Under this regular column titled 'Expert Answers', we pose questions of both general and technical interest to well-known geophysicists who are considered authorities in a certain area within the geophysical domain and get their 'expert' answers. As these answers could have an individualistic tone, we request the answers from more than one expert in any area.

In this issue, we have selected the following general question and include the answers given by John Lorenz and Scott Cooper (FractureStudies, LLC, NM, USA), and Stephen Laubach (University of Texas at Austin, USA). We thank them for encouraging us with their responses. Readers are encouraged to send us their feedback and even the questions they would like to get answered by experts.

The order in which the answers appear below is the order in which we received them.

\- *Satinder Chopra*

***Q. The terms cracks, fissures, fractures, and faults are often used interchangeably in geoscientific discussions, despite each having a distinct meaning. Could you clarify the definitions of these terms and explain why it is important to accurately distinguish between them in the context of oil and gas exploration? Additionally, what methods would you recommend for gaining a thorough understanding of these geological features, such as through the use of cores, logs, seismic data, and other techniques?***

**Expert answer -1 by John Lorenz* and Scott Cooper***

A fracture nomenclature/classification system should be easily understood, be widely accepted, and allow precise communication of ideas and information between geoscientists. It should also be useful for preliminary estimations of the effects of a fracture system on reservoir plumbing.

Here we will summarize some of the existing natural-fracture terminology and classification complexities, but we will promote a system based on the mechanical origin of fractures, one that is practical and easily understood and that is, in fact, already in general if unofficial usage.

During this discussion it should be kept in mind that fracture-classification schemes are artificial constructs superimposed on structures that occur in a spectrum of forms rather than being naturally binned. It is also possible to fracture rock in one manner, then reactivate it in another form so that the result is a compound structure displaying the characteristics of two fracture types. These complications have necessitated terms for in-between fracture categories such as *hybrid*, *mixed-mode*, and *oblique-slip* fractures. For a fuller description and history of the variety of 50-60 terms for natural fractures and fracture classification systems used in the English-language literature we would point the reader to the gory eight-page discussion in our *Applied Concepts in Fractured Reservoirs*, pages 1-8 (Lorenz and Cooper, 2020).

### DEFINITION

In geologic usage, *fracture* is a generic term for a mechanical discontinuity in a rock. The discontinuity is typically planar, and it is commonly associated with a partial or complete loss of cohesion in the rock mass across the fracture plane. Natural fractures are brittle to brittle-ductile strain-accommodation structures that develop when rock is subjected to a stress anisotropy greater than its strength.

A common alternate term for such breaks is *joint*. "Fracture" and "joint" were borrowed from general



*FractureStudies LLC., Edgewood, NM, USA. Email: john@fracturestudies.com; scott@fracturestudies.com

English vocabulary for scientific use. We prefer the former term since a rock can break and *fracture*, whereas *joint* is related to the verb "to join" and, inherently, implies a structure connecting two rock masses rather than separating them. "Joint" is commonly paired with the term *vein* to indicate a mineralized joint, thus "vein" is a second term for what is basically the same mechanical structure, and in discussions it seems that the difference between *joint* and *vein* usually needs clarification. The same information, in a more easily understood albeit longer form, is conveyed by *mineralized fracture* vs. *unmineralized fracture*. The use of a less common term such as "scission" or "cesura" from the start of geologic studies might have made it easier to carve out and define a unique geologic term, but that is water over the dam.

A variety of nomenclature systems have been and are being used by different disciplines, different authors, and by those doing fracture work in the laboratory, on outcrops, and in the subsurface. Several nomenclatures have been used across the century-and-a-half of the study of fractured rock (see Pollard and Aydin, 1988), and even by the same author in different stages of a career.

Fracture nomenclatures have been constructed using different bases for classification, for example geometry (e.g., dip angles), the relationship to structure (e.g., cross-fold vs. fold-parallel), mechanical origin (e.g., extension vs. shear), or electrical signature in a geophysical log (e.g., conductive vs. resistive). Nelson (2001) constructed a four-fold fractured-reservoir system based entirely on the ratio of fracture permeability and porosity compared to those values found in the reservoir matrix rock. Scale is important too: "fractures" that are recognized as offsets of bedding in seismic traces at the scale of tens or hundreds of meters might be called "faults" in outcrop, whereas even the smaller breaks called "fractures" along mid-ocean ridges are measured in kilometers or tens of kilometers.

## FRACTURE TYPES

Despite the historical variety of nomenclature systems, only two basic fracture types are common in rock. These are distinguished by their mechanical mode of origin: *extension fractures,* also called *Mode I fractures,* and *shear fractures* or *Mode II fractures.* Fracture walls move apart in opposite directions normal to the fracture plane to form extension fractures, whereas the walls move in opposite directions parallel to the fracture plane to form shear fractures. Some authors note the possibility of rotational shear along a fracture plane and call these relatively rare structures *Mode III fractures*. *Mode IV* fractures, also called *compaction bands*, are the uncommon tabular zones along which the rock masses on either side of the fracture plane have moved towards each other, collapsing porosity. The "Mode" nomenclature for fractures is more common in academic than industry literature.

### *Extension fractures*

The orientation of an extension fracture is controlled by the *in situ* stress system: fracture propagation follows the plane defined by the maximum and intermediate compressive stresses at the time of fracturing, i.e., the fracture plane forms normal to the minimum compressive stress. Because the weight of overburden strata typically provides the maximum compressive stress in an undeformed sedimentary basin, that principal stress, and therefore most extension fractures in such basins, are vertical. Since bedding in these settings is commonly horizontal, most extension fracture sets are also normal to bedding (Figure 1). Extension fractures may form as inclined planes if the stress system is tilted in more complex structural settings, and vertical fractures may become tilted if the rock was folded after it fractured. Parallel extension fractures form *sets* with uniform strikes. Younger fracture sets formed within different stress systems can be imposed on older sets to form a *fracture system* of intersecting sets (Figure 2).

Rock is a weak material compared to the tectonic and gravitational forces acting on it in the subsurface. Moreover, rock is typically brittle and susceptible to fracturing, so almost all rock masses of interest to the hydrocarbon industry are fractured to some degree. Note, however, that the tensile forces that easily pull rock apart to create *tensile* or *tension fractures* in the laboratory are almost non-existent in subsurface sedimentary strata. Nearly all structures called "tension fractures" outside the laboratory were formed in extension by dilatancy of a rock mass, within stress systems that were compressional in all three dimensions. This is a subtle but important and commonly misunderstood point of natural-fracture mechanics (see Hillis 2003, and discussions in Lorenz and Cooper, 2020). The low stress anisotropies needed to create extension fractures are commonly incapable of extending fracture planes across the mechanical heterogeneities created by bedding or intercalated lithologies, thus many extension fracture sets are strata-bound and confined to, or better developed within, the more brittle layers of a sedimentary sequence. Extension fractures are typically taller and more widely spaced in thicker beds, and they are typically less planar in heterogeneous lithologies such as conglomerates.


***Figure 1***: *Vertical, bed-normal, strata-bound extension fractures terminate at shale partings in sandstone, limiting their contribution to vertical permeability within the sedimentary sandstone-shale package. This example shows Mesaverde Sandstone from Colorado.*


***Figure 2***: *Aerial photograph of superimposed sets of extension fractures, which could create relatively isotropic horizontal permeability provided they have similar widths and degrees of occlusion by mineralization. This example shows Cedar Mesa Sandstone from Utah.*

Fractures provide pathways for the migration of fluid within and between formations, and the minerals dissolved in those fluids may be precipitated within the fracture *widths* between fracture walls (Figure 3). Fracture *apertures* commonly remain as voids within incompletely mineralized fractures. The composition of other formation fluids is such that they may dissolve and remove earlier mineralization and even some of the host rock along a fracture, leaving larger, irregular apertures (Figure 4) and, ultimately, creating caves and even karsted terranes. Some authors equate "width" and "aperture", but the difference is important: widths can be used to determine percent strain accommodated by a set of fractures, but the ability of fluid to flow along a fracture is determined by its aperture. Remember, however, that the direction of fluid flow in a reservoir is controlled primarily by pressure gradients.

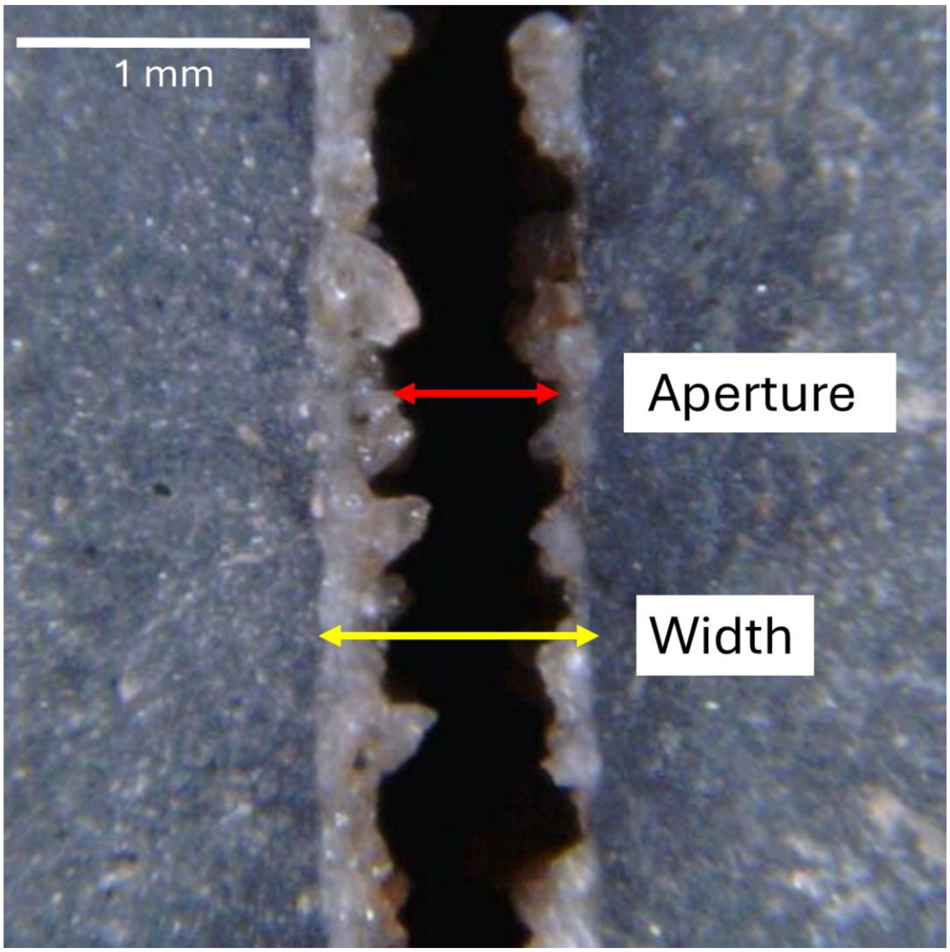



***Figure 3***: *Fracture width vs. fracture aperture. Width is the distance between the fracture walls in the host rock, aperture is the void space between the walls diminished by mineralization if any. This example shows Gothic Shale from Utah.*

Extension fractures have also been called "*axial splitting*" or "*longitudinal splitting*" fractures, "*cleavage*" fractures, and "*load-parallel extension*" fractures. Most authors describing "*regional*" and "*tectonic*" fractures, a classification based on geographic distributions, are referring to extension fractures.

The faces of extension fractures may be ornamented with diagnostic *plume structures* and *arrest lines*, and the terminating fringes can display *twist hackle* (Kulander et al., 1990; Lorenz and Cooper, 2018). These features rarely develop in coarser-grained rock, and they may be covered by mineralization or removed by dissolution.

*Figure 4: Dissolution along a fracture plane in the Arbuckle dolomite of Kansas created highly irregular fracture widths that were later partially filled with calcite mineralization.*

*Figure 5: A set of parallel-striking extension fractures enhance the in situ lateral permeability above matrix permeability along fracture strike. The least compressive stress at the time of fracturing was in the horizontal plane and normal to fracture strike, i.e., from left to right in this photograph. This example shows Raton Formation from Colorado.*

Since they form as parallel planes (Figure 5), sets of extension fractures can create horizontally anisotropic permeability in a reservoir, with fracture-controlled $K_H$:$K_h$ ratios of over 1000:1 being reported as early as the middle of the last century (e.g., Elkins and Skov, 1963). Such fracture-permeability systems can be exploited with horizontal wells and must be considered when drilling infill wells and injecting fluids. Since they are commonly strata-bound, extension fractures typically contribute little to vertical fluid flow within stratified reservoirs.

### *Shear fractures*

Shear fractures are a more ductile response to the imposition of stress on rock. A rock may be ductile due to its basic composition (i.e., most limestones are more ductile than most sandstones) or it may have been rendered more ductile by elevated temperatures and confining pressures. Unlike extension fractures, shear fracture planes form at an oblique angle to the maximum *in situ* compressive stress: ideally, they are oriented at a plus or minus 30° angle to the maximum compressive stress, at a plus or minus 60° angle to the least compressive stress, and parallel to the intermediate compressive stress. They commonly form as intersecting, mechanically-related *conjugate pairs* (Figures 6 and 7). Again, all three stresses acting on the rock were compressive at the time of fracturing: no tension was involved.


***Figure 6***: *A set of shear fractures with opposing, intermediate dip angles forms a conjugate pair with opposing dip-slip offset, indicating that the maximum compressive stress at the time of fracturing was vertical. The fracture faces are ornamented with steps, indicating a few millimeters of shear offset. This fracture system will enhance permeability over matrix values in all three dimensions, provided the fracture widths are not occluded. This example is from Abo Sandstone from New Mexico.*

Ideal conjugate pairs that form where the maximum compressive stress is vertical have dip azimuths in the direction of the least compressive stress. In strike-slip structural settings, however, strike-slip conjugate pairs have vertical dip angles, and in thrust settings the pairs have low-angle (thrust-oriented) dips. The opposing legs of conjugate pairs may also develop *un*equally such that larger, widely spaced shear planes and faults are complemented by more numerous but smaller, opposite-dipping *antithetic* shear fractures.

The surfaces of shear fractures are commonly ornamented by a variety of structures including *striations,* *lineations, gouge,* and *steps* (Figure 8) (see Petit, 1987; Lorenz and Cooper, 2018). The form of ornamentation depends on the amount of shear offset and the magnitude of the compressive stress acting across the fracture plane during offset. As with extension fractures, the widths of shear fractures may be modified by mineralization and/or dissolution, filling or enhancing fracture apertures respectively, and likewise degrading or enhancing permeability along the fracture planes. Gouge-filled shear fractures, however, can form permeability barriers.

***Figure 7***: *A set of vertical, bed-normal, right- and left-lateral strike-slip conjugate fractures, formed in a stress regime where the maximum compressive stress was in the horizontal plane, bisecting the acute conjugate angle, i.e., from top to bottom of the photograph. We are looking at a silty zone within the Mancos Shale in New Mexico. Shear fractures may also form as low-angle reverse-dip-slip conjugate pairs.*

*Deformation bands*, also called *shear bands*, commonly form conjugate pairs (Figure 9). These are variations on shear fractures where the offset is accommodated by compaction and grain crushing within narrow, tabular zones rather than along discrete planes.

The term *fault* usually designates larger shear planes that may be associated with folded bedding and/or significant bedding offsets adjacent to the fault, and fault gouge or fault breccia along the fault plane (Figure 10). Some authors suggest that any shear plane should be called a "*fault*", proposing that smaller shear surfaces with limited displacement should be called "*microfaults*". However, we are loathe to replace "shear fracture" with "microfault" due to the additional deformation usually inferred by a reader from the term "fault".

It is almost impossible to quantify the dimensions of bin sizes for fractures since there are so many applications across a variety of disciplines. Terms such as "large," "significant," "small," and "micro" are subjective and need to be quantified for each study: many of the bedding offsets considered to be "large" in outcrop would not be large enough in the subsurface to have seismic signatures.

***Figure 8**: The face of a shear fracture displaying lineations and stepped mineralization indicating oblique shear and offset both before and after mineralization. This example shows Madera Limestone from New Mexico.*

***Figure 9**: Conjugate shear pairs may also form as deformation bands, tabular zones where small amounts of shear offset have crushed grains and collapsed porosity within the rock. Deformation bands resemble shear fractures in image logs, but they degrade permeability and severely compartmentalize a reservoir. What looks like ridges of mineralization in the poorly cemented sandstone are the resistant zones of crushed grains. This example is from Morrison Formation in New Mexico.*

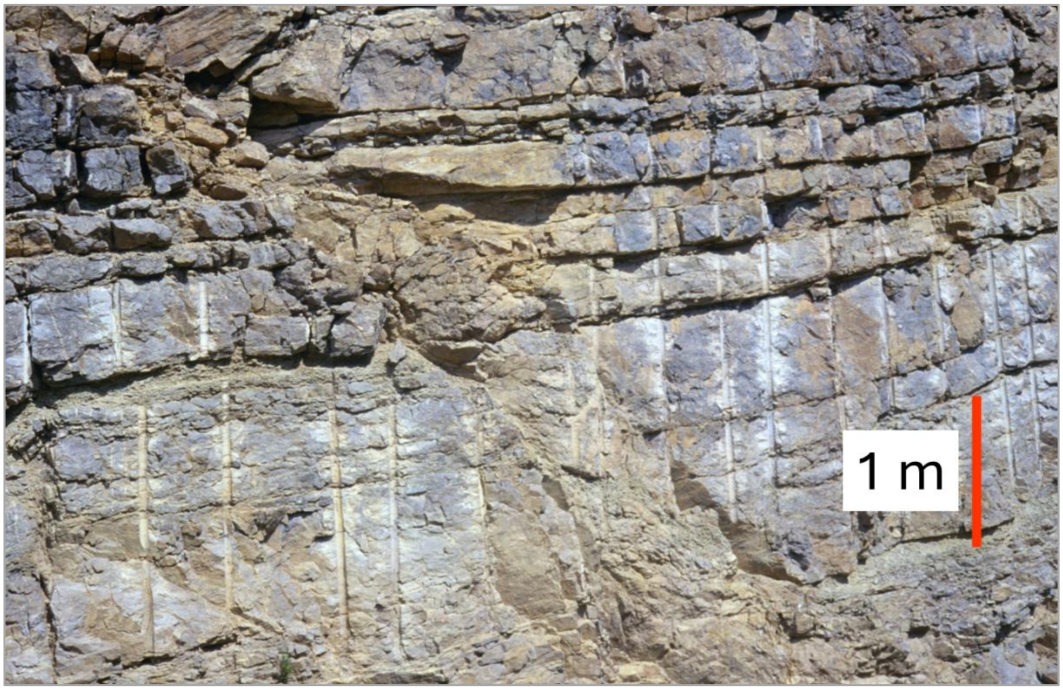



***Figure 10***: *A strike-slip fault with a component of vertical offset, displaying a zone of fault rock consisting of fault breccia and gouge about half a meter thick along the fault plane. The fault strikes oblique to the plane of the photograph and is both narrower and closer to vertical than shown in the photo. This example shows Madera Limestone in New Mexico.*

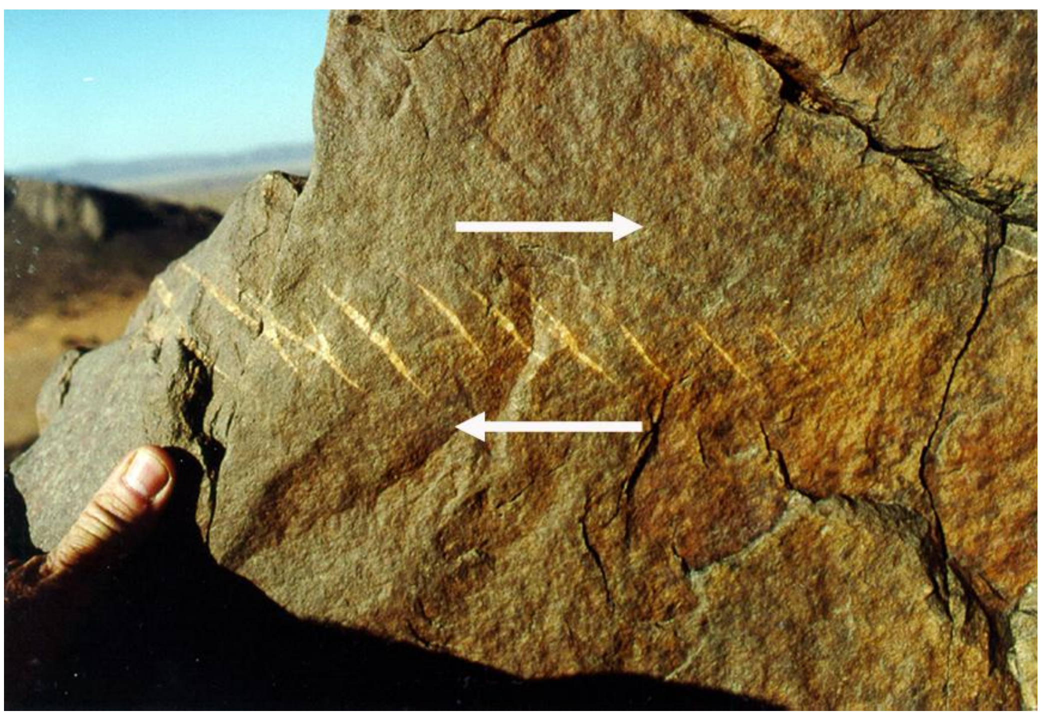


***Figure 11***: *A train of en echelon tension gashes within a relatively wide shear zone in an orthoquartzite marks the rock as having been relatively ductile at the time of fracturing. This example shows Ougarta Sandstone from Algeria.*

Fault terminations are often associated with secondary accommodation structures including *bed-parallel shear* and smaller shear fractures extending obliquely from the fault tip that have been called *pinnate, feather,* and *horsetail* fractures. Bed-parallel shear is also common in folded but un-faulted strata.

A bit further into the ductile range of the brittle-ductile transition, a rock mass can accommodate shear in the form of trains of short *en echelon* extension fractures (Figure 11). The individual fractures within such trains have low aspects ratios, i.e., they are short and fat, pinching out abruptly at either end. These structures have been called *tension gashes* or *gash fractures*. The width of the train of gashes defines the width of the zone of ductile deformation within a rock mass, which commonly narrows as deformation progresses, sometimes bending gashes into "S" shapes. Tension gashes commonly form pairs of conjugate trains.

The effectiveness of any set of fractures in influencing permeability within a reservoir is controlled in part by the degree of permeability along individual fractures (which is in turn controlled by fracture apertures, and in part by the degree of fracture development, i.e., the spacing and interconnectivity of fractures). Systems of shear fractures have greater irregularity due to offsets in the hills and valleys ("*asperities*") on the fracture face, so they are often more permeable than equivalent extension fractures. They also have the potential to be better interconnected both laterally and vertically within a reservoir since they commonly form as intersecting conjugate pairs and since they are more likely to cut across bedding boundaries. Assessing fracture type and classifying the fractures in a reservoir is a primary objective when making preliminary estimations of the effect of a fracture system on reservoir plumbing.

### OTHERS

Since they were part of the query, we should also define the terms *crack* and *fissure*. *Crack* is a basket term that usually applies to small, un-mineralized structures, commonly irregularly planar, and that commonly do not provide complete separation of the rock mass. Cracks may form in either extension or shear. This poorly defined term is not widely used in geologic literature.

*Fissure* is another nebulous term that can mean pretty much what an author wants it to mean. Often it refers to a large (both wide and long), open, planar structure that originated at some surface and narrowed as it propagated into the rock mass. Fissures are commonly filled with material from an external source. A few authors have applied this term to extension fractures (e.g., Warpinski, 1991, but not in subsequent writings).

This discussion has covered labels for the major categories of natural fractures in rock. It does not include discussions of *microfractures* (see Hurley et al., 2024), or *anticracks* such as *compaction bands* (see Liu et al., 2015) and *stylolites* (see Nelson, 1981).

## METHODS FOR GAINING AN UNDERSTANDING OF FRACTURE SYSTEMS

A fracture analyst must use as many data sources as possible and understand their contributions and limitations. Each type of dataset provides only a few pieces of the puzzle when building both conceptual or quantitative fracture-permeability models. The most common sources of fracture data include the following:

-Core data. These datasets are limited in scale relative to the size of a reservoir but provide samples of actual fractures whereas most other data sources are representations of fractures. Cored fractures often display diagnostic fracture-face ornamentation, providing clues to fracture type and distribution by lithology, and offer unambiguous measurements of fracture apertures and types of mineralization.

-Downhole geophysical (image) logs (Figure 12). These logs also provide local data but typically across much thicker sections of strata, and they come with superb data-analysis packages. Such logs often offer the only data on *in situ* fracture strikes.

-Geophysical surveys. Geophysics provides three-dimensional views of fracture distributions, orientations, and some of their effects over large and thick volumes of rock. Factors such as lithologic heterogeneity, multiple fracture sets, and in situ stress anisotropies can influence seismic signals.

-Reservoir engineering tests. Engineers offer significant insights into the effectiveness of fracture systems, i.e., the difference between laboratory-derived matrix permeabilities from core plugs, and an estimation of reservoir system permeabilities calculated from well tests, gives an estimation of the contribution of fractures to

***Figure 12**: Image-log representation of two parallel extension fractures in a shale that were subjected to dissolution and enhancement of the fracture apertures. The image log and analyst captured a commendable representation of the fractures despite their irregularity. The fractures are vertical; the wellbore is inclined. This example shows Mancos Shale in Wyoming.*

reservoir permeability. Production patterns across a field can also give insights on fracture orientations and heterogeneities, again remembering that production signatures are the integration of multiple downhole factors.

Books have been written about techniques for collecting fracture data, analyzing that data, and using it to understand fracture systems and their effects on fluid flow. We would, of course, refer the reader to Lorenz and Cooper (2018, 2020), as well as to Nelson (2001). There is no single silver-bullet technique that can be used for a complete understanding of fracture systems. Fracture analysts must be familiar with and work with as many different data sources as are available to them.

## CONCLUSIONS

A "fracture"-based lexicon of shear and extension fractures is systematic, simple and flexible. Unlike "joint" and "vein", "shear fracture" and "extension fracture" indicate a mechanical origin. The fracture-based nomenclature system is easily modified with descriptors to indicate numerous fracture characteristics such as dip angle, sense of offset, and degree of mineralization that influence fluid flow. Most fractures that have been described in the literature can be fit into this fracture-based classification system, where more information is conveyed to a reader with less ambiguity than when using terms such as joint, fissure, crack, and vein.

The recognition of fracture type provides a first and necessary step in understanding the effects of a fracture system on fluid flow in a reservoir. The data needed to make such classifications and interpretations can come from many sources, each providing important and often overlapping information.

## REFERENCES


Elkins, L. F., and A. M. Skov, 1963, Cyclic water flooding in the Spraberry utilizes "end effects" to increase oil production rate: J. Pet. Technol., **15**(8), 877–884. SPE-545-PA. https://doi.org/10.2118/545-PA

Hillis, R.R., 2003, Pore pressure/stress coupling and its implications for rock failure; in Van Rensberg, N. P., Hillis, R. R., Maltman, J. J., and Morley, C. K. (eds), Subsurface Sediment Mobilization, Geological Society, London, Special Publication **216**, 359-268. https://dx.doi.org/10.1144/GSL.SP.2003.216.01.23

Hurley, N. F., T. E. Playton, and J. Schembre-McCaber, 2024, Microfracture classification, quantification, and petrophysical behavior in the Tengiz and Korolev carbonate reservoirs, Kazakhstan; Am. Assoc. Pet. Geol. Bull., **108**(8), 1537–1567. https://doi.org/10.1306/03132422024

Kulander, B. R., S. L. Dean, and B. J. Ward, 1990, Interpretation and logging of natural and induced fractures in core*;* AAPG Methods in exploration series, no. 8, 1-88.

Liu, C., D. D. Pollard, K. Gu, and B. Shi, 2015, Mechanism of formation of wiggly compaction bands in porous sandstone: 2. Numerical simulation using discrete element method; J. Geophys. Res.: Solid Earth, **120**, 8152-8168. https://doi.org/10.1002/2015JB012372.

Lorenz, J. C., and Cooper, S. P., 2018, Atlas of Natural and Induced Fractures in Core; John Wiley and Sons Ltd. http://dx.doi.org/10.1002/9781119160014

Lorenz, J.C., and Cooper, S.P., 2020, Applied Concepts in Fractured Reservoirs, John Wiley and Sons Ltd. http://dx.doi.org/10.1002/9781119055938

Nelson, R. A., 1981, Significance of fracture sets associated with stylolite zones; Am. Assoc. Pet. Geol. Bull., **65**(11), 2417-2425. https://doi.org/10.1306/03B599AE-16D1-11D7-8645000102C1865D

Nelson, R. A., 2001, Geologic Analysis of Naturally Fractured Reservoirs, 2nd ed.; Gulf Professional Publishing. Boston.

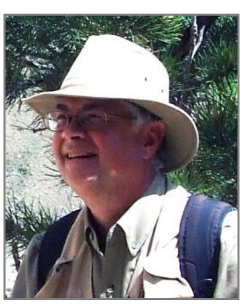
Petit, J. P., 1987, Criteria for the sense of movement on fault surfaces in brittle rocks: J. Struct. Geol., **9**(5/6), 597-608. https://doi.org/10.1016/0191-8141(87)90145-3

Pollard, D. D., and A. Aydin, 1988, Progress in understanding jointing over the past century, Geol. Soc. Am. Bull., **100**(8), 1181-1204. https://doi.org/10.1130/0016-7606(1988)100<1181:PIUJOT>2.3.CO;2

Warpinski, N. R., 1991, Hydraulic fracturing in tight, fissured media; J. Pet. Technol., **43**(2). 146-152, 208-209. https://doi.org/10.2118/20154-PA


## BIOGRAPHY

**John Lorenz** earned an undergraduate degree from Oberlin College in 1972. After serving in the Peace Corps, Morocco, he earned an M.Sc. at the University of South Carolina (1975), and a Ph.D. at Princeton University (1981). John worked for the U.S. Geological Survey, and for Sandia National Laboratories. He has been an independent consultant since 2007, partnering with Scott Cooper in 2008 to form FractureStudies LLC, a consultancy that specializes in fractured reservoir characterization, and which has counted over 50 companies as clients around the world. John served as the Elected Editor (2001-2004) and then as President (2009-2010) of the American Association of Petroleum Geologists. His published papers and presentations cover fractures in reservoirs from Alaska to Texas to Iraq. John has worked closely with the oil and gas industry on problems involving reservoir dimensions and on the *in-situ* permeability of fractured reservoirs, gaining extensive hands-on experience with core analysis and fieldwork.



**Scott Cooper** has spent the last 20 years working projects related to outcrops and subsurface fracture characterizations, $CO_2$ sequestration, and security-related issues. He received a B.S. in geology from the South Dakota School of Mines and a Master of Science in geology from the New Mexico Institute of Mining and Technology. His thesis topic was characterization and modeling of natural fractures in strata at Teapot Dome, and his fracture database is used in teaching various industry modeling programs. Scott was a Senior Member of the Technical Staff at Sandia National Laboratories, working on natural-fracture projects with applications to reservoir characterization, production and $CO_2$ sequestration. More recently, he has had fun working in partnership with Dr. John Lorenz at FractureStudies LLC as consultants, addressing issues related to naturally fractured reservoir issues around the world. Scott and John have published two widely used textbooks on fractured reservoirs: the *Atlas of Natural and Induced Fractures in Core* (2018), and *Applied Concepts in Fractured Reservoirs* (2020).