral lineations.

Rods are polycrystalline mineral lineations formed by rod-shaped concentrations of a particular mineral, commonly quartz (Figure 13.23). The rods may appear in cross section to be isolated cylindrical masses, rootless fold hinges, or boudinaged layers or fold limbs. Thus they can in some cases also be classified as constructed structural lineations. They vary from approximately one to several tens of centimeters in diameter and typically occur parallel to a foliation plane and to the local orientation of fold hinges.

In many metamorphic rocks, mineral cluster lineations form small elongate concentrations or clusters of individual minerals on the scale of a millimeter to a several centimeters (Figure 13.24). The texture of the minerals in the clusters is no different from that in any other part of the rock. The lineations may be quite subtle, as when they are defined by small polycrystalline trains of muscovite and of quartz in a quartz–feldspar–muscovite schist, or they may be strikingly obvious, as when they are defined by elongate clusters of quartz, of feldspar, and of biotite in a gneiss (Figure 13.24). The lineations generally lie in a foliation plane, but in the case of a so-called pencil lineation, the rock fabric is dominated by a strong mineral cluster lineation, and no foliation is evident.

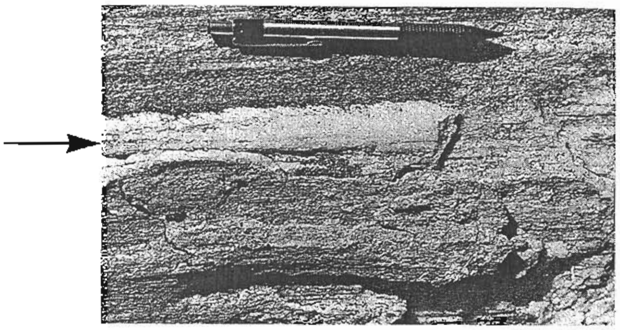

Figure 13.23 Quartz rod lineations. Rods are generally parallel to local fold hinges, and they may be isolated fold hinges or boudinaged fold limbs. In some cases, therefore, they could be classified as structural lineations as well.

Mineral slickenlines appear as streaks developed on slickensides in fault zones (Figure 13.25). The streaks are probably the remnants of mineral grains or aggregates sheared out in the slickenside material, but the grain size is so small that individual mineral grains usually cannot be identified, even with a hand lens.

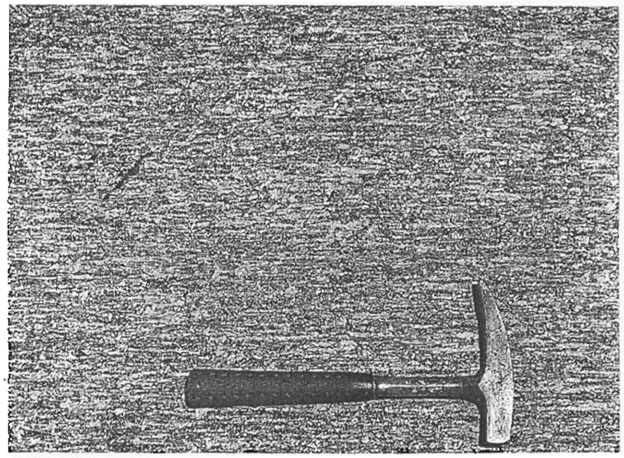

Figure 13.24 Mineral cluster lineation in a quartz–feldspar–biotite schist defined by elongate concentrations of quartz and feldspar and of biotite.

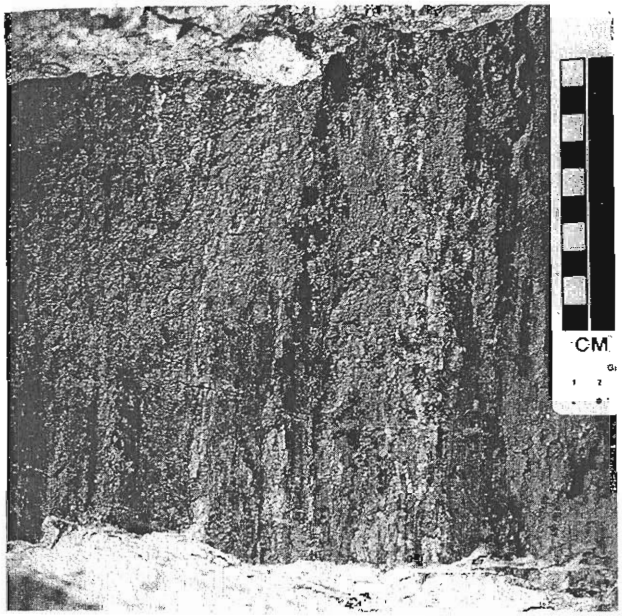

Figure 13.25 Mineral slickenlines on the slickenside of a fault surface.

These lineations may not always be distinguishable from structural slickenlines such as those shown in Figure 4.8*A*, *B*, and the two types of lineations commonly occur together.

Nonfibrous overgrowths are concentrations of one mineral—commonly quartz—around inclusions or grains of another mineral such as garnet or pyrite. Both nonfibrous and fibrous overgrowths are often referred to collectively by the genetic term pressure shadows. Such overgrowths may define a polycrystalline mineral lineation if the overgrowths are elongate and have a preferred orientation. Mineral grains in the overgrowth do not necessarily have a dimensional or crystallographic preferred orientation, so the lineation is defined strictly by the dimensional preferred orientation of the overgrowth (see Figure 13.26*B*).

Mineral Grain Lineations

Three types of mineral grain lineations commonly occur in rocks. They are formed by acicular (needle-shaped) minerals, by elongate mineral grains, and by mineral fibers, respectively. The grain shape may, but need not, be simply related to the crystallography.

Some mineral grains, such as amphiboles and sillimanite, naturally grow with a prismatic or acicular habit. If their long axes have a preferred orientation, such minerals define an acicular habit lineation. If one crystallographic axis (the *c* axis in amphiboles and sillimanite, for instance) parallels the long axis of each mineral grain, the lineation is parallel to a crystallographic preferred orientation.

Under some conditions, elongated grain lineations may form in a rock by deformation of preexisting equant mineral grains into aligned elongate forms. Such mineral grains approximate triaxial ellipsoids in shape, and the lineation is parallel to the longest axis of the ellipsoids (see Figure 13.19C). These lineations are similar to the discrete lineations described in Section 13.7. Crystallographic axes usually are aligned as well, but that alignment need not be parallel to the morphologic alignment of the mineral grains.

Mineral fiber lineations are formed by very elongate crystal grains of a particular mineral—commonly quartz, calcite, chlorite, or serpentine. The structure and composition of the mineral fibers are so distinct from those of the rock in which they occur that it is clear the fibers have grown in the rock during deformation. They

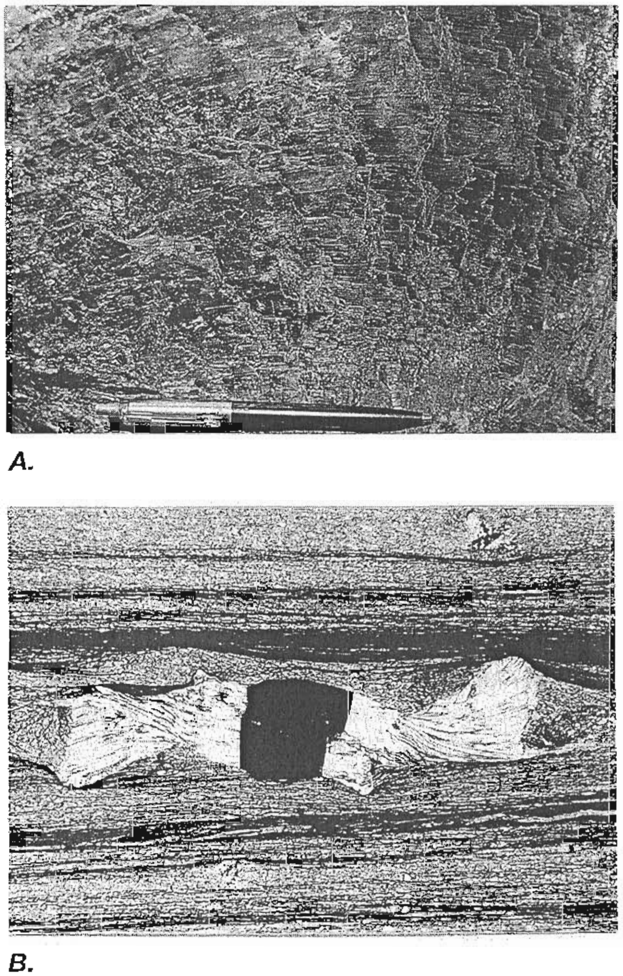

Figure 13.26 Mineral fiber lineations. *A*. Curvilinear serpentine slickenfibers on a fault surface. *B*. Quartz fiber overgrowths on a pyrite grain in phyllite.

occur packed densely together in fibrous sheets or bunches in which all the fibers are strongly aligned in either a linear or a curvilinear arrangement (Figure 13.26).

Mineral fiber lineations are commonly found as surficial lineations both in fibrous **vein fillings** in veins and as slickenfiber lineations along fault planes (Figure 4.8*C*, and 13.26*A*). In both cases, the mineral fibers have a very strong preferred orientation, which is generally at a high angle to the vein wall and at a low angle to the fault surface. Mineral fiber lineations may also form a penetrative lineation, where they occur in strongly oriented fibrous overgrowths on crystals or particles throughout the rock (Figure 13.26*B*). These lineations are common in low-grade metamorphic rocks.

If the fibers in any of these mineral fiber lineations are strongly curved (Figure 13.26*A*), or if they occur on planes that have a wide diversity of orientation (Figure 10.17*C*–*E*) it may be difficult to define a unique lineation for the rock. Nevertheless, the study of these mineral fibers can yield significant information about the deformation and its history during the fiber growth.

The very strong linear preferred orientation of the fibers need not reflect a comparable preferred orientation of their crystallographic axes. Many mineral fiber lineations display nearly random distribution of crystallographic axes, although most quartz and calcite fiber lineations have a strong crystallographic preferred orientation.

13.9 Associations of Lineations with Other Structures

Lineations rarely are the only structure in an area, and the way they are related to other structures can help us understand the structural history. The fabric of some rocks is completely dominated, at least locally, by a lineation. Pencil gneisses, are characterized by a strong pencil lineation. Many lineations, however, are parallel to and lie within foliations or other planar features, and many are geometrically related to fold axes. A given area commonly contains different types of lineations, which may all have the same orientation, although that is not necessary.

Lineations and Foliations

Some lineations are defined at least in part of foliations, and of course these types must be parallel to that foliation. Intersection lineations (Figure 13.20*A*), including pencil cleavage (Figure 13.20*B*), must be parallel to the surfaces that defines them.

Other lineations are defined by features that characterisrically lie in a foliation. Acicular mineral grains may be oriented parallel to a plane, defining a foliation, and they may also have a preferred orientation within the plane, defining an acicular habit lineation. Fold hinge lineations, fold mullions (Figure 13.22*A*), and in many cases rods (Figure 13.23) depend on folding for their linear character. If the folds are associated with an axial surface foliation, then these lineations must be parallel to that foliation. Discrete lineations and mineral cluster, acicular habit, and elongated grain lineations also commonly lie in a foliation defined by platy minerals.

Some lineations, such as boudin lines, mineral fiber lineations, and structural and mineral slickenlines, are not defined by a foliation and do not contribute to the definition of one. Whether such lineations parallel a foliation depends on the geometry of the deformation.

Lineations, of course, may develop on surfaces other than foliations. Slickenlines and slickenfibers are often found on fault surfaces, and slickenfibers may be found on bedding surfaces in some circumstances, especially associated with flexural-slip folds. Fold hinge lineations, boudin lines, and fold mullions must be parallel to the lithologic layers in which they develop. Intersection lineations involving lithologic layering, of course, must lie in the plane of the layering.

Lineations and Folds

The relationship between folds and lineations can be of major importance in our efforts to decipher the structural geometry of an area and interpret the conditions under which the structures formed. Some lineations, such as fold hinge lineations, fold mullions (Figure 13.22*A*), and rods (Figure 13.23) are generally parallel to the regional distribution of fold hinges. An intersection lineation defined by a folded surface and by the axial foliation to the folds also parallels the fold axis if the folding is close to cylindrical. Mineral lineations also are commonly parallel to fold hinges.

Because lineations are generally smaller-scale structures than folds, and because small-scale structures commonly reflect the geometry of large-scale structures, it may be easier to map the geometry of fold hinges by mapping the orientation of the appropriate lineations. The parallelism of a particular lineation with the hinges of a particular generation of folds, however, must be established independently.

Lineations such as boudin lines, acicular mineral grains, elongate mineral grains, and mineral cluster lineations, as well as discrete lineations and overgrowth lineations, may be found either parallel or perpendicular to fold axes. Some lineations, such as acicular habit lineations, have also been observed to be parallel to fold axes in hinge zones but perpendicular to them on the limbs. Slickenfiber lineations on folded bedding surfaces are usually perpendicular to the associated fold hinge. They are most strongly developed on the limbs and fade to nonexistent in the hinge zone.

Less often, lineations are found at arbitrary angles to fold axes. Such a geometry is usually the result of the deformation of earlier lineations, as discussed in more detail in Chapter 16. Other possibilities cannot be dismissed, however, and each situation requires individual investigation.

Lineations often can be used to infer the distribution and geometric characteristics of the deformation in an area. We postpone discussion of these topics until after Chapter 15, where we introduce the concept of strain as a measure of deformation (see Section 16.7).

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