

Conjugate Fracture Pairs in the Molina Member of the Wasatch Formation, Piceance Basin, Colorado: Implications for Fracture Origins and Hydrocarbon Production/Exploration

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ABSTRACT

The sandstones of the Molina Member of the Wasatch Formation in the Piceance basin of northwestern Colorado contain a suite of fractures that have a conjugate-pair geometry. The fractures are vertical and intersect at an acute angle of between 20 and 40 degrees. Although direct evidence of shear is rare, the fracture surfaces commonly display small steps. The fracture geometries suggest that the maximum compressive stress during fracturing was in the plane of the acute angle of the conjugate fractures: the steps are interpreted as broken-face manifestations of very low angle en echelon fractures, formed within exceptionally narrow zones of incipient shear.

In contrast to the highly anisotropic permeability enhancement created by sub-parallel vertical extension fractures in the underlying Mesaverde Formation, the conjugate pairs in the Molina sandstones should create a well connected and relatively isotropic mesh of fracture conductivity. Increases in stress magnitudes and anisotropy during production drawdown of reservoir pressures should cause shear offsets along the fractures, initially enhancing permeability.

INTRODUCTION

The Molina Member is a sandy unit within the mudstone-dominated late Paleocene/early Eocene Wasatch Formation in the Piceance basin of northwestern Colorado (Johnson et al., 1994). Deposited in a unique fluvial environment (Lorenz et al., 1996), the sandstones that comprise this unit are relatively homogeneous internally, ranging from about 10 to 40 ft. in thickness. The total thickness of the Molina Member is about 300 ft at its type section near the town of Molina on the southwestern edge of the basin (Donnell, 1969). The sandy Molina Member abruptly overlies the Atwell Gulch Member of the Wasatch Formation, and is overlain by the Shire Member. The type section of the Molina

Member outcrops along the western edge of the Piceance basin, and dips gently northeastward into the subsurface. Sandstones of the Wasatch Formation produce natural gas from several fields in the central parts of the basin

The sandstones of the Molina Member are pervasively naturally fractured. However, in striking contrast to the sub-parallel, vertical extension fractures that are common in the sandstones of the underlying Mesaverde Formation (Lorenz and Finley, 1991), fractures in the Molina typically occur as conjugate pairs. The geometry of these pairs and the distinctive structural features found on fracture faces suggest that the conjugate Molina fractures originated under conditions of combined dilation

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and incipient shear, with the maximum and minimum horizontal compressive stresses in the horizontal plane.

Most natural fractures enhance the permeability of a system, especially in low-permeability reservoirs. However, a conjugate-fracture mesh should provide a fracture-permeability system with significantly less anisotropy than a sub-parallel array of extension fractures. During draw-down of reservoir pressures, the permeability of such a

mesh may also be reactivated in shear, and, at least initially, should be less susceptible to closure than sub-parallel extension fractures.

The conditions under which conjugate fractures instead of vertical-extension fractures form, are suggested by the differences in the fracture characteristics, as described below. These characteristics offer preliminary insights on how to explore for conjugate-fracture hydrocarbon plays.



Figure 1 - Conjugate pairs on a bedding surface of the Molina Sandstone, boot for scale

FRACTURE DESCRIPTIONS

Natural fractures in the Molina sandstones are typically vertical to near-vertical, and form conjugate pairs. The axis of intersection of the two fracture planes is vertical (Fig. 1). (Conjugate fracture pairs with horizontal intersection axes are common in other formations, but have not been noted in the Molina sandstones). The acute angles formed by the conjugate Molina fracture pairs vary from about 20 to 40

degrees, somewhat less than the theoretical conjugate angle of 60 degrees. The orientations of the fracture pairs vary along the outcrops, but generally have an east-northeast/west-southwest trend (Fig. 2). Locally, a third, younger set is developed, trending approximately normal to the acute-angle bisector. This third set is interpreted as a surficial stress-relief phenomenon, and will not be considered further.

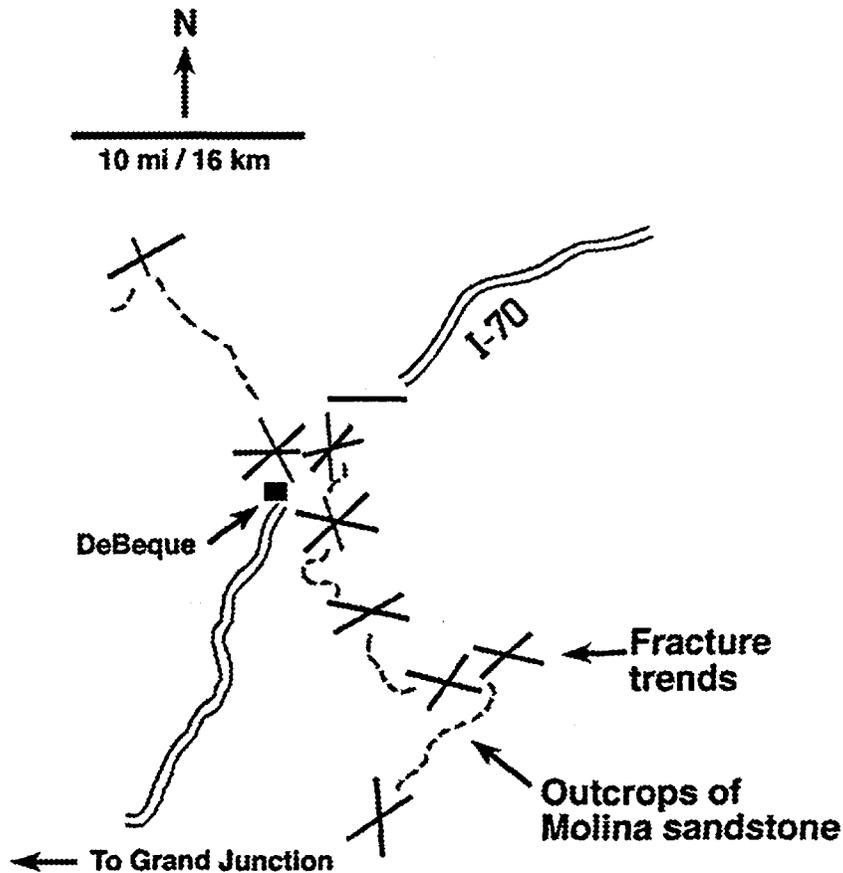


Figure 2 -Map of conjugate fracture trends in Outcrops of the Molina-Member Sandstones on the western edge of the Piceance basin

Because the Molina sandstones are typically internally homogeneous, most fractures extend top to base of the sandstone bodies. The fractures do not, however, extend between sandstones, across the thinner muddy beds that separate them. Extensive plan-view exposures of the sandstone surfaces are rare, but in the absence of sedimentary heterogeneities, an interconnected conjugate fracture mesh should extend to the lateral limits of the individual sandstone beds.

Exposed faces of the conjugate fractures rarely display slickensides (only one example noted in two

summers of field work) or other indications of shear offset. Neither are they marked by the hackle marks, ribs, or plumose structure that may be associated with extension fracturing. Rather, these fracture surfaces typically display small (fractions of an inch), similarly-oriented steps or offsets of the main fracture planes (Fig. 3). These steps have short, abrupt risers that are nearly normal to the overall trend of the fracture. The steps of the risers have vertically oriented crestlines, and their steep slopes face outward from the acute angle of intersection of the conjugate fracture planes (Fig. 4).

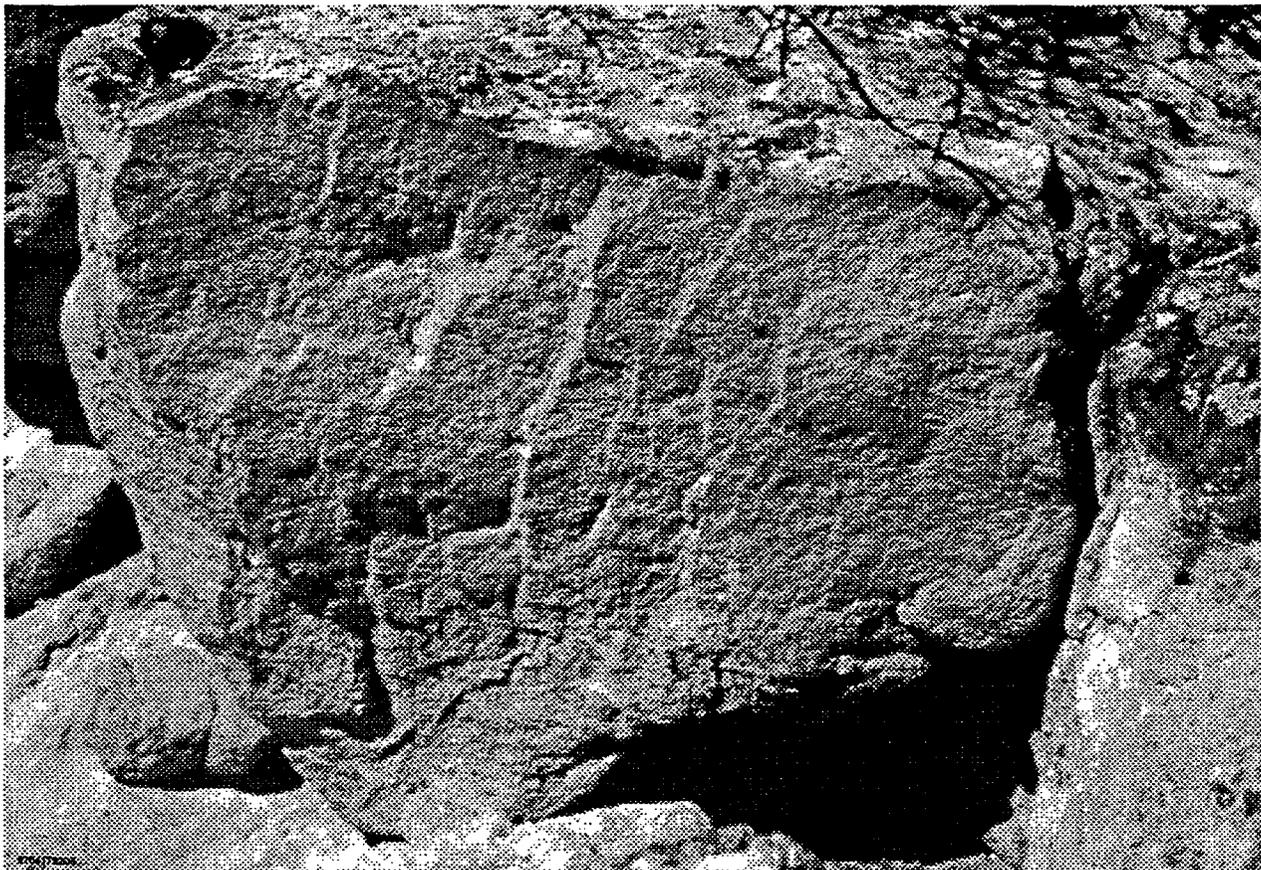


Figure 3 - En echelon steps on the surfaces of conjugate Molina fractures-
(fracture face is approximately one foot high)

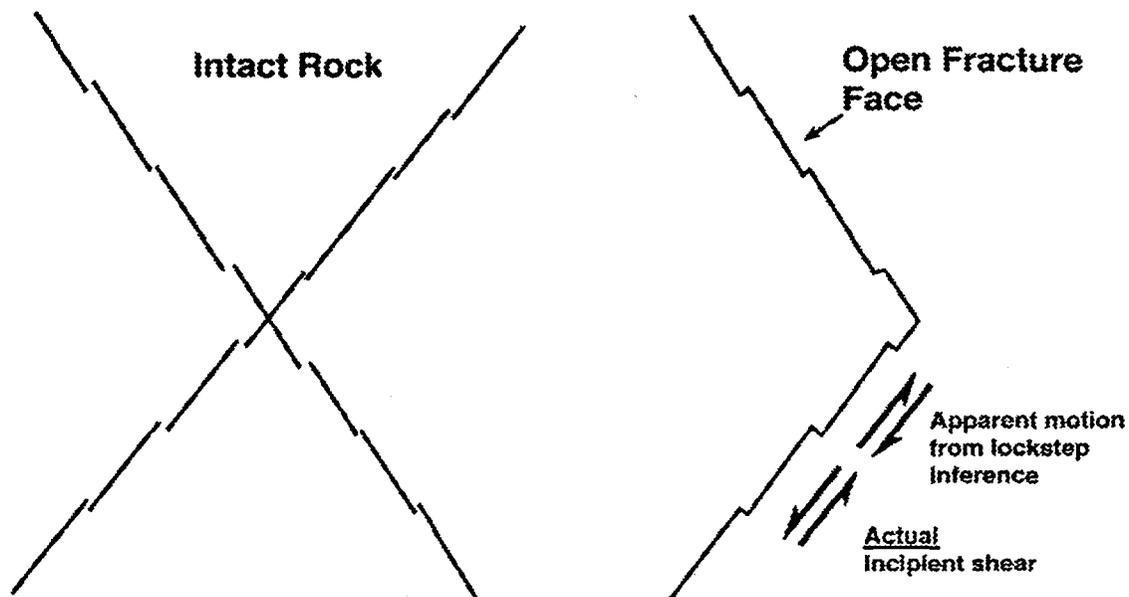


Figure 4 - Schematic showing steps on the surfaces of conjugate Molina fractures

Locally, one half of the fracture pair may be better developed than the other. Similar stepped conjugate fracture pairs occur in other Wasatch sandstones within the Piceance basin, but such pairs are best developed in the Molina Member and this is the focus of the present paper.

CONDITIONS OF CONJUGATE FRACTURE FORMATION

The bisector of the acute angle of a conjugate fracture pair is commonly interpreted to indicate the orientation of

the maximum compressive stress at the time of fracturing (e.g., Bucher, 1921). Using this convention, the maximum compressive stress at the time of fracturing of the Molina Member was horizontal and oriented approximately east-northeast/west-southwest. It can also be specified that the minimum stress was horizontal and south-southeast, while the intermediate stress was vertical. Since the overburden stress was *not* the maximum compressive stress (as is more commonly the case in unthrust strata), it may be inferred that the stress

differential was large and that either the maximum compressive stress was relatively high or that the minimum compressive stress was relatively low.

These stress orientations are generally parallel to those that can be reconstructed from the east-northeast striking vertical extension fractures in the underlying Mesaverde Formation in this part of the basin (as reported by Verbeek and Grout, 1984; 1985). (The only difference is that although the extension fracture planes in the Mesaverde Formation were defined by the maximum and intermediate compressive stresses, it cannot be specified whether the maximum stress was vertical, or horizontal and east-northeast. Analogy to the Wasatch conjugate fractures would suggest the latter).

Because of this reconstructed parallelism in stress orientations, the fractures in the two formations are inferred to have formed during the same event of east-northeast/west-southwest compression despite their significantly different characteristics. (In other, more deeply buried parts of the basin, however, there are significant differences between the fractures in the two formations: Verbeek and Grout, 1985; Lorenz and Finley, 1991). The stresses that caused fracturing may have been related to Laramide compression between the thick-skinned thrust blocks of the Uncompahgre Uplift on the southwest side of the basin and the White River Uplift to the northeast, with basin-scale dilatancy in the orthogonal direction.

The significant difference in fracture characteristics between the two formations may be due to a combination of differing mechanical properties and

different confining stresses, related to petrologic composition and depth of burial. The exact nature and mechanics of these controls is unclear at this stage of study, but whereas the Molina Member is composed of petrographically clean, well-sorted but poorly cemented sandstones, the Mesaverde sandstones are lithologically immature, and well cemented with numerous diagenetic stages of secondary quartz, calcite, and authigenic clays (Lorenz et al., 1989). Brittle mechanical properties favor extension fracturing over conjugate or shear fracturing (Griggs and Handin, 1960), and the Mesaverde sandstones are inferred to have been more brittle at the time of fracturing.

Although the greater depths of burial of the Mesaverde would have initially created greater confining stresses, negating some of the brittle character of these sandstones, the confining stresses would have been largely if not totally negated by elevated pore pressures associated with maturation of the organic components of the Mesaverde strata (Lorenz and Finley, 1991). Therefore it may be explainable why the Wasatch sandstones contain conjugate fractures, whereas vertical extension fractures were created in the Mesaverde sandstones under the same regional stress conditions.

The attempt was made in the field to interpret the steps on the conjugate fracture surfaces in the manner of slickensides, where conventionally, asymmetric steps can be used to infer sense of motion. In this interpretation (which is not universally accepted), shear motion was in the direction opposite that in which the two halves of the fracture "lock up" against

the steep risers of the steps. However, this interpretation was discarded because 1) the sense of motion indicated would suggest that the *minimum* rather than the maximum compressive stress was in the direction of the bisector of the acute angle between the conjugate pairs, and 2) these are not the accretionary slickensided steps to which this technique is usually applied.

Rather, these steps are better interpreted to represent subtle, en

echelon extension fractures, nearly parallel to the main fracture trend. These formed along a narrow, localized, incipient shear zone (Fig. 5), in a mechanism of combined dilatancy and shear as suggested by Smith and Durney (1992). The steep risers are, in fact, merely the broken rock connecting the en echelon fracture segments along separated fractures (Fig. 4). They are not present in plan view where the rock is intact, and are not part of the in situ fracture geometry.

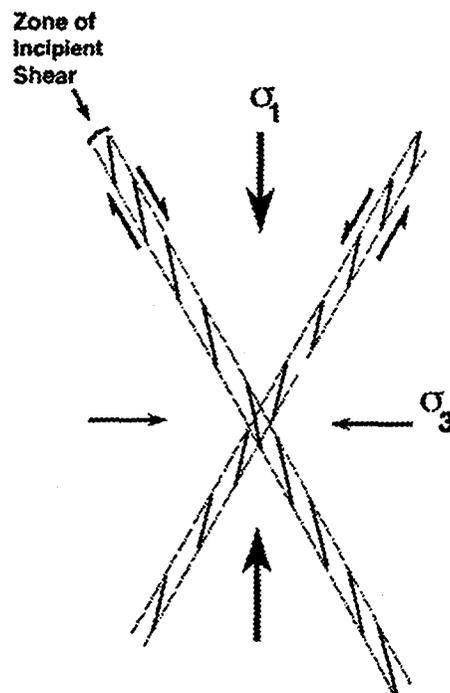


Figure 5 - Schematic showing dilatant shear fracture arrays forming along conjugate fracture planes

In this interpretation, such an echelon extension fractures would be a low-deformation end member of the spectrum that includes conjugate arrays of short veins and tension gashes in more highly tectonized strata (e.g., Beach, 1975). Smith (1996), in fact speculated that such "strongly divergent" conjugate fracture arrays as described here may exist, but that they had not yet been reported in the literature. The spectrum of structures may also include extension fractures as a member even lower on the scale of deformation; pervasive extension fractures can be traced laterally into conjugate pairs in some formations (e.g., the Gallup Sandstone of west-central New Mexico; personal observation), and there have been reports of conjugate pairs (with vertical intersection axes) that transition laterally, via gradually decreasing conjugate angles, into domains of vertical extension fracturing (Duschatko, 1953; Barton, 1983).

IMPLICATIONS FOR RESERVOIR MANAGEMENT AND EXPLORATION

Although it has yet to be demonstrated empirically (primarily because there are few reservoirs where data are sufficient to document conjugate fractures and their effects), conjugate fractures should have significant implications for reservoir management. The first is that the fracture-related permeability enhancement over matrix values is potentially greater, and the horizontal drainage patterns of a conjugate fracture mesh are potentially much more isotropic, than provided by an array of sub-parallel extension fractures. Thus there

is a potential for increased production rates and more efficient drainage of the reservoir. Even short fractures of conjugate pairs are likely to intersect and thus to provide long-distance lateral permeability continuity, whereas short or even intermediate-length sub-parallel fractures commonly terminate blindly within matrix rock.

The second consideration is individual fracture permeability. Conjugate fractures should be susceptible to shear during increases in stress differential and confining stress magnitude brought on by production and pressure drawdown, because they are inclined to the principal stress axes. If the stress changes are small, asperity offset during shearing should increase fracture permeability of the system. However, if drawdown is large and the stress changes are sufficient to cause significant shearing, fracture permeability could potentially be damaged and plugged by comminuted rock.

Once conjugate fracture meshes are deemed desirable exploration targets, an understanding of the conditions that change extension fracturing into conjugate fracturing can lead to an exploration rationale, focusing on areas where such conditions are likely to have been obtained. A preliminary, theoretical assessment of these conditions, considering fracture angles, failure envelopes, and circle sizes as depicted on Mohr diagrams, suggests that conjugate fracturing is favored in areas where the confining stresses and/or the stress differential were increased, and/or where the rock properties were such that rock strength was relatively low. Conjugate fracture pairs may also occur in domains of the rock that were

subjected to local extension (Smith and Durney, 1992), such as the outside hinges of even subtle flexures.

Empirical observations support these theoretical criteria in many instances: the less well cemented, less brittle strata in a succession are more likely to contain conjugate fractures (e.g., the Molina vs. the Mesaverde, as noted earlier, and the weakly cemented Jackpile sandstone vs. Gallup Sandstone of west-central New Mexico: Moensch and Schlee, 1967). Related conjugate-fracture vein and tension-gash arrays are also more common in ductile limestones than they are in brittle sandstones (e.g., Shainin, 1950).

SUMMARY

Natural fractures in the sandstones of the Molina Member of the Wasatch Formation occur as conjugate fracture pairs. Fracture characteristics and theoretical considerations suggest that the sandstones were not well cemented and were under reasonably high confining stresses (e.g., they were not brittle) at the time of fracturing. The fractures are interpreted to have formed under conditions of a northeast-striking and horizontal maximum compressive stress, which bisects the acute angle of the fracture pairs. The vertical overburden stress was the intermediate stress at the time of fracturing. Sub-parallel, vertical extension fractures formed in the underlying Mesaverde Formation under the same regional stress conditions, the difference being related qualitatively to differences in material properties and local stress conditions.

Strata that contain conjugate fracture sets should make better reservoirs than strata that contain only sub-parallel extension fractures. The conditions under which conjugate fracture pairs would form in preference to extension fractures should therefore be used to predict the location of conjugate-fracture exploration targets.

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