GEOLOGIC NOTE

Terminology for structural discontinuities

Richard A. Schultz and Haakon Fossen

ABSTRACT

Strain localization structures such as fractures, stylolites, and deformation bands have important effects on reservoir performance but lack a consistent terminology. Advances in the recognition and interpretation of such structures now motivate a comprehensive framework that stresses their similarities instead of their differences. We review and assess the classical terms for localized geologic structures, followed by a comprehensive nomenclature that accounts for joints, faults, fractures, anticracks, shear zones, and deformation bands in compact and high-porosity rocks. Geologic structural discontinuities are defined by their lengths and by the sense and rate of displacement change across them. For example, structural discontinuities having negligible thickness, and consequently, a discontinuous displacement across them, are called sharp discontinuities. Depending on the sense of displacement (opening, shearing, or closing), these structures are called cracks, faults, or anticracks. However, structural discontinuities having a measurable thickness in outcrop or hand specimen and a continuous change in displacement across them are called tabular discontinuities. Correspondingly, these types of deformation bands are called dilation bands, shear bands, or compaction bands. The class of structural discontinuity, i.e., sharp or tabular, depends on the properties of the deforming rock. Consistent characteristics and patterns of these structural discontinuities, and their displacement-length scaling relations, demonstrate the rich yet consistent varieties of strain localization that are

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manifested in crustal rocks in general, and reservoir rocks in particular.

INTRODUCTION

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). They are important geologic structures because they reveal types and phases of deformation, and their kinematics, patterns, and orientations 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 geoengineering, landscape geomorphology, hydrogeology, and petroleum geology.

However, deformation bands originally identified as thin, tabular zones of cataclasis, pore collapse, and grain crushing (e.g., Engelder, 1974; Aydin, 1978), now encompass five kinematic varieties of bands, 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 structures, i.e., fractures and 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, for a review and discussion of these attributes for deformation bands). Despite these commonalities, however, a consistent terminology that encompasses all the variations noted above is not yet available in the literature, although progress is being made toward this end (for example, see Aydin, 2000). In this article, we first review the main terms used to describe structural discontinuities in rock. Following a discussion and synthesis of this material, we propose a coherent framework for these interesting and important structures.

A REVIEW OF REPRESENTATIVE TERMS

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 consideration of their origins (e.g., Goodman, 1976, 1989; Priest and Hudson, 1976; Bieniawski, 1989). 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, p. 52–53; Priest, 1993, p. 1; Hudson and Harrison, 1997, p. 20). By implication, cataclastic deformation bands, solidified igneous dikes, or veins in sedimentary host rock, for example, that are stronger and/or stiffer than their surroundings would 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 two opposing walls that is both discontinuous and small relative to the longest dimension. According to this definition, cracks, faults, veins, igneous dikes, stylolites, pressure-solution surfaces, and anticracks would be considered as discontinuities.

Fracture

The term ''fracture'' is commonly used in structural geology and related fields. According to Jaeger (1969, p. 73) and others, a fracture is the pair of distinct surfaces of separation (either opening or shear) in a material. Griggs and Handin (1960) considered joints and faults, in experiments and also in the field, as two types of fractures, with joints accommodating dilation without shear and faults accommodating shear displacement, as did Reid et al. (1913) and Lahee (1961) from a strictly field geology perspective.

The influential study prepared by the National Academy of Sciences (Committee on Fracture Characterization and Fluid Flow, 1996) and Aydin (2000) defines fracture as "a structure defined by two surfaces or a zone across which a displacement discontinuity occurs" (p. 798). Their examples of fracture types include (1) dilatant-mode fractures, such as joints, veins, and dikes; (2) contraction- or compaction-mode fractures, such as pressure-solution seams and compaction bands; and (3) shear-mode fractures, such as faults. A fracture using this broader basis refers to a structural heterogeneity whose opposing surfaces are displaced relative to one another, regardless of its mode of displacement or mechanics of formation. Van der Pluijm and Marshak (1997, p. 115–116) used fracture as a general and scale-invariant term for a surface in a material across which there has been loss of continuity (i.e., a discontinuity in displacement) and strength. They include joints, veins, dikes, and faults as types of fractures. Neuendorf et al. (2005) define a fracture as any surface across which no cohesion is observed, and include both cracks and faults under the term. In contrast, Price and Cosgrove (1990) restricted the term fracture to dilatant or mixed-mode (obliquely opening) cracks. Pollard and Aydin (1988) suggested that the term fracture be reserved for those ambiguous cases in which the sense of displacement (e.g., opening, closing, or shear) is not unequivocally determined.

Joint

A "joint" has been defined as a crack or fracture on which there has been no visible shear displacement (e.g., Neuendorf et al., 2005) or no visible displacement at all (Hodgson, 1961; Price, 1966; Ramsay and Huber, 1987). Based on their review and evaluation of the literature, Pollard and Aydin (1988) recommended that joints be defined as fractures having field evidence for predominantly opening displacements between their opposing walls. Additionally, the opening or separation of the joint walls implies that a joint can also be defined by a discontinuous (opening) displacement across it (e.g., Van der Pluijm and Marshak, 1997, p. 140).

Anticrack

An "anticrack" can be defined as a planar or tabular zone that accommodates localized contractional strain (e.g., Fletcher and Pollard, 1981; Mollema and Antonellini, 1996; Pollard and Fletcher, 2005, p. 16–19). A "tabular zone" is one having a measurable width. Contraction can result from volume reduction, such as physical and chemical compaction in sandstones (e.g., Mollema and Antonellini, 1996; Sternlof et al., 2005), mineralogical phase changes in deep mantle rocks (e.g., Green et al., 1990), and dissolution (wet diffusion) that produces disjunctive (spaced) pressure-solution cleavage and stylolites (e.g., Engelder and Marshak, 1985). Many workers envision pressure-solution cleavage and stylolites accommodating the localized contractional strain kinematically as anticracks.

Deformation Band

Earlier researchers variously called the fractures Lüders' bands (Friedman and Logan, 1973) and braided shear fractures (Engelder, 1974); Aydin (1978) and Aydin and Johnson (1978) applied the term "deformation band" to describe thin tabular zones of shear strain that occur within porous rocks. With some exceptions, this term is now routinely used to label these structures (e.g., Johnson, 1995; Davis and Reynolds, 1996, p. 317). Analogous structures in soil, sand, and clay are referred to in the soil mechanics literature as "shear bands" (e.g., Davis and Selvadurai, 2002).

Fault

"Faults" are generally defined as planar or zonal structures (meter-scale or larger) across which appreciable shear displacement discontinuities occur (e.g., Billings, 1972, p. 174). Price (1966) and Hobbs et al. (1976) restricted the term fault to a single plane, which has then been called a slip plane or shear fracture. In detail, the slip plane is associated with a thin zone of intensely crushed or smeared rock. For small faults, this zone can be less than 1 mm (0.03 in.) thick, whereas for larger faults, it is commonly found to be several centimeters or decimeters thick. This zone is now commonly referred to as the fault core (Caine et al., 1996). The fault core is generally considered to be part of the fault because most of the fault displacement is taken up within the core (e.g., Chambon et al., 2006).

Surrounding the fault is the fault damage zone, which is the volume of brittle deformation around and related to a fault (e.g., Peacock et al., 2000). In some contexts, the term fault includes not only discrete slip surfaces, fault rock, or fault core composed of the products of friction and wear, but also the surrounding damage zone (e.g., Childs et al., 1997; Aydin, 2000; Du Bernard et al., 2002; Davatzes et al., 2005). Thus, three different definitions of a fault are in use: a slip plane; a tabular zone of intense shear deformation (the fault core); and a complete structure composed of one or more main slip surfaces, fault core material, and the confining damage zone.

Fault Zone

According to Hobbs et al. (1976, p. 300), Davis and Reynolds (1996, p. 269), Van der Pluijm and Marshak (1997, p. 166), Johnson (1995), and Neuendorf et al. (2005), a ''fault zone'' is a tabular region that contains many parallel or anastomosing fault surfaces. The term is most commonly used when a fault is considered to be a single plane or slip surface, in which case, a fault zone is a set of subparallel slip planes. A slightly different usage of this term has been introduced by Childs et al. (1997), who pointed out that many faults with more than decimeters of offset are bounded by paired slip surfaces enveloping more or less complex zones of deformation. They regard the sheared volume between the two bounding slip surfaces as the fault zone. In many cases, this volume is equivalent to the fault core, although this would depend on both the strain between the bounding faults and the scale of observation.

Shear Zone

Shear zones do not have a uniform definition in the literature. They have been defined as relatively narrow zones of predominantly large ductile shear strains (i.e., nonlocalized flow) that may also include a small fraction of faults (Hobbs et al., 1976, p. 266). Van der Pluijm and Marshak (1997, p. 167) defined a ''shear zone'' as a zone of definable width in which the rock deforms ductilely (i.e., without localization of shearing onto discrete planes; see also Crider and Peacock, 2004), by cataclasis (fracturing, crushing, and frictional sliding of grains or rock fragments), crystal plasticity, or a combination of the two. Johnson (1995) defined shear zone as localized shearing within a tabular zone of given width that may also exhibit volumetric change (dilation or contraction) across the zone. Davis and Reynolds (1996, p. 503–508) and Mandl (2000, p. 103) classified shear zones by a deformation mechanism into brittle, semibrittle, brittle-ductile, and ductile shear zones. Ramsay (1980), in his classic article, differentiated between brittle, brittle-ductile, and ductile shear zones. In his terminology, brittle shear zones are simply brittle faults where the fault has a measurable thickness. Moreover, markers would be discontinuous across a brittle shear zone, but continuous across a ductile shear zone at the scale of observation. Lastly, Neuendorf et al. (2005) defined a shear zone as a tabular zone of rock that has been brecciated by many parallel fractures, sigmoidal mineral-filled veins, cleavage or foliation planes, grain-size reduction, or mylonitization, paralleling the generic usage of this term in the minerals industry.

Damage Zone

Originating from an engineering design using brittle materials (e.g., Broek, 1986; Lawn, 1993), a ''damage zone'' is a dense population of small defects such as cracks that are approximately equal in size; the defects serve as precursors to the localization of a large defect, which either grows more rapidly than the others or differs sufficiently from them to be considered as a separate element (Kanninen and Popelar, 1985, p. 90). Thus, cracks and faults can be thought of as propagating out of their precursory damage zones to become the dominant structural discontinuity in their part of the rock mass (e.g., McGrath and Davison, 1995; Fossen and Hesthammer, 2000; Pollard and Fletcher, 2005, p. 355; Schultz and Siddharthan, 2005). However, damage can also occur in the wall rocks of an already established fault, resulting in widening of the damage zone (e.g., Shipton and Cowie, 2001). In fact, the term damage zone is sometimes restricted to fracturing around a fault that is produced as a by-product of displacement accumulation on the fault itself (e.g., Neuendorf et al., 2005). Peacock et al. (2000) suggested a general definition of a fault damage zone as the area of fracturing around and related to a fault. Kim et al. (2004) defined a damage zone as "the volume of deformed wall rocks around a fault surface that results from the initiation, propagation, interaction, and build-up of slip along faults" (p. 503), thereby including both pre- and synfaulting damage.

DISCUSSION AND SYNTHESIS

Several common themes emerge from the literature review summarized above. First is the desire for a term that encompasses all the types of localized structures that may be encountered, such as those discussed in the previous section. Second is the wish to define these structures in such a way that scale-dependent definitions are avoided (see, for example, Wojtal, 1989; Price and Cosgrove, 1990; Van der Pluijm and Marshak, 1997; Mandl, 2000, for representative and thoughtful discussions of scale-dependent terminology). Third is the need to respect differences in the characteristics or properties of the structures that have led to certain classical, and therefore potentially widespread, definitions. Fourth is a desire to balance the simplicity of terminology with generality of application.

One issue that suggests augmentation is the previous practice of considering cracks, joints, or faults as a single surface. Field examination shows instead that these structures are defined by a pair of surfaces, or fracture walls, that have been relatively displaced by opening or by shearing (Figure 1). For example, a crack or joint is open between its two walls; 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 must be considered, at a minimum, 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 a gouge or another deformed material and, like cracks, join at a tip where the displacement magnitude decreases to zero. In the case of deformation bands, the walls can be identified by a comparatively rapid change in displacement gradient or porosity, although they tend to be less distinct than the clean sharp breaks typical of joints and fault planes (e.g., Aydin, 1978).

A "brittle fracture" implies the creation of surfaces that have a decreasing resistance to continued deformation (i.e., a strain-softening response in the postpeak part of the stress-strain curve for the rock; Jaeger, 1969; see also Hudson and Harrison, 1997). Brittle deformation additionally implies the localization of strain into a discrete planar element (e.g., Pollard and Fletcher, 2005, p. 334). The term fracture thus implies a local reduction in strength and/or stiffness and (in many cases) an associated increase in fluid conductivity between the pair of surfaces. 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 itself not be considered to be a fracture according to this definition, although the contact between the stiff igneous rock and the soft country rock may qualify if it is weaker, or less stiff, than both the igneous dike and country rock.

Fault walls may be separated by a gouge; those of a stylolite, by an insoluble residue such as clays. In both cases, these structures will reduce the local permeability. Deformation bands typically have either increased or, more commonly, decreased porosity and permeability within them; grain-size reduction may also characterize the interior of a deformation band. As a result, cracks, joints, faults, stylolites, and deformation bands all contain various materials between their walls that differ significantly from the host rock that surrounds them.

The term discontinuity has two disparate 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, 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

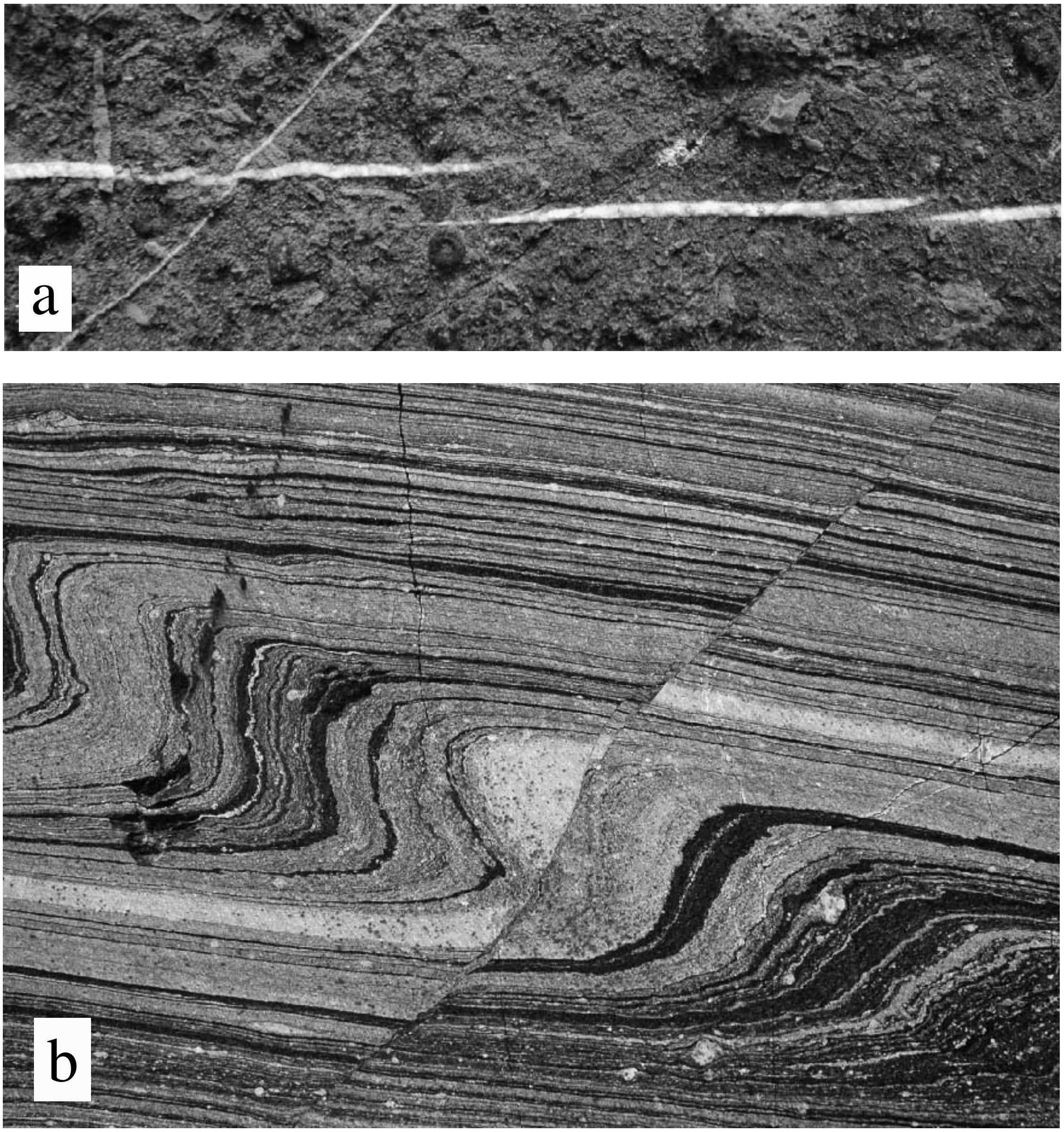


Figure 1. (a) Photo of veins cutting Ordovician limestone from Langøya, Oslo, Norway, about 5 mm (0.19 in.) thick showing two host-rock surfaces displaced from each other. The veins are discontinuous in dimension and discontinuous in displacement. (b) Photo of a normal fault cutting folded Caledonian mylonitic gneisses in Bergen, Norway; mylonitic layers are 1–5 cm (0.39–1.96 in.) thick. The fault is discontinuous in dimension and discontinuous in displacement.

of discontinuity refers to the rate of change of displacement across the structure (e.g., Johnson, 1995; Borja, 2002). Fractures having a discrete stepwise change in displacement across them, such as cracks and faults (or slip surfaces), are said to have, or to be, displacement discontinuities. In contrast, shear zones and deformation bands exhibit a continuous displacement across them. Interestingly, the boundary element modeling approach developed by Crouch and Starfield (1983, p. 208–210) and used by many researchers in geologic fracture mechanics clearly illustrates how both of these types of structures can be easily represented by specifying the properties of the filling material along with the strengths of the enclosing walls. This mechanics-based approach parallels the geologic observations summarized in this section that motivate the integration of terminology espoused in this article.

Table 1. Suggested Terminology for 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 field 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 strength or stiffness that occurs between a pair of discrete planar surfaces
Tabular discontinuity	A structural discontinuity having a continuous change in 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 a field evidence for predominantly opening displacements between the opposing walls
Anticrack	A sharp structural discontinuity having a field evidence for predominantly closing displacements between the opposing walls
Deformation band	A tabular structural discontinuity having a continuous change in strength or stiffness across a relatively narrow zone in porous rocks
Fault	A sharp structural discontinuity defined by slip planes (surfaces of discontinuous shear 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	The volume of deformed rocks around a structural discontinuity that formed at any stage in the evolution of the structure

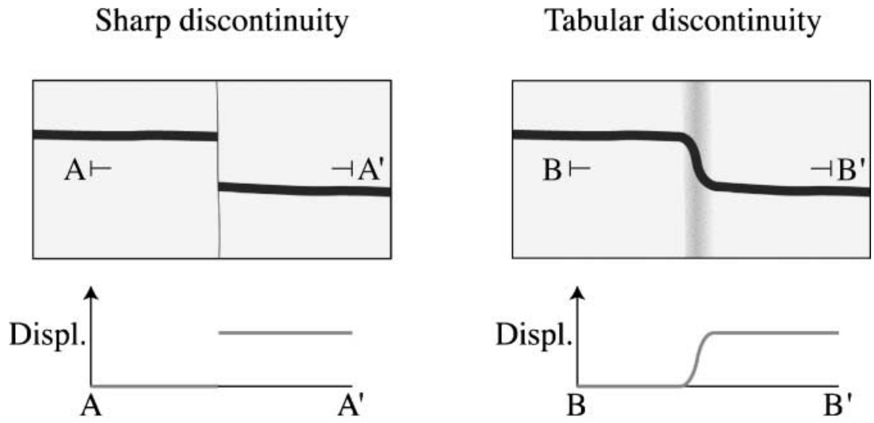
Useful terminology must also consider the scale of the structure relative to its surroundings. A geologic unit is considered to be continuous or homogeneous when its properties at the scale of the structure are statistically constant, leading to homogeneous values and behavior (Priest and Hudson, 1981). Rock units with spatially variable properties at a given scale are called discontinuous or heterogeneous. We adopt a terminology for structures that are consistent with their surroundings being characterized as effective homogeneous continua.

SUGGESTED TERMINOLOGY

On the basis of the preceding discussion, the term ''structural discontinuity'' is suggested in this article to encompass the various types of localized geologic structures discussed above. A structural discontinuity is defined here to be 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 field of originally adjacent points on the opposing walls that is small relative to the longest dimension (Table 1).

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). Sharp structural discontinuities (Figure 2) have a discontinuous change in strength and/or stiffness that occurs between a pair of discrete planar surfaces; sharp discontinuities are associated with a stepwise change in the displacement distribution across them, leading to the mechanically

Figure 2. Schematic illustration of the rate of change of displacement (Displ.) across a structural discontinuity.



descriptive terms "displacement discontinuity" (e.g., Crouch and Starfield, 1983, p. 80–84; Pollard and Segall, 1987; Pollard and Aydin, 1988) and "strong discontinuity" (Borja, 2002; Aydin et al., 2006) in the theoretical mechanics literature. Tabular structural discontinuities have a continuous change in strength and/or stiffness that occurs across a relatively thin band (i.e., continuous shearing across a tabular structure 1 mm [0.03 in.] thick). These structures show a continuous change in normal or shear strain (i.e., an increase in the displacement gradient) across them and were called "weak discontinuities" by Borja (2002) and Aydin et al. (2006). Note that, in this context, weak does not imply that these structures are mechanically weak, which they may or may not be. We therefore prefer the term "tabular discontinuities" over weak discontinuities (Table 1).

In general, a good correlation between the width of the structure and the displacement continuity is seen, especially in the early development of a structure (Aydin et al., 2006). Specifically, 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, however, is one in which the thickness of the structure that accommodates most of the offset is clearly resolvable in hand sample or outcrop. This corresponds to a band with a thickness exceeding a few grain or block diameters, typically exceeding 1 mm (0.03 in.). Sharp discontinuities typically are associated with stepwise, discontinuous displacement gradients across them, whereas tabular ones exhibit more gradual and continuous displacement gradients (Figure 2). A detailed view of compaction bands, which are a type of deformation band, shows how the thickness of a tabular discontinuity can attain values of several centimeters (Figure 3).

The term discontinuity refers to the dimensions parallel to the structure, such as horizontal length or vertical (or downdip) height. In general, the 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 localized structures having either abrupt or continuous changes in displacement across them.

A fracture is a subtype of structural discontinuity. Following the intent of the literature and the foregoing discussion, a fracture is defined here as a sharp structural discontinuity having a local reduction in strength and/or stiffness and an initial increase in fluid conductivity between the opposing pair of surfaces; the displacement is discontinuous across the fracture. Cracks, joints, and faults are all different types of fractures (Table 1).

Most geologic fractures are brittle structures, in the sense (Rutter, 1986; Knipe, 1989) that they break or shear the rock using pressure-dependent deformation mechanisms (e.g., grain cracking and frictional sliding). 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).

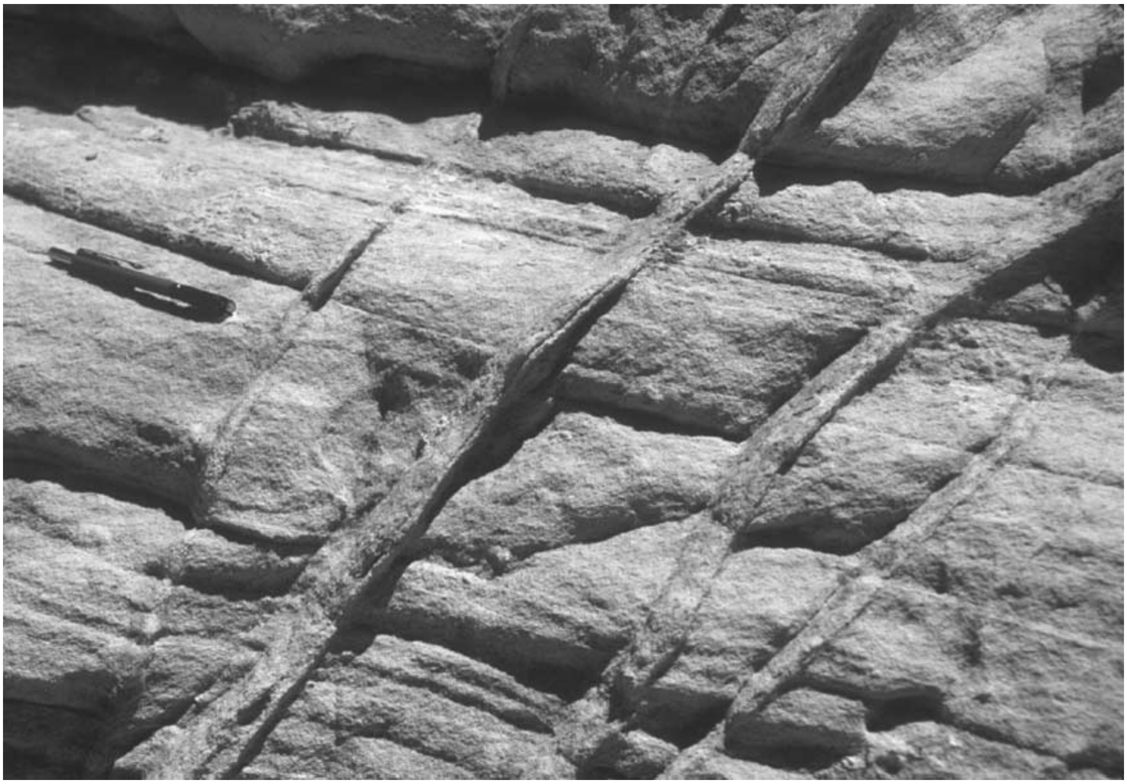


Figure 3. Compaction bands (tabular discontinuities) in Navajo Sandstone from southern Utah attain maximum thicknesses exceeding 1 cm (0.39 in.) (pencil along bedding for scale). Sedimentary bedding is not offset along the bands, indicating a predominantly contractional strain between the two well-defined band walls. The bands are discontinuous in dimension but continuous in displacement.

A kinematic classification of structural discontinuities is constructed by evaluating the sense, and continuity, of displacement relative to the plane of the structure. In the field, the geologist would examine and demonstrate the two key parameters: displacement sense and displacement continuity, as shown in Figure 4. Assessing the displacement sense is straightforward, as the methods of cross-cutting 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).

The issue of whether a fault should be considered to be a single, solitary structure or a zone can now be considered. As emphasized by many, including Aydin and Johnson (1978), Johnson (1995), Crider and Peacock (2004), Davatzes et al. (2005), and Schultz and Siddharthan (2005), a fault is an end-product of shearing in a rock, and there is more to a fault than just the slip surface (e.g., Rice, 1992; Caine et al., 1996; Aydin, 2000; Mandl, 2000; Shipton and Cowie, 2001; Scholz, 2002). Certainly, the fault plane that is recognized by geologists by its smooth, polished, and grooved or corrugated surface accommodates a large fraction of the offset, but other elements that formed before and after the fault plane nucleated are also important to recognize and include as parts of the structure (Figure 5). The definition of a fault as a pair of planes that accommodates the offset is necessary, but not sufficient, to encompass the major characteristics of this important structure.

Based on the foregoing discussion, a fault is primarily a sharp structural discontinuity, defined by its

Figure 4. 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).

DISPLACEMENT SENSE	DISPLACEMENT CONTINUITY: Sharp Discontinuity	DISPLACEMENT CONTINUITY: Tabular Discontinuity
Opening	Crack (Joint, Dike, Sill, Hydrofracture)	Dilation band Dilational shear band
Shearing	Fault; also Slip surface	Shear band; also Shear zone
Closing	Stylolite	Compactional shear band Compaction band

fault planes (surfaces of discontinuous displacement) and related structures, including fault core and damage zones (e.g., cracks, deformation bands, slip surfaces, and other structural discontinuities) that formed at any stage in the evolution of the structure (Table 1). Commonly associated structures, such as drag or faulted fault-propagation folds, are associated elements not included in the term fault, although clay smearing or other early forms of strain localization may be included. A fault zone is a set of relatively closely spaced faults having similar strikes. A brittle shear zone is 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. In order of maturity, or degree of strain localization, a brittle shear zone precedes a fault, which precedes a fault zone.

THE ROLE OF LITHOLOGY AND ROCK PROPERTIES

The physical properties of a rock affect its strength, deformability (see Bell, 1993, p. 165–179; Evans and Kohlstedt, 1995, for concise syntheses), and the types of structural discontinuities that form within it (see also Crider and Peacock, 2004). One such property, the porosity of the rock, exerts a primary influence on the type of structural discontinuities that form (see reviews and discussions by Wong et al., 1992; Fossen et al., 2007) and on the resulting permeability of the discontinuity relative to that of the host rock.

A good correlation between the amount of porosity in a rock or sediment and the volumetric changes it undergoes during deformation (e.g., Wong et al., 1992, 2004; Evans and Kohlstedt, 1995; Davis and Selvadurai, 2002) is observed. For example, a compact rock (Paterson and Wong, 2005) with

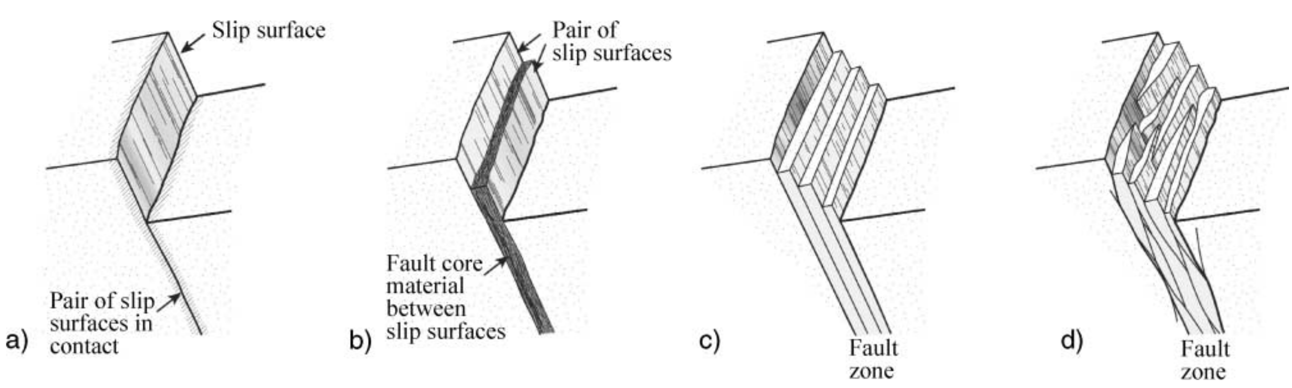


Figure 5. Illustration of a fault and related structures.

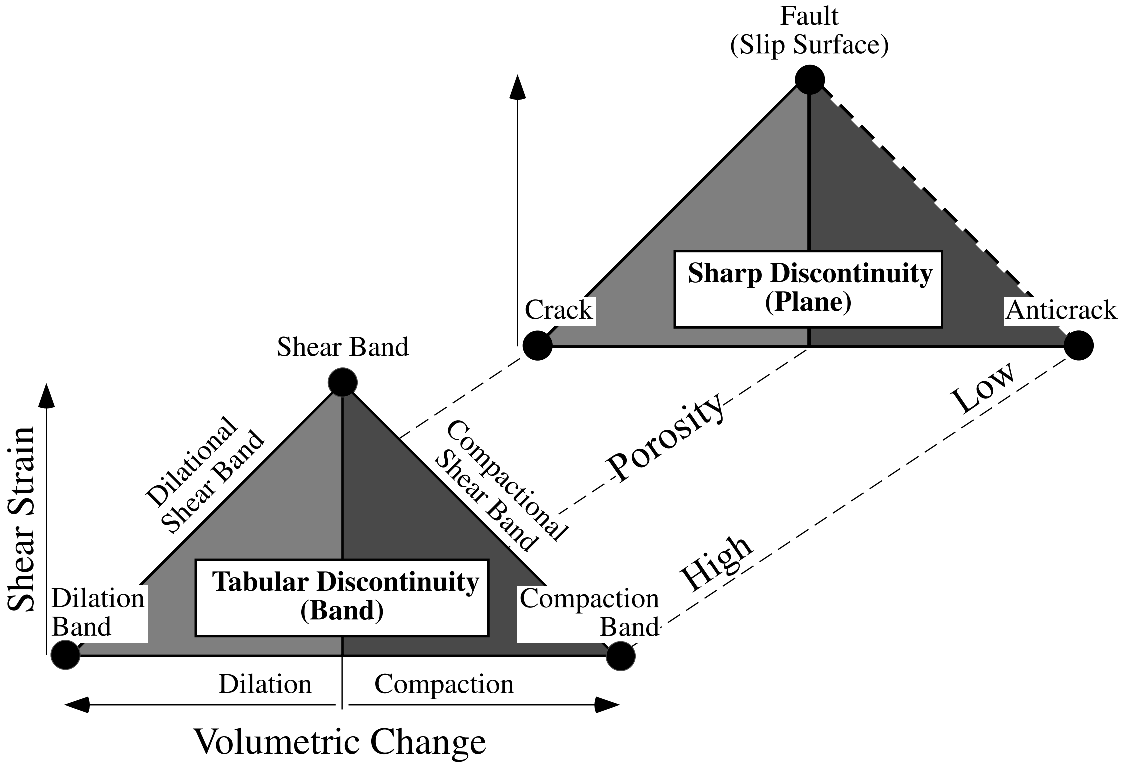


Figure 6. Classification of structural discontinuities in relation to the porosity of the host rock. The lower left diagram assumes a porous host rock, such as sandstone, chalk, and many limestones and tuffs. Tabular discontinuities (deformation bands) form most easily in porous rocks, with the type of band depending on the relative amounts of shear strain and volume change they accommodate. The upper right diagram assumes a compact (low porosity) rock, such as a granite, gneiss, or basalt. Sharp discontinuities (fractures) characteristically form in these rocks. In particular cases, anticracks (stylolites) may form given appropriate conditions of pressure, temperature, and host-rock composition. Although sharp discontinuities can also form in porous rocks, tabular discontinuities rarely, if ever, occur in compact rocks.

negligible porosity, such as a granite, or a low-porosity soil (called ''overconsolidated''), typically expands in volume during shearing, leading to dilatant behavior and localized zones of concentrated shear. In contrast, a rock with high porosity (>10–20%), or a high-porosity sediment (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 macroscopic flow (e.g., Evans and Kohlstedt, 1995; Paterson and Wong, 2005).

The porosity of a rock influences the type of structural discontinuity, i.e., sharp or tabular, that forms within it (e.g., Johansen et al., 2005; Aydin et al., 2006). Tabular structural discontinuities (deformation bands) in the brittle regime form in high-porosity rocks, such as sandstone, chalks, some pyroclastic tuffs, and highly porous limestones, whereas sharp structural discontinuities (joints and faults) form in rocks with any value of porosity. Although other variables, such as stress state, mineralogy, and pore-water conditions, appear to influence the type of structural discontinuities that form in a rock, tabular structural discontinuities are clearly restricted to formation in rocks having the larger values of porosity characteristic of reservoir rocks.

This dichotomy in structure type (sharp vs. tabular structural discontinuities), for compact or porous rocks, is illustrated in Figure 6. Here, the kinematics of the structural discontinuities also must be specified before the structural discontinuities can be named. By specifying the kinematics, a broad class, such as deformation bands (see also Figure 4), can be divided into its five kinematic classes (i.e., dilation bands, dilational shear bands, shear bands, compactional shear bands, and compaction bands), depending 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.

PERMEABILITY AND PETROPHYSICAL PROPERTIES

Discontinuities have a range of petrophysical properties that make them somewhat unpredictable in a petroleum reservoir (e.g., Aydin, 2000; Fossen et al., 2007). In general, sharp discontinuities conduct fluids in the strike and dip directions, and thus improve permeability, particularly in compact, nonporous rocks. This is the case where petroleum accumulations occur in fractured basement rocks (Landes et al., 1960; Koning, 2003), and are also important in highly porous and low-permeable reservoir rocks such as the chalk reservoirs of the southern North Sea (Agarwal et al., 1997). Fracturing of cap rocks, particularly during uplift, deformation, and folding, can also create increased permeability that allows hydrocarbons to leak out of the trap (Roberts and Nunn, 1995; Wang and Xie, 1998). Sharp discontinuities occurring in highly porous rocks can also restrict flow perpendicular to the structures. This effect occurs because of the thin zone of very fine-grained cataclastic fault rock that occurs in association with slip surfaces.

Tabular discontinuities with a component of compaction generally reduce porosity and permeability. Because compactional shear bands are the most common type of tabular discontinuity encountered in highly porous rocks (e.g., Aydin et al., 2006; Fossen et al., 2007), this is the most common effect such structures have in petroleum reservoirs. Dilation bands are less frequently observed, although dilation is thought to occur at an early (low-strain) stage during the development of shear bands (Aydin and Johnson, 1983; Parry et al., 2004). The practical consequence of dilation associated with tabular discontinuities is currently thought to be negligible given the apparent rarity of these types of structures. The negative effect of compactional shear bands on fluid flow is greater, with reported reductions in permeability up to several orders of magnitude (e.g., Antonellini and Aydin, 1994; Lothe et al., 2002). However, because of their narrow thickness, they must occur in large numbers to significantly reduce productivity (Fossen and Bale, 2007). Anticracks in the form of stylolites are common in carbonate reservoirs, where they represent clay-rich seams that likely hinder fluid flow across them. Faults are composite structures containing both sharp and tabular discontinuities, as discussed above. Hence, their petrophysical properties in a reservoir situation are variable and not always easy to predict, as discussed by several authors (Childs et al., 1997; Yielding et al., 1997; Aydin, 2000; Bailey et al., 2002).

CONCLUSIONS

The classification framework described in this article for structural discontinuities encompasses all three end members of kinematics (opening, shear, and closing displacements) for two classes of rocks (compact and porous). The framework can easily be expanded to accommodate varieties of structural discontinuities that occur in rocks that localize strain by different mechanisms such as may be found in carbonate or clay-rich rocks.

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