PART II Brittle Deformation

PART II of this book focuses on the structures formed in rocks predominantly by brittle deformation—that is, the breaking of rocks along well-defined fracture planes or zones. Depending on the relative motion that occurs across the fracture plane, the fractures are either extension fractures or shear fractures. We describe the general characteristics of these two types of fractures in Chapter 3. Faults are shear fractures in rocks generally at the scale of an outcrop or greater. Larger faults are commonly structures of major tectonic importance. We introduce the general characteristics of faults in Chapter 4. In Chapters 5, 6, and 7, we discuss the characteristics and tectonic significance of each of the three major types of faults: normal, thrust, and strike-slip.

Having described the structures of predominantly brittle origin that we observe in rocks, we next turn our attention to understanding how and why these structures form. Rocks break when they are subjected to an excessive amount of force; we introduce in Chapter 8 the concept of stress as a measure of the intensity of forces applied to a material. In Chapter 9 we review experimental evidence and theory about how the stress imposed on a rock is related to the types of fractures that form and to the mechanism of formation. With this background, we then return, in Chapter 10, to the interpretation of brittle structures that we find in the Earth. By understanding the mechanisms by which fractures form, and by being able to interpret the evidence we observe in the rocks, we can deduce the physical conditions that prevailed in the rock during this fracturing process, thereby opening another window on the tectonic evolution of the Earth's crust and the dynamic processes that drive that evolution.

Beyond their use in investigating the tectonic evolution of the Earth's crust, fractures are of major importance to our environment and to the continued viability of our society. First, because fractures often serve as conduits for ground water, they are the site of preferential weathering and thereby control the form of much of the Earth's topography. Indeed, some of the world's most inspiring land forms, such as Yosemite Valley in California, the Grand Canyon, the Alps, the islands of the Mediterranean, and Ayer's Rock in Australia owe much of their form to preferential erosion caused by the presence of fractures.

Furthermore, because fractures provide conduits for the migration of fluids through solid rock, they are of great significance in the migration of ground water, of hydrocarbons, and of hydrothermal and/or metamorphic fluids. Thus they are significant in the fields of hydrogeology, geothermal heat extraction, and oil and gas migration and recovery. In addition, fractures affect the location of hydrothermal mineral deposits and the integrity of nuclear waste disposal sites, which must safely contain their lethal waste for 10,000 years or more. As a consequence of this association with the world economy and the safety of future generations, understanding the characteristics of fractures and the conditions of their formation is of very real social importance.

Finally, because the cohesion of the rocks is lost across fracture surfaces, they are planes of weakness in the rock. This inherent weakness must be accounted for in the building of dams, bridge abutments, tunnels, mines, and similar engineering projects.

CHAPTER

3 Fractures and Joints

Fractures (from the Latin *fractus,* which means "broken") are surfaces along which rocks or minerals have broken; they are therefore surfaces across which the material has lost cohesion. Fractures are distinguished by the relative motion that has occurred across the fracture surface during formation. For extension fractures, or mode I fractures, the relative motion is perpendicular to the fracture walls (Figure 3.1*A*). For shear fractures the relative motion is parallel to the surface. For mode II shear fractures, the motion is a sliding motion perpendicular to the edge of the fracture (Figure 3.1*B*); for mode III shear fractures, it is a sliding motion parallel to the fracture edge (Figure 3.1*C*). A fracture that has components of displacement both parallel and perpendicular to the fracture surface is an oblique extension fracture, or mixed mode fracture.

Fractures are among the most common of all geologic features; hardly any outcrop of rock exists that does not have some fractures through it. Because the outcrop scale is easy to observe and is the basis of all field geology, we emphasize the descriptive characteristics of fractures at the outcrop scale.

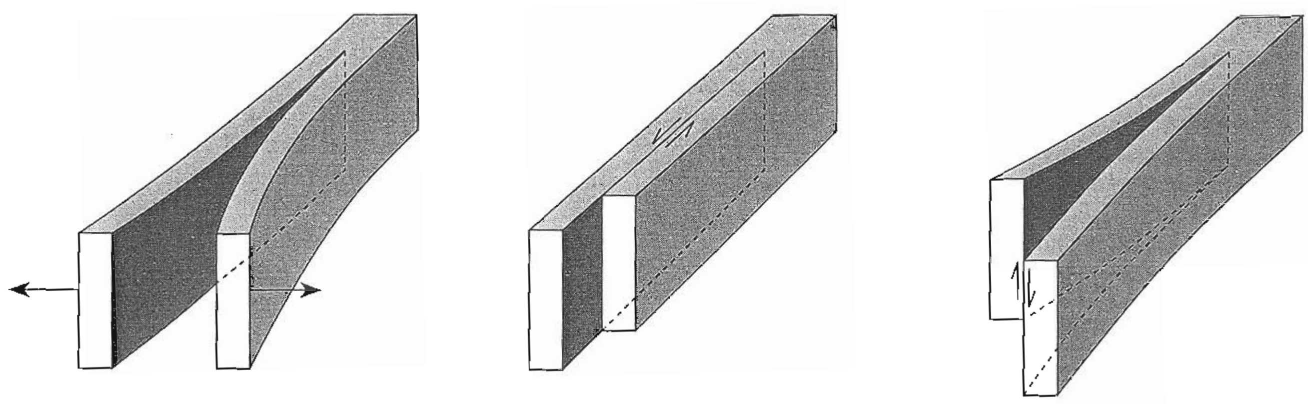
The study of geologic history of fractures is notoriously difficult. Evidence bearing on the mode of fracture formation and the relative time of formation of different fractures is often ambiguous. As planes of weakness in the rock, fractures are subject to reactivation in later tectonic events, so some of the observable features of a fracture may be completely unrelated to the time and mode of its formation.

The investigation of fracturing comprises four general categories of observations: (1) the distribution and geometry of the fracture system, (2) the surface features of the fractures, (3) the relative timing of the formation of different fractures, and (4) the geometric relationship of fractures to other structures.

3.1 Classification of Joints and Extension Fractures

Most outcrops of rock exhibit many fractures that show very small displacement normal to their surfaces and no, or very little, displacement parallel to their surfaces. We call such fractures joints.[1] If there is no shear displacement, a joint is an extension fracture. A joint with very small shear displacement, however, may be an extension fracture on which shear displacement has later accumulated.

[1] Unfortunately, there is no universally accepted definition of the term *joint*. The definition set down here is conservative in that fractures satisfying this definition would be called joints by every other definition of the term.



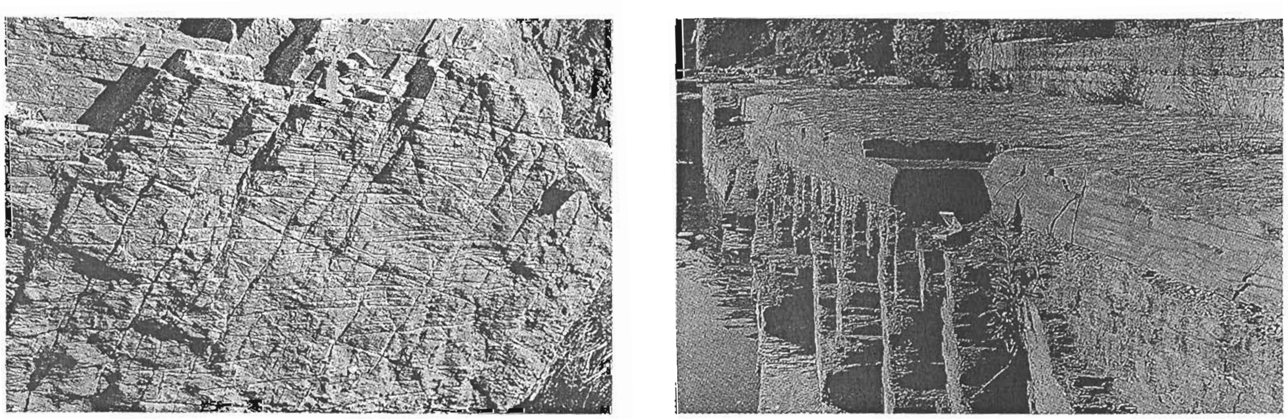
A. Extension (mode I) *B.* Shear (mode II) *C.* Shear (mode III)

Figure 3.1 The distinctions among the major types of fractures are based on the relative displacement of the marerial on opposite sides of the fracture *A*. Extension, or mode I, fraetures. The relative displacement is perpendicular to the fracture. *B*. Shear fractures, mode II. Relative displacement is a sliding parallel to the fracture and perpendicular to the edge of the fracture. C. Shear fractures, mode III. Relative displacement is a sliding parallel to the fracture and to the edge of the fracture.

If many adjacent joints have a similar geometry, the fractures collectively are called a joint set. Systematic joints are characterized by roughly planar geometry, regular parallel orientations, and regular spacing (Figures 3.2 and 3.3*A*). Nonsystematic joints are curved and irregular in geometry, although they may occur in distinct sets of regional extent (Figure 3.3*B*). Nonsystematic joints nearly always terminate against older joints which commonly belong to a systematic set (Figure 3.3*B*). Because most joints we see are systematic, the term *joint* is generally used to refer to them. A joint zone is a quasi-continuous fracture that is composed of a series of closely associated parallel fractures and that extends much further than any of the individual fractures (Figure 3.3*A*, *C*). In practice, such a joint zone is also called simply a joint.

Most outcrops contain more than one set of joints, each with a characteristic orientation and spacing. Two or more joint sets affecting the same volume of rock constitute a joint system[2] (Figures 3.2 and 3.3*D*). If systematic joints of one set consistently terminate

[2] Note that the terms *joint system* and *systematic joint* have different meanings and should not be confused.



A. *B.*

Figure 3.2 Joints. *A*. Ourcrop showing a joinr system made up of three distinct sets of joinrs. *B*. Joints of different orientarions terminaring againsr lithologic conracts.

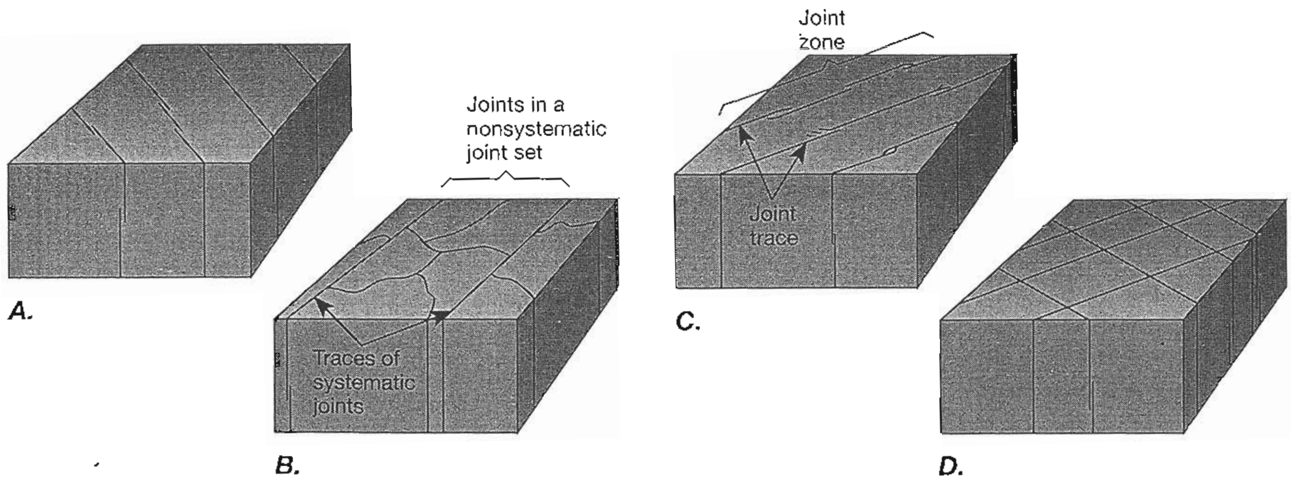


Figure 3.3 Diagrammatic views of joint sets and joint systems. *A*. Geometry of a systematic joint set. *B*. Typical pattern of nonsystematic joints and their characteristic termination against systematic joints. *C*. Joint zones forming quasi-continuous joints of much larger extent than the individual fractures. *D*. Two sets of mutually intersecting joints. Joints in each set cut joints of the other set. There is no consistent relationship whereby joints of one set terminate on joints of the other set.

against the joints of another set, they are referred to as **cross joints**. Joint sets and systems may persist over hundreds to thousands of square kilometers, each set displaying a constant or only gradually varying orientation (Figure 3.4; see also Figure 3.12). Such systems can show up as lineaments on high-altitude photographic and radar images (Figure 3.4).

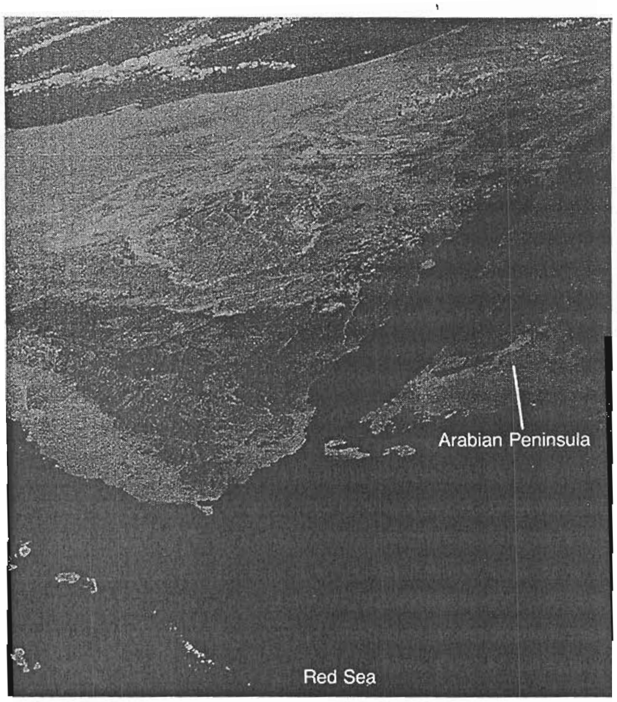


Figure 3.4 Fracture-controlled topography, Sinai peninsula, Egypt. Gulf of Aqaba to right about 200 km long.

In some circumstances it is useful to refer to joints in terms of their relationship to other structures. Thus strike joints and dip joints are vertical joints parallel to the strike or dip of the bedding, and bedding joints are parallel to the bedding. Joints that cut a fold or some other linear feature at high angles are also called cross joints, and those in other orientations are **oblique joints** or **diagonal joints**.

Sheet joints, sheeting, or **exfoliation joints** are curved extension fractures that are subparallel to the topography and result in a characteristic smooth, rounded topography (Figure 3.5). Sheet joints may be found in many kinds of rocks, but the characteristic topography is best displayed in plutonic rocks in mountainous regions where the joints appear to cut the rock into sheets like the layers of an onion. Many sheet joints apparently formed later than other joint sets, although in some cases they predate late phases of intrusive activity, as evidenced by dikes present along the joints.

Columnar joints are extension fractures characteristic of shallow tabular igneous intrusions, dikes or sills, or thick extrusive flows. The fractures separate the rock into roughly hexagonal or pentagonal columns (Figure 3.6), which are often oriented perpendicular to the contact of the igneous body with the surrounding rock.

Other types of extension fractures are common in deformed rocks. **Veins** are extension fractures that are filled with mineral deposits. The deposit may be massive

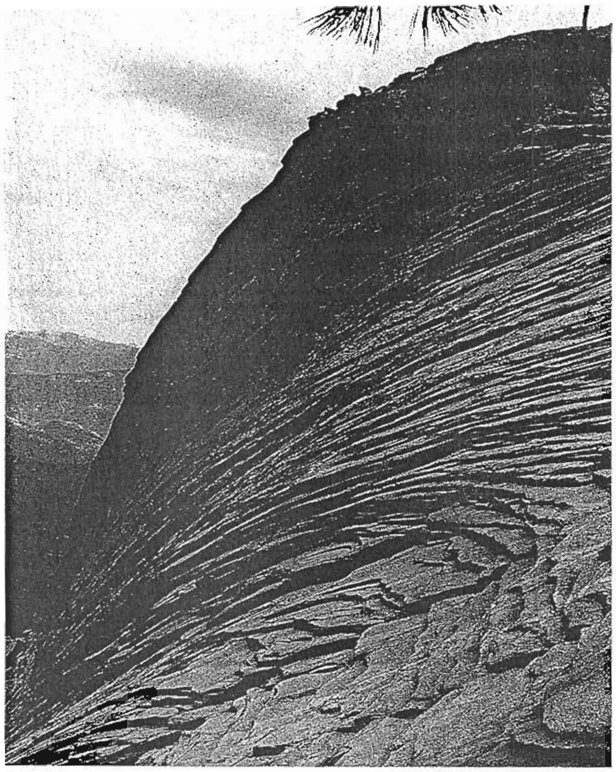
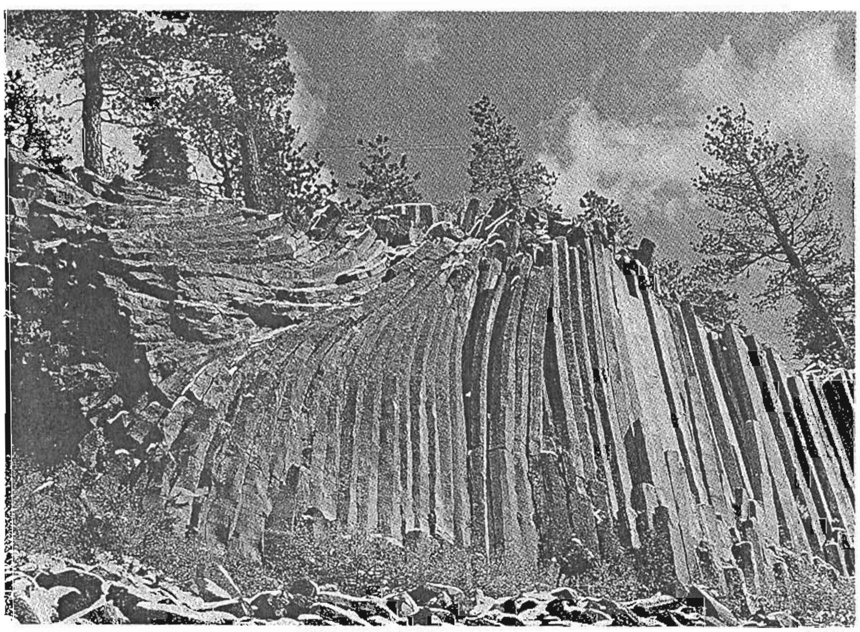


Figure 3.5 Sheer joints in granitic rock ar Little Shuteye Pass, Sierra Nevada.

or composed of fibrous crystal grains such as quartz or calcite. The fibrous fillings cau be very useful in interpreting the deformation associated with opening of the vein, as we discuss in detail in Sections 13.8 and 14.6.

Pinnate fractures, or feather fractures, are extension fractures that form *en echelon* arrays along brittle shear fractures (Figure 3.7). The acute angle between the extension fracture and the fault plane is a unique indicator of the sense of shear along the fault, and it points in the direction of relative motion of the block containing the fractures (see also the discussion in Section 4.2).

Gash fractures are extension fractures, usually mineral-filled, that may form along zones of ductile shear in the same orientation as the pinnate fractures. They are generally S- or Z-shaped, depending on the sense of shear along the zone. The photograph in Figure 3.8 shows two *en echelon* sets of gash fractnres (white veins) arrayed along crossing shear zones. The Z-shaped and S-shaped veins to the left and right, respectively, show the "top down" sense of shear along each zone of fractures. The orientation of planar gash fractures can be used in the same way as feather fractures to determine the sense of shear on the associated shear zone. Extension fractures may also be associated with other structures, including folds and igneous intrusions, as described in Section 3.5.



A.

B.

Figure 3.6 Columnar jointing. Devil's Postpile National Monument, California. *A.* Columnar joinring in an andesitic flow. Nore rhat the orientarion of rhe columns varies from vertical to a shallow plunge. *B.* Cross section of rhe columnar joints.

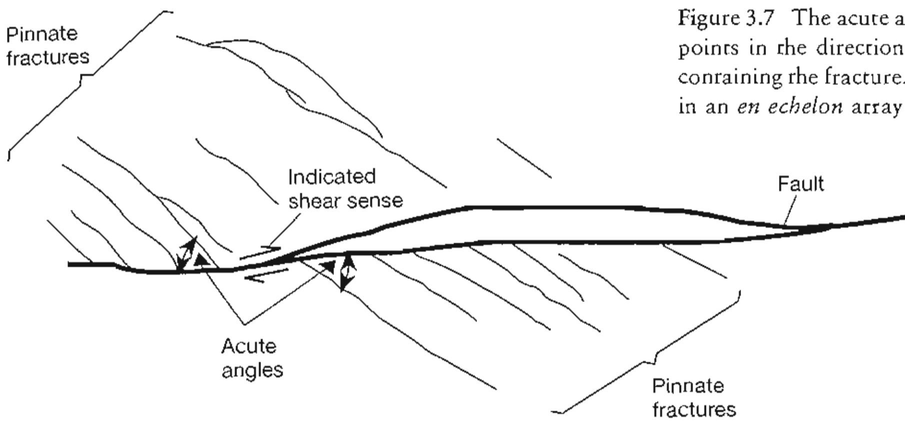


Figure 3.7 The acute angle between the fracture and the fault points in the direction of relative motion of the fault block containing the fracture. Pinnate fractures, or feather fractures, in an *en echelon* array along a brittle fault.

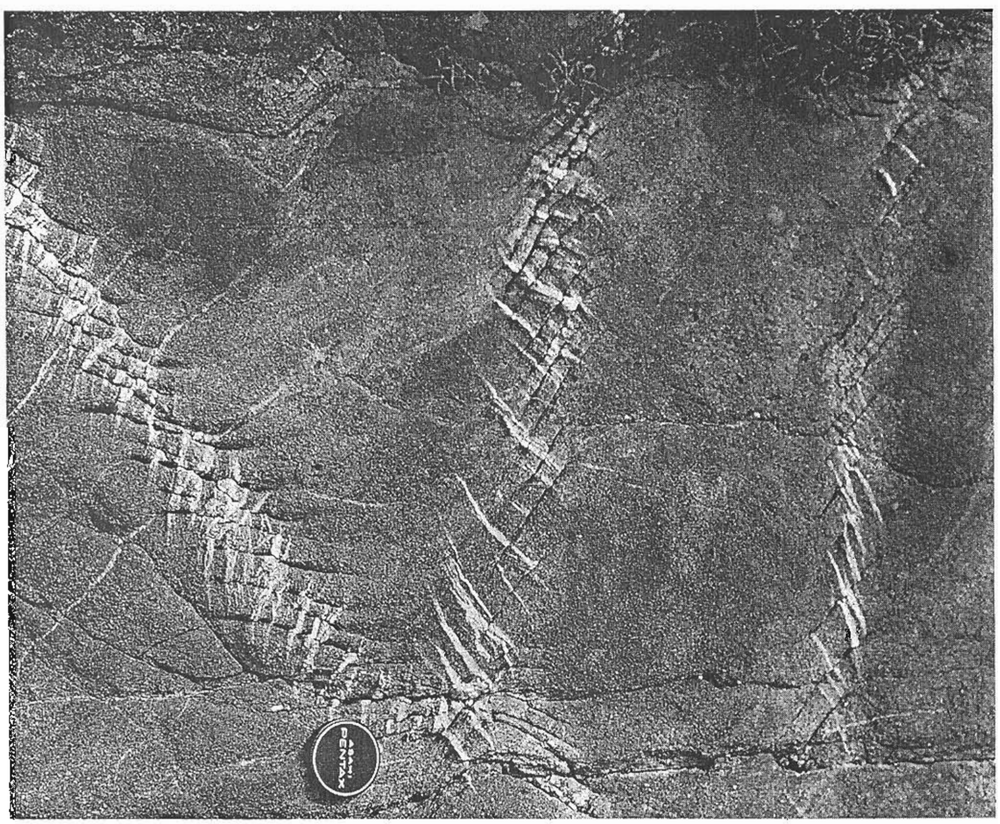


Figure 3.8 Gash fractures (white veins) are extension fractures that commonly develop in a shear zone. Dark seams are solution features. Gash fractures are aligned along differently oriented planar shear zones that make an angle of approximately 50° with each other. The ends of the fractures tend to bisect the angle between these shear zones.

3.2 Geometry of Fracture Systems in Three Dimensions

In any study of the origin of fractures in rocks, we need to collect data on each fracture set that includes the orientation of the fractures, the scale of the fractures, the spacing of the fractures and their relationship to lithology and bed thickness, and the spatial pattern and distribution.

Orientation of Fractures

The orientation of fractures can help us identify fracture sets and infer the orientation and extent of the tectonic forces that produced them. In general, we collect representative orientations of all the major fracture sets in each outcrop, over a large area, and rely in part on consistency of orientation to correlate sets from one outcrop to another.

Interpretations that rely too heavily on orientation data, however, have resulted in significant misunderstanding. For example, because shear fractures commonly intersect at an angle of roughly 60°, it is often incorrectly assumed that all fractures that intersect at such an angle are shear fractures. Similarly, the consistent orientation of joints relative to other structures is often taken to be indicative of a genetic relationship. Although such interpretations cannot be ruled out a priori, they are unreliable unless corroborated by other evidence.

More than one orientation of fracture may be associated with a single fracturing event, and it is important to understand the relationships among fractures instead of blindly measuring every orientation of fracture surface available in the hope that statistical analysis will compensate for lack of careful observation. Genetically related fractures may differ in orientation as a result of segmentation and twisting of the fracture plane, curving of the plane, reorientation of the fracture into parallelism with a local planar weakness in the rock, or branching of the fracture into two or more orientations. Some fractures may be of only local extent and may even result from human activity such as excavation or blasting. Careful study is therefore required to identify the significant data.

The orientation of genetically related fractures may differ from one lithology to another; on the other hand, the fractures in various rock types may result from different events. Figure 3.9, for example, contains the same data as Figure 2.12, except that in this split rose diagram, the joints in coal are plotted in the top half, and those in the shale in the lower half. The joint patterns from the two lithologies are distinctly different. Careful investigation has led to the conclusion that the joints in the coal formed first. Gentle folding of the region then broadened the distribution of the earlier joint orientations, and finally the joints in the shale formed. Separating the joints by lithology, therefore, is important in decifering the history of joint formation.

Orientation data on fractures are conveniently collected and compared by using orientation histograms, rose diagrams, or spherical projections, all of which we discussed in Section 2.5.

Scale and Shape of Fractures

Individual fracture planes are not of indefinite extent. Field observations indicate that a joint may terminate by simply dying out (Figure 3.10*A*), by curving and dying out (Figure 3.10*B*), by branching and dying out (Figure 3.10*C*), by curving into a preexisting joint (Figure 3.10*D*, *E*, *F*), or by segmenting into an *en echelon* set of small extension fractures (Figure 3.10*G*). The amount of displacement across the joint decreases toward the joint

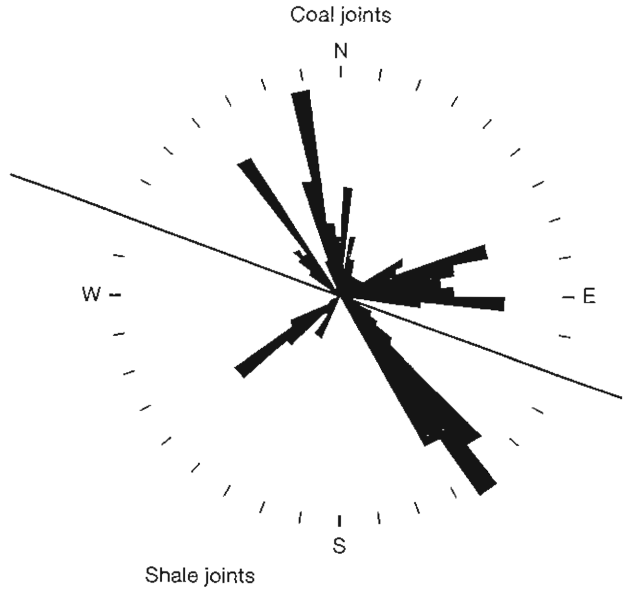


Figure 3.9 A split rose diagram showing the strikes of joints in coal in the upper half of the diagram and those in shale in the lower half. Note the difference in orientation of the joints in the two rock types.

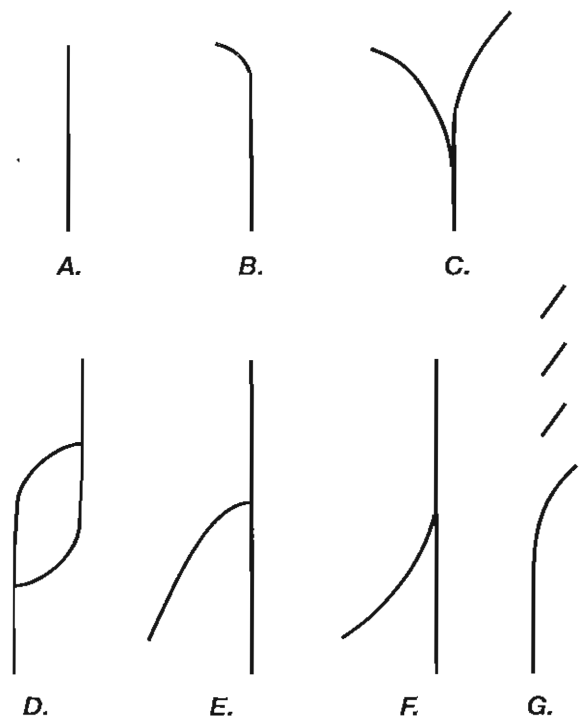


Figure 3.10 Terminations of individual joints. *A.* Dying out of a straight joint. *B.* Curving and dying out of a joint. *C.* Branching and dying out of a joint. *D.* Two overlapping joints, each curving toward a perpendicular intersection with the other. *E.* One joint curving toward a perpendicular intersection with another. *F.* One joint curving toward a parallel intersection with another. *G.* Dying out of a joint in a series of *en echelon* fractures.

termination. In a given joint set, individual joint traces or joint zones (see Figure 3.3C) range in length from a few centimeters to many meters—and even up to kilometers in the case of master joints. Fractures also exist at a scale down to the microscopic level; such fractures are better referred to as microfractures than as joints.

The shape of individual joints depends largely on the rock type and on its structure. In uniform rock, such as granite, argillite, or thin-bedded rocks of uniform composition, individual joint planes tend to be roughly circular to elliptical in shape, with the long axis horizontal. In sedimentary sequences involving rocks of highly different mechanical properties, such as interbedded sandstone and shale, one dimension of a joint is commonly constrained by the upper and lower contacts of the bed in which the joint forms, and the joint tends to be of much greater extent parallel to bedding than across it. Joints in individual beds of one lithology often end against beds of another lithology (Figure 3.2B).

The shape of master joints is not well known because of the difficulty of seeing the third dimension. In areas of great vertical relief, however, joints can be traced to a depth of more than 1 km.

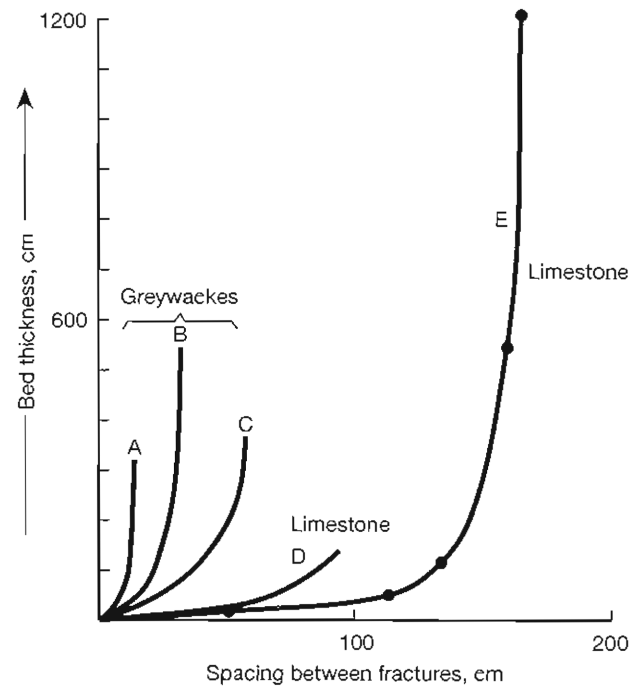


Figure 3.11 Relationship between bed thickness and fracture spacing measured in sandy layers in wackes (data sets A, B, and C) and in limestones (data sets D and E). For data set A, the shale interlayers are less than 5 cm thick, and for B and C they are greater than 5 cm thick.

Spacing of Fractures

The spacing of fractures in a systematic set can be measured in terms of either the average perpendicular distance between fractures or the average number of fractures found in a convenient standard distance normal to the fractures. The average spacing of joints tends to be remarkably consistent, and it depends in part on the rock type and on the thickness of the bed in which the fractures are developed (Figure 3.11). Data sets A through C are measurements made in the sandy layers of a sequence of wackes from several locations with different thicknesses of shale interbeds. Data sets D and E are from different limestones. Two features of the plot are significant. First, the spacing between adjacent joints increases with increasing bed thickness up to a maximum value independent of the thickness. Second, the maximum spacing is considerably greater for the limestones than for the wackes, which demonstrates the effect of lithology independent of the thickness of the beds.

Spatial Pattern and Distribution of Fracture Systems

The most useful method of studying the pattern and distribution of fracture sets is to plot maps of the location and orientation of the fractures. In areas of very good exposure, it may be possible to map joints individually and to trace out the relationship of joints to one another and to lithology. On such maps, we can plot the strikes and dips of the fractures, their relationship to other local structures, and the amount and direction of shear (if any) on the fractures.

In most cases, there is neither enough exposed rock nor enough time available to permit such detailed mapping. Usually data from outcrops scattered over a large area are plotted on a map. From these data one constructs form lines, or trajectories, of the individual joint sets by projecting the strikes of joints in the same set between data points. Figure 3.12 shows such a map for an area on the Appalachian plateau. The consistency of orientation of joints over such large areas indicates that they record regional tectonic conditions.

3.3 Features of Fracture Surfaces

The features on the surfaces of a fracture can provide information critical to interpretation of the fracture's origin. Many joints display a regular pattern of subtle ridges and grooves called hackle that diverges from a point or a central axis. The pattern is known as plumose

Figure 3.12 Map of joints in the Appalachian Plateau in New York state. The lines are consrructed parallel to the dominant strike of joints measured in local outcrops throughout the area.

structure or as a **hackle** plume (Figure 3.13), named for its resemblance to the shape of a feather. Plumose structure is present on joints in a variety of rock types, but it is most clearly displayed in rocks of uniform fine-grained texture, when the surface is illuminated at low angles. Figure 3.13 shows plumose structure developed in two rock types.

The characteristic features of a hackle plume are illustrated in Figure 3.14*A*. The main joint face displays the hackle plume with hackle lines that diverge from an axis. Toward the edges of the main joint face, the joint plane may segment into a series of planes that are slightly twisted from the main joint face. The twisting may inctease gradually away from the axis (lower half

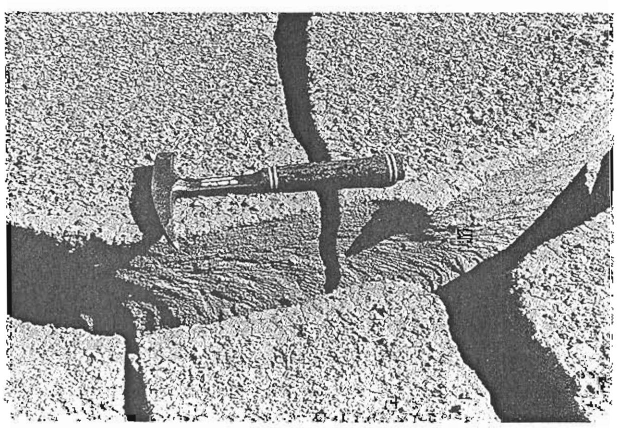


Figure 3.13 Plumose structure, or hackle plumes, in *A* mudstone, and *B* chalk.

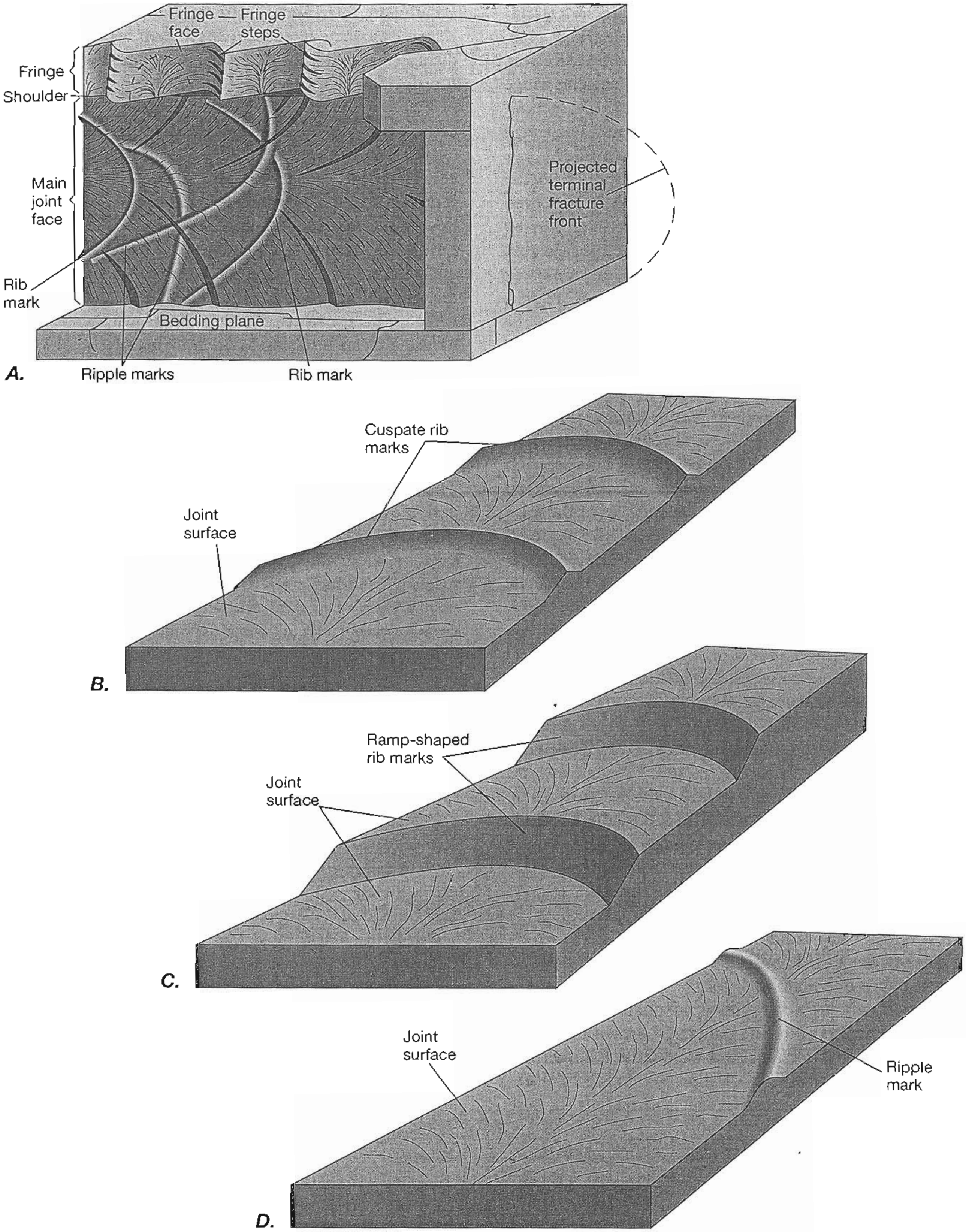


Figure 3.14 Schematic block diagrams illustrating surface markings on joint faces. *A*. Features that characteristically appear on the surface of a systematic joint. *B*. Cuspate rib marks. *C*. Ramp-shaped rib marks. *D*. Ripple marks.

of Figure 3.14*A*), or it may develop abruptly at a shoulder (top of Figure 3.14*A*) to form a hackle fringe composed of an *en echelon* set of extension fractures, or fringe faces, connected to one another by cnrving fringe steps. The fringe faces themselves may show second-order hackle plumes with associated fringes. The fringe is aligned along the trend of the main joinr face.

Fringe faces at the edge of a joint should not be confused with pinnate fractures and gash fractures, even though they are all extension fractures that form *en echelon* arrays. Fringe faces usually make a considerably smaller angle with the main joint face than pinnate or gash fractures make with the shear surface. Moreover, in three dimensions, fringe faces are restricted to the edge of a joint surface, which commonly displays plumose structure, whereas pinnate and gash fractures oceur along the entire shear fracture.

In some cases, curvilinear features called rib marks and ripple marks cross the lines of hackle on the fracture face. The rib marks either are euspate in cross section (Figure 3.14*B*) or are composed of smoothly curved ramps connecting adjacent parallel surfaces of the joint face (Figure 3.14*C*; see also Figure 3.13*D*). They tend to be perpendicular to the hackle lines. The ripple matks are rounded in cross section and oblique to the hackle lines (Figure 3.14*D*). Hackle plumes form a variety of different patterns (compare Figure 3.13), which can characterize particular sets of joints and which reflect important differences in the fracturing process.

Plumose structure is a unique feature of brittle extension fractures that distinguishes them from shear fractures. The direction of divergence of the hackle lines is the direction in which the fracture propagated, and the lines of hackle form normal to the fracture front. When traced back along the plume axis, the hackle is usually found to radiate from a single point, which is the point of origin of the fraeture. Rib matks are interpreted to be arrest lines where fracture propagation halted temporarily. Ripple marks are interpreted to form during very rapid fracture propagation, in which case they are called Walner lines. By careful study of the surfaces of joints, therefore, we can learn a great deal about where fractures initiated and how they propagated. (The use of hackle plumes is treated in greater detail in the next section. And we discuss the interpretation of joints further in Chapter 9 after we have examined the mechanics and mechanisms of fracture formation.)

In some cases a fracture displays slickenside lineations on its surface, indicaring that shear has occurred on the fracture (see Sections 13.7, 13.8, and 14.6). Slickenside lineations may be defined by parallel sets of ridges and grooves, by light and dark streaks of fine-grained pulverized rock, or by linear mineral fibers (see Figures 13.25, 13.26). Because extension fractures commonly accumulate small amounts of shear displacement during tectonic movements subsequent to their formation, such displacements do not necessarily indicate that the fracture formed by shearing.

Joints and other fractures may have a thin deposit of mineral—such as quartz, feldspar, calcite, zeolites, chlorite, and epidote—along their surfaces. These mineral layers indicate either that the fracture was open or that fluids under pressure were able to force it open, flow along the fracture, and deposit minerals from solution. In some cases, a fracture is clearly associated with a zone of alteration in the surrounding rock, indicating diffusion of material into or out of the rock surrounding the fracture. Some joints have been affected by dissolution resulting in open fissures.

3.4 Timing of Fracture Formation

The interpretation of fracture sets relies on determination of the timing of their formation relative to other fracture sets and strnctures. Although these relationships are often ambiguous, especially for extension fractures, we can make a few generalizations.

Where more than one set of joints is developed, younger joints terminate against older joints because an extension fracture cannot propagate across a free surface such as another extension fracture. In Figure 3.3*B*, for example, the nonsystematic joints are clearly younger than the systematic ones. Many such terminations are at a high angle, forming T-shaped intersections, and the younger extension fracture may curve toward a high-angle intersection where it approaches an older fracture (Figure 3.10*E*). Low-angle intersections also occur in some joint systems (Figure 3.10*F*).

In many cases, however, joints form a mutually cross-cutting system, so the relative ages of the joints are ambiguous. This relationship can arise in several ways. If the first-formed joint is cemented by mineral deposits, it no longer acts as a free surface, and a later joint can cut across the older one. Subsequenr dissolution of the mineral deposit leaves an ambiguous cross-cutting relationship. An early shallow joint in a layer may be cut by a later deeper joint that propagates up to one side of the older joint, continues underneath it, and propagates back to the opposite side, leaving a joint intersection for which the interpretation of relative time of formation is ambiguous (Figure 3.15*A*). The relative age can be decifered only if the hackle on the younger joint can be examined to determine the propagation direction of the fracture front. Two joints of the same orientation may also initiate from the same place on opposite sides of an older fracture (Figure 3.15*B*). Those two joints appear as a continuous joint, leaving am-

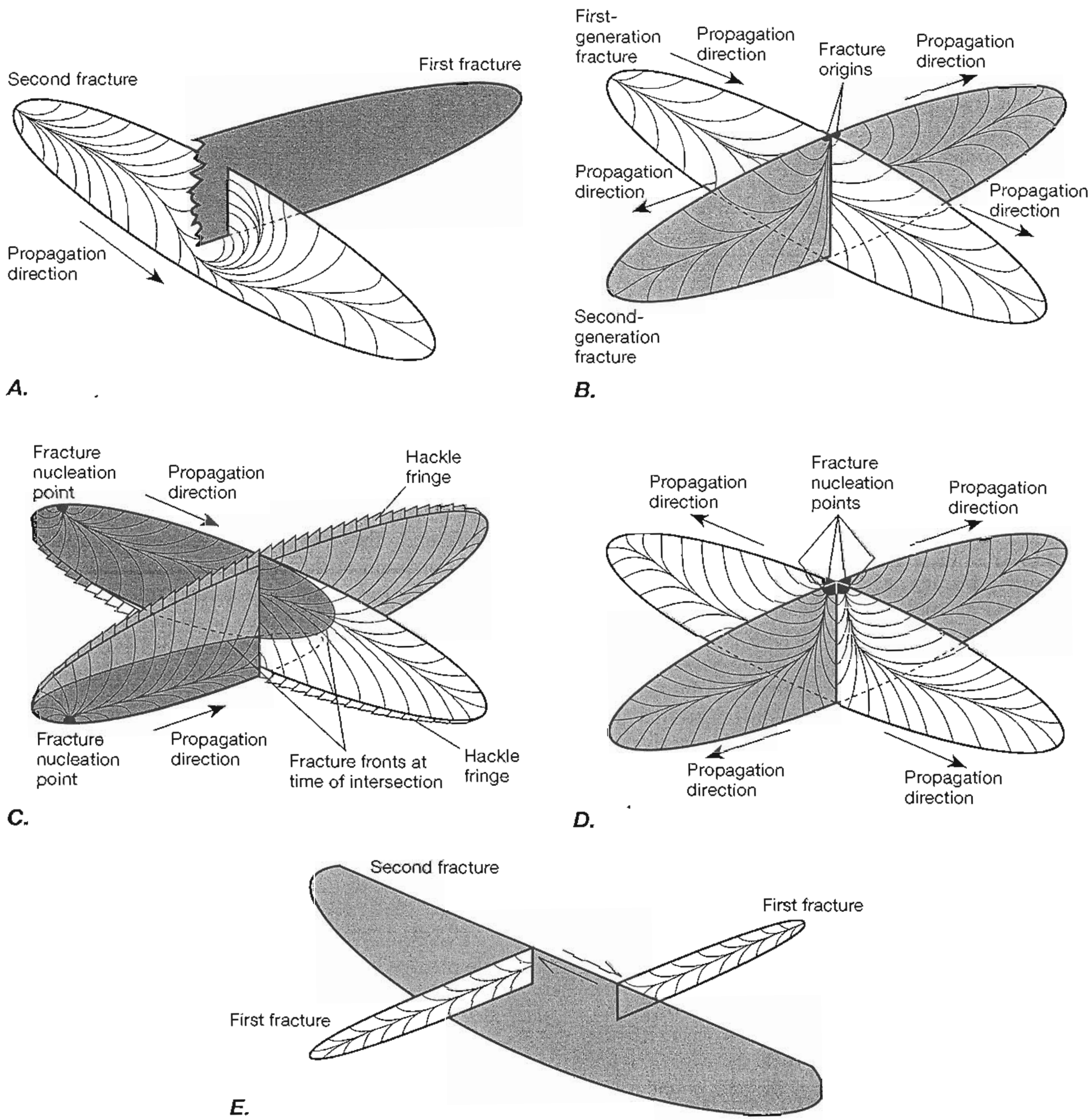


Figure 3.15 Origin of fracture intersections. Solid arrows indicate the general direction of fracture propagation. *A.* An early shallow fracture (dotted pattern) cut by a later deeper fracture. The intersection relationship would be ambiguous were it not for the distinctive hackle pattern. *B.* Two coplanar fractures originate at adjacent points on opposite sides of an earlier fracture to produce an ambiguous intersection. The hackle patterns resolve the ambiguity at the intersection and make the origins of the fractures clear. *C.* Two intersecting fractures that originated in different orientations at the top and bottom of the layer. The shaded portions of the fracture surfaces and the fracture fronts (heavy lines) indicate the geometry of the propagating fractures at the time the two fracture fronts intersected. Hackle patterns indicate that the top of fracture A and the bottom of fracture B were the earliest to form at the intersection. *D.* Three fractures, two of them coplanar, originate at the same point producing an intersection indistinguishable, from the one shown in part *B*, except for the telltale hackle pattern. *E.* Shear offset of an early fracture on a later shear fracture produces an apparent termination of the older fracture against the younger.

biguous the interpretation of the intersection with the earlier fracture.

Two joint sets could, in principle, also form during the same fracturing event. Joints could originate in one orientation at the top of a layer and propagate down, and in another orientation at the bottom of a layer and propagate up (Figure 3.15*C*). Their intersection would then show inconsistent relative-age relationships, because at different points along the intersection, the hackle lines would indicate that different joints had formed earliest. A similar fracture geometry would be created if the three joints formed at the same time and place (Figure 3.15*D*). It is possible to distinguish the histories illustrated in Figure 3.15*B* and *D* only by examining the hackle plume geometry on the joint surfaces. Inconsistent relationships can also result when shear displacement occurs on a later fracture. The offset first fracture can then appear to be a younger fracture terminating against the second fracture (Figure 3.15*E*). For all the cases illustrated in Figure 3.15, the hackle plume geometry is of critical importance in interpreting the fracturing history of joints.

Several structures indicate that extension fractures can form in sediments before they have consolidated into rock. When such fractures form before the deposition of overlying sediments, the open fractures may be filled by the sediment subsequently deposited on top. Mudcracks are one obvious example. If a steeply dipping fracture forms in uncompacted sediments and becomes mineralized before compaction is complete, the mineralized fracture may form a series of folds to accommodate the shortening associated with the subsequent compaction of the sediment. Extension fracturing of unconsolidated sediment in the presence of high pore-fluid pressure can result in the formation of clastic dikes. The opening of the fracture creates a low-pressure area into which pore fluid rushes, carrying unconsolidated material of contrasting lithology. The existence of such structures proves that some joints, at least, can form very early in the history of a rock.

Fractures that cross-cut a geologic boundary or a geologic structure clearly postdate the formation of that boundary or structure. For example, a joint set that cuts across an intrusive contact is younger than the intrusive event, and joints that maintain a constant orientation across folded layers must have formed after the folding. Fractures that are clearly affected by a geologic structure are older than that structure. A joint set that changes orientation over a fold but everywhere maintains the same angular relationship with the bedding could either predate or be synchronous with the folding, but it is not likely to be younger.

If one set of joints is consistently mineralized or has igneous rocks injected along the fractures, then it must be older than the mineralizing or intrusive event. If a second set of joints in the same rocks is free of the mineralization or intrusion, then it probably formed after the mineralizing or intrusive event.

Applying criteria such as these has shown clearly that joints can form at any time in the history of a rock—from the earliest time, when it is still unconsolidated sediment to the latest time when the joints postdate all other structures in the rock. It is likely, therefore, that more than one mechanism produces joints. We discuss possible mechanisms in Chapter 10.

3.5 Relationship of Fractures to Other Structures

Fractures Associated with Faults

Fractures often form as subsidiary features spatially related to other structures. If such a relationship can be documented, the fractures can provide information about the origin of the associated structure.

In some cases, faults are accompanied by two sets of small-scale shear fractures at an angle of approximately 60° to each other with opposite senses of shear. These are called conjugate shear fractures. Figure 3.16 shows data for a system of conjugate fractures that developed in an area closely associated with a known fault. The rose diagram shown in Figure 3.16*B* is plotted in the vertical plane normal to the strike of the fault, and the distribution of fracture dips is plotted below the horizontal line. The orientation of the fault is also indicated on the figure. The major set of fractures is clearly parallel to the fault; the second and less well-developed set is approximately 65° from the first set.

Extension fractures associated with faulting include pinnate fractures and gash fractures, which were described in Section 3.1 (Figures 3.8 and 3.9).

Fractures Associated with Folds

Fractures often develop in rocks in association with folding. A variety of orientations, related symmetrically to the fold, have been reported. It is convenient to refer the orientations to an orthogonal system of coordinates (a, b, c) related to the fold geometry and the bedding. The b axis is parallel to the fold axis, which in most cases is a line lying in the bedding plane that has the same orientation regardless of the attitude of the folded surface (Figure 3.17). The a axis lies in the bedding plane perpendicular to the fold axis, and the c axis is everywhere perpendicular to the bedding.

Figure 3.17 is a diagrammatic illustration of the orientations of fractures that have been reported from folds. Fractures parallel to the plane of the a and c axes

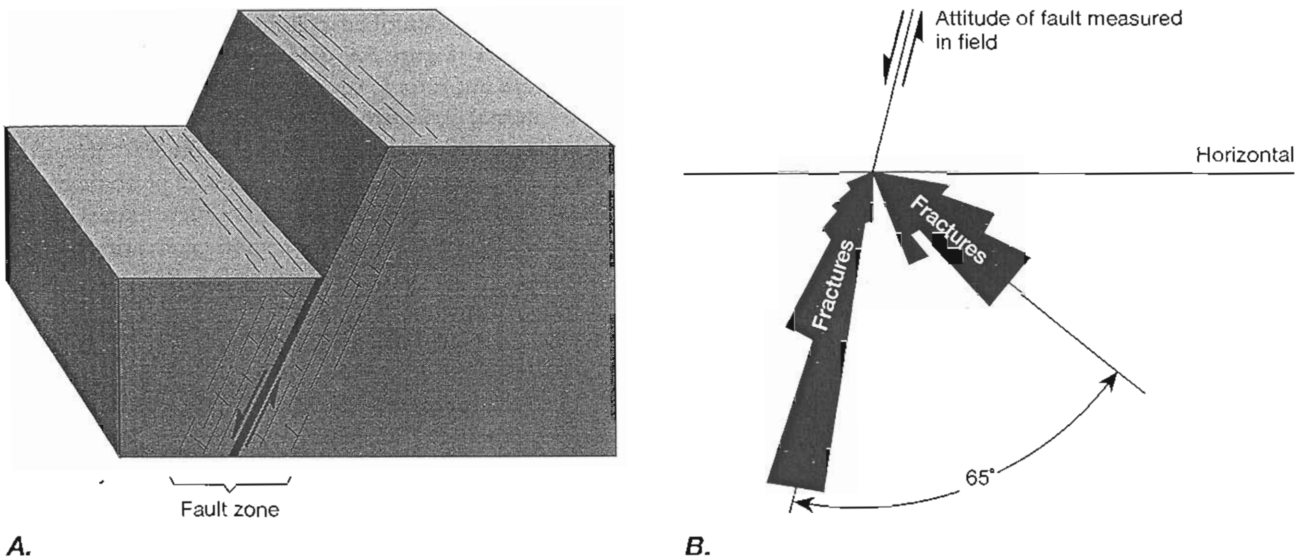


Figure 3.16 Shear fractures associated with faulting. *A*. Normal fault with dominant parallel shear fractures (long lines) and subordinate conjugate shear fractures (short lines). *B*. Rose diagram plotted in the vertical plane, showing the distribution of dips of two sets of fracrures associated with a normal fault.

and to the plane of the b and c axes are called ac fractures and bc fractures, respectively. The fractures shown in sets *A*, *B*, and *D* are all perpendicular to the bedding. In sets *A* and *B*, the ac fractures and the bc fractures, respectively, bisect the acute angle between the two other fracture sets, which are oblique fractures. In set *D*, the bc fractures bisect the obtuse angle between the oblique fractures. The inclined fractures in sets C and *E* are parallel to the fold axis b. Those in set C make a low angle with bedding, and those in set *E* make a high angle with bedding.

Fractures in sets *A* and *D* are particularly common on fold limbs. Sets *B* and *E* tend to be associated with the convex sides of a fold where the curvature is strong-

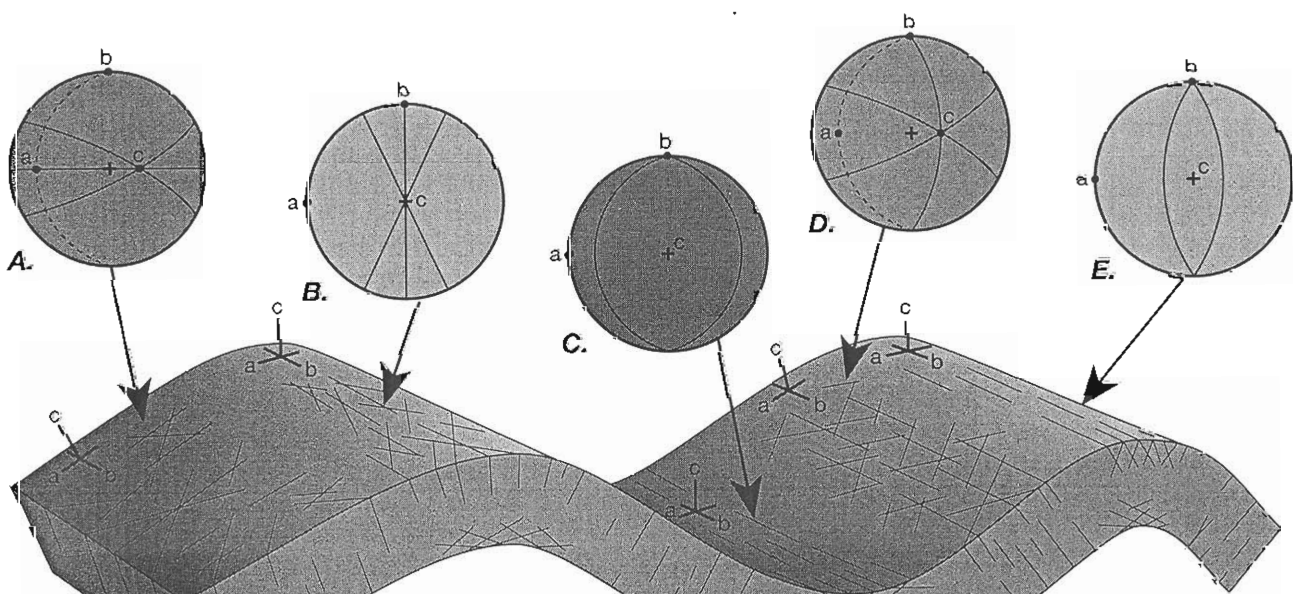


Figure 3.17 Fracrures associated wirh folds. The stereographic projections show the orieurations of the coordiuare system, the bedding where it is nor horizoutal (dotted great circles), and the fractures (solid great circles).

est. And set C occurs on the strongly curved concave sides of folds.

It is possible that the fractnres of all these orientations formed in association with folding, that the ac and bc fractures are extension fractures, and that the oblique and inclined fractures are shear fracrures. Thar interpretarion is not justified, however, simply on the basis of fracture pattern and orientation. Such fractures have been shown to predate the folding in some cases, and to postdate it in others, and as we have remarked before, the presence of shear displacement on a fracture does not necessarily mean that the fracture originated as a shear fracture. In order to make a well-documented interpretation of complex fracture systems, it is critical ro describe all the characreristics of the various fracture sets that we have discussed. This includes citing specific evidence for extensional or shear displacement and fracturing, the spatial distribution of fractures, and evidence suggesring the relarive sequence of formation of the fractures in different scts.

Fractures Associated with Igneous Intrusions

Fractures form an association with igncous intrusions, and some types occur *only* within the igneous rock. We have already described columnar jointing in sills and thick flows (Figure 3.6) and sheet joints or exfoliation structure in plutonic rocks (Figure 3.5). In many cases, the internal structure of plutonic rocks is telated in a simple manner to the orientations of other fractures that develop. Especially near the margins of plutonic bodies, platy minerals such as mica and tabular mineral grains may be aligned parallel to one another, creating a planar structure in the rock called a **foliation.** Elongate mineral grains also may be aligned parallel to one another within the foliation, creating a linear structure called a **lineation** (see Chapter 13).

We can describe the orientations of fractures with respect to these structures by using coordinate axes (a, b, c) where a is parallel to the lineation, b lies in the foliation perpendicular to a, and c is perpendicular to the foliation. Joints commonly form parallel to c and thus perpendicular to the foliation. If they are also parallel to the lineation, thcy are referred to as ac joints; if perpendicular to the lineation, they are called cross joints or bc joints. Diagonal joints also occur, usually at an angle of about 45° to the lineation and normal to the foliation. Cross joints (bc) typically contain pegmatitc dikes or hydrothermal deposits.

Additional Readings

Bahat, D., and T. Engelder. 1984. Surface morphology on cross-fold joinrs of the Appalachian plateau, New York and Pennsylvania. *Tectonophysics* 104: 299–313.

Beach, A. 1975. The geometry of en-echelon vein arrays. *Tectonophysics* 28: 245–263.

Engelder, T., and P. Geiser. 1980. On rhe use of regional joint sets as trajectories of paleostress fields during rhe development of the Appalaehian Plateau, New York. *Journal of Geophysical Research* 85: 6319–6341.

Kulander, B. R., and S. L. Dean. 1985. Hackle plume geometry and joint propagation dynamics. In *Proceedings of the International Symposium on Fundamentals of Rock Joints, Björkliden, 15–20 Sept. 1985,* ed. Ove Stephansson. Luleå, Sweden: Swedish Natural Scieuce Research Council; Centek Publishers.

Kulander, B. R., C. C. Barton, and S. L. Dean. 1979. The application of fracrography ro core and outcrop fracture investigations. U.S. Dept. of Energy, METC/SP-79/3; National Technical Information Service, U.S. Dept. of Commerce, Springfield, Va., 22161.

Ladeira, F. L., and Price, N. J. 1981. Relatioușhip between fracture spacing and bed thickness. *J. Struct. Geol.* 3: 179–183.

Price, N. J. 1966. *Fault and joint development in brittle and semibrittle rock.* New York: Pergamon Press.