CHAPTER

1 Introduction to Geologic Structural Discontinuities

1.1 Localized Deformation Structures in Rock

In This Chapter:

- *Types and expression of structural discontinuities in geology*
- *Displacement modes for geologic structural discontinuities*

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,

Fig. 1.1. Examples of **discontinuities in a rock mass** as seen through the eyes of a rock engineer. Several joint planes are visible, including vertical ones exhibiting plumose structure that define the vertical face of the exposure, another vertical set perpendicular to the plane of the exposure that is restricted to certain of the horizontal sandstone layers, and sub-horizontal joints that mark separation along the bedding planes. A few inclined cracks in the uppermost massive bed suggest bedding-plane slip of that layer (top to the right) along the subjacent interface. The section shown is part of the Permian Elephant Canyon Formation exposed in southern Devils Lane graben, Canyonlands National Park, Utah.

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

Discontinuity	Mechanical defect, flaw, or plane of weakness in a rock mass without regard to its origin or kinematics
Structural discontinuity	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
Sharp discontinuity	A structural discontinuity having a discontinuous change in displacement, strength, or stiffness that occurs between a pair of discrete planar surfaces
Tabular discontinuity	A structural discontinuity having a continuous change in displacement, strength, or stiffness that occurs across a relatively thin band
Fracture	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
Joint	A sharp structural discontinuity having field evidence for discontinuous and predominantly opening displacements between the opposing walls
Anticrack	A sharp or tabular structural discontinuity having field evidence for predominantly closing displacements between the opposing walls
Deformation band	A tabular structural discontinuity having a continuous change in displacement, strength, or stiffness across a relatively narrow zone in porous rocks
Fault	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
Fault zone	A set of relatively closely spaced faults having similar strikes
Shear zone	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
Damage zone	A zone of increased deformation density that is located around a discontinuity that formed at any stage in the evolution of the structure

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.

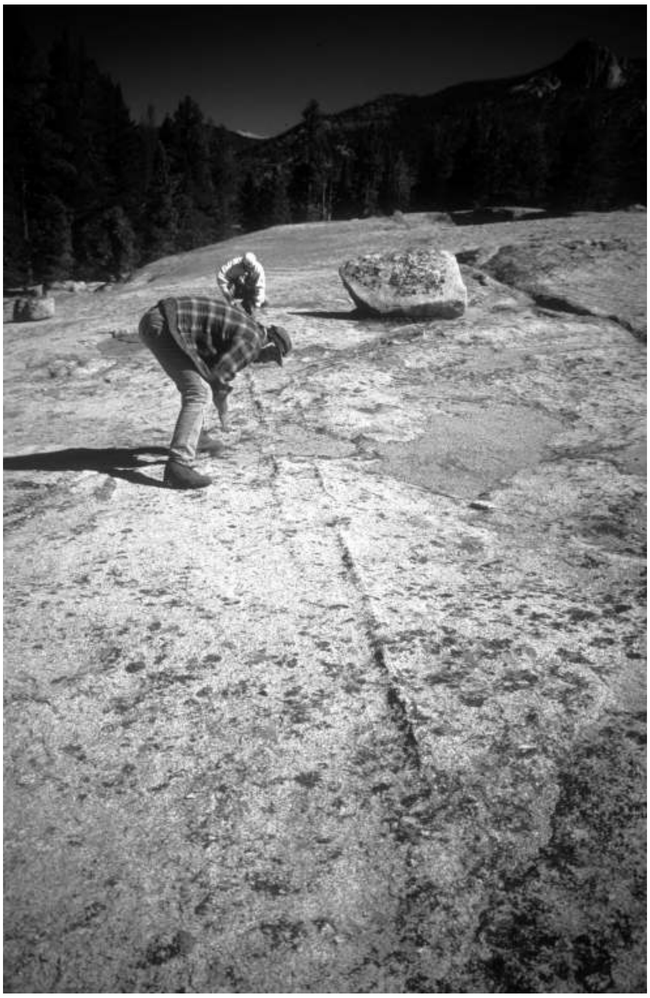

Fig. 1.2. Several thin, parallel joints from a granitic pluton near Ward Lake, California, are visible to the naked eye. Closer examination reveals that these joints are filled with epidote and other hydrothermal minerals that were present in the fluid that circulated within the joints as they dilated and propagated at mid-crustal depths.

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

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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.

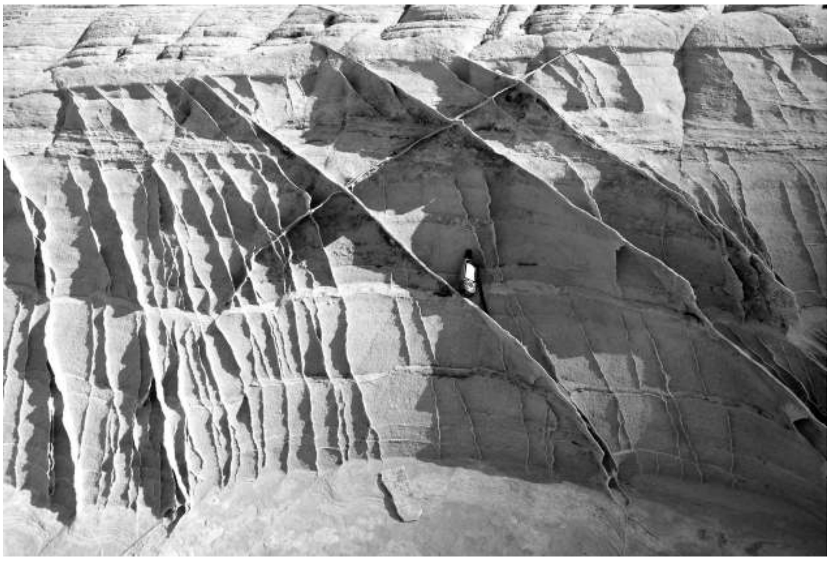

Fig. 1.5. Deformation bands are an important deformation mechanism in porous rocks such as sandstone, and they define intricate and informative arrays as in this fine example in Navajo Sandstone from southern Utah. The sub-horizontal bedding can be seen to be cut by two oppositely dipping sets of shear-enhanced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

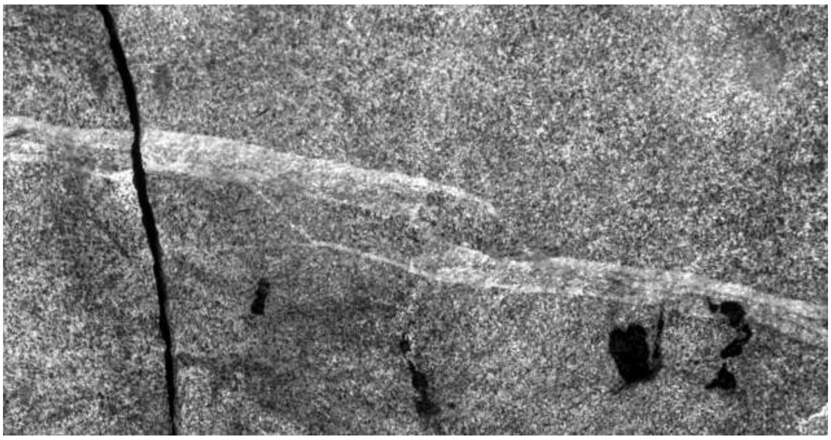

Fig. 1.6. A pair of echelon igneous dikes is shown in granitic rock of the central Sierra Nevada near Donner Lake, California. Each dike segment beyond the overlap region, where the dikes are linked, exhibits a separation of host rock by ~ 10 cm, with the intervening void within the dike being filled 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

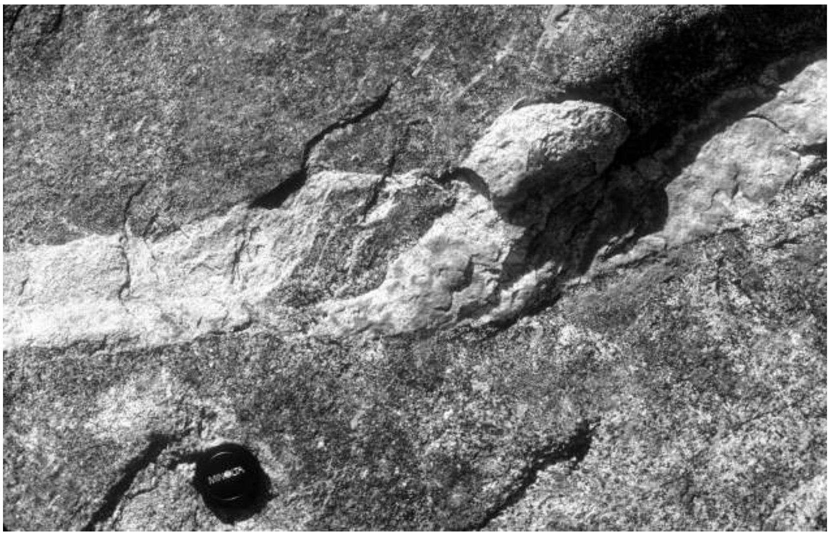

Fig. 1.7. The detailed shape of the dike tip is clearly revealed by this view of the stepover between a pair of closely spaced igneous dikes. The dike segment width, normal to its trace, is ~10 cm (camera lens cap for scale). Dike shapes such as these can be predicted very well by representing the dikes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

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.

Discontinuity, part 1: Finite Dimensions

Discontinuity, part 2: Displacement Gradient

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 "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 "upscaling" 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_{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;