Planar breaks in rock are one of the most spectacular, fascinating, and important features in structural geology. Joints control the course of river systems, the extrusion of lava flows and fire fountains, and modulate groundwater flow. Joints and faults are associated with bending of rock strata to form spectacular folds as seen in orogenic belts from British Columbia to Iran, as well as seismogenic deformation of continental and oceanic lithospheres. Anticracks akin to stylolites accommodate significant volumetric strain in the fluid-saturated crust. Deformation bands are pervasive in soft sediments and in porous rocks such as sandstones and carbonates, providing nuclei for fault formation on the continents. Faults also form the boundaries of the large tectonic plates that produce earthquakes—and related phenomena such as mudslides in densely populated regions such as San Francisco, California—in response to tectonic forces and heat transport deep within the Earth. Faults, joints, and deformation bands have been recognized on other planets, satellites, and/or asteroids within our Solar System, attesting to their continuing intrigue and importance to planetary structural geology and tectonics.

Fractures such as joints and faults have long been recognized and described by geologists and engineers as expressions of brittle deformation of rocks (e.g., Price, 1966; Priest and Hudson, 1976; Gudmundsson, 2011; Peacock et al., 2018). They are important geologic structural discontinuities as they reveal types and phases of deformation, and they can be used to constrain paleostrain and paleostress magnitudes. Furthermore, they affect fluid flow in petroleum and groundwater reservoirs in a variety of ways, ranging from highly permeable fracture zones in limestones or crystalline rocks to sealing fault structures in hydrocarbon reservoirs. As a result, they have important practical implications in such fields as structural geology, geo-engineering, landscape geomorphology, hydrogeology, and petroleum geology (e.g., Cook et al., 2007).
On the other hand, deformation bands, identified as thin, tabular zones of cataclasis, pore collapse, and/or grain crushing (e.g., Engelder, 1974; Aydin, 1978), now encompass five kinematic varieties, from opening through shearing to closing senses of displacement that may or may not involve cataclasis (e.g., Aydin et al., 2006). Both classes of discontinuity—fractures and deformation bands—share common attributes, such as approximately planar or gently curved geometries, small displacements relative to their horizontal lengths, echelon or linked geometries, displacement transfer between adjacent segments, variable effect on fluid flow, and systematic variation in displacement magnitude accommodated along them (see Fossen et al., 2007, 2017, for a review and discussion of these attributes for deformation bands). Building on these commonalities, a consistent terminology that encompasses all the variations noted above is available (for example, see Aydin et al., 2006; Schultz and Fossen, 2008) and utilized here.

In this chapter, we review the main types of structural discontinuities in rock. Aspects of rock mechanics and lithology that influence the type of structural discontinuity that can form will be reviewed. The related concept of modes of displacement that has proven so useful in studies of joints, faults, and other types of geologic discontinuities will then be outlined in the context of this framework. Subsequent chapters will explore the development, expression, patterns, and geological significance of these fascinating elements of rock deformation.

1.2 What Is a Structural Discontinuity?

In rock engineering, a discontinuity is a general term meant to include a wide range of mechanical defects, flaws, or planes of weakness, in a rock mass without regard to consideration of their origins (e.g., Fookes and Parrish, 1969; Attewell and Woodman, 1971; Goodman, 1976, 1989; Priest and Hudson, 1976; International Society for Rock Mechanics, 1978; Bieniawski, 1989; Fig. 1.1). This term includes bedding planes, cracks, faults, schistosity, and other planar surfaces that are characterized by small shear strength, small tensile strength, reduced stiffness, strain softening, and large fluid conductivity relative to the surrounding rock mass (Bell, 1993, p. 37; Brady and Brown, 1993, pp. 52–53; Priest, 1993, p. 1; Hudson and Harrison, 1997, p. 20). By implication, cataclastic deformation bands and solidified igneous dikes or veins in sedimentary host rock, for example, that are stronger and/or stiffer than their surroundings might not be considered as a discontinuity by a rock engineer.

Pollard and Segall (1987) defined a discontinuity as “two opposing surfaces that are bounded in extent, approximately planar compared to the longest dimension, and having a displacement of originally adjacent points on the opposing walls that is both discontinuous and small relative to the longest dimension.” According to this definition, cracks, faults,
1.2 What Is a Structural Discontinuity?

veins, igneous dikes, stylolites, pressure solution surfaces, and anticracks would be considered as discontinuities. The term “structural discontinuity” encompasses a wide range of localized geologic structures, over a broad range of scales, strain rates, rock types, formation mechanisms, and tectonic environments.

The most common types of geologic structural discontinuities are listed in Table 1.1. An explanation of the genesis and context of these terms can be found in Schultz and Fossen (2008), with deeper exploration of their utility and significance contained in subsequent chapters.

**Structural discontinuities are defined by a pair of surfaces**, or fracture walls, that have been displaced (by opening or by shearing) from their original positions. For example, a crack or joint is open between its two walls (Fig. 1.2); these walls join smoothly at a crack or joint tip, defining the maximum horizontal or vertical extent of this structure in the rock. Similarly, a fault (Figs. 1.3–1.4) must be considered to be a pair of planes that are in frictional contact; a single fault plane begs the question of what was sliding against it. These paired fault walls or planes may be separated by gouge or other deformed material, and like cracks, join at a tip (Fig. 1.3) where the displacement magnitude decreases to zero. In the case of deformation bands (Fig. 1.5), the walls can be identified by a comparatively rapid change in displacement gradient or porosity, although they can be more indistinct than the clean sharp breaks typical of joints and fault planes (e.g., Aydin, 1978).
Table 1.1 Geologic structural discontinuities

<table>
<thead>
<tr>
<th>Discontinuity</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural discontinuity</td>
<td>A localized curvilinear change in strength or stiffness caused by deformation of a rock that is characterized by two opposing surfaces that are bounded in extent, approximately planar compared to the longest dimension, and having a displacement of originally adjacent points on the opposing walls that is small relative to the longest dimension</td>
</tr>
<tr>
<td>Sharp discontinuity</td>
<td>A structural discontinuity having a discontinuous change in displacement, strength, or stiffness that occurs between a pair of discrete planar surfaces</td>
</tr>
<tr>
<td>Tabular discontinuity</td>
<td>A structural discontinuity having a continuous change in displacement, strength, or stiffness that occurs across a relatively thin band</td>
</tr>
<tr>
<td>Fracture</td>
<td>A sharp structural discontinuity having a local reduction in strength and/or stiffness and an associated increase in fluid conductivity between the opposing pair of surfaces</td>
</tr>
<tr>
<td>Joint</td>
<td>A sharp structural discontinuity having field evidence for discontinuous and predominantly opening displacements between the opposing walls</td>
</tr>
<tr>
<td>Anticrack</td>
<td>A sharp or tabular structural discontinuity having field evidence for predominantly closing displacements between the opposing walls</td>
</tr>
<tr>
<td>Deformation band</td>
<td>A tabular structural discontinuity having a continuous change in displacement, strength, or stiffness across a relatively narrow zone in porous rocks</td>
</tr>
<tr>
<td>Fault</td>
<td>A sharp structural discontinuity defined by slip planes (surfaces of discontinuous displacement) and related structures including fault core and damage zones that formed at any stage in the evolution of the structure</td>
</tr>
<tr>
<td>Fault zone</td>
<td>A set of relatively closely spaced faults having similar strikes</td>
</tr>
<tr>
<td>Shear zone</td>
<td>A tabular structural discontinuity having a continuous change in strength or stiffness across a relatively narrow zone of shearing; shear and volumetric strains are continuous across the zone, and large or continuous (linked) slip surfaces are rare or absent</td>
</tr>
<tr>
<td>Damage zone</td>
<td>A zone of increased deformation density that is located around a discontinuity that formed at any stage in the evolution of the structure</td>
</tr>
</tbody>
</table>

A brittle fracture implies creation of these surfaces under conditions of relatively small strain and with a decreasing resistance to continued deformation (i.e., a strain-softening response in the post-peak part of the stress–strain curve for the rock; Jaeger, 1969; see also Hudson and Harrison, 1997; Chapter 8). Brittle deformation additionally implies localization of strain into one or more discrete planar elements, whereas ductile deformation implies nonlocalized, spatially distributed deformation (e.g., Pollard and Fletcher, 2005, p. 334). The term “fracture” thus implies a local reduction in strength and/or stiffness and an associated increase in fluid conductivity between the pair of surfaces.
1.2 What Is a Structural Discontinuity?

Cracks, joints, and faults are, as a consequence, various types of brittle fractures. A solidified igneous dike that cuts a weaker and/or less stiff sedimentary sequence, however, would not be considered to be a fracture according to this definition, although the contact between the igneous rock and the country rock may qualify if it is weaker, or less stiff, than the igneous or country rock.

Fractures are seen to be a pair of surfaces that separate their displaced surroundings from what is between them (e.g., Johnson, 1995). Joints in the subsurface are filled by a variety of liquids including groundwater (e.g., Engelder, 1985; National Academy of Sciences, 1996), natural gas (Lacazette and Engelder, 1992), and petroleum (Dholakia et al., 1998; Engelder et al., 2009). Joints filled by solidified hydrothermal, diagenetic, or magmatic minerals are called veins and igneous dikes (Figs. 1.6 and 1.7), respectively. Rubin (1995b) calls igneous dikes “magma-filled cracks” to emphasize the mechanical basis for dike dilation and propagation. In all of these examples, it becomes important to determine whether the filling material was there...
Introduction to Geologic Structural Discontinuities

Fig. 1.3. Normal faults exposed on this dip slope of Upper Cretaceous carbonate rock (Garumnian Formation, Collado de Fumanyá) from the Spanish Pyrenees demonstrate a consistent spacing and clear fault terminations. The shadowed indentations are dinosaur footprints that predate the faults.

Fig. 1.4. A prominent normal fault cuts through a precursory zone of deformation bands in this view of "Aydin’s Wall" that formed in Entrada Sandstone east of the San Rafael Swell in eastern Utah. The bright sunlit high-angle planes are large slip surfaces whose corrugations are inherited from the architecture of the deformation band network. A second normal fault at the upper right defines this area as a fault zone having two major subparallel strands.
1.2 What Is a Structural Discontinuity?

Fig. 1.5. Deformation bands are an important deformation mechanism in porous rocks such as sandstone, and they define intricate and informative arrays as in this fine example in Navajo Sandstone from southern Utah. The sub-horizontal bedding can be seen to be cut by two oppositely dipping sets of shear-enhanced compaction bands and a sub-vertical set of pure compaction bands. Stratigraphic restriction of these band sets can be observed.

Fig. 1.6. A pair of echelon igneous dikes is shown in granitic rock of the central Sierra Nevada near Donner Lake, California. Each dike segment beyond the overlap region, where the dikes are linked, exhibits a separation of host rock by ~10 cm, with the intervening void within the dike being filled by a sequence of hydrothermal (light-toned) and igneous (dark-toned) fluids that have since crystallized, preserving the extensional strain in the pluton. The later crack in the left-hand part of the image (that cuts the dike) also demonstrates that a fracture must be defined by a pair of subparallel walls or surfaces, rather than a single plane.

Initially, inside the joint, as it dilated and propagated, or whether the filling material came afterwards and simply occupied the volume within the joint (e.g., Laubach et al., 2010).

Fault walls may be separated by gouge (e.g., Chambon et al., 2006); those of a stylolite, by insoluble residue such as clays (e.g., Fletcher and Pollard, 1981; Engelder and Marshak, 1985; Pollard and Fletcher, 2005, p. 17); shear
zones contain a variety of interesting rocks and fabrics (e.g., Fossen and Cavalcante, 2017). Deformation bands typically have either increased or decreased porosity within them (e.g., Aydin et al., 2006); grain-size reduction may also characterize the interior of a deformation band (e.g., Aydin, 1978; Davis, 1999; Fossen et al., 2007). As a result, cracks, joints, faults, stylolites, and deformation bands all contain various materials between their walls that can differ significantly from the host rock that surrounds them.

The term “discontinuity” has two distinct meanings when applied to localized structures. First, joining of the paired crack or fault walls at the fracture tips defines the dimensions of the fracture, such as its length, width, or height. Fractures that have discrete lengths are called discontinuous (e.g., Pollard and Segall, 1987) and this is the basis for the field of engineering fracture mechanics (because discontinuous fractures end at the fracture tips). The second, and more recent, use of “discontinuity” refers to the rate of change of displacement across the structure (e.g., Johnson, 1995; Borja, 2002). Fractures having a discrete step-wise change in displacement across them, such as cracks and faults (or slip surfaces), are said to have, or be, a displacement discontinuity. In contrast, shear zones and deformation bands may exhibit a continuous displacement across them. The boundary element modeling approach developed by Crouch and Starfield (1983, pp. 208–210) and used by many researchers in geologic fracture mechanics clearly illustrates how these (strong and weak) discontinuities can both be easily represented in a fracture model by specifying the properties of the filling material along with the strengths of the enclosing walls. This computational approach parallels the geologic work summarized in this section that motivates the integration of terminology espoused in this book.

The scale of the structure relative to its surroundings is also important to consider. For example, the rock cut by a structure is commonly taken as an

Fig. 1.7. The detailed shape of the dike tip is clearly revealed by this view of the stepover between a pair of closely spaced igneous dikes. The dike segment width, normal to its trace, is ~10 cm (camera lens cap for scale). Dike shapes such as these can be predicted very well by representing the dikes as dilatant cracks propagating through a continuous elastic medium.
1.2 What Is a Structural Discontinuity?

“effective continuum” (e.g., Pollard and Segall, 1987, and references therein). A geologic unit is considered to be continuous when its properties at the scale of the structure are statistically constant, leading to homogeneous values and behavior (Priest and Hudson, 1981). Rock units with spatially variable properties, such as joint sets, at a given scale are called discontinuous. In mechanics, a continuous material is said to be simply-connected, whereas a discontinuous one is multiply-connected (e.g., Nehari, 1952).

An outcrop of columnar-jointed basaltic lava flows (e.g., Fig. 1.8) provides an informative example of relative scale (Schultz, 1996). For a scale of observation of millimeters to centimeters, the rock within a column is intact basaltic rock, and it can be idealized by those properties. At significantly smaller scales, grain size and microcracks become important enough that the assumption of a continuous material may not apply. For a scale of a few meters, however, the rock unit can be described as intact basalt partly separated into irregular blocks by numerous discontinuous fractures (i.e., the columnar joints). Because this scale of observation is comparable to the scale of the fracturing (or equivalently, the block size), the flow must be considered as a discontinuum within which the properties of the rock and fractures both must be considered to understand and represent the behavior of the flow, as in the example shown in Fig. 1.8. An approach called block theory (Goodman and Shi, 1985; Priest, 1993, pp. 246–250) would be the method of choice here. At dimensions for which the scale of observation greatly exceeds (e.g., by a factor of 5–10) the block size or fracture spacing, such as would be found on an aerial or satellite image, the lava flow can be described as an effective continuum (Priest, 1993) and a rock mass (see also Bieniawski, 1989; Schultz, 1993, 1995a,b, 1996; Fig. 1.1). Various methods for “upscaleing” rock

Fig. 1.8. View of columnar joints in basalt near Donner Lake, California, looking down the column axes; rock hammer for scale.
properties from laboratory-scale measurements to outcrop or larger scales are routinely used in the oil and gas industry, including geostatistics and geomodels (e.g., Christie, 1996; Rogers et al., 2016).

To summarize, a 10-cm core of the basaltic rock within a basalt column, and a 10-m outcrop of jointed basalt, are both effectively continuous at their respective scales, although the values for strength, deformability, and hydrologic properties will differ in detail for each scale. The lava flow is discontinuous at scales of observation comparable to the grain or block size. Rock engineers have coined the acronyms CHILE (continuous, homogeneous, isotropic, linearly elastic) and DIANE (discontinuous, inhomogeneous, anisotropic, non-elastic) to describe the characteristics of rock units at the particular scale of interest (see Hudson and Harrison, 1997, pp. 164–165). Continuum methods such as fracture mechanics work well with CHILE materials, but processes at the block or grain scale, such as grain reorganization and force chain stability (e.g., Cates et al., 1998; Mandl, 2000, pp. 100–101; Mair et al., 2002; Peters et al., 2005) within a deformation band, for example, require methods such as distinct element or particle flow codes instead to explicitly represent these DIANE materials (e.g., Antonellini and Pollard, 1995; Morgan and Boettcher, 1999). In this book we adopt terminology and analysis techniques for structures consistent with CHILE behavior of their surroundings, while recognizing that the total geologic system of rocks and structural discontinuities functions more like a DIANE system.

To summarize the preceding discussion and paralleling Pollard and Segall (1987):

- A structural discontinuity is a localized curviplanar change in strength or stiffness caused by deformation of a rock that is characterized by two opposing surfaces that are bounded in extent, approximately planar compared to the longest dimension, and having a displacement of originally adjacent points on the opposing walls that is small relative to the longest dimension.

Quantification of “small” displacements of rock on either side of a structural discontinuity can be done by means of a displacement–length diagram (Fig. 1.9), which is a standard tool in geologic fracture mechanics and structural geology (e.g., Cowie and Scholz, 1992a; Dawers et al., 1993; Clark and Cox, 1996; Schlische et al., 1996; Fossen and Hesthammer, 1997; Schultz, 1999; Cowie and Roberts, 2001; Scholz, 2002, pp. 115–117; Olson, 2003; Schultz et al., 2008a, 2013; Fossen, 2010a,b; Fossen and Cavalcante, 2017). As can be seen on Fig. 1.9, longer faults are associated with systematically larger displacements, or shear offsets ($D_{\text{max}}$ on the diagram), so that faults accommodate offsets between 0.1% and 10% of their lengths, with smaller variations found for faults in a particular area. Other types of geologic structural discontinuities, such as joints and deformation bands (including the compaction band variety), and shear zones, also show a consistent displacement–length scaling relation (e.g., Vermilye and Scholz, 1995; Olson, 2003; Fossen et al., 2007;
1.2 What Is a Structural Discontinuity?

Rudnicki, 2007; Schultz et al., 2008a, 2013; Tembe et al., 2008; Schultz, 2009; Schultz and Soliva, 2012; Fossen and Cavalcante, 2017) with the details dependent on the kinematics and mechanics of the structure.

Two general classes of structural discontinuities are now recognized in structural geology and rock mechanics, following Borja and Aydin (2004) and Aydin et al. (2006). These are summarized in Table 1.2.

- Sharp structural discontinuities have a discontinuous change in displacement, strength, or stiffness that occurs between a pair of discrete planar surfaces; sharp discontinuities are associated with a discontinuous (abrupt) change in the displacement distribution across them, leading to the mechanically descriptive terms “displacement discontinuity” (e.g., Crouch and Starfield, 1983, pp. 80–84; Pollard and Segall, 1987; Pollard and Aydin, 1988) and “strong discontinuity” (Borja, 2002; Aydin et al., 2006) in the mechanics literature.

- Tabular structural discontinuities have a continuous change in displacement, strength, or stiffness that occurs across a relatively thin band. These structures show a continuous change in normal or shear strain (i.e., an increase in the displacement gradient) across them and are called “weak discontinuities” by, e.g., Borja (2002) and Aydin et al. (2006).

In these definitions, the terms “sharp” and “tabular” describe the variation in displacement, or offset, that is accommodated between the two opposing surfaces, such as opening, closing, or shearing displacements, rather than a tensile, shear, or compressive strength. Specifically,
Table 1.2  Geomechanical classification of structural discontinuities according to the rate of change of displacement across them (sharp planes with discontinuous displacement vs. tabular zones with continuous displacement) and by kinematics (displacement sense across the structure)

<table>
<thead>
<tr>
<th>DISPLACEMENT SENSE</th>
<th>Sharp Discontinuity</th>
<th>Tabular Discontinuity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening</td>
<td>Crack (Joint, Dike, Sill, Hydrofracture)</td>
<td>Dilation band</td>
</tr>
<tr>
<td>Opening + shear</td>
<td>Mixed-mode crack</td>
<td>Dilational shear band</td>
</tr>
<tr>
<td>Shearing</td>
<td>Fault (Slip patch)</td>
<td>Shear band; also Shear zone</td>
</tr>
<tr>
<td>Shear + closing</td>
<td>None</td>
<td>Compactional shear band</td>
</tr>
<tr>
<td>Closing</td>
<td>Stylolite</td>
<td>Pure compaction band</td>
</tr>
</tbody>
</table>

- A “sharp discontinuity” is one in which the thickness of the structure is very close to zero. This corresponds to two planes in contact or in close proximity.
- A “tabular discontinuity” is one in which the thickness of the structure that accommodates most of the offset is measurable at the scale of interest, such as a thin section, hand sample, outcrop, or a satellite image.

In general, there is a good correlation between the width of a structure and its displacement continuity (e.g., Aydin et al., 2006). Sharp discontinuities typically are associated with discontinuous displacement gradients across them, whereas thicker, tabular ones exhibit more gradual and continuous displacement gradients across them.

Sharp discontinuities (Table 1.2) typically form under peak stress levels in the rock (see Chapter 3), involving cracking and/or shearing processes. These are typically referred to as fractures in geology and discontinuities in rock engineering, and usually accommodate either shearing (via frictional sliding) or opening displacements.

Tabular discontinuities, on the other hand, commonly referred to as deformation bands or shear zones, can accommodate the full range of kinematics across their widths, including dilation, shear, compaction, and combinations of these (e.g., Besuelle, 2001a,b; Aydin et al., 2006; Fossen et al., 2007, 2017; Fossen and Cavalcante, 2017). A type of deformation band in which compactional normal strains predominate over shear strains across the band is called a compaction band (Mollema and Antonellini, 1996; Sternlof et al., 2005; Aydin et al., 2006; Eichhubl et al., 2010). Two varieties are recognized as pure compaction bands (Fig. 1.10), which accommodate essentially compactional...
1.2 What Is a Structural Discontinuity?

strain and resemble stylolites in soluble rock, and shear-enhanced compaction bands, which accommodate both compactional and shear strains (Fig. 1.11). Depending on the stress state and grain-scale characteristics of the host rock, such as porosity and grain size, the thickness of a tabular discontinuity can attain values of several centimeters.

A sharp discontinuity has a significant displacement over a very narrow zone, leading to a significant or “strong” effect on its surroundings. A tabular discontinuity, on the other hand, exerts a less significant, or weaker, effect on
its surroundings. As a result, certain processes, such as mechanical interaction or displacement transfer between closely spaced structural discontinuities, may be more effective, or may operate over larger distances, for sharp discontinuities than for tabular discontinuities.

The term “discontinuity” refers to the dimensions parallel to the structure, such as horizontal length or vertical (or down-dip) height, as shown in Fig. 1.11. In general, the width or thickness is a very small fraction of the discontinuity’s length or height. With these kept in mind, the term “structural discontinuity” can easily be used to encompass those having either abrupt or continuous changes in displacement across them.

A fracture is a subtype of structural discontinuity. It is defined in Table 1.1. Most geologic fractures are brittle structures, in the sense (Rutter, 1986; Knipe, 1989) that they break or shear the rock as a result of pressure-dependent deformation mechanisms (e.g., grain cracking, Pollard and Aydin, 1988; frictional sliding, Byerlee, 1978; Scholz, 2002, pp. 53–100). This strain-softening behavior explains why cracks and faults can both be considered to be types of fractures. However, cracks that propagate by temperature-dependent deformation mechanisms, such as void growth ahead of the crack tip, are also known from high-temperature settings; these are referred to as “ductile fractures” (e.g., Eichhubl, 2004).

The definitions of structural discontinuity and fracture given in Table 1.1 require that the rock surrounding the discontinuity be an effective continuum. For example, grain-scale diffusion or cracking implies a different scale than flow in gouge, which is different in scale from fault population statistics. In other words, you have to get far enough out of, for example, the fault gouge to see the fault itself, and then to see that the fault has a width and a length, with fault tips within the host rock. This is a less restrictive requirement than the CHILE (continuous, homogeneous, linearly elastic) or DIANE (discontinuous, inhomogeneous, anisotropic, non-elastic) assumptions that may come into play with more detailed investigations, however. Specifying statistically homogeneous and continuous properties outside the discontinuity (an effective continuum) clearly defines the appropriate scale of observation at which these definitions are meant to apply.

Structural discontinuities that do not rupture the entire rock mass are characteristically discontinuous in length in one or more directions (e.g., Davison, 1994). That is, discontinuities end, or terminate, where the displacements across them go to zero (the discontinuity tips, or tipline; Figs. 1.3 and 1.12b). However, many discontinuities open or intersect at surfaces such as the ground, excavation faces, or other discontinuities; here, the discontinuity does not have a sharp termination as it would if it ended inside the rock. Discontinuities that completely rupture a rock, causing it to break apart, have no physical terminations.

Discontinuities with lengths less than the dimensions of the rock in which they occur have clearly defined terminations: these are called
bounded discontinuities. Sometimes the discontinuity intersects another planar element such as the Earth’s surface or another discontinuity. In this case the discontinuity is considered to be unbounded at the intersection yet is bounded by the rock elsewhere; this is called a semi-bounded discontinuity. Faults that intersect the ground surface, for example, are semi-bounded discontinuities. This distinction of bounded vs. unbounded discontinuities can be important in applying engineering principles, such as those embodied by the Coulomb friction and Mohr circles, as well as stress intensity factors, to naturally and artificially occurring structural discontinuities in the Earth (e.g., Palmer and Rice, 1973; Rudnicki, 1980; Pollard and Segall, 1987; Li, 1987; Rubin, 1995b; Gudmundsson, 2011). This is because discontinuity propagation occurs at its tips, along with most of the close-range mechanical (stress) interaction that governs whether closely spaced discontinuities will link.

A kinematic or displacement-based classification of structural discontinuities is constructed by evaluating the sense, and continuity, of offset, or displacement of initially contiguous points, relative to the plane of the structure (e.g., Griggs and Handin, 1960; Pollard and Aydin, 1988; Jamison, 1989; Wojtal, 1989; Johnson, 1995; Aydin, 2000; Aydin et al., 2006). In the field, the geologist or rock engineer would examine and demonstrate the two key parameters: displacement sense and displacement continuity, as shown in Table 1.2. Assessing the displacement sense is straightforward—the methods of crosscutting and shear-sense criteria are available in any structural geology text. Assessing the continuity of displacement across the structure reduces in most cases to determining the width of the structure and then examining if the opening, shearing, or closing displacement is smoothly varying across the zone (i.e., a continuous displacement) or if it changes abruptly (i.e., a discontinuous displacement). More often than not, there is a correlation between width of the structure and the displacement continuity (i.e., continuous shearing across a tabular structure 1 mm thick), especially in the early development of a structure.
1.3 The Role of Lithology and Rock Properties

The physical properties of a rock affect its strength, deformability (see Bell, 1993, pp. 165–179, Evans and Kohlstedt, 1995, and Paterson and Wong, 2005, for concise syntheses), and the types of structural discontinuities that form within it (see also Crider and Peacock, 2004). In particular, the porosity and grain size, along with grain sorting (Cheung et al., 2012), grain angularity, lithology, and degree of diagenesis (cementation), of a rock or soil exert a primary influence on the types of structural discontinuities that form (see reviews and discussions by Wong et al., 1992, 2004; Bürgmann et al., 1994; Aydin, 2000; Pollard and Fletcher, 2005, p. 382; Aydin et al., 2006; Fossen et al., 2007; Laubach et al., 2010; Cheung et al., 2012; Wong and Baud, 2012).

There is a good correlation between the amount of porosity in a rock or soil and the volumetric changes it undergoes during deformation (e.g., Evans and Kohlstedt, 1995; Davis and Selvadurai, 2002; Wong et al., 1992, 2004). For example, a “compact” rock (Paterson and Wong, 2005) with negligible porosity, such as a granite or basalt, or a low-porosity soil (called “over-consolidated”), typically expands in volume during shearing, leading to dilatant behavior and localized zones of concentrated shear. In contrast, a rock with high porosity (e.g., $n > 10–20\%$), or a high-porosity soil (called “normally consolidated”), generally contracts in volume during shearing, leading to porosity reduction and distributed deformation. In the rock mechanics literature, brittle deformation is associated with localized dilatancy and strain localization, whereas ductile deformation is associated with nonlocalized macroscopic flow (e.g., Evans and Kohlstedt, 1995).

A good correlation also exists between the porosity of a rock and the type of structural discontinuity—sharp or tabular—that forms in it (e.g., Aydin et al., 2006; Eichhubl et al., 2009). Tabular structural discontinuities (deformation bands) form most easily in high-porosity granular rocks, like sandstone, some pyroclastic tuffs, siliceous mudstones, and porous limestones, whereas sharp structural discontinuities (cracks and faults) form in rocks of any value of porosity. Although other variables such as stress state, diagenesis, mineralogy, and pore-water conditions appear to influence the type of structural discontinuities that form in a rock (e.g., Davatzes et al., 2005; Laubach et al., 2010), tabular structural discontinuities are clearly restricted to formation in rocks having non-negligible values of porosity.

This dichotomy in structure type (sharp vs. tabular structural discontinuities) is illustrated in Fig. 1.13 after Schultz and Fossen (2008). Here, the kinematics of the structural discontinuities also must be specified before the structural discontinuities can be named (e.g., Peacock et al., 2018). By specifying the kinematics, a broad class such as deformation bands (see also Table 1.2) can be divided into its five kinematic classes (i.e., dilation bands, dilational shear bands, shear bands, compactional shear bands, and...
1.4 Displacement Modes

Displacement modes depend on the relative amounts of volumetric change (dilation or compaction) and shear strain accommodated across the structural discontinuity. Similarly, cracks and faults can be distinguished by the amounts of opening or shear displacements across them. These diagrams indicate the initial types of geologic structural discontinuities (e.g., sharp or tabular) that can occur in a rock, depending on its porosity.

1.4 Displacement Modes

The approach developed in this book for structural discontinuities is based on the deformation of rock or other material in a local coordinate system that is defined by the plane of the structural discontinuity (Irwin, 1957; Sih et al., 1962; Paris and Sih, 1965; Sih and Liebowitz, 1968; Pollard and Segall, 1987; see Kies et al., 1975, for an historical overview). Analysis of the stresses and displacements associated with structural discontinuities...
(sharp or tabular) of any displacement mode lays the foundation for the field of \textit{geologic fracture mechanics} that therefore includes all types of geologic structural discontinuities, including fractures and bands.

Suppose we observe a vertical joint that cuts a thin sedimentary layer (as in Fig. 1.14). In order to investigate this joint using the concept of displacement modes and the techniques of fracture mechanics, we can orient this structural discontinuity most conveniently with its plane parallel to the \(x\)-axis and centered at the origin of this local \(xy\)-coordinate system, as shown in Fig. 1.15 (see also Crouch and Starfield, 1983, p. 91; Lawn, 1993, p. 3). In this case the horizontal layer containing the discontinuity (as in Fig. 1.14) defines the \(xy\)-plane and is represented for clarity in Fig. 1.15 as being thin in the vertical, \(z\)-direction. The fracture’s dimension in this \(xy\)-plane is called its \textit{length} (see Fig. 1.12a).

Stresses acting in the \(xy\)-plane, such as layer-parallel shear, compression, or tension, are called “\textit{in-plane stresses}” and those acting perpendicular to this plane (having a \(z\)-component) are called “\textit{out-of-plane}” or “anti-plane” stresses (e.g., Pollard and Segall, 1987, pp. 316–317). The \(xy\)-plane can be thought of as the Earth’s surface, with a vertically or steeply dipping structural discontinuity in map view cutting down into the layer (Figs. 1.14 and 1.15). Although the layer itself is shown as thin in this example, the definition of displacement mode applies regardless of layer thickness. This means we can

\begin{figure}
\centering
\includegraphics[width=\textwidth]{geologists-examining-joint.jpg}
\caption{Geologists examine a sub-vertical joint exposed in a thin horizontal sedimentary layer in New York State.}
\end{figure}
1.4 Displacement Modes

Fig. 1.15. Defining the reference plane of interest, such as the horizontal plane shown here, is needed to determine whether the stresses that load a structural discontinuity are (a) in-plane (layer-parallel) or (b) out-of-plane. The structural discontinuity is shown as an ellipse on the surface of the layer. The two-dimensional stress states associated with in-plane loading (“top view”) and out-of-plane loading (“cross-strike view” and “along-strike view”) are shown along with the axis of rotation implied by the shear stresses for each planar view.

Start with the joints that cut a large granitic pluton, such as those shown in Fig. 1.2, or the rotated normal faults as shown in Fig. 1.3, and define our coordinate systems using these structural discontinuities and these layers. In-plane stresses can produce rock rotations about vertical axes, as in strike-slip tectonics, whereas anti-plane stresses can induce rock rotations about horizontal axes, as in normal or thrust faulting.

The three displacement modes (also called loading modes in engineering) are defined in the upper set of diagrams in Fig. 1.16; these are oriented as is typical in engineering treatises (e.g., Paris and Sih, 1965; Sih and Liebowitz, 1968; Kanninen and Popelar, 1985, p. 139; Broek, 1986, p. 8; Atkinson, 1987; Lawn, 1993, p. 24; Anderson, 1995, p. 53; Tada et al., 2000, p. 2; see also Dmowska and Rice, 1986; Pollard and Fletcher, 2005, p. 372). They were defined originally in the engineering context for design of ships, bridges, railroads, and buildings (e.g., Kanninen and Popelar, 1985; Broek, 1986; Lawn, 1993; Anderson, 1995). Structural discontinuities that accommodate more than one principal (or “pure”) displacement mode are called “mixed-mode.” For example, a crack (mode-I) that opens obliquely is called a mixed-mode crack (mode I-II or I-III depending on the sense of shearing along the crack walls; see Chapter 2). The shearing modes (II and III) are commonly introduced in engineering fracture mechanics treatises to explain crack propagation paths (mixed-mode I-II cracks) or breakdown of the crack tip during propagation (mixed-mode I-III) (e.g., Erdogan and Sih, 1963; Sih, 1974; Ingraffea, 1987; Lawn, 1993, p. 23; Lin et al., 2010).
The displacement modes have long been applied to the analysis and interpretation of **geologic structural discontinuities** (e.g., see Brace and Bombolakis, 1963; Segall and Pollard, 1980; Pollard et al., 1982, 1993; Engelder, 1987; Pollard and Segall, 1987; Aydin, 1988; Pollard and Aydin, 1988; Cowie and Scholz, 1992b; Engelder et al., 1993; Schultz and Balasko, 2003; Pollard and Fletcher, 2005; Aydin et al., 2006; Okubo and Schultz, 2006). For example, a deformation band that accommodates both shearing and volumetric dilation (i.e., a dilational shear band; see Table 1.2) would be a **mixed-mode tabular structural discontinuity**, with the order of the mode numerals indicating the relative amounts of each component (greater magnitude listed first; i.e., mode-II-I or III-I for the case of shear displacement (mode-II or mode-III) exceeding the dilational displacement). A shear-enhanced compaction band is one having subequal amounts of compactional and shear deformation (e.g., Eichhubl et al., 2010) although a separate displacement mode for these tabular structural discontinuities is not used in practice. Although the displacement modes need not imply particular mechanics (such as mode-II faults or deformation bands, which accommodate shear displacement by different physical mechanisms), Chemenda et al. (2011) have drawn such a distinction in their

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**Fig. 1.16.** The three displacement modes of a structural discontinuity are identified relative to the reference plane (here, the unshaded $xy$-plane) and the edge, or tipline, of the discontinuity. The upper diagrams are oriented following standard engineering practice, with mode-II shearing defined as being normal to the leading edge and mode-III shearing being parallel to the leading edge (Tada et al., 2000). The lower diagrams are rotated so that the reference ($xy$-) plane is horizontal (after Twiss and Moores, 2007, p. 38; Kulander et al., 1979), as is the case for many geologic situations (e.g., Fig. 1.14); modes II and III are defined relative to the tipline.
interpretation of plumose structure being related to precursory dilation bands, rather than to joints, in sedimentary rocks.

The displacement mode diagrams can be made more intuitively applicable to geologic situations by rotating them so that the reference $xy$-plane becomes the horizontal plane; this is shown by the lower set of diagrams in Fig. 1.16. If the discontinuity opens (or dilates) in the in-plane direction, it is called mode-I (mode “one,” not mode “eye”), analogous to a joint, vein, or dike (e.g., Pollard et al., 1982; Segall and Pollard, 1983a,b; Pollard and Aydin, 1984, 1988; Kulander and Dean, 1985; Delaney et al., 1986; Pollard, 1987; Rubin, 1993b). If the discontinuity accommodates shearing in the $xy$-plane (with the shear or displacement sense normal to the fault’s vertical edge, as in Fig. 1.16, upper-center diagram, or, correspondingly, the $xy$-plane contains the slip vector), it is mode-II, analogous to a strike-slip fault in map view (e.g., Chinnery, 1961, 1963, 1965; Rodgers, 1980; Segall and Pollard, 1980; Rispoli, 1981; Aydin and Page, 1984; Pollard and Segall, 1987; Petit and Barquins, 1988; Davison, 1994). Out-of-plane (i.e., sub-vertical) shearing along the discontinuity (with the shear or displacement sense parallel to the fault’s vertical edge, as in Fig. 1.16, upper-right diagram) corresponds to mode-III, analogous to a normal or thrust fault seen in map view (e.g., King and Yielding, 1984; Aydin and Nur, 1985; Pollard and Segall, 1987; Davison, 1994; Willemse et al., 1996; Crider and Pollard, 1998; Gupta and Scholz, 2000a). Mode-I structural discontinuities are discussed in detail in Chapter 4; sharp mode-II and mode-III structural discontinuities (faults) are considered in Chapter 6.

A sharp or tabular structural discontinuity can thus be categorized as:

- Mode-I: opening along a structural discontinuity (called “opening mode”).
- Mode-II: in-plane shear along a structural discontinuity (called “shearing mode”).
- Mode-III: out-of-plane shear along a structural discontinuity (called “tearing mode”).

The mode-I case with a horizontal reference plane (Fig. 1.16, lower-left diagram) was used by DeGraff and Aydin (1987) and Pollard and Aydin (1988) to illustrate crack propagation paths for a vertically dipping joint. Segall and Pollard (1980), Pollard and Segall (1987, their figure 8.18), Li (1987), and others note that a strike-slip fault corresponds to a mode-II structural discontinuity in map view and a mode-III structural discontinuity exposed in cross-sectional view. The reoriented mode-II diagram in Fig. 1.16 (lower center) follows those of Marone (1998b, his figure 15) and Pollard and Segall (1987, their figure 8.16a). Similarly, a normal or thrust fault corresponds to a dipping (i.e., nonvertical) mode-III structural discontinuity in map view and a mode-II structural discontinuity exposed in cross-sectional view (e.g., Aydin,
Determination of the displacement mode in relation to the shear sense is also important in the study of deformation bands (e.g., Aydin, 1978; Aydin and Johnson, 1978, 1983; Schultz and Balasko, 2003; Aydin et al., 2006; Okubo and Schultz, 2006).

Although many geologic structural discontinuities can have a component of displacement in the other sense, in most cases one mode predominates. For example, a fault may have a width of perhaps a meter, with comparable amounts of opening or dilation, along with strike-parallel displacement (“offset”) of many kilometers. Because the parallel component is so much larger than the normal component, one can neglect the small normal component because, in nature, the parallel component will dominate the changes in stress and displacement associated with the fault. Similarly, the normal component of displacement across dilatant cracks is considerably greater than the parallel component. Even mixed-mode cracks, with oblique dilation, are seen to work much like pure mode-I cracks (see Chapters 4 and 9), with the oblique component serving as a modifying factor in the stress and displacement fields about the crack.

Another variety of structural discontinuity can be defined by noting that material displacements perpendicular to the discontinuity surface result from a volume loss across the structure. Pressure solution surfaces, or stylolites (Twiss and Moores, 1992), have been likened to anticracks (Fletcher and Pollard, 1981; Füten and Robin, 1992; Zhou and Aydin, 2010, 2012) that are common in soluble rocks such as carbonates when subjected to large compressive stresses. These structures are included here as the anticrack class of structural discontinuity (e.g., Jamison, 1989; Wojtal, 1989) even though they physically represent a very different process than bond breakage in a rock. However, their growth and interaction are similar in many respects to other types of structural discontinuities (Dunne and Hancock, 1994; Benedicto and Schultz, 2009; Zhou and Aydin, 2010).

Anticracks have the opposite kinematic significance to cracks, and their stress and displacement fields can sometimes be represented by using a mode-I crack with a compactional sense of strain across it (e.g., Fletcher and Pollard, 1981; Rudnicki and Sternlof, 2005; Sternlof et al., 2005; Rudnicki, 2007; Tembe et al., 2008; Meng and Pollard, 2014), resulting in closing (or interpenetrating) discontinuity walls. Mollema and Antonellini (1996) suggested using “anti-mode-I” for their anticracks, as did Green et al. (1990); the term “mode –I” (minus one) has also been used informally to describe these structures (Scholz, 2002, p. 331). Introducing a negative sign before “mode-I” elegantly conveys the kinematic significance of anticracks but it may also blur the important physical distinctions between cracks and the several varieties of anticrack-like structures (e.g., Fletcher and Pollard, 1981; Knipe, 1989) such as pressure-solution seams (stylolites) and pure compaction bands (Eichhubl et al., 2010). As shown in Table 1.2, anticracks...
can be either sharp or tabular, permitting both stylolites and pure compaction bands to be investigated kinematically and, to a degree, mechanically, as anticrack structural discontinuities.

1.5 Using Geologic Fracture Mechanics in Research and Practice

Throughout this book and your study of fracture mechanics applied to geologic structural discontinuities, you will repeatedly encounter a number of major concepts, such as stress concentration or displacement–length scaling. Sometimes these concepts or principles that are based on mechanics are readily apparent, as for example when working out the growth history of a set of tectonic joints or in reconstructing the sequence of fault segment linkage by measuring the displacement profiles along the faults. In other situations, however, you might not think that fracture mechanics would apply. For example, the lateral margins of regional-scale detachment structures in Tertiary-age extensional terranes, of thrust sheets in a Paleozoic contractional orogen, and of landslides that scallop out a mountainside, all likely nucleated, and continued to function, as particular types of fault arrays. Many problems in finite strain started as small, infinitesimal strains and developed from there (for example, see papers by Chinnery (1961), Aydin and Nur (1982), Aydin and Page (1984), ten Brink et al. (1996), and Kattenhorn and Marshall (2006) on strike-slip tectonics; Cowie and Scholz (1992b) and Schultz et al. (2006, 2008a, 2013) on fault displacement–length scaling; Willems (1997) and Soliva et al. (2008) on fault growth and linkage; Niño et al. (1998) and Cooke and Kameda (2002) on fold-and-thrust belts; Martel (2004) on slope failure and landslide nucleation; and Fossen and Cavalcante (2017) on shear zones). These phenomena obey the laws of fracture mechanics even though the strains involved may ultimately attain large, finite values (such as several tens of percent or more). Once the rules that govern how fractures operate are identified, the sequence of deformation can become clear regardless of how complicated a structural suite has eventually become.

The material in this book will also provide a number of new tools and techniques that should become part of a geologist’s arsenal in the field. For example, we will explore how to decipher what the shape of the termination of a dike or fault means mechanically, and what that says about how the fracture grew. Several reliable rules of thumb for relating the amount of offset or opening displacement to the length of a structural discontinuity will be developed that can be used, in real time, by a field geologist to produce better interpretations, maps, and cross sections. In sum, a clearer appreciation can be gained from this book of research being done at the cutting edge of geologic fracture mechanics in structural geology and tectonics.
1.6 Review of Important Concepts

1. Fractures are a class of geologic structural discontinuity that involve discontinuous displacements across their surfaces. Fractures tend to be weaker, and less stiff, than the surrounding host rock, making them important geologic flaws and stress concentrators as well as conduits for enhanced fluid flow.

2. Deformation bands are a class of geologic structural discontinuity that accommodate a continuous, smoothly varying displacement across their widths. The type of deformation band depends on its kinematics, leading to five kinematic varieties, and on its micromechanics (such as cataclasis within a compactional shear band).

3. Structural discontinuities are identified in the field by using a displacement-based classification scheme. The two main (engineering) end-members of displacement sense are normal (mode-I) and parallel (mode-II, III) to the discontinuity surface, leading to opening-mode and shearing-mode structures, respectively. Closing-mode structures are also encountered in rock.

4. Structural discontinuities whose walls have been displaced normal (perpendicular) to the discontinuity surface are cracks (having opening displacements) and anticracks (stylolites and pure compaction bands, both having primarily closing displacements). Fractures or deformation bands whose walls have been displaced parallel to the surface are called faults (if the displacement is discontinuous across the fracture) or shearing deformation bands (having continuous displacements across the deformation band), respectively.

5. Strike-slip faults are mode-II structures in map view, and mode-III structures in cross-sectional view. Conversely, dip-slip faults (normal and thrust) are dipping, nonvertical mode-III structures in map view, and mode-II structures in cross-sectional view. These mechanical idealizations of fault surfaces are helpful to understand the patterns of faults and the strains that develop with these types of structures.

6. Deformation bands form in porous granular geomaterials such as soils and porous rock, but are not observed in compact rocks. Conversely, fractures can form in compact or porous rocks depending on factors such as stress state, mineralogy, and pore-water conditions.
1.7 Exercises

1. Define the following terms: fracture, crack, joint, dike, fault, fault zone, anticrack, and deformation band, giving an example of each of these, that you have encountered in the field or in a similar first-hand situation, that best illustrates the components of the definitions developed in this chapter.

2. What is the definition of a geologic structural discontinuity? How can you explain or defend each of the parts of the definition given your experience?

3. Describe the relationship between the physical properties of a host rock and the initial type of structure formed. How do these physical properties relate to lithology?

4. Summarize the engineering classification of fractures and deformation bands based on displacement mode. Place the main types of fractures, including dip-slip and strike-slip faults, into this scheme while accounting for the orientation of the viewing plane (e.g., map view or cross-sectional view).

5. What is the difference between a tabular and a sharp geologic discontinuity? Provide examples of each along with your justification.

6. Describe the difference between the plane-stress and a plane-strain assumptions and give an example of a geologic situation, such as a cross section or deformation of a sedimentary basin, that clearly illustrates each.

7. Give the displacement mode for each of the structures shown in map view: (a) strike-slip fault; (b) thrust fault; (c) normal fault; (d) stylolite. How would the displacement mode for each change if the structures were viewed in cross-section instead?
Introduction to Geologic Structural Discontinuities

What is a Structural Discontinuity?

Displacement Continuity

Strong (discontinuous): Sharp discontinuity
Weak (continuous): Weak discontinuity

Mode I
Mode II
Mode III
Anticrack

Displacement Sense/Modes

Opening Mode
Shearing Modes
Closing Mode

Role of Lithology

Porous rock
Compact rock

How Defined

Why Important

Fractures

Cracks
Joint
Vein
Dike, Sill
Hydrofracture

Faults
Dip-Slip
Normal
Reverse
Thrust
Oblique-Slip
Strike-Slip
Left-Lateral
Right-Lateral

Deformation Bands

Dilation Band
Dilational Shear Band
Isochoric Shear Band
Compactional Shear Band
Cataclastic Band
Non-Cataclastic Band
Shear-Enhanced Compaction Band
Pure Compaction Band

Anticracks

Stylolites

Why Important

Role of Lithology