

Dynamically Compatible Fractures in Sandstone Outcrops

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SUMMARY

An outcrop of the Chinle Formation in north-central New Mexico exposes two lithologically dissimilar sandstones. The sandstones are cut by different but dynamically compatible fracture types. Fracturing within the well-cemented sandstone consists of a set of closely-spaced parallel extension fractures, whereas the fractures in an adjacent bed of moderately-cemented, higher-porosity sandstone form a set of paired conjugate dip-slip shear fractures. Fractures of both sets have N-S strikes and originated within one stress system. The difference between the two sets is attributed to the differences in the mechanical properties which controlled the fracture failure modes of the two beds.

The two fracture systems will govern significantly different permeability and fluid-flow patterns within the two sandstones. Flow potential in the bed cut by parallel extension fractures will be highly anisotropic due to high fracture-parallel permeability and limited lateral fracture connectivity, whereas flow in the sandstone cut by the conjugate shear fractures will be less anisotropic due to lateral fracture interconnectivity.

THEORY

Griggs and Handin (1960, their Figure 1) showed that the fracture response of samples deformed under triaxial compression in the laboratory changes from extension to shear to pervasive deformation as the inherent ductility of the samples, controlled by lithology, increases.

Hancock (1985, 1986) subsequently coined the term “dynamically compatible fractures” to describe the different but mechanically-related fracture sets that can form in adjacent, lithologically-dissimilar formations subjected to the same stress conditions, where differences in the inherent ductilities of the formations dictate the type of fracture response (extension vs shear) of the rock.

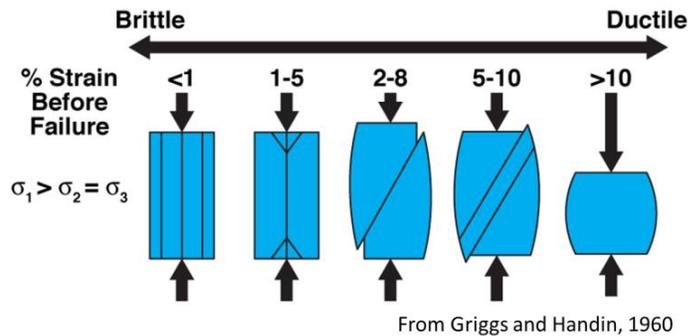


Figure 1 from Griggs and Handin (1960, page 349). Failure mode of the samples changes from extension (left) to shear (middle) to ductile flow (right) as sample ductility, controlled by changes in lithology, increases towards the right. All failures occurred while the samples were in compression in all three axes. (Griggs and Handin noted that this figure is a “schematic representation of the spectrum from brittle failure to ductile flow, with typical strains before fracture...”.) In addition to changes in lithology, greater compressive stress magnitudes and elevated temperatures drive the failure mode to the right, towards the shear-fracture field, whereas higher internal pore pressure within a sample, lower temperatures, and higher strain rates make the sample effectively more brittle, driving the failure mode to the left and towards the extension-fracture field.

OUTCROP EXAMPLE

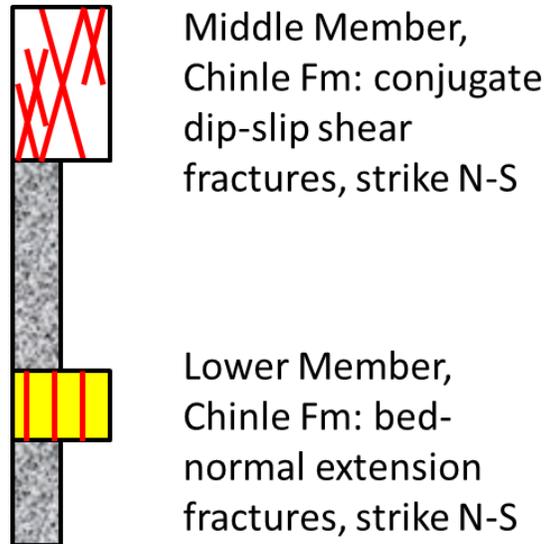
An easily accessible example of dynamically-compatible fracture sets, consisting of extension fractures in a relatively brittle bed and shear fractures in an adjacent, more ductile bed, is present in two sandstones of the Triassic Chinle Formation near Romeroville in north-central New Mexico. Road cuts on both sides of U.S. Highway 84 immediately south of Interstate Highway I-25 at Romeroville, exit 339, expose the two sandstones. One unit is a fine-grained, well-cemented, deep-red, lenticular sandstone up to three meters thick, the other is a fine-grained, moderately-cemented tan sandstone that is at least 10 meters thick. The two sandstones are separated by a largely covered interval of red mudstone that is on the order of 10 meters thick. Bedding is tilted 8° - 10° to the east but it is otherwise undeformed.

The well-cemented, red sandstone is cut by a set of closely-spaced, bed-normal fractures, with surfaces that are uniformly marked by plume structure indicating that the fractures formed

in extension. In contrast, the moderately-cemented tan sandstone is cut by a fracture set consisting of a pair of conjugate shear fractures with parallel strikes and opposing dips. The shear surfaces are pervasively marked by “non-congruent” (e.g., Doblas, 1998, Petit and Laville, 1987) shear steps indicating minimum-offset, normal, dip-slip shear. The fracture orientations indicate that fractures in both beds formed when the maximum compressive stress was vertical, the intermediate stress was horizontal trending N-S, and the minimum compressive stress was horizontal trending nearly E-W, and they probably formed before bedding had been tilted. Both fracture sets can be plausibly interpreted to have formed within a single stress system.



A bed of deep red, well-cemented, fine-grained sandstone (red arrow) of the Triassic, Lower Chinle Formation is overlain by a thicker bed of tan, moderately-cemented, fine-grained sandstone of the Middle Chinle Formation (white arrow) south of I-25 at the Romeroville exit, north-central New Mexico. The two beds are separated by a largely covered interval of muddy strata. View is towards the southeast.



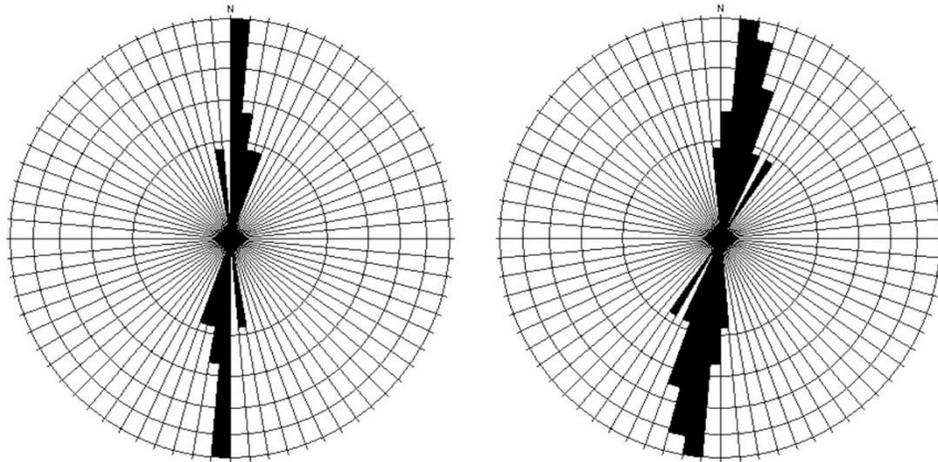
A schematic depiction of the two fracture sets in the two beds of the Chinle Formation. Conjugate dip-slip shears occur in the tan, Middle Member of the Chinle Formation and bed-normal extension fractures are present in the red, Lower Member of the Chinle Formation. Not to scale.



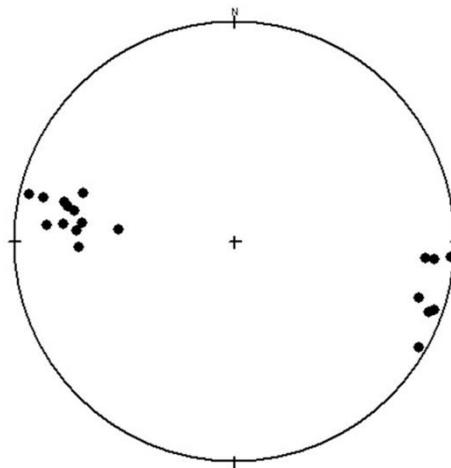
Closely-spaced, N-S striking extension fractures formed in the well-cemented, cross-bedded deep red sandstones of the non-marine, Lower Member of the Chinle Formation. Left, view is parallel to the N-S striking, bed-normal fractures. The bed is lenticular, with a maximum exposed thickness of three meters. Right: The fracture faces are marked by well-developed plume structures and local remnant patches of calcite cement. Muddy intraclasts at the base of the sandstone create a local variation in the mechanical properties of the unit, causing fracturing to be less well developed. Short, non-systematic, E-W cross fractures formed during road construction. Bedding is tilted, striking 340° - 160° and dipping 8° - 10° to the east. Post-fracture tilting of the beds causes the bed-normal extension fractures to have present-day non-vertical dips.



Conjugate, N-S striking, dip-slip shear fractures in the tan, cross-bedded sandstone of the Middle Member of the Chinle Formation. This unit is less well cemented and more porous than the lower red unit, and therefore responded to the same stresses in a more ductile fashion. Left, conjugate shear fractures form an ideal “X” pattern in outcrop (see also the stereoplot presented below). The conjugate angle formed by most of the fractures is somewhat narrower than the ideal 60° intersection. The right photo shows an example of the pervasive stepped ornamentation found on these shear faces. These are non-congruent steps: counter-intuitively, the missing block moved upward against the steps and the block shown in the photo moved downward. However, offset was minimal, being insufficient to produce slickensides. Bedding is tilted, with a strike of about 330° - 150° and a dip angle of 8° - 10° to the east.



Left: rose plot showing measured strikes of 11 extension fractures, marked by plume structure, in the well-cemented red sandstone. The average strike is 5° - 185° . Right, rose plot showing measured strikes of 19 dip-slip conjugate shear fractures, marked by shear steps, in the overlying, moderately-cemented, tan sandstone; average strike is 10° - 190° , nearly parallel to that of the extension fractures.



A pole-to-plane stereoplote of the conjugate fracture set in the tan sandstone, uncorrected for the eastward 8° - 10° dip of the strata. The fractures dip both eastward and westward, forming a dip-slip conjugate pair.

DISCUSSION

The structural setting of the outcrops at Romeroville at the southern end of the Laramide, eastward-directed, Rocky Mountain thrust system suggests that the strata were subjected to several stress events, but the system of two dynamically-compatible fracture sets at this location records only a single fracturing event. The structural and kinematic implications of the N-S striking fractures are not discussed here. Rather, the thrust of this discussion is that the Romeroville outcrops have significant implications for fluid flow in reservoirs, and that a complex structural history is not required to create variable flow networks in a formation.

Assuming all of the fracture planes are open and equally conductive to fluid flow (i.e., that one set is not preferentially plugged with mineralization), the two fracture sets at Romeroville would control significantly different flow patterns with implications for analogous reservoirs. The bed-parallel horizontal permeability in both beds would be anisotropic, greatest in the N-S direction parallel to fracture strikes. However, E-W, cross-strike permeability within the red sandstone would be limited to matrix permeability values since although the extension fractures are closely spaced they do not intersect. In contrast, cross-strike, E-W flow within the tan sandstone would be able to zig-zag along the interconnected conjugate fracture planes, and E-W system permeability would be somewhat greater than matrix permeability although not as great as the N-S, fracture-parallel permeability.

In addition, shear fractures commonly cut vertically across minor bedding planes whereas extension fractures do not, so the vertical fracture-controlled permeability system is more likely to be continuous across sedimentary heterogeneities within the tan sandstone than within the red sandstone.

A similar system of dynamically-compatible fracture sets in two sandstones was described by Lorenz et al. (2002) in cores cut from oil reservoirs of the Spraberry Formation at a depth of 7000 ft. in the Permian Basin. The conjugate shear fractures in one bed have a strike-slip rather than a dip-slip orientation, but they are dynamically compatible with the extension fractures in an associated bed 140 ft. higher in the section since the average strike of the extension fractures bisects the acute intersection angle formed by the conjugate shear-fracture pair. Tracer tests conducted in the reservoirs showed significantly different flow patterns within

the two units. The fracture difference is attributable to the mechanical properties of the two beds caused by variations in petrography and diagenesis.

The Romeroville outcrops illustrate that adjacent units of a reservoir may have significantly different fracture-controlled fluid-flow patterns even if the units underwent the same structural/stress history. The outcrops highlight the need for direct measurements of subsurface fracture systems (e.g., Lorenz and Cooper, 2018) before starting higher-level modeling and seismic-interpretation efforts, and before developing production and enhanced-recovery strategies.

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