The Interplay of Fractures and Sedimentary Architecture: Natural Gas from Reservoirs in the Molina Sandstones, Piceance Basin, Colorado

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Introduction

The Molina Member of the Wasatch Formation produces natural gas from several fields along the Colorado River in the Piceance Basin, northwestern Colorado (Fig. 1).

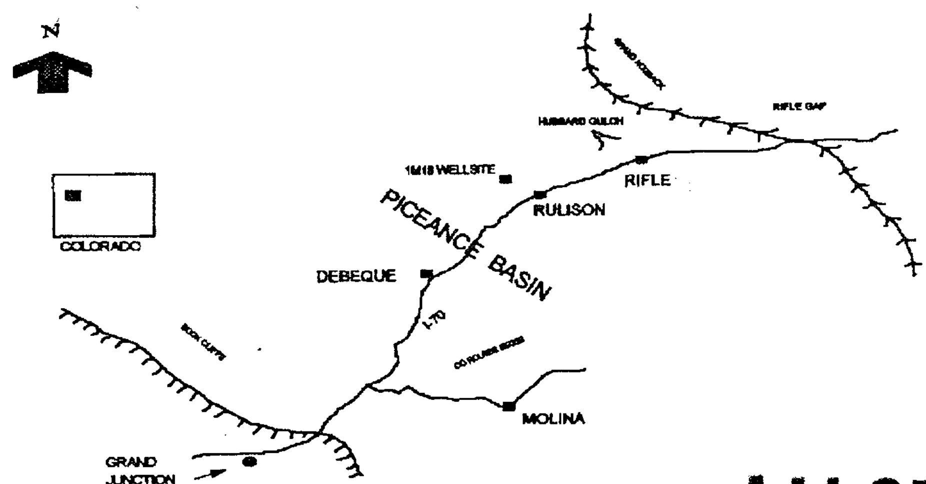

Figure 1. Location map of the Piceance basin, northwestern Colorado

The Molina Member is a distinctive sandstone that was deposited in a unique fluvial environment of shallow-water floods. This is recorded by the dominance of plane-parallel bedding in many of the sandstones. The Molina sandstones crop out on the western edge of the basin, and have been projected into the subsurface and across the basin to correlate with thinner sandy units of the Wasatch Formation at the eastern side of the basin. Detailed study, however, has shown that the sedimentary characteristics of the type-section Molina sandstones are incompatible with a model in which the eastern sandstones

are its distal facies equivalent. Rather, the eastern sandstones represent separate and unrelated sedimentary systems that prograded into the basin from nearby source-area highlands. Therefore, only the subsurface "Molina" reservoirs that are in close proximity to the western edge of the basin are continuous with the type-section sandstones. Reservoirs in the Grand Valley and Rulison gas fields were deposited in separate fluvial systems. These sandstones contain more typical fluvial sedimentary structures such as crossbeds and lateral accretion surfaces. Natural fractures play an important role in enhancing the conductivity and permeability of the Molina and related sandstones of the Wasatch Formation. The fractures in this formation commonly consist of conjugate fracture pairs, with the bisector of the acute angle lying in the horizontal plane and oriented approximately east-west (with minor but consistent variation across the basin). The fracture surfaces support the interpretation of the fractures as conjugate shear pairs, with small en echelon offsets indicative of lateral offset. The offsets should result in significant turbulence during flow of gas along a fracture. However, the fracture pairs have created an intersecting mesh, in which the anisotropy of the horizontal permeability should be significantly less than that in systems of parallel, vertical-extension fractures such as are found in the sandstones of the underlying Mesaverde Formation (Lorenz and Finley, 1991).

Objectives

The Molina Member of the Wasatch Formation in the Piceance Basin, Colorado, produces natural gas from a series of naturally fractured fluvial sandstones. The objective of this study is to provide a geological model that explains and predicts areas of gas production in terms of optimum fracture and sandstone development.

Approach

The Molina sandstone outcrops were studied in the field in order to determine their environment of deposition and stratigraphic relationships. Types and distributions of sedimentary structures for the different types of sandbodies were noted, and referenced to known models of depositional environment (Lorenz et al., 1996). In order to determine paleoflow and the potential for sandstone continuity across the basin, 1) crossbedding and parting lineation vectors were plotted on geographic indexes, 2) petrographic compositions were compared on different margins of the basin, and 3) depositional facies in different locations were compared for potential equivalency. Fracture characteristics (surface ornamentation, relative strikes) were measured in order to determine the origin of the fractures and their potential for enhancing conductivity within the formation. Geophysical logs from gas wells were correlated across the basin in the subsurface in order to trace depositional facies and sandbody continuity. These data were analyzed in order to produce a conceptual model of the distribution and conductivity of the Molina sandstones within the Piceance basin.

Project Description

1. Fracturing: Conjugate fracture pairs are typical of the Molina Member sandstones at its type section (Fig. 2). A mesh of conjugate fractures creates permeability

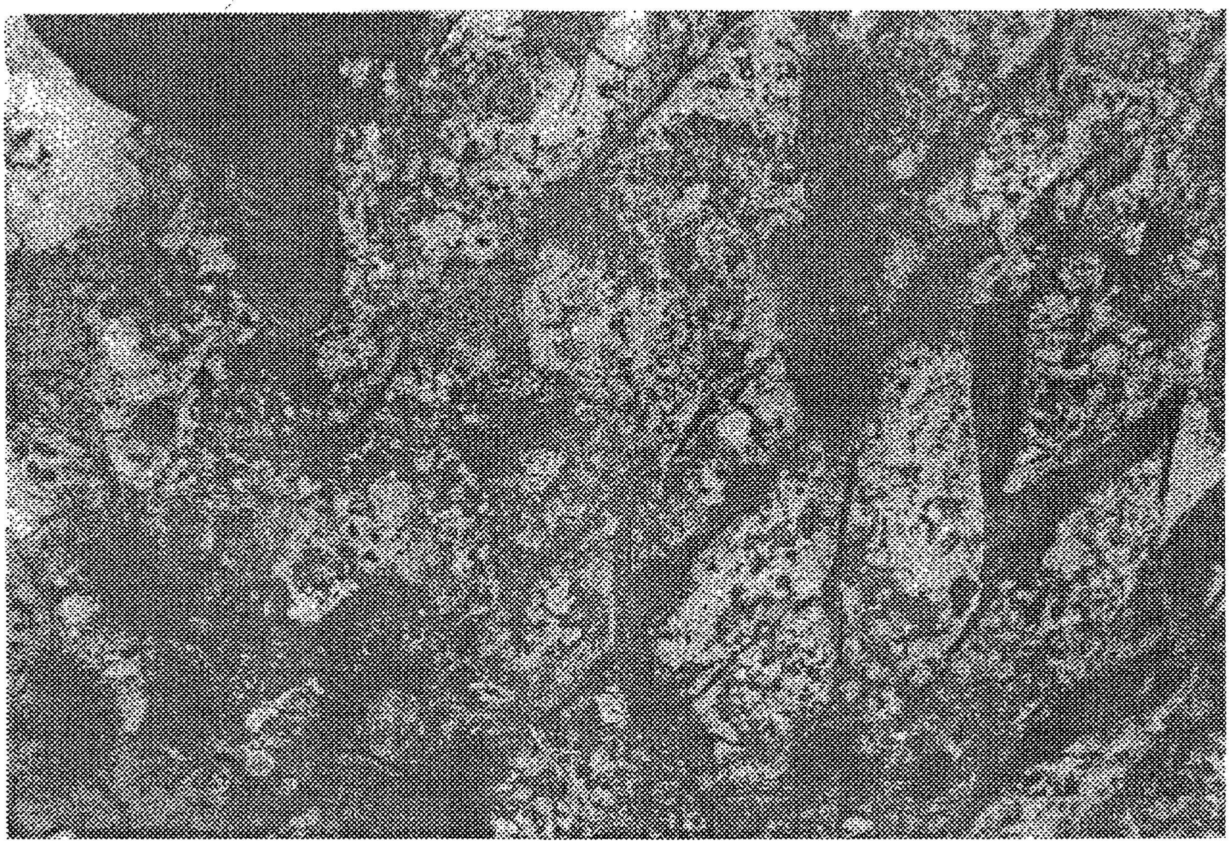

Fig. 2. Conjugate fractures in the Molina sandstone

enhancement over matrix-rock permeabilities, and yet allows permeability to be relatively isotropic horizontally. Steps are common on the surfaces of the Molina conjugate fractures, creating roughness and tortuosity. They are caused by incipient shear along the fracture plane. Conjugate fracture pair orientations (Fig. 3) suggest that the maximum horizontal tectonic compression was generally in the east-west direction, but rotated slightly across the basin.

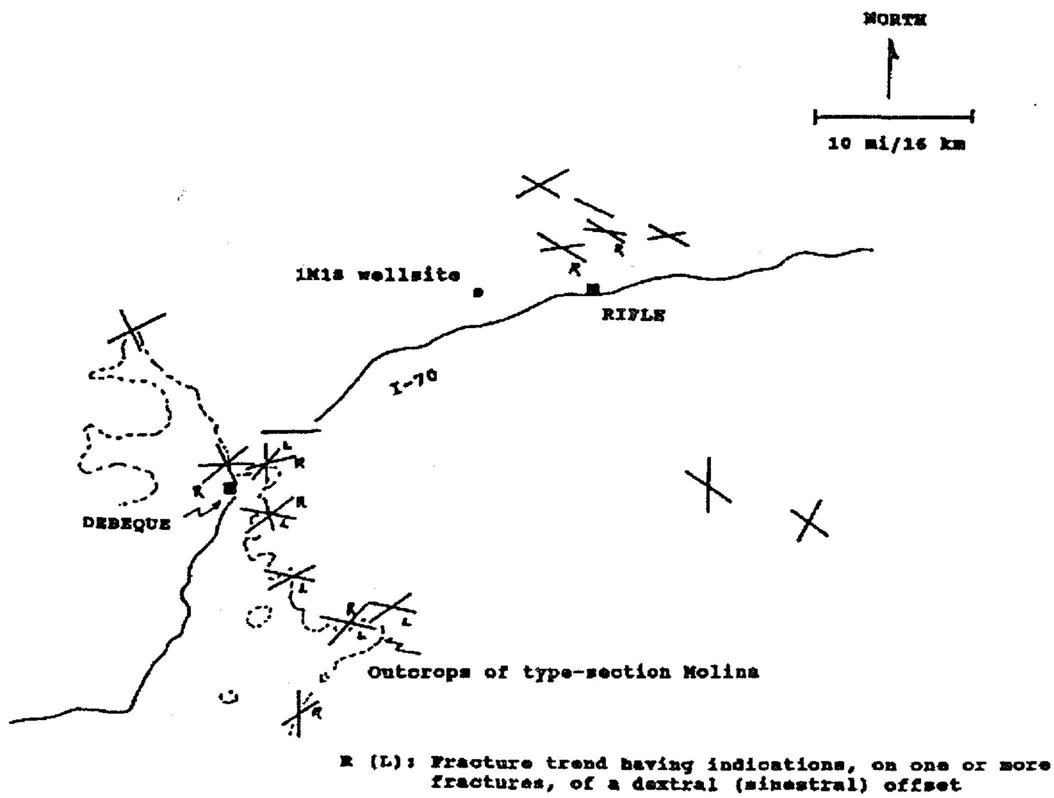

Fig. 3. Generalized fracture trends in the Molina and related sandstones

2. Depositional Environment: Plane-parallel bedding (Fig. 4) is abundant in the Molina sandstones. It is the dominant or even exclusive sedimentary structure in many

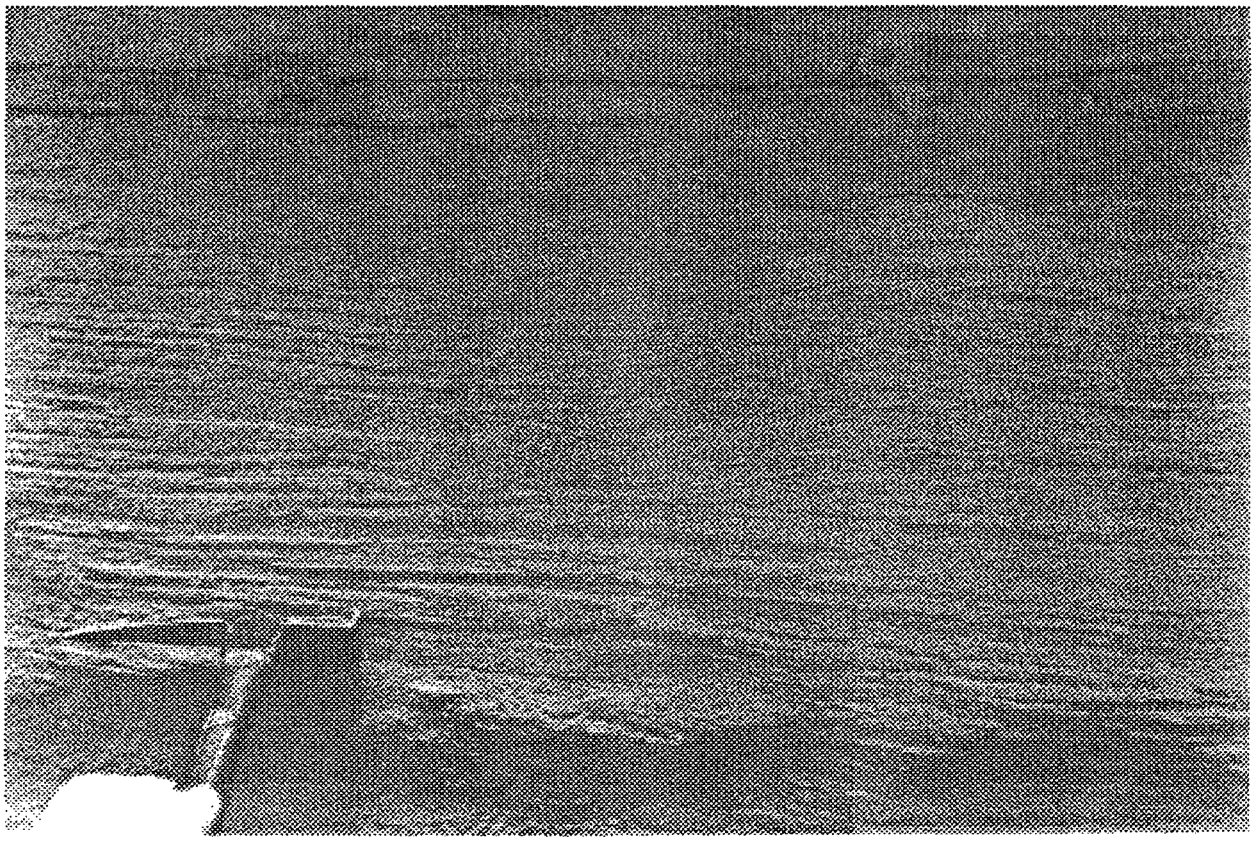

Fig. 4. Plane-parallel bedding in Molina sandstone

beds. This feature forms when sands are deposited during floods by fast-moving but shallow waters. Some Molina sandstones show lateral accretion structures, indicative of meandering fluvial systems. These are inferred to be the record of the fluvial regime that existed between flooding.

The type-section Molina Member sandstone on the southwestern edge of the basin consists of amalgamated tabular beds, many formed entirely of these planar-bedded sandstones. The Medano Creek in south-central Colorado is suggested to be the modern depositional-environment analog of the Molina. The Medano Creek is choked with sandy sediment due to the migration and encroachment by nearby sand dunes. It is ephemeral, flowing only in the spring, when it consists of multiple shallow channels filled with surging antidunes that deposit sand in plane-parallel beds.

Rapid sedimentation of the Molina sandstones, as from a flood, is indicated by a number of specific sedimentary structures, including 1) syn-sedimentary compaction faults, where sand was deposited too fast to dewater during deposition, and therefore compacted via faulting soon afterward; 2) rising-water crossbedding, showing horizontal topset layers that accreted with rising waters, and dipping foresets that filled in hollows in front of the structure; 3) soft-sediment deformation, which is common as a result of local fluidization due to dewatering of the undercompacted, rapidly deposited sands.

3. Stratigraphy: Paleocurrent vectors derived from crossbedding and parting lineation (Fig. 5) show that the type-section Molina was deposited in rivers that flowed

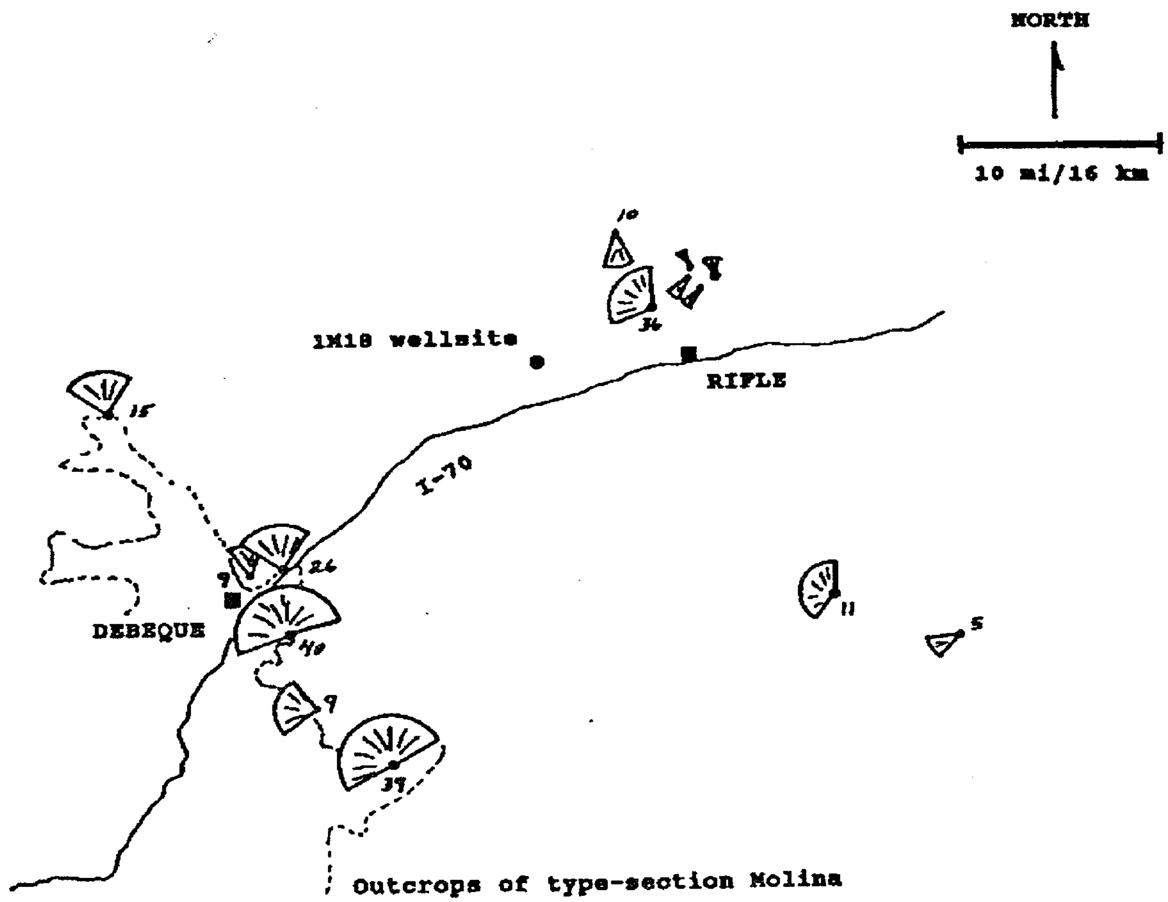

Fig. 5. Paleoflow directions in Molina and related sandstones

dominantly north-northwestward. Sandstones at the eastern edge of the basin, however, were deposited in streams that flowed *toward* the Molina system, and which could therefore not be distal facies equivalents of it. A facies distribution map of the Molina and related sandstones at mid-level within the Wasatch Formation suggests that the Molina depositional environment was unique, and that the meandering/braided systems of the similar sandstones on the eastern side of the basin were not the distal equivalents to it.

An extensive, tabular sandstone caps a mesa at Hubbard Gulch near the town of Rifle on the eastern edge of the basin. Although this sandstone is superficially similar to the type-section Molina, it is composed of meander-belt sedimentary structures (crossbedding and lateral accretion surfaces). Sedimentologically, stratigraphically, and compositionally, this and other sandy units within the Wasatch Formation at the eastern edge of the basin cannot be the distal facies equivalent of the Molina.

Results

Conjugate fracture pairs such as those found in the Molina sandstone form when the maximum compressive stress is in the horizontal plane. These outcrop patterns are projected to extend into the subsurface, where they enhance the permeability and conductivity of the sandstones. Because the conjugate fractures intersect, they should create nearly isotropic horizontal permeability enhancement (as opposed to parallel, vertical-extension fractures that create highly elliptical horizontal permeability). Reservoir permeability is expected to be enhanced by these fractures over and above matrix values in most of the Molina and Molina-equivalent sandstones across the basin.

The sandstones at the type section of the Molina Member of the Wasatch Formation are interpreted to have been deposited during rising-water floods in shallow channels of a fluvial system on a low-gradient alluvial fan. Meandering fluvial systems dominated between floods, resulting in mixed deposits of two fluvial types.

The Molina sandstones proper do not extend in a sheet across the basin. Rather, they are limited in extent to the southwestern part of the basin. Other fluvial sandstones were deposited elsewhere at the margins around basin, resulting in similar deposits in similar stratigraphic positions. However, these are not distal facies of the Molina. Molina and Molina-related sandstones are discontinuous across the basin, resulting in local developments of sandstone reservoirs.

Application

Fractures in the Molina Member and its equivalents are conjugate fracture pairs. The bisector of the acute angle between these pairs lies in the horizontal plane, and trends generally east-northeast in the Molina Member. In the equivalent sandstones at the eastern margin of the basin, the bisector trends west-northwest, indicating a change in the stress trajectory across the basin. This conjugate fracture system adds significantly to the conductivity of the Molina sandstones.

There are two models for the distribution of Molina and Molina-related sandstones across the Piceance basin (Fig. 6): Alternative "A" (the preferred model)

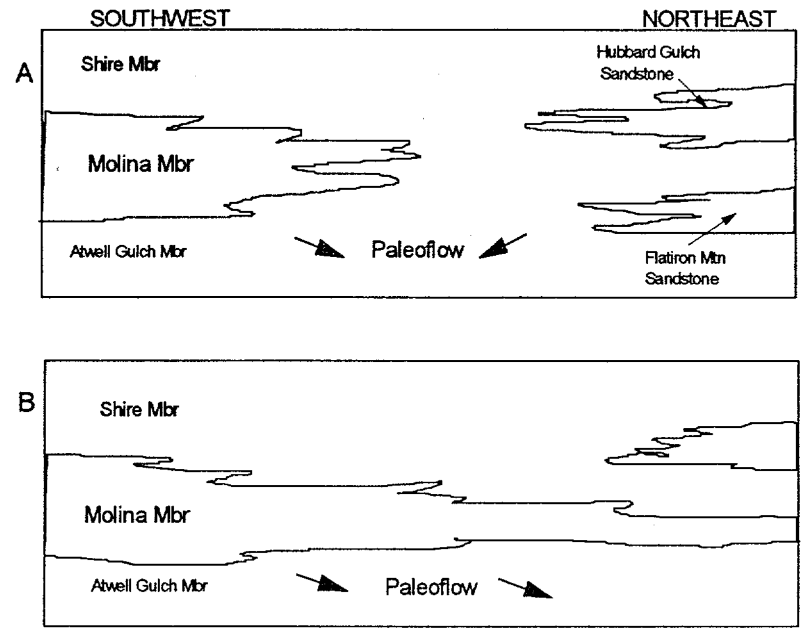

Fig. 6. Alternative models for Wasatch Formation stratigraphy

shows a complex depositional system in which streams prograded into the center of the basin from several source-area highlands around the basin, depositing different types of sandstones. Alternative "B" is a layer-cake model that has been used by previous authors (e.g., Donnell, 1969; Johnson et al., 1994). Although geometrically simple and therefore appealing, is unlikely in a fluvial environment. Data presented here do not support it.

Core taken from the DOE 1-M-18 well in the Rulison Gas field near the center of the basin, and other gas-productive horizons in this and the Grand Valley Gas field, were assumed to be from the Molina Member. However, sedimentary structures suggest an affinity to the meandering/braided systems of the eastern part of the basin, not the flood-dominated system of the type-section Molina to the west.

Contract Information

This work was performed under contract number DE-AC04-94AL85000, administered by Tom Mroz at the Federal Energy Technology Center in Morgantown, WV. The period of performance was October 1995 to October 1996.

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