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Excerpt
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1 Introduction

1.1 Aims

Rock fractures occur in a variety of geological processes and range in size from plate boundaries at the scale of hundreds of kilometres to microcracks in crystals at the scale of a fraction of a millimetre. This chapter provides a definition of a rock fracture as well as of some of the mechanical concepts used in the analysis of fractures. Some of these definitions are preliminary and more accurate ones will be provided in later chapters. The primary aims of this chapter are to:

- Provide a definition of a rock fracture.
- Indicate some of the many earth-science topics and processes where fractures play a fundamental role.
- Provide definitions of stress, strain, constitutive equations, and material behaviour.
- Explain the one-dimensional Hooke's law.
- Summarise some basic fracture-related definitions in structural geology.
- Discuss the basic information needed to solve fracture problems.
- Define and explain boundary conditions, rock properties, and rock-failure criteria.
- Explain accuracy, significant figures, and rounding of numbers.
- Explain the basic units and prefixes used.

1.2 Rock fractures

A **rock fracture** is a mechanical break or discontinuity that separates a rock body into two or more parts (Fig. 1.1). The continuity or cohesion of the rock body is lost across a fracture. A fracture forms in response to stress. More specifically, the rock breaks and forms a fracture when the applied stress reaches a certain limit, namely the **rock strength**. The stress associated with the fracture formation may be normal or shear or both. An ideal **brittle fracture** shows no effects of plastic (or ductile) deformation on the fracture surface. Thus, the two halves of a solid body broken by an ideal brittle fracture can be fitted back together perfectly. For rocks and most solid materials, however, there is normally some, and sometimes considerable, plastic deformation associated with the propagation of a fracture, particularly at its tips.

Fig. 1.1 Tension fracture in the rift zone of North Iceland. View (looking) north, the fracture is located in a Holocene (less than 10 ka-old) pahoehoe (basaltic) lava flow. Behind the persons is a normal fault in the same lava flow. Tension fractures such as this one form when the tensile stress in the rock reaches its tensile strength (0.5–6 MPa). The somewhat irregular shape of the fracture is largely attributable to its path being partly along existing (mainly hexagonal) columnar (cooling) joints in the lava flow.

As a noun, the word ‘fracture’ denotes the structure, the **crack**, but as a verb it indicates the **process** by which the material breaks or the crack forms. Thus, we distinguish between a rock fracture (a noun), namely a structure, and to fracture a rock (a verb), which means the process responsible for the fracture formation. In the latter sense, the word fracture is often regarded as being synonymous with **rupture.**

Rock fractures are the most common outcrop-scale structures in the Earth’s crust (Figs. 1.1–1.5). Their sizes vary from microcracks that dissect small grains or crystals to mid-ocean ridge segments and transform faults that form parts of the boundaries of the Earth’s lithospheric plates.

The way by which fractures form and develop plays a vital role in many theoretical and applied fields of earth sciences and engineering. Fields within the earth sciences where rock fractures are of fundamental importance include structural geology, tectonics, volcanology, seismology, field geology, hydrogeology, geothermics, geological hazard studies, and petroleum geology and geophysics. Fields within engineering where rock fractures play an important role include general rock mechanics, tunnelling, civil engineering, petroleum engineering, and general engineering geology.

As an example of the importance of fractures in geological processes, consider volcanic eruptions. Most of the magma transported to the surface in volcanic eruptions such as the one in Fig. 1.2 is through rock fractures that are driven open by the magma pressure. When the magma in the fractures solidifies, they become inclined sheets (Fig. 1.2) or subvertical dykes (Fig. 1.3). Other examples of fluid transport through rock fractures are mineral veins

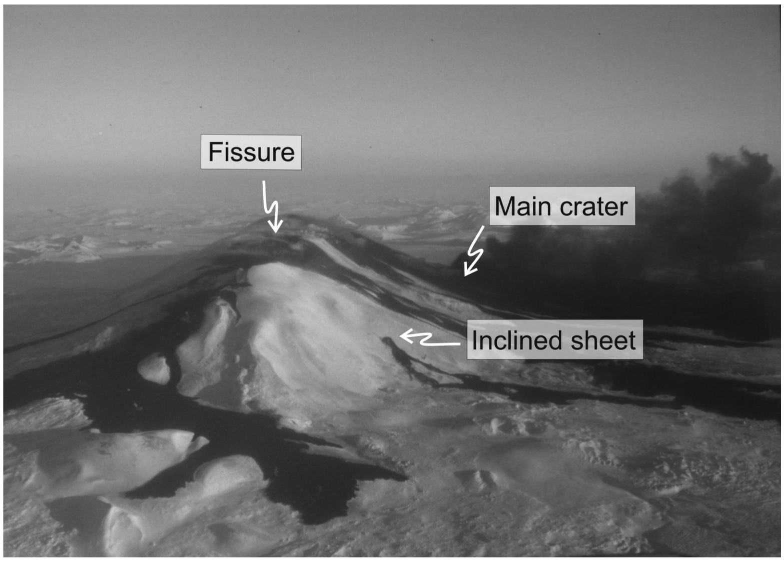

Fig. 1.2 Eruption of the volcano Hekla in South Iceland in January 1991 was partly through vertical dykes (the main volcanic fissure along the top of a volcano) and partly through inclined sheets (seen on the slopes of the volcano). Dykes and inclined sheets are hydrofractures or, more specifically, magma-driven fractures. Hydrofractures and tension fractures (Fig. 1.1) are both extension fractures.

(Fig. 1.4). The veins form as a result of transportation of hot water in geothermal fields, in volcanic areas as well as in sedimentary basins. Also, all tectonic earthquakes are related to fractures; more specifically, to faults (Fig. 1.5).

1.3 Notation and basic concepts

A rock fracture forms when certain mechanical conditions are satisfied. To solve mechanical problems associated with rock fractures, such as their initiation, propagation paths, and fluid transport, we must understand and use some basic concepts from the mechanics of solids and fluids.

Many of the concepts and techniques discussed in the following chapters are well known in such earth-science fields as hydrogeology, reservoir engineering, petrophysics, earthquake mechanics, rock mechanics, rock physics, and structural geology. However, many of the definitions used are primarily applicable to one or two of these special fields and are not easily translated into a useful conceptual framework for other fields. Furthermore, the notation used in the different fields varies widely and may lead to confusion. In this book a unified notation is adopted as far as is possible, and all the formulas and concepts are presented in such a way that a solution of a fracture problem in one field of earth sciences can be easily applied to another.

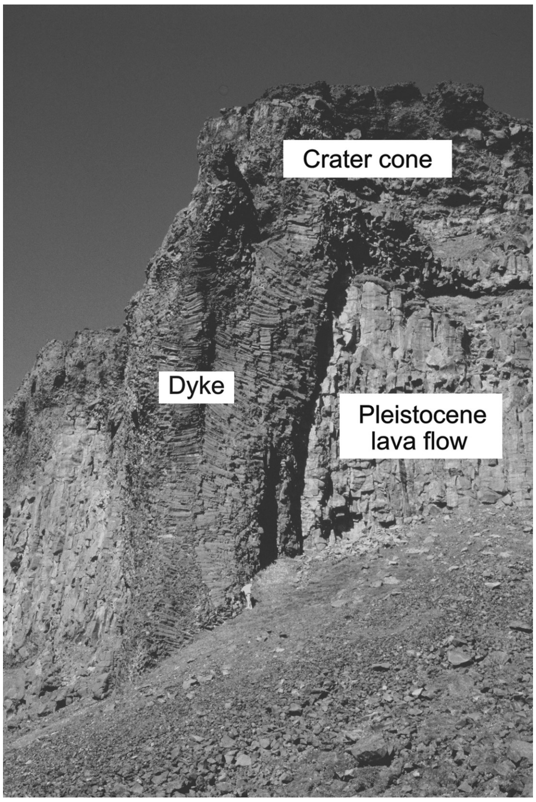

Fig. 1.3 Vertical dyke exposed in a river canyon in North Iceland. View northeast, the dyke is the feeder of (it supplied magma to) the crater cone and associated lava flow. The dyke is of Holocene age, about 6 m thick in the lower part of the exposure, but about 13 m thick where it meets the crater cone (cf. Fig. 1.6; Gudmundsson *et al.*, 2008).

Clearly, however, some **symbols** must be used in more than one meaning. This follows for two reasons. First, there are more parameters and constants used in the equations than there are letters in the alphabets used. Second, the standard notation in each field is followed as much as possible. For example, the Greek letter μ (mu) is commonly used for dynamic viscosity in fluid mechanics and hydrogeology, and is thus used in the equations for fluid transport in rock fractures. But μ is also the standard symbol for an important concept in rock physics, namely the coefficient of internal friction. Even in solid mechanics the same symbols are used in different meanings. For example, the letter G is commonly used for an elastic constant called shear modulus (the other commonly used symbol for that constant is μ, which already has two other meanings). But G is also a standard symbol in fracture mechanics for a concept referred to as the energy release rate during fracture propagation. Normally, the different meanings of the symbols are clear from the context. However, to make the meaning as clear as possible, and to make the chapters more readable and the mathematics easier to follow, most symbols used are defined where they first occur in each chapter, and commonly the definition is repeated in the chapter. In addition, a list of the main

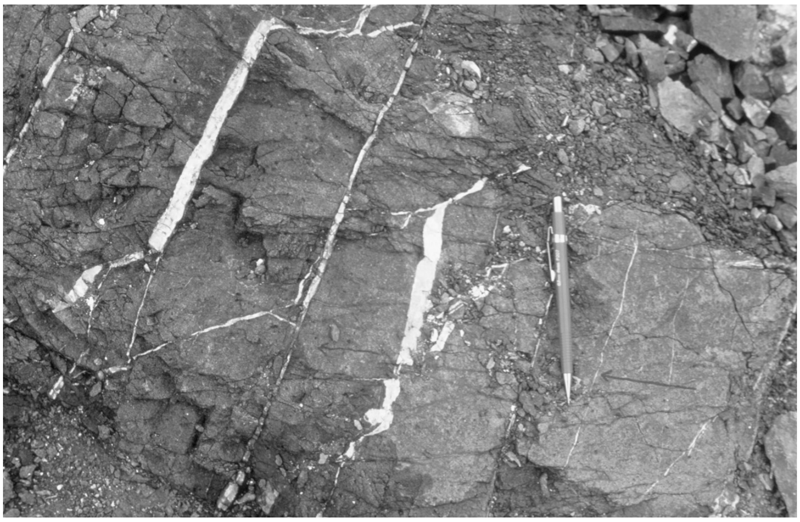

Fig. 1.4 Mineral veins seen in a horizontal section (at the surface) of a basaltic lava flow in North Iceland. Most mineral veins are extension fractures, that is, hydrofractures. The 15-cm-long pencil provides a scale.

symbols used is provided at the end of most chapters. While this makes the text somewhat longer, it should be of help to many readers and make it easier to read the chapters and sections of chapters, and to use the equations, independently of the rest of the book.

Many important words, concepts, facts, and definitions are printed in **bold**. **Figures** are referred to as follows: Figure 1.5 or (Fig. 1.5) indicates figure number 5 in Chapter 1, as is done above. In the photographs, the view indicated means the direction in which the photographer is looking. Thus, **view north** means that the photographer was looking (facing) north when the photograph was taken. All **formulas** and **equations** are referred to by numbers in parentheses. Thus, Eq. (1.2) means equation number 2 in Chapter 1. **Worked examples** at the ends of chapters are referred to by numbers. Thus, Example 5.1, or (Example 5.1), refers to details that are given in example number 1 in Chapter 5. Some examples are derivations of formulas, but most are calculation exercises where specific numerical data are given, commonly taken directly from the technical literature. In **Appendices A–E** at the end of the book there are data on crustal rock and fluid properties as well as lists of the base SI units (and many derived units), the SI prefixes (such as kilo, mega, and giga), the Greek alphabet, and some mathematical and physical constants. While the examples commonly use data that may differ somewhat from those in Appendices D and E (data on rocks and crustal fluids), the appendices should be useful in solving some of the **Exercises** at the ends of the chapters, as well as solving general problems related to rock fractures and associated fluid transport. Most exercises refer only to the material of the chapter to which they belong, but some assume knowledge of the earlier chapters as well.

The purpose of this section is to provide preliminary explanations and definitions of some of the main concepts used in the book. More accurate definitions and detailed discussions of many of these and related concepts are provided in the subsequent chapters. Analysis of

Fig. 1.5 Part of a normal fault in the rift zone of Southwest Iceland. View northeast, the normal fault, located in a Holocene pahoehoe lava flow, has a vertical displacement (throw) of about 40 m, and an opening (aperture) of as much as 60 m. The cars on the roundabout provide a scale.

rock fractures requires an understanding of stress, strain, and the stress–strain relations. A brief preliminary definition and clarification of these topics should thus be helpful.

1.3.1 Stress

Stress is a measure of the intensity of force per unit area. The unit of stress is the pascal, Pa, where 1 Pa = 1 N m^{-2}. Using this simple definition, the formula for stress σ is

$$\sigma = \frac{F}{A} \tag{1.1}$$

where F is the force in newtons (N) and A is the area in square metres (m^2) on which the force acts. We use the symbol σ when the force that generates the stress is normal to the area on which it acts. Thus, σ is the **normal stress** (Fig. 1.6). When a force operates parallel with the plane of interest, such as a fault plane, it is a shear force and generates shear stress.

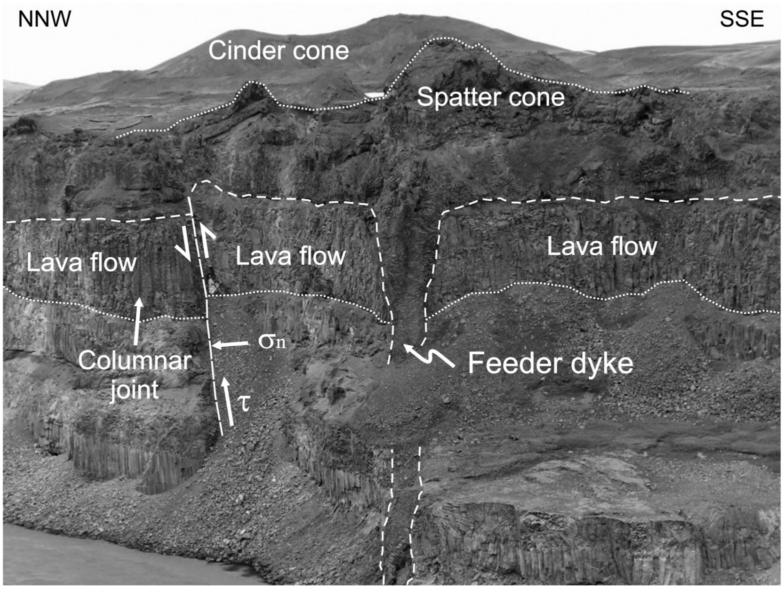

Fig. 1.6 Normal stress σ_n and shear stress τ on a reverse fault close to the feeder dyke in Fig. 1.3. The fault is presumably an old normal fault that was reactivated as a reverse fault due to the horizontal stress generated by the pressure of the nearby feeder dyke. The normal stress on the reverse fault is denoted by σ_n and the shear stress by τ. The contacts (dotted lines) between the lava flows, as well as their columnar joints (primarily vertical fractures), are indicated (cf. Gudmundsson *et al.*, 2008).

We use the symbol τ for **shear stress**, so that

$$\tau = \frac{F}{A} \tag{1.2}$$

where F is here the shear force (or force component) acting parallel with a plane whose area is parallel with the direction of the force is A.

Stress as defined in Eqs. (1.1) and (1.2) is really a **vector** and referred to as the **traction,** the **traction vector,** or the **stress vector.** To explain why it is a vector, recall that vector quantities have both size (or magnitude) and direction. The direction is the line of action of the quantity. By contrast, **scalar** quantities have only size (or magnitude); no other information is needed to specify them. For example, if a fault length is specified as 10 km, then 10 km is a scalar quantity. Similarly, temperature, mass, and time are scalars. The velocity of tectonic-plate movements, specified at a point as 10 mm per year due east, is a vector quantity. Similarly, a force of 100 N at an angle of 30° to a fault plane striking due north as well as a geothermal gradient (the rate of temperature increase with depth in the crust) are vector quantities.

The quantity in Eq. (1.1) is a vector because force is a vector and area A is a scalar and so is its reciprocal, A^{-1}. The product of a vector and a scalar is a vector, so that σ in Eq. (1.1) is a vector. As is explained in Chapter 2, the **state of stress at a point** is the collection of all stress vectors, for planes of all possible directions, at that point. This three-dimensional collection of stress vectors specifies the complete stress at the point and is not a vector but rather a second-order tensor. Thus, **stress is a tensor**, not a vector. But the **component** of the stress in any particular direction is a vector. In geology, materials science, and mechanical engineering it is common to refer to the stress in a given direction; for example, the stress on a fault plane or stress on a crystal slip plane. In this book, we shall not use the term traction (for the stress vector), but rather stress, both for the stress vector and the stress tensor.

In mechanical engineering, materials science, and the mathematical theory of elasticity, tensile stresses are much more common and important than compressive stresses. This follows because fracture propagation in, say, an aeroplane or a geothermal pipe at the surface is much more likely to be due to tensile stresses than compressive stresses. As a consequence, tensile stresses are considered positive and compressive stresses negative. In geology, geophysics, rock mechanics, and soil mechanics, however, compressive stresses dominate. Almost anywhere in the Earth's crust, there are compressive stresses. Only the uppermost parts of areas of active rifting, or the contact zones with fluid-filled reservoirs, are likely to develop outcrop-scale tensile stresses. Thus, in these scientific fields tensile stresses are commonly regarded as negative, whereas compressive stresses are positive.

It is generally recognised that it is more natural to derive many of the basic equations for stress, strain, and elasticity on the assumption of tensile stress being positive. However, Mohr's circles of stress (Chapter 2), for example, look awkward if a tension-positive convention is used in geology. Some authors define tensile stress and strain as positive while deriving the main equations and then as negative (and compressive stress and strain as positive) in geological and geophysical applications (Jaeger, 1969). Others use the definition that a positive displacement will always act in a negative coordinate direction (Davis and Selvadurai, 2002). And there are other variations on this theme. In this book **tensile stresses** (and **strains**) are generally regarded as **negative** and **compressive** stresses and strains as **positive**. The negative signs for tensile stresses and strains, however, are commonly omitted, since it is clear from the discussion that they are implied. Also, some stress and strain values are treated as absolute values, in which case the signs are also omitted. This should not cause any confusion since the signs are carefully explained in all the worked examples.

1.3.2 Strain

When loads are applied to a solid rock body, it deforms. The deformation of the body can occur in three main ways, namely through rigid-body translation, rigid-body rotation, and changes in its internal configuration. In this book, only the last type of deformation, that is, changes in the internal configuration of the body, is referred to as strain. Some authors use strain and deformation roughly as synonyms, but here strain is regarded as only one of three ways by which a solid body can respond to loads. The other two ways, rigid-body translation and rotation, are **deformation but not strain.**

More specifically, the fractional change in a dimension of a rock body subject to loads is **strain**. For an elongated body, such as a bar-shaped piece of rock, subject to tensile or compressive force, strain is the ratio of the change in length or extension of the body, ΔL, to its original length L. Denoting strain by the symbol ε we have, for one-dimensional tensile

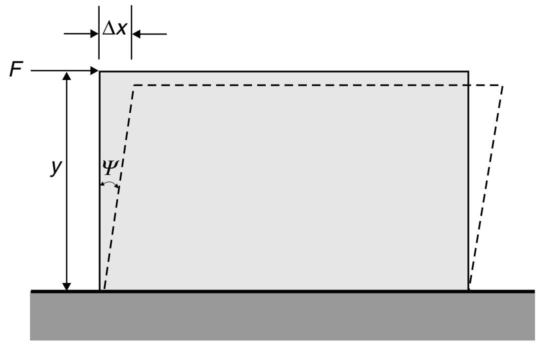

Fig. 1.7 Shear strain γ defined. The deflection or movement of the upper face of the body relative to the lower face is Δx, y is the vertical distance between the faces, and Ψ is the angle generated by the deflection.

strain,

$$\varepsilon = \frac{\Delta L}{L} \tag{1.3}$$

Since Eq. (1.3) represents a length divided by a length, ε is dimensionless, that is, a pure number, and has **no units**. Strain is often expressed as a percentage, that is,

$$\varepsilon\% = \frac{\Delta L}{L} \times 100 \tag{1.4}$$

Equation (1.3) gives one-dimensional **normal strain**. For a shear force F, the **shear strain** γ is given by

$$\gamma = \frac{\Delta x}{y} = \tan \psi \tag{1.5}$$

where Δx is the deflection or movement of the upper face of the body relative to the lower face, with y being the vertical distance between the faces (the height of the body) and ψ the angle generated by the deflection (Fig. 1.7).

1.3.3 Mechanical behaviour

Several concepts from solid mechanics should be introduced at this stage to make the subsequent discussion more precise. These concepts relate to the general mechanical behaviour of materials; here the focus is on rocks. Many of these concepts are given a more rigorous definition in subsequent chapters. These and the following definitions from structural geology (Section 1.4) are presented in a brief, summary fashion. You may want to skip them on first reading, and come back to them when needed while reading other chapters.

By the **mechanical behaviour** of a rock we mean how the rock responds to forces or loads: more specifically, what relation between force and displacement or between stress and strain the rock shows when loaded. In solid mechanics, the word **load** normally means the forces, stresses, or pressures applied to the body and external to its material. In geology, loading can also refer to displacements applied to a rock body. Under load, the rock may deform elastically or fracture or flow. The way the rock deforms under load varies depending on the mechanical properties of the rock, the strain rate, the temperature, and the state of stress. Rock behaviour can be described by several ideal models. In mechanics and materials science these models, which describe the behaviour of ideal materials based upon their internal constitution, are referred to as **material equations** or **constitutive equations**.

If the rock reverts to its original shape when the load is removed, the rock behaviour is **elastic.** Strictly, for a rock behaviour to be elastic, its return to the original shape once the load is removed should be instantaneous. If the rock behaviour follows Hooke's law, as described below, it is referred to as **linear elastic**. Under short-term loads, particularly at low temperatures and pressures (close to the Earth's surface), most solid rocks behave as approximately linear elastic so long as the strain is less than about 1%. Many rocks, because they contain pores that are partly or totally filled with fluids, show time-dependent shape recovery. Such a time-dependent elastic behaviour is called **viscoelastic** (also poroelastic). If the rock does not return to its original shape when the applied load is removed, its behaviour is **inelastic**.

Some rocks, when a critical stress is reached, behave as **plastic**. Plastic deformation is permanent; when the load is removed, the rock does not return to its original shape. Plasticity means that the rock is permanently deformed by a load without developing a fracture. For plastic deformation or flow to occur in a rock body, a certain stress level must be reached or exceeded. This stress level, at which plastic deformation occurs, is known as the **yield stress**. In some materials, plastic deformation occurs as soon as the yield stress is reached. Many rocks, however, show time-dependent plastic deformation. Such a time-dependent plastic deformation, which is common at high temperatures and pressures in the lower crust and in the mantle, is called **creep**.

Commonly, there is some plastic deformation in a rock before it fractures. If the plastic deformation before fracture is minor and essentially limited to a region close to the tip of the fracture, then the rock behaviour and the fracture are said to be **brittle**. Thus, the brittleness of a rock is indicated by a fracture developing without appreciable prior plastic deformation. If, however, there is extensive plastic deformation in the rock before fracture, the fracture is said to be **ductile** and the rock is said to be **tough**. Fractures may thus be classified as brittle or ductile according to the strain in the solid at which they occur. With brittle fracture, there is little if any plastic deformation and change of body shape before fracture. Many rocks, particularly close to the Earth's surface, fail through the development of brittle fractures. When ductile fractures form, the plastic deformation that begins once the yield stress is reached reduces the cross-sectional area of a part of the body, say the central part of a bar under axial tension, resulting in **necking**. The fracture that eventually develops in the necked region is the result of shear stresses; that is, the ductile fracture occurs when the material shears at 45° to the direction of the axial tension. Some rock fractures, particularly those formed at high temperatures and pressures, may be described as ductile.

A tough material absorbs a great deal of energy before it fractures. **Toughness** is a fundamental concept in fracture mechanics in general and in the mechanics of rock-fracture formation in particular. If no fracture develops in the rock when loaded but rather large-scale