An Outcrop Example of Variable Fracture Mode in a Sandstone

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Summary

The fracture-failure mode of a given sandstone is not a constant. This is illustrated in two sets of unrelated, dissimilar fractures that occur in the arkosic sandstones of the Permian Abo Formation in central New Mexico, where a set of older, dip-slip conjugate shear fractures strikes 70° to an unrelated set of younger vertical extension fractures. The significant change in fracture mode was controlled by either changes in the external stress environment or by modifications of the inherent mechanical properties of the rock during cementation and diagenesis. This suggests that modeling and predicting fracture-controlled permeability in reservoirs should consider not only deformation-related strain magnitudes and orientations but also the potential for varying mechanical properties in the rock.

Field Example

A striking example of variations in fracture mode within a given lithology is present in outcrops of the Abo Formation in central New Mexico. This formation is a non-marine Permian unit consisting of well-cemented, deep-red, arkosic sandstones and interbedded red mudstones. Road-cuts at mile post 186 along U.S. Highway 60, about 18 miles west of Mountainair and 21 miles west of Bernardo, New Mexico, expose near-horizontal strata of the Abo Formation consisting of interbedded units of very-coarse-grained lenticular fluvial-channel sandstones several meters thick with local mud rip-up clasts, better-sorted coarse-grained splay sandstones 10-30 cm thick, and massive overbank mudstones centimeters to a few meters thick.

Two families of systematic natural fractures cut the Abo sandstones at this location, recording two separate fracture events:

1. An older F1 fracture set consisting of a pair of NE-SW striking dip-slip conjugate shear fractures cuts the coarse, channel-fill sandstones. The shear-fracture faces are ornamented predominantly with "non-congruent" steps formed of unaltered host rock. Bedding is sufficiently irregular and the magnitude of shear offset is small enough that the amount of offset cannot be measured in most cases. Locally the shear faces where bedding is offset by up to 20 cm are marked by accretionary, slickensided "congruent" steps formed of comminuted host rock (see Doblas, 1998; Petit and Laville, 1987; Lorenz and Cooper, 2018a, for fractographic descriptions and definitions). The F1 fractures record a vertical maximum compressive stress, and a bed-parallel minimum compressive stress oriented approximately NW-SE.
2. A younger F2 fracture set, its age relative to the F1 fractures determined by abutting relationships, consists of a set of NW-SE striking, vertical extension fractures that are oriented on average 70˚ oblique to the conjugate shear fractures. The F2 fractures have rough faces that display no fractographic ornamentation; they cut across the millimeter-scale sand grains in the well-cemented rock without any trace of shear offset. The F2 fracture set records brittle extension failure in the Abo sandstones when the minimum compressive stress was parallel to bedding, trending approximately NE-SW.

View looking to the northeast, parallel to the NE-SW strikes of the F1 dip-slip conjugate shear fractures in an arkosic, lenticular, fluvial-channel sandstone that is about 1.5 m thick at the right of the photograph. The red arrows point to three common reference points for this and the associated photograph below. The surfaces of these shear fractures are invariably marked with mm- to cm-scale, incongruent shear steps (e.g., Hancock, 1985) as shown in the next photo, indicating a minimal (mm-scale or less) magnitude of dip-slip shear offset. Locally the fracture-face asperities display vertical striae and slickensides indicating a slightly greater degree (cm-scale) of shear offset in the same direction. The conjugate shear fractures transition to NE-SW-striking vertical extension fractures to the left where the bed thins, providing an example of Hancock's (1986) "dynamically compatible" fractures, where rocks with different material properties fracture in different modes under the same stress conditions.

Incongruent shear steps ornament the faces of the Abo F1 conjugate shear fractures. This photo of the underside of an inclined shear fracture shows steps that record small-scale, normal, dip-slip offset. The NE-SW striking fracture surface dips away from the viewer with a 70° dip angle. This block moved downward relative to the missing block (despite the apparent lock-up that this would entail), with an offset of a few millimeters at most.

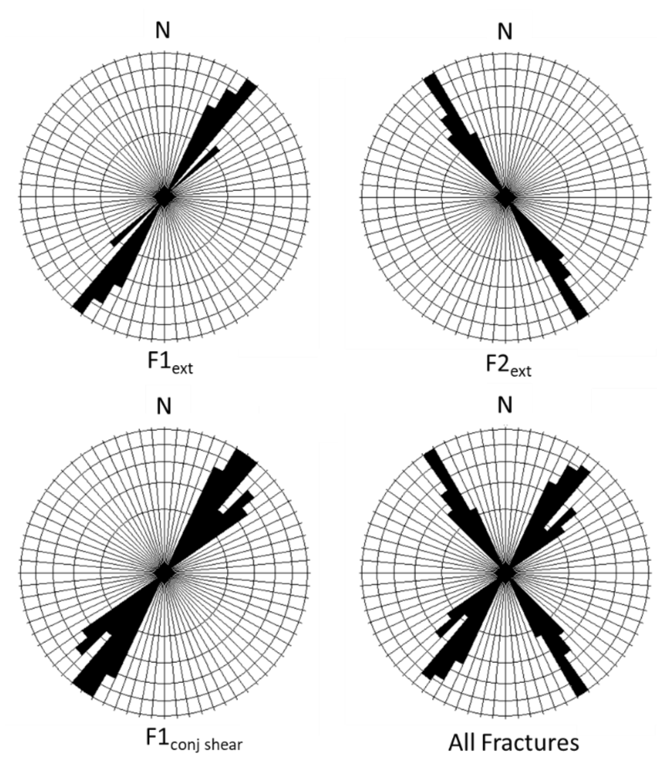
View looking to the northwest, parallel to the NW-SE strikes of the F2 vertical extension fractures in the same lenticular, fluvial, arkosic channel deposit. The F2 extension fractures have rough but generally planar faces: plume structure that forms on many extension fractures did not form here because they are too coarse grained. Fracture spacing is much less than bed thickness, and spacing does not diminish to the left where the bed thins. Spacing was controlled by percent strain, not by bed thickness. The red arrows point to the three common reference points in this and the associated photograph above.

Scattered crystals of dolomite were deposited in a hollow opened by shear along the face of a slickenlined, F1 dip-slip conjugate shear fracture in an Abo channel sandstone. Some of the fractures of all types are mineralized with scattered mm- to cm-scale crystalline dolomite and calcite. Shear offset on this fracture, marked by the patchy top-to-bottom striations, was sufficient to create slickensides on the fracture-face asperities.

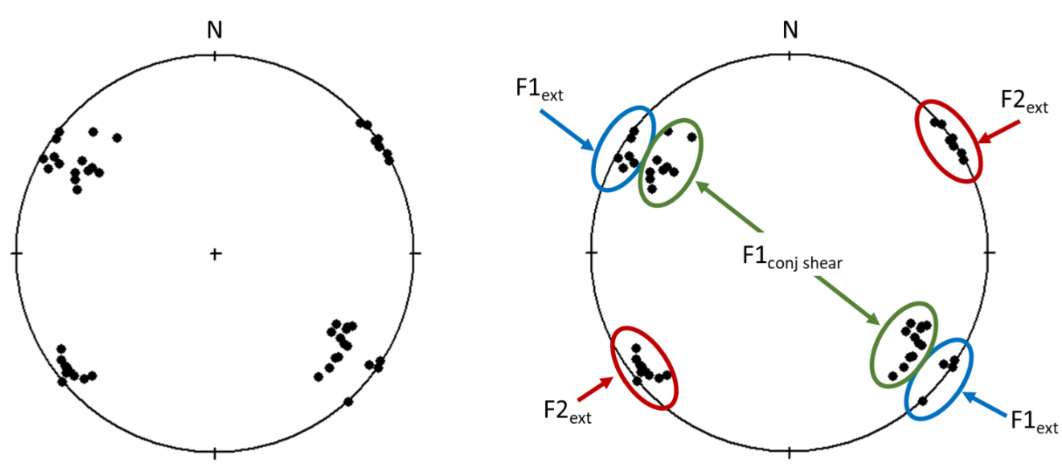
The F1 and F2 fracture sets intersect at an angle of approximately 70˚, showing that they formed under two unrelated stress systems. The distinctly different failure modes show that either the mechanical properties of the rock (i.e., its strength and ductility, depending on original composition of the lithology and its cementation/diagenesis history), or external conditions (i.e., the temperature, pore pressure, and the confining stress magnitudes), were different during the two fracture events. By analogy to the Griggs and Handin laboratory tests, see the discussion below, the coarse, lenticular Abo sandstones probably had brittle-ductile properties when the F1 shear fractures formed, but these sandstones had become either inherently or effectively more brittle by the time of the later F2 extension fracturing.

It is entirely likely that both the mechanical properties and the stress conditions evolved together. However, the controlling factors cannot be separated or specified with the data available from this outcrop although a thin-section/geochemical study of the diagenesis of the rock might offer insights.

Within this basic F1/F2 binary system there is an interesting additional degree of variation. The F1 fracture set is in fact itself a compound family consisting of parallel-striking $F1_{ext}$ extension fractures and $F1_{conj\ shr}$ shear fractures. These two related, dynamically-compatible subsets of the F1 fracture system have mutually-exclusive distributions based on lithology, with the shear fractures occurring in the thicker, coarser-grained channel sandstones and the extension fractures occurring in the thinner, and somewhat finer-grained overbank splays. The parallel strikes (their average strikes differ by only 1.3˚) suggest that the two F1 sets formed under the same stress orientations, and abutting relationships show that both are older than the NE-SW striking F2 extension fractures. The $F1_{conj\ shr}$ shear fractures record relatively ductile rock in the coarse channel-fill sandstones, whereas the contemporaneous, parallel-striking $F1_{ext}$ extension fractures record relatively brittle rock in the thinner, finer-grained splay sandstones during the F1 fracture event.



Rose plots of a representative population of 60 fractures from the Abo sandstones at Mile Post 186 on route U.S. 60 between Mountainair and Bernardo, New Mexico. Inclined, $F1_{conj\ shear}$, normal dip-slip shear fractures and the related vertical $F1_{ext}$ extension fractures strike approximately NE-SW, whereas the vertical $F2_{ext}$ extension fractures strike about NW-SE.



Unlabeled (left) and labeled (right) upper hemisphere steroplots of the same representative 60 fractures from this outcrop of the Abo sandstones on U.S. route 60, New Mexico.

An earlier companion piece to the present article (Lorenz and Cooper, 2018b) described an outcrop where two adjacent layers with fundamentally different lithologies and mechanical properties fractured simultaneously in fundamentally different but "dynamically compatible" modes. That example contrasts with the Abo example described here, where two fundamentally different, sequential fracture families formed in the *same* layer due to temporal changes in the mechanical properties of that layer and/or the environment of deformation.

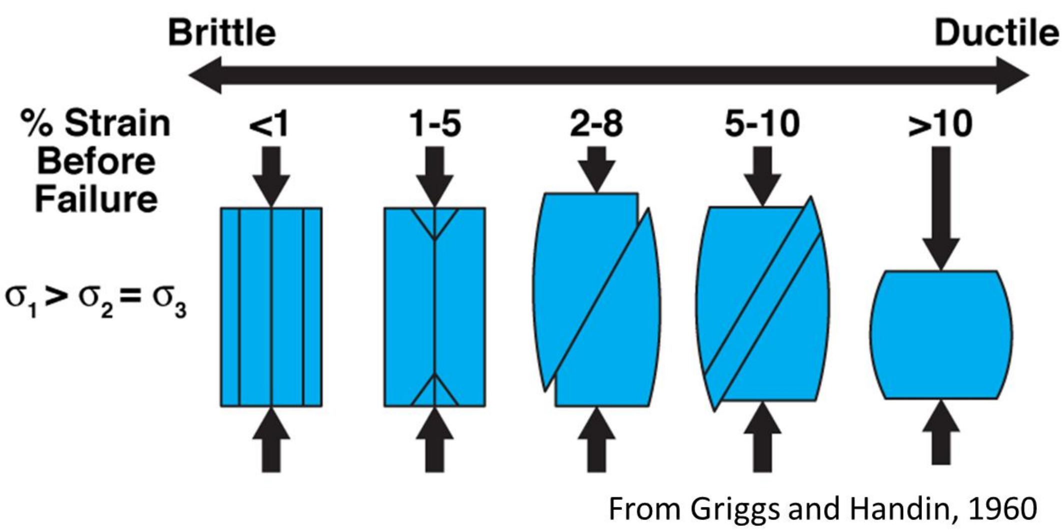
Theory

The experimentally-derived figure published by Griggs and Handin (1960, see their figure below) shows that the mode of failure in a rock when confined by asymmetric compressive stresses changes from brittle extension fracturing to brittle-ductile shear fracturing ("faults") to plastic deformation ("uniform flow") with increasing ductility of the sample. Ductility can change with variations in lithology: for example, extension fractures are common in brittle dolomites and quartzites whereas shear fractures are more likely to form in relatively ductile limestones and in poorly-cemented sandstones, and unfractured plastic deformation is typical of even more ductile rock such halite. Fracture mode can similarly change for a single basic lithology due to subtle alterations in composition and the related ductility during cementation and diagenesis.

Griggs and Handin also recognized that the fracture mode of a specific, unchanging lithology can range from brittle to ductile due merely to changes in the environment at depth, i.e., with increases in the in situ temperature and/or confining stresses. These external conditions control an effective ductility that is superimposed on the inherent, lithologically-controlled ductility of a rock.

Thus, the stress and temperature conditions as well as mechanical properties together control the fracture response of a rock to anisotropic compressive stresses. Given the variability possible in geologic conditions, these different factors can operate in any sequence, and they can be cumulative. For example, a poorly-cemented sandstone that would fail in brittle-ductile shear can become well-cemented during diagenesis such that it fractures in a more brittle, extensional mode at a later time. The failure mode of that rock can then be pushed back into the brittle-ductile shear field of deformation if it is subjected to elevated temperatures and confining pressures during subsidence and burial. However, if the fluid/pore pressure within the now deeply-buried rock increases to near the level of the external confining stresses, the fracture mode can shift back *again* to the more brittle field of extensional fracture.

Pore pressure is important, but it does not create internal tensile stresses within the rock and it does not create natural hydraulic fractures. Rather, pore pressure negates a percentage of the confining stresses, creating low effective confining stress conditions under which rock becomes brittle and can fail in extension (not tension) or shear in the subsurface.



From Griggs and Handin (1960, their Figure 1, page 349). Failure mode of the samples changes from extension (left) to shear (middle) to ductile flow (right) as the intrinsic sample ductility based on lithology increases towards the right. All failures occur while the samples are in compression in all three axes, none of the failures are tensile. Griggs and Handin note that this figure is a "schematic representation of the spectrum from brittle failure to ductile flow,…" Increasing the compressive stress magnitudes and elevating the temperatures drive failure mode to the right and towards the brittle-ductile shear and ductile fields. Raising the internal pore pressure within a sample would make it effectively brittle, driving the failure mode to the left, towards brittle, extension fracturing (e.g., Robinson, 1959; Robinson and Holland, 1969).

Discussion

These outcrops suggest that care must be taken when modeling the development of fracture systems based on stresses calculated from the geometries of structural deformation of the layers. Stress orientations alone are insufficient input data for models that predict fracture orientations and intensities; the potential for varying mechanical properties of the rock should also be considered. Moreover, fracture systems, including intensities, distributions, and type, can be compound, superimposed one onto another, and these possibilities must be considered when reconstructing or predicting fracture-controlled permeability systems.

Conclusions

Deformation under two different external stress/pore-pressure conditions, and/or diagenesis that changed the lithology and mechanical properties of the rock between two tectonic strain events, plausibly account for the presence of two distinctly different F1 and F2 fracture sets within the coarse channel sandstones of the Abo Formation at this location. F1 fractures form a normal dip-slip conjugate pair; F2, consisting of a set of vertical extension fractures, strike oblique to the F1 fractures. The preferred mode of fracturing of a rock is not constant.

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