Fracture, Fracture Everywhere

Part I

RASOUL SORKHABI, Ph.D.

Rock fractures are ubiquitous because rocks in the Earth's upper crustal levels are brittle. However, fractures show considerable variations due to their origin, geometry and rock properties. Given the petroleum industry's major shift in recent years to exploit tight reservoirs, there is now greater interest in rock fracture studies because open fractures, whether natural or hydraulic, provide the essential permeability for fluid flow in such reservoirs. A fresh understanding of rock fractures is thus timely. In this two-part article, we first review the geometry and characteristics of rock fractures. In part two, the geomechanics of fractures will be discussed.

The term 'fracture' includes any break or **structural discontinuity** in rocks in which two rock fracture surfaces (usually planar) are separated by a narrow slit, far shorter than the length or height of the fracture. Fracturing happens because of the **loss of cohesion** in the rock and is a typical expression of **brittle deformation** in the Earth's upper crust (in contrast to the flow and folding structures which occur at crustal depths under ductile conditions).

Fractures are the most common structural features that are found in all types of rocks (igneous, sedimentary and metamorphic) and in all plate-tectonic settings, from continental rifts and mid-ocean ridges to subduction trenches and continental collisions. Knowledge of fractures is important for scientific, technological as well as economic purposes. Fractures are essential parts of the geological processes that form mountain belts, sedimentary basins, coastlines, ocean floors, earthquakes, and so on. Fractures also provide fluid pathways for the movement of groundwater, oil and gas, ore deposits, and magma.

Scientific investigations of fractures date back to the nineteenth century and have grown rapidly in recent decades. These investigations include rock observations and structural mapping at micro and macro levels, experimental and analogue works, geometrical and geomechanical analysis, and numerical modelling and simulation.

In petroleum field operations, we often distinguish

Well-developed joint sets on flagstones at St. Mary's Chapel, Caithness, Scotland.

Mike Norton/Wikipedia

between **natural** (naturally occurring) fractures and those of **drilling-induced** and **hydraulic** (induced by fluid injection for fracturing rocks) origin. Even though natural fractures are found in all rocks, they are not all the same, and the simple term of 'natural fractures' does not do justice to their complexities. Characterisation of fractures based on scientific principles and data is thus crucial for their utilisation in resource exploration and production.

Fractures Come in Various Forms

Fracturing occurs at various scales from mineral to tectonic plate, and is generated in numerous forms by a number of distinct processes. Fracture is a collective term for a variety of breaks in rocks.

On a mineral grain scale, fracture is crystal breakage along uneven or curved surfaces; it requires external force applied to the crystal. (Fracture is different from crystal cleavage, the tendency of the mineral crystal to split along one or more smooth planes, which is related to the arrangement of chemical bonding in the mineral lattice.) On a thin-section of rock specimen, we can observe micro-fractures which may be **intragranular** (restricted to individual grains) or **intergranular** (cutting across several grains).

In outcrops of sedimentary rocks, bedding planes and joints are probably the most eye-catching rock fractures. **Bedding planes** separate layers of successive sedimentary rocks due to changes in lithology or other sedimentary properties. The term **joint** was first used by miners who thought that the rocks were 'joined' along these planes like building blocks. Joints do not show visible shearing but are **dilational** (opening) or **extension fractures** formed by tensile stress. Other types of extension fractures include **fissures** (wide openings filled with air, water or other fluids), **veins** (mineral-filled), and **dykes** (vertical, wide fractures filled with plutonic or volcanic rock).

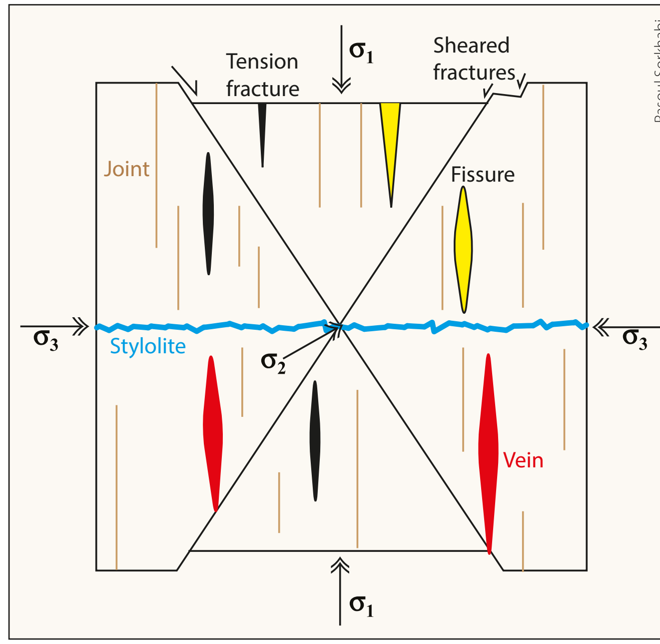
Natural fractures are found in all rocks but they are not all the same

Sheared fractures, on the other hand, show relative movement (slip) of two fracture walls parallel to the fracture plane (slip surface). Sheared fractures usually have displacements of millimetre to centimetre scale, while faults have larger displacements. Faults often have polished or striated surfaces (called slickensides) that result from frictional sliding of fault walls. Geologists can use slickenlines (grooves on the fault surface) to determine the direction of faulting.

In the petroleum and groundwater industries, fracture often refers to reservoir-scale joints and other open, extension fractures that have positive implications for subsurface fluid flow. In this limited sense, large faults, for example, are regarded as a different feature. Thus we often hear about 'fractures and faults' in reservoir rocks, which is like saying there are 'animals and dogs on our farm'. Faults indeed represent a significant type of fracturing and are genetically associated with many other types of fractures. (For various types of faults, see the two-part article 'Know Your Faults', *GEO ExPro*, Vol. 9, Nos. 5 and 6).

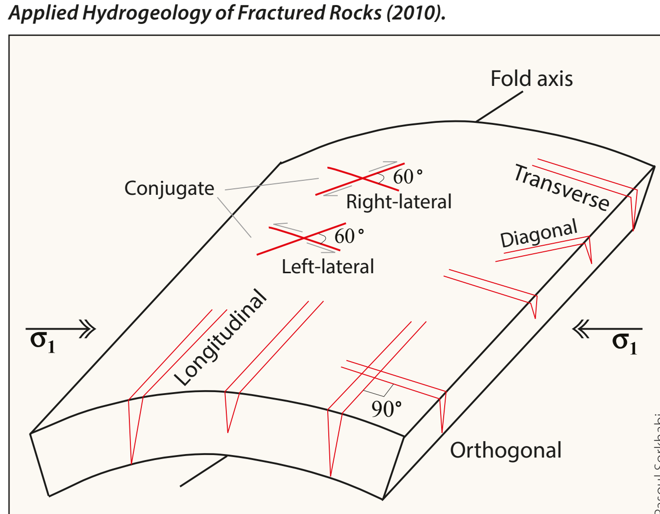
Some special types of fractures are also noteworthy here. **Mud cracks** (desiccation fractures) are polygons of extensional fractures that develop in highly clay-rich sediments due to shrinkage and loss of water. **Cleats** are natural, open-mode fractures in coal beds filled with natural gas or water. **Deformation bands** are millimetre-wide, planar features in high-porosity sandstones that show little offset but are characterised by low-porosity, low-permeability bands due to mineral grain flow, fracturing or cementation; they cluster around faults.

Some fractures form spectacular features on satellite images; they are also important for fluid movements on a crustal scale. **Lineaments** are physiographic lines on a regional extent that indicate deformation of rocks by major faulting or folding. **Ocean-floor fracture zones** extend beyond the mid-ocean ridges to continental margins.



Various types of fracture on a conjugate normal fault structure. Modified from Haakon Fossen, Structural Geology (2010).

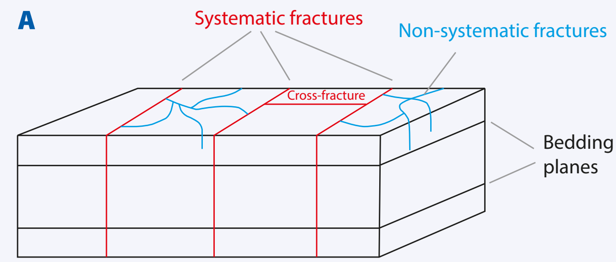
A geometric classification of fractures into longitudinal, transverse (cross), conjugate, diagonal (oblique), and orthogonal fractures developed on a fold structure. These field-based concepts were formulated by geologists in the first half of the 20th century. Modified from Singhal and Gupta, Applied Hydrogeology of Fractured Rocks (2010).



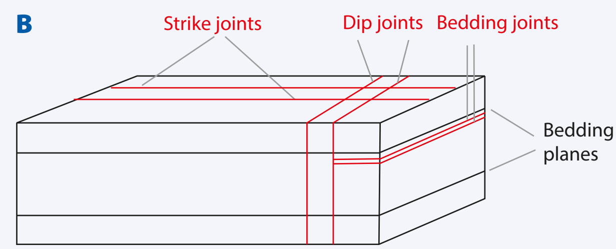
Fracture Characterisation

A comprehensive fracture characterisation involves mapping, measuring and documenting a number of parameters including the following:

1. **Type** of fracture and its **infilling** (whether open or filled).
2. Association of fracture with particular **lithology, structure** (fault, fold or no structure), deformation history (**age**), and present (in-situ) **stress field**.
3. Systematic rock fractures often develop in one or more **fracture sets**. It is important to map and quantify these fracture sets and work out their relative ages.
4. Attitude of fractures include **strike** (with respect to North) and **dip** angle (from 0° horizontal to 90° vertical) and direction (dip direction is always perpendicular to strike direction). These data can be displayed on stereographic equal-area plots. Fracture strike trends can also be plotted on a rose diagram or a histogram.
5. **Fracture length** indicates the lateral persistence of the structure. Trace lengths of <1m are very low persistence, while those of >20m are very high persistence fractures.
6. **Spacing** of fractures and its relation to bed thickness or structural position (fault-related, fold-related, or none) are crucial data. At outcrops, fracture spacing can be measured by a tape along a scanline. Observations show that very stiff layers have more joints than very weak layers; and for a given lithology, thinner beds have closely-spaced joints. The International Society for Rock Mechanics (ISRM) has recommended the following scale for classifying fracture spacing: extremely close spacing (<0.02m), very close spacing (0.02–0.06m), close spacing (0.06–0.2m), moderate spacing (0.2–0.6m), wide spacing (0.6–2.0m), very wide spacing (2.0–6.0m), and extremely wide spacing (>6.0m). Fracture frequency is defined as the number of fractures per metre length. It is thus the inverse of fracture spacing. **Fracture frequency** is equal to 1/fracture spacing.
7. **Population**: The occurrence of fractures can be quantified in 1D (fracture frequency for a given length), 2D (fracture intensity for a given area), and 3D (fracture density for a given volume).
8. **Aperture** is the perpendicular distance between the adjacent rock walls (fracture surfaces) of a fracture. It may be open (containing air, water or other fluid) or closed (infilled by fault rock or some other injected material). Aperture may be tight (<0.25mm) for closed fractures or wide (>10mm) for open fractures. Aperture decreases along the length of a fracture toward the fracture front. Aperture may also change along the height of a fracture due to asperities (see below). Often the terms 'equivalent', 'hydraulic', and 'mechanical' apertures are used depending on the methods and purpose of their estimation.
9. Fracture walls do not have perfect parallel, smooth surfaces but contain roughness and irregularities called **asperities**, which reduce fracture permeability. Some knowledge of asperities may thus help better modelling of fluid flow through the fracture.
10. **Fracture stiffness** (measured in Pascal/mm) describes the stress-deformation of the fracture with respect to normal stress (normal stiffness or resistance to closure) and shear stress (shear stiffness or resistance to shear displacement). Data on fracture stiffness are hardest to obtain because they involve geomechanical laboratory or in-situ experiments of fractured rocks.
11. **Fracture connectivity**: intersection of natural fractures provides a permeability network for fluids, whereas disconnected, isolated fractures are not hydraulically effective. The chance of fracture connectivity increases with larger population and lengths of fractures in a given rock volume.
12. **Petrophysical properties** of fractures including porosity and permeability.



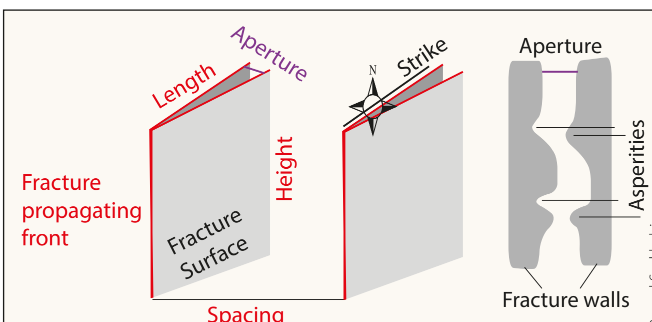
*In 1961 AAPG Bulletin (Vol. 45), R.A. Hodgson published his studies of joint patterns developed on rocks in Arizona and Utah, in which he distinguished between **systematic joints**, which are planar, parallel and evenly spaced, and **non-systematic joints**, which are irregular in their form, orientation and spacing. Systematic joints form 'pervasive fracture sets' perpendicular to bedding surfaces and may be linked by 'cross-joints'. Fracture sets may intersect at a constant **dihedral angle**; conjugate fractures have dihedral angles of 30°–60°, while orthogonal fractures are at right angles (nearly 90°). Non-systematic joints are curved and often terminate at bedding surfaces.*



*Based on the orientation of fractures with respect to bedding fractures (notably joints) are classified into **strike joints** (in plan view, parallel to the strike of bedding plane), **dip joints** (perpendicular to bedding), and **bedding joints** (parallel to bedding in both plan and vertical view).*

Rasoul Sorkhabi

Anatomy of rock fractures.

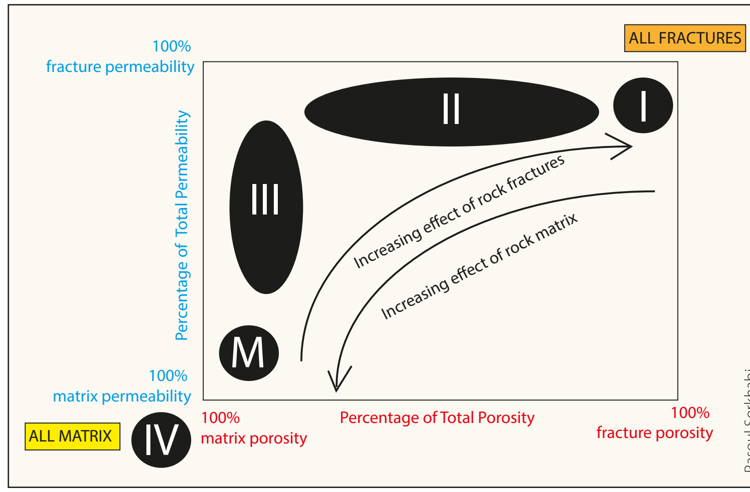


Fractured Reservoirs

All reservoir rocks are fractured to some degree and usually by more than one process. Nevertheless, the term 'fractured reservoir' refers to a tight reservoir (matrix permeability < 0.1 mD) in which natural fractures play a significant permeability role for fluid flow (water, oil or natural gas). In these reservoirs, therefore, the mapping and characterisation of fractures in a 3D geological model and the quantification of the petrophyscial properties of fractures is of paramount importance for drilling and production.

In his book *Geologic Analysis of Fractured Reservoirs*, Ronald Nelson has described a classification of reservoirs based on the porosity and permeability of both rock matrix and fractures. Four types are thus distinguished:

- In **Type I reservoirs**, fractures provide the essential porosity and permeability (e.g. Amal field, Libya; Ellenburger fields, Texas). These reservoirs have high declining curves per well.
- In **Type II reservoirs**, fractures provide the essential permeability (e.g. Agha Jari field, Iran; Rangely, Colorado).
- In **Type III reservoirs**, fractures contribute to the permeability of an already producible reservoir (e.g. Kirkuk, Iraq; Cottonwood Creek, Wyoming).
- In **Type IV reservoirs**, fractures actually act as fluid barriers (e.g. Beaver Creek, Wyoming; Houghton, Kansas). These reservoirs are structurally compartmentalised.

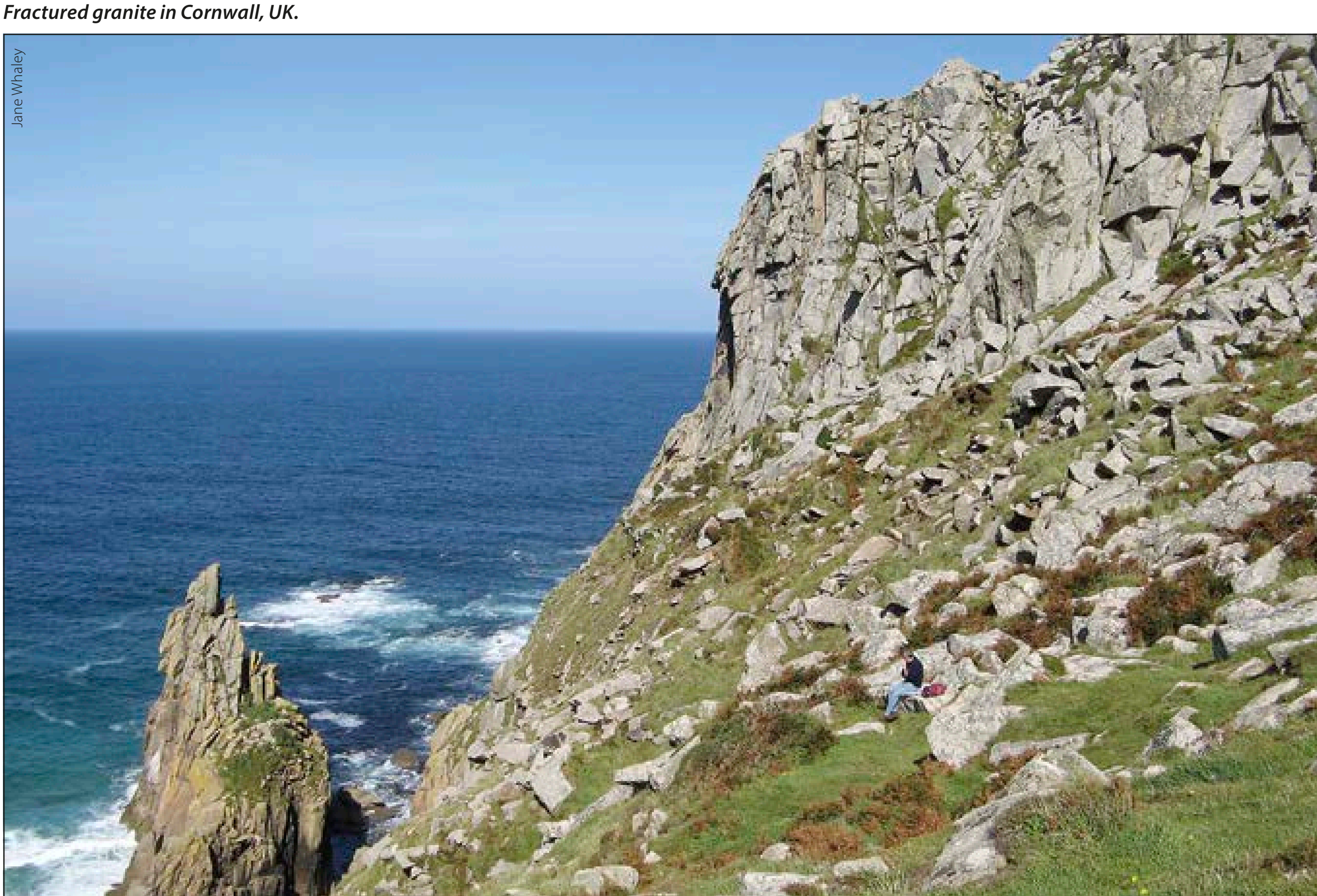


Classification of reservoirs based on petrophysical properties of rock fractures. Modified from Ronald Nelson, Geologic Analysis of Fractured Reservoirs (2001).

Subsurface fractures always pose a challenge to exploration and production. In the petroleum, geothermal and groundwater industries, therefore, a wide variety of materials, tools and techniques are utilised to identify, map and characterise fractures. These include basin tectonics, outcrop analogues, cores, borehole imaging logs, seismic sections, in-situ stress data, well flow tests, geomechanical experiments, and so forth. ■

References available online

Fractured granite in Cornwall, UK.



Fracture, Fracture Everywhere Part II

How and why do fractures occur in rocks?

RASOUL SORKHABI, Ph.D.

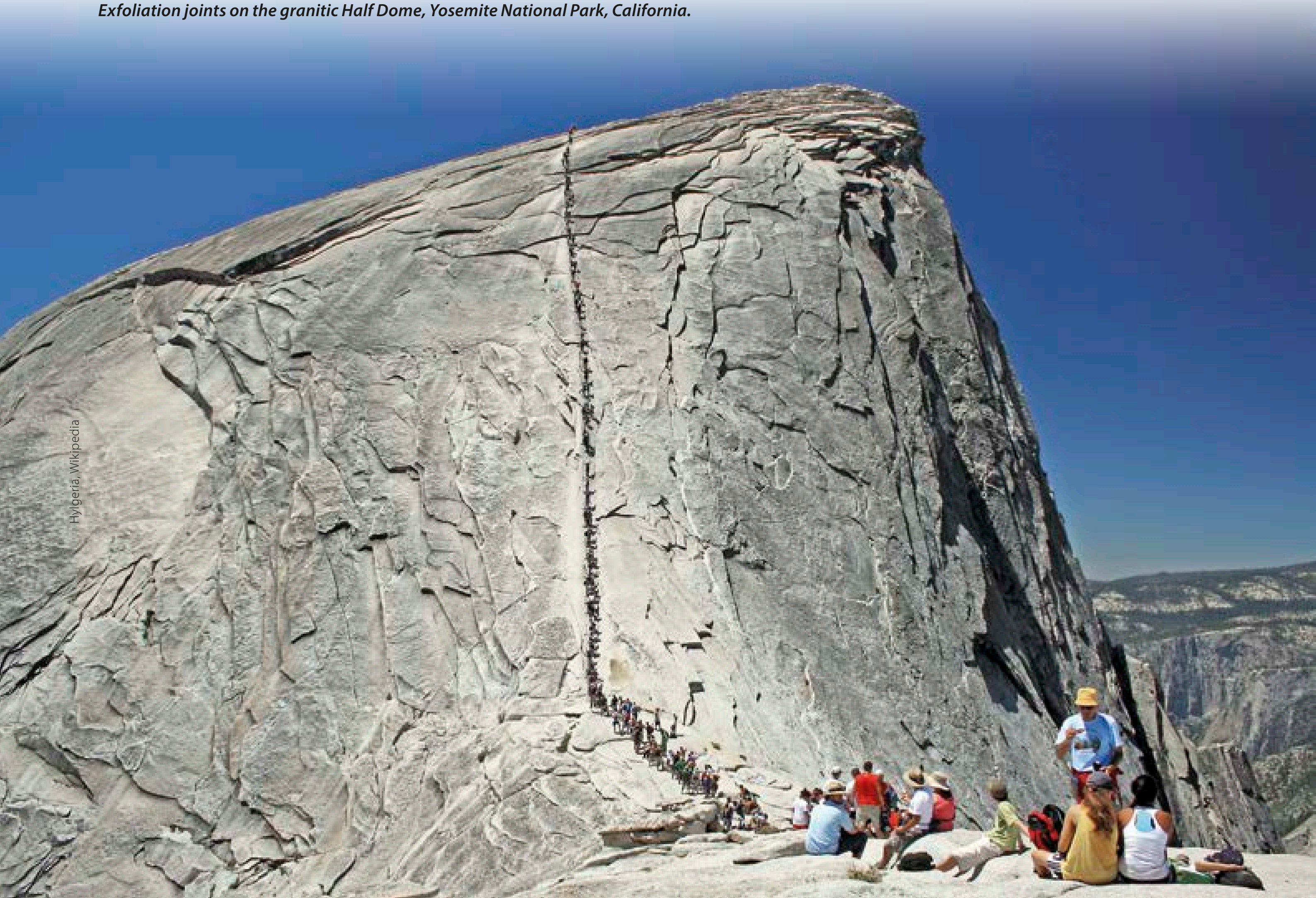
Fractures including joints and faults are commonly found in rocks and are important fluid pathways – hence their significance for petroleum, groundwater, and geothermal resources as well as hydrothermal circulations within Earth's deep crust. In the first part of this article (*GEO ExPro*, Vol. 11, No. 3), we looked at the types, geometry and characteristics of rock fractures. In this concluding part, we will discuss the origin and mechanics of fractures to better understand their occurrence.

The Origin of Rock Fractures

Rock fractures, like other geologic structures, form by **gravitational force** involving pressure and density changes. These take place due to a variety of **tectonic**, **thermal** or **fluid pressure** processes operating on rocks. Based on their origin, rock fractures may be categorized as:

1. **Tectonic fractures:** clusters of joints found in the vicinity of major faults and folds represent brittle deformation in rocks due to tectonic stresses. Motion of global tectonic plates is the major cause of tectonic stresses, especially at plate boundaries.
2. **Hydraulic fractures:** formed by increased pore fluid pressure in a rock body. This process may occur naturally in the subsurface, in the so-called overpressure zones due to rapid sedimentation rates, thrust loading of rock over sediments, thermal expansion of pore fluid, dewatering of hydrous minerals (like illite, gypsum and opal), or transformation of kerogen to hydrocarbon (which results in volume increase). Artificial hydraulic fracturing, as in the stimulation of shale gas, is done by pumping fluids and proppants into the subsurface formation.
3. **Unloading or pressure-release joints:** formed in rocks which are brought to the surface by uplift and erosion, and therefore the rock cools, shrinks and fractures.
4. **Exfoliation joints:** typically formed in eroded granite bodies in which sets of surface-parallel, curved fractures split the rock dome into onion-like layers or slabs.

Exfoliation joints on the granitic Half Dome, Yosemite National Park, California.



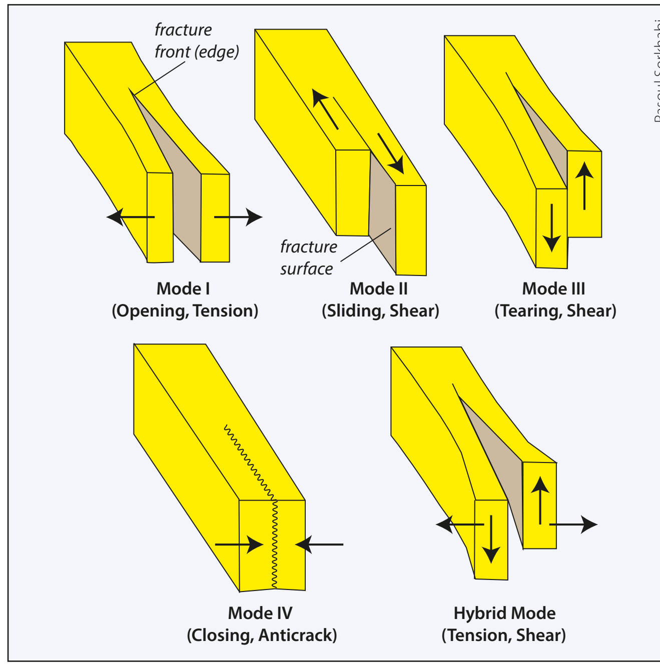
Pressure-release due to the removal of overburden (vertical stress) coupled with some degree of horizontal stress play important roles in this type of jointing.

5. **Cooling or columnar joints in volcanic rocks:** these are produced from the rapid cooling and shrinking of lava as it ascends to earth's surface.

Fracture Modes

Based on the relative movement of fracture surfaces, rock fractures are classified into four 'modes'.

Mode I fractures are **tensile (opening) fractures** in which two fracture surfaces move away from each other. Joints are basically Mode I fractures. In contrast, **shear fractures** involve the relative movement of rock blocks parallel to the fracture surface. Shear fractures may have lengths at the scale of millimeters (microscopic) (called microfaults) or at the scale of centimeters (minor faults); large (meter-length) shear fractures are properly called faults. Shear fractures include **Mode II** or **sliding** fractures, in which the relative movement is perpendicular to the fracture front (as in strike-slip faults), and **Mode III** or **tearing** mode, in which the relative movement is parallel to the fracture front (as in dip-slip faults). **Hybrid fractures** combine both tension (Mode I) and shear (Mode II or III) movements. **Mode IV** or **closing** fractures are mineral-scale anti-cracks; stylolites (pressure solutions) are typical examples of this mode.



Various 'modes' of fractures depending on the relative movement of fracture surfaces.

Stress: Principal, Normal and Shear

Stress (σ) and pressure (P) are both defined as force (F) per unit area (A), and have the unit of pascal. One pascal (Pa) is one newton per square meter (or 1 kg cm^{-1} s^{-2}); 100,000 pascal is equal to one bar or 0.98 atmospheres of pressure; one megapascal (MPa or 10^6 Pa) equals 10 bars and one gigapascal (GPa or 109 Pa) equals 10 kilobars. One bar is 14.503 pounds per square inch (psi) and one psi is 6895 Pa.

Stress differs from pressure in that it also includes a sense of directionality (vertical or horizontal); in other words, stress is a vector quantity while pressure is a scalar quantity. Pressure (P) at a given depth is given $\rho g z$ where ρ is density of the material (rock or fluid), g is gravitational acceleration (9.8 m/s^2) and z is the target depth.

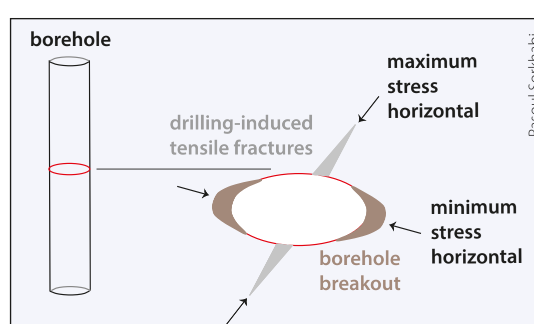
In his 1942 book *The Dynamics of Faulting and Dyke Formation with Application to Britain*, the Scottish geologist Ernest Masson Anderson (1877–1960) formulated the stress field of a three-dimensional rock body in terms of three **principal stress** axes – maximum or greatest (σ_1), intermediate (σ_2), and minimum or least (σ_3). All these stresses acting upon a rock body are compressional but may have different magnitude and direction. In normal faults, σ1 (rock overburden) is vertical and extension takes place in the direction of σ_3. In reverse (thrust) faults σ_1 is horizontal and σ_3 is vertical, and thrust shortening takes place in the direction of σ_1. In strike-slip faults, σ_2 is vertical while both σ_1 and σ_3 are horizontal, and slip occurs at an angle of 45° or less to the orientation of σ_1. **Mean stress** is the arithmetic average of the three principal stresses ($\sigma_1 + \sigma_2 + \sigma_3$ divided by 3). (For more information refer to 'Know Your Faults, Parts I and II,' *GEO ExPro*, Vol. 9, Nos. 5 and 6.)

Isotropic (uniform) stress or **confining pressure** is a situation in which a body is compressed by equal pressure in all directions; it may be lithostatic stress (a subsurface point under the weight of a rock overburden) or hydrostatic stress (a point enclosed by water). (Note that in some scientific literature, hydrostatic pressure and confining pressure are used as synonyms). Often, however, tectonic forces alter confining pressures; therefore, stress is not equal in all directions. **Deviatoric stress** is measured as total stress minus mean stress acting upon the rock body. **Differential stress** is measured as σ_1 -σ_3. If differential stress exceeds the strength of the rock, the rock deforms (and eventually ruptures). Differential stress may be compressional, tensional, or shear, which also determines how the rock deforms in response to the stress.

Compression is the stress that shortens (squeezes) a rock body; **tension** elongates (stretches) the rock body in two opposite directions. **Normal stress** (σ_n) acts perpendicular to a rock surface; it may be compressional (positive) or tensile (negative). **Effective normal stress** is normal stress minus pore fluid pressure. **Shear stress** (σ_s or τ) acts parallel to the rock surface and causes two rock units to slide over each other; in other words, shear stress changes the angles in a rock body.

Geologists also distinguish between **paleostress** (stress that acted upon rocks in a given area in the geological past) and **in-situ** or **contemporary stress**, which can be inferred from plate motions, earthquakes or borehole data.

Horizontal stresses in a borehole related to borehole breakout and drilling-induced tensile fractures.



Mohr Envelope and Coulomb Failure

We are now in a better position to delve more into geomechanics and study how rocks fail and fracture under stress. We owe this analytical knowledge largely to a group of French physicists and scientists: Guillaume Amontons (1663–1705), Charles-Augustin de Coulomb (1736–1806), Claude-Louis Navier (1785–1836) and L. Hartmann, as well as the German engineer Christian Otto Mohr (1835–1918), European engineer Richard Edler von Mises (1883–1953), English engineer Alan Arnold Griffith (1893–1963), and Austrian soil engineer Karl von Terzaghi (1883–1963). These scientists developed powerful mathematical diagrams and equations that calculate and thus predict the development of rock fractures in relation to stresses applied to rocks.

Graphical representation of rock failure or fracture, called Mohr diagram, includes the relationship between shear stress (σ_s or τ) on the vertical axis and normal stress (σ_n) on the horizontal axis of the diagram, and the distance of rock stress (represented by a circle) from a line called the **Mohr envelope of failure**. Various scientists have attempted to quantify the criteria when the stressed rock exceeds the failure envelope and thus fractures either by tension or by shear.

In 1699, Guillaume Amontons suggested that the shear force parallel to a rock surface necessary to initiate slip in the rock is directly proportional to the normal force acting upon the surface. The proportionality constant μ is called the coefficient of internal friction (a term introduced by Navier in 1833). Therefore, we can write:

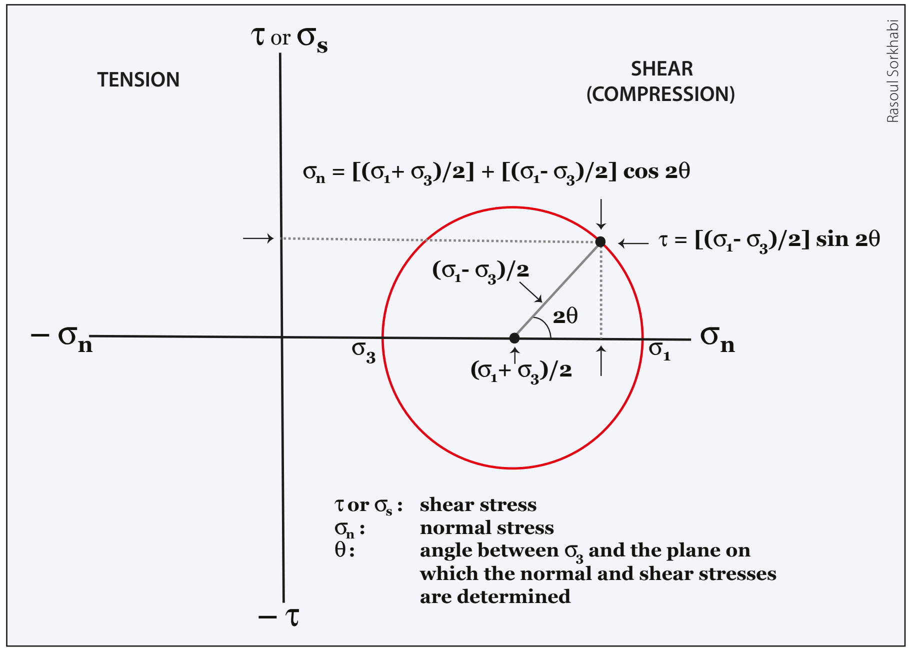
$\tau = \mu\ \sigma_n$

For solid rocks, the value of μ ranges from 0.47 to 0.7; for general calculations it is assumed to be 0.6.

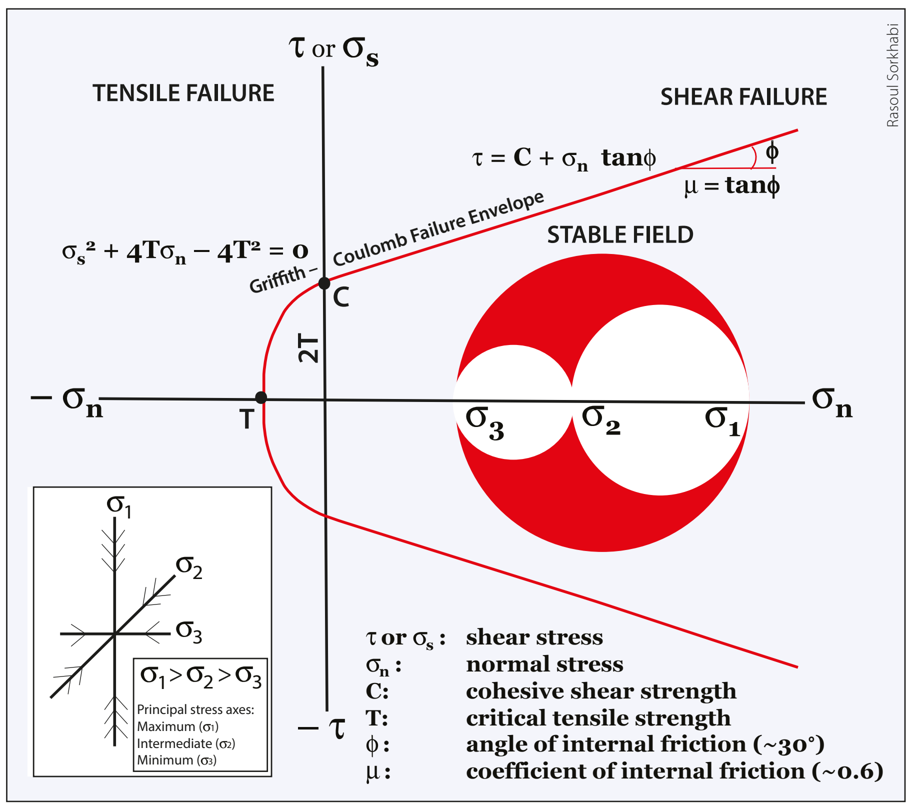
In 1773, Charles Coulomb verified and refined Amontons' equation. He recognized that a rock fractures only if the cohesive strength (C) of the rock is exceeded. In other words:

$\tau = C + \mu\ \sigma_n$

The constant C represents the critical shear strength of the rock (or resistance of the rock to shear stress) when normal stress is zero. Rocks also have a critical **tensile strength**, plotted as the point T, on the Mohr diagram. Cohesive strength of a rock is twice its tensile strength ($C = 2T$).



Mohr circle and calculations of normal stress and shear stress on a plane



Mohr envelop of failure using Griffith-Coulomb criteria. Depending on the position of the Mohr's circle of stresses, there are three fields: Stable (below the failure envelope), critically-stressed (touching the failure envelope), and unstable (beyond the failure envelope in which the rock may fracture by tension or by shear). Three principal stress axes are also depicted.

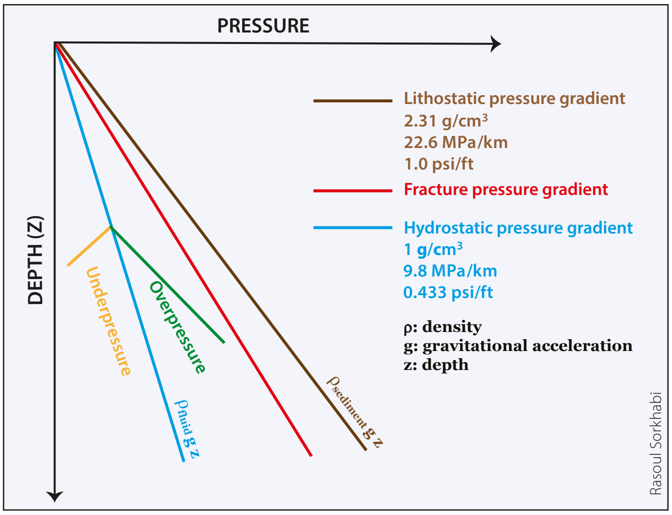
Further work by Navier and Mohr in the 19th century advanced our understanding of rock failure. The following equation quantifies the line of shear failure on Mohr diagram and is called Coulomb-Navier, Coulomb-Mohr or simply **Coulomb criterion of failure**:

$\tau = C + \sigma_n\ \tan\varphi$

where φ is the angle of internal friction (about 30° for sand grains).

The Mohr diagram indicates that as the normal stress increases we also need more shear stress to fracture the rock.

The Coulomb criterion describes the



Calculations of subsurface pressures for fluid (water) and sedimentary rocks based on their pressure gradients. Fracture pressure is the stress sufficient to fracture a rock. It is related to pore fluid overpressure. Fracture pressure gradient is usually 18-20 MPa/km. Fracture pressure can be determined from leak-off tests.

Plumose fracture in argillite, Proterozoic Appekkuny Formation, Montana. Fracture surfaces often display plume-like features; the axis of the plume indicates the direction of fracture propagation (parallel to σ_1). The fracture probably originates from a heterogeneity in the rock (such as inclusions and sedimentary structures). The average velocity of fracture propagation has been measured to be half the speed of sound waves. The presence of plumose features suggest that the fracture is still in open (tensile) mode.

failure of rocks by shear (the right side of Mohr diagram), but is not applicable to tensile fracturing (left side of the diagram). Experimental work has shown that the Mohr envelope for tensile failure is shaped like a parabola, and the point *T* (critical tensile strength of a rock) represents the intersection of Mohr envelope and the horizontal axis (normal stress). The value of *T* varies for rocks. In 1920, Alan Griffith noted that this variation is due to the existence of microscopic cracks, flaws, grain boundaries and pore spaces in rocks; these random, pre-existing features, from which tensile fractures originate, are collectively called **Griffith cracks**. When a Griffith crack is oriented perpendicular to tensile stress, the crack easily propagates at its ends in a direction perpendicular to σ_3, the minimum principal axis. When the crack is oriented perpendicular to a compressive stress, it tends to remain closed. **Griffith criterion** for tensile failure on the Mohr envelope is:

$$\sigma s^2 + 4T\sigma_n - 4T^2 = 0$$

In summary, a combined Griffith-Coulomb criterion is the best available model for quantifying the fracturing of rocks by tension or shear. In ductile regimes, where the Mohr envelope is expected to flatten and a maximum shear stress is reached, other formulations such as **Von Mises criterion** should be used to describe rock deformation.

References and Further Reading:

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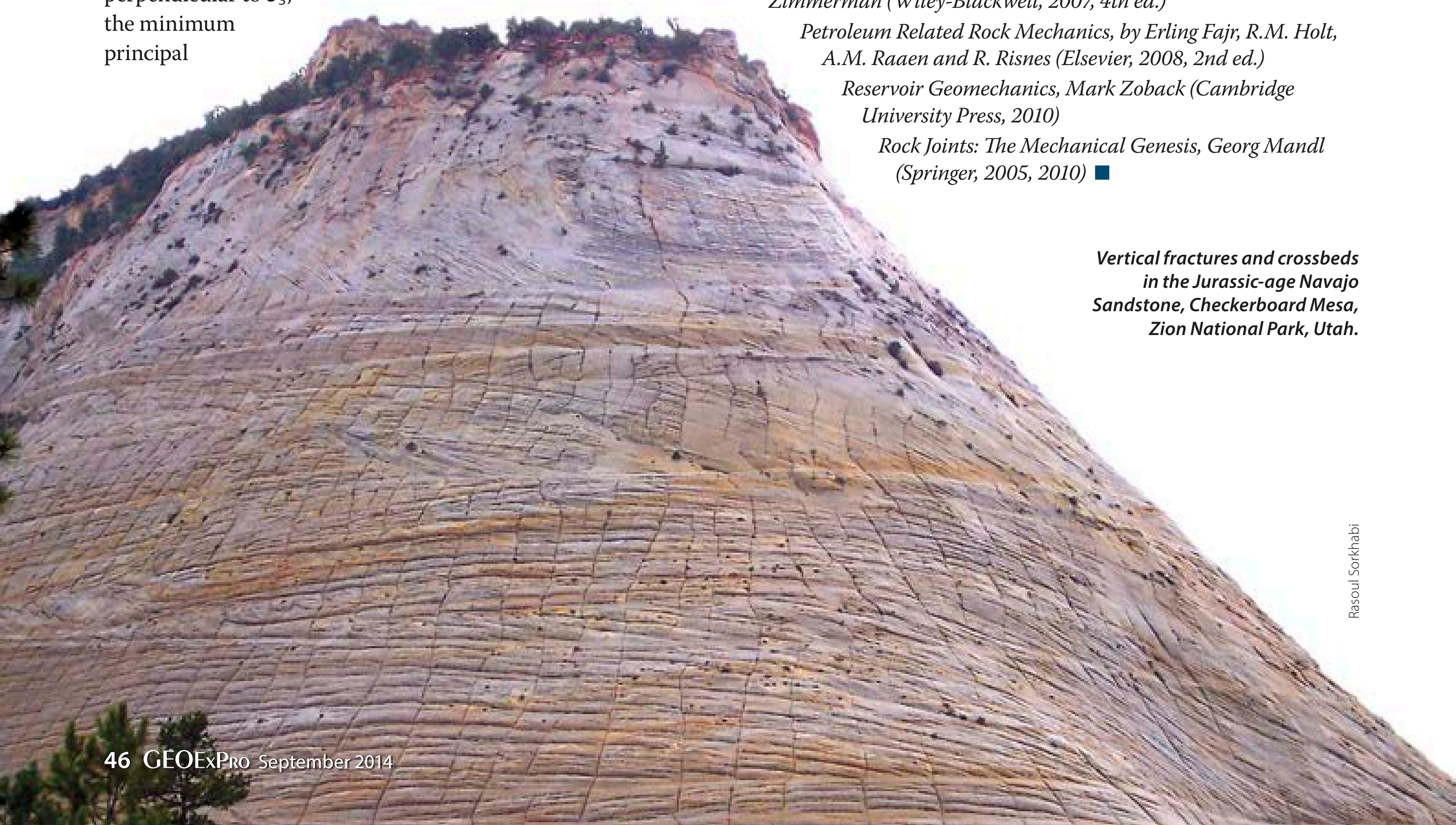

Vertical fractures and crossbeds in the Jurassic-age Navajo Sandstone, Checkerboard Mesa, Zion National Park, Utah.