Fracture stratigraphy: Predicting fractures from small-scale lithologic and textural changes

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ABSTRACT

Fracture prediction in hydrocarbon reservoirs remains problematic, despite advances in an understanding of mechanical properties and fracture development. We investigate two structurally and stratigraphically complex cores in the Heath Formation to address the growing need for knowledge of fracture stratigraphy as a tool for fracture prediction. We observed five major stratigraphic units hosting drastically different fracture patterns where changes in fracturing can be correlated to stratigraphic and diagenetic variation down to the microscopic scale.

INTRODUCTION

Natural fractures are necessary for enhanced production of unconventional oil reservoirs. Regardless, natural fractures remain difficult to predict. Gale (2014) states that *"Being able to predict fracture-size ranges, and thereby the natural fracture porosity and permeability enhancement, requires an understanding of the fracture stratigraphy; assumptions about size ranges and mechanical stratigraphy may lead to large errors in estimates of these parameters."* As more vertically heterogeneous reservoirs are targeted for oil and gas production, studies of fracture stratigraphy become more useful for fracture prediction, and thus a production prediction tool within fractured reservoirs. We analyzed two densely fractured cores in the Heath Formation from central Montana to show how geologic data including stratigraphy, mineralogy, fracture characterization, and petrography can be used to resolve and understand fracture stratigraphy.

The Mississippian-age Heath Formation recently has been targeted as a tight-oil play. It is a known source of oil for the overlying Tyler Formation, and has generated over 30 billion barrels of oil (Bottjer, 2014). The Heath is a lithologically variable unit that comprises organic-rich mudstones/marlstone, limestone, dolomite, anhydrite, and coal. Deposition occurred largely in an east-west trending, shallow marine embayment that extended across Montana. Formation-scale heterogeneity is largely a product of shoreline fluctuations and climate change during deposition.

PROCEDURES

Natural Fracture Characterization

Natural fractures were logged in cores from two wells in the Heath Formation, the Reese 1 and the Padre 1A. Fracture data collected included fracture depth (top and bottom), length, dip-angle, aperture (healed and open), spacing, mode (opening or shearing), shear-sense, termination style, fill mineralogy, and intersection-angle with other fractures, obtained using manual standard fracture measurement techniques. The fractures measured were then separated into fracture domains based on their characteristics and integrated with other geologic data outlined in this report to determine a fracture stratigraphy.

Core Description

The sedimentologic features of each core were logged at a scale of 1 inch = 2 feet. Observations included general lithology, texture, bedding and sedimentary structures, fossil content, and bioturbation intensity. Data were plotted as a graphic log.

Thin Section Analysis

Twelve thin sections were cut from the Reese 1 core and produced using standard techniques. Nine were oversized thin sections and four were standard sized. Thin sections were stained for calcite and ankerite. Sample selection was focused on fractured intervals, and major fractures were the central focus thin section analysis.

X-ray Diffraction Analysis

X-ray diffraction (XRD) samples were sampled based on lithology changes at a 3 to 37 foot spacing with an average spacing of ~14 ft. Fifteen bulk and clay samples were analyzed for mineralogy. Clay samples were analyzed using both glycolated and heat treated samples to calculate expandability for montmorillonite (mixed layer illite/smectite). XRD peaks were picked manually and subsequently verified using Topaz® analysis software. Data were normalized for total clay, total carbonate, anhydrite, and other (quartz, feldspar, etc.) based on the common lithologies observed in the cores.

Core Panel Integration

All data were compiled into a core panel as a visual representation and integration tool for both cores. Components of the core panel include core gamma log, a drafted core description and fracture sketch, XRD data represented as pie charts, and thin section photographs with descriptions plotted with respect to depth. The core panels were divided into intervals separated by flooding surfaces, significant changes in lithology and/or texture, and structural detachment surfaces for analysis. Components of each interval were then analyzed for structural, mineralogical, and stratigraphic elements.

RESULTS

Natural Fracture Results

The major natural facture types observed include: 1) vertical mineralized joints (Fig. 1b); 2) inclined, slickensided shear fractures (Fig. 1a); 3) short, bed-limited, fracture sets; 4) bed-parallel shears; 5) bedding-parallel veins with fibrous mineral fill (termed "beef" by Buckland and De la Beche, 1835) (Fig. 1a); 6) pre-compaction fractures (Fig. 1c); and 7) fracture zones/swarms (Fig. 1a). Similar fracture styles tend to cluster in zones, confined to a specific stratigraphic unit.

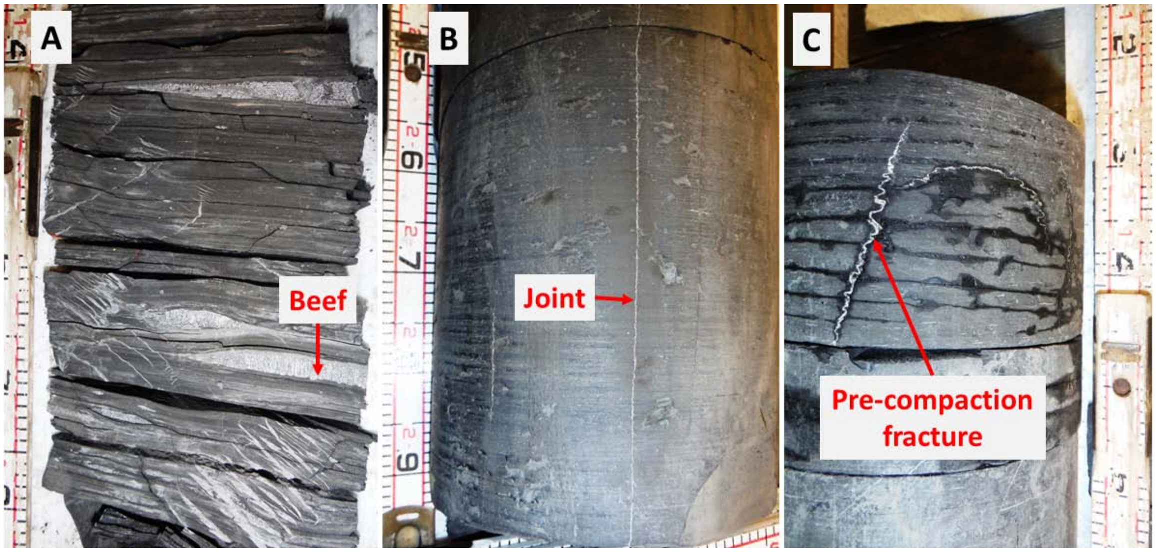

Figure 1. Some fracture types including A) a shear fractures (as seen by lamination offset) and beef zone, B) a mineralized vertical joint, and C) a pre-compaction fracture.

In both cores, natural fractures are organized into distinct fracture domains that correspond to lithologic units. In stratigraphic order, these fracture domains are: 1) densely-spaced cleats in coal; 2) dominantly joints; 3) mostly shear fractures; 4) short, bed-limited fractures; and 5) highly variable fracturing. The highly variable fracture interval is subdivided into four subintervals – two intervals of joints, one interval of shear fractures, and the upper-most interval of both shear fractures and beef. Two low-angle detachments, defined by densely spaced low-angle shear fractures and intersecting bed-parallel shears, are present in both cores.

Changes in fracturing are abrupt across sharp lithologic boundaries, ranging from the half-meter to millimeter scale. The conventional wisdom that fracture spacing decreases with decreasing fractured bed or lamination thickness (Ladeira and Price, 1981) holds true in thinly laminated intervals (for vertical fractures), however this relationship is less evident in intervals with low-angle shear fractures, bed-parallel shears, and beef.

Core Description Results

Combined, the two cores comprise four informal members of the Heath Formation: the Potter Creek coal, the Cox Ranch shale, the Heath limestone, and the upper shale member.

The Potter Creek coal, observed only in the Reese 1 core, is one foot thick and overlies a root-penetrated mineral paleosol developed in siliciclastic facies. This member is an impure/argillaceous coal that comprises 58% TOC by weight.

The Cox Ranch shale, present in both cores, ranges from 57 to 70 ft thick. This member consists of organic-rich, calcareous mudstone to marlstone with intercalated limestone and dolostone. Shelly, marine bioclasts are abundant and are commonly densely concentrated in the laminae and layers. Bioturbation is variable, ranging from absent to intense. Flooding surfaces within the Cox Ranch interval are recognizable in both cores and provide high-resolution correlations.

The Heath limestone, present in both cores, is about 20 feet thick. This member consists of anhydritic, calcareous dolostone to dolomitic limestone that grades up into crystalline anyhydrite. Some calcareous mudstone/marlstone beds are also present. Anhydrite in the carbonate beds is largely displaced. The crystalline anhydrite ranges from laminated to brecciated. In the Padre 1A, some crystalline anhydrite appears replaced by silica/clay.

The upper shale member is present in both cores, but the entire thickness of the unit is not represented. The cored section ranges 9 to 14 feet thick. This unit comprises calcareous mudstone/marlstone with interbedded marine limestone and dolostone. Bioclastic, shelly laminae are locally present in the mudstone facies.

Thin Section Analysis Results

Twelve thin sections from the Reese 1 core reveal complex fracturing and diagenesis. Fracture-parallel layers of mineral fill suggest crack-seal mechanisms for fracture development with up to three different layers of minerals. This indicates mineral replacement within fractures, (e.g. calcite and chlorite). Petrographic analysis supports observations in core suggestive of multiple deformation events. Younger fractures abut into older fractures in core and thin section. These same fractures show small amounts of fill from the younger fractures bulging into older, orthogonal fractures (Fig. 2).

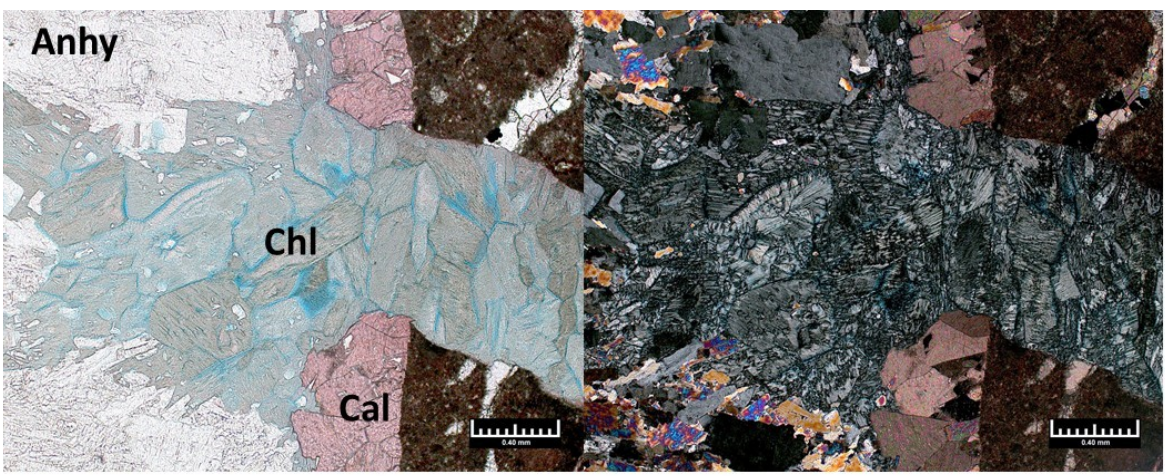

Figure 2. Thin section photomicrographs showing a younger fracture bulging into an older fracture partially reopening the older fracture. Anhy = anhydrite; Chl = chlorite; Cal = calcite; Magnification = 50X; Left is PPL; Right is XPL.

Further evidence of a relationship between fracturing and diagenesis is found in thin sections from the upper shale and Cox Ranch. In the upper shale, a relatively large-aperture fracture has up to four mineral fills including chlorite, dolomite, anhydrite, and calcite, partially due to mineral-replacement. In the Cox Ranch, a discontinuous fracture crosses a succession of three laminae: shale, organic silty shale, and dolomite. The fracture is fully healed by dolomite and calcite in the lower shale lamina. The intervening clay/organic silty shale lamina is not fractured. The fracture reappears and is propped open by euhedral dolomite crystals in the dolomite lamina preserving fracture porosity.

X-Ray Diffraction Analysis Results

Thirteen samples were analyzed for XRD mineralogy – 11 from the Reese 1 well and four from the Padre 1A well. The major mineralogical components include clay, carbonate, anhydrite, and quartz (Fig. 3). Small amounts of plagioclase, pyrite, apatite, analcime, celestine, gypsum, and barite were also found. The major component averages are: 19% clay (ranging 0-51%), 43% carbonate (ranging 2-89%), 19% quartz (ranging 1-44%), and 13% anhydrite (ranging 0-88%). In the Padre 1A core, samples were not taken from facies with abundant anhydrite; hence, this mineral phase is underrepresented in the XRD data. Differentiation of clays shows the dominant clays as mixed-layer illite/smectite and illite with trace amounts of chlorite and kaolinite in most samples.

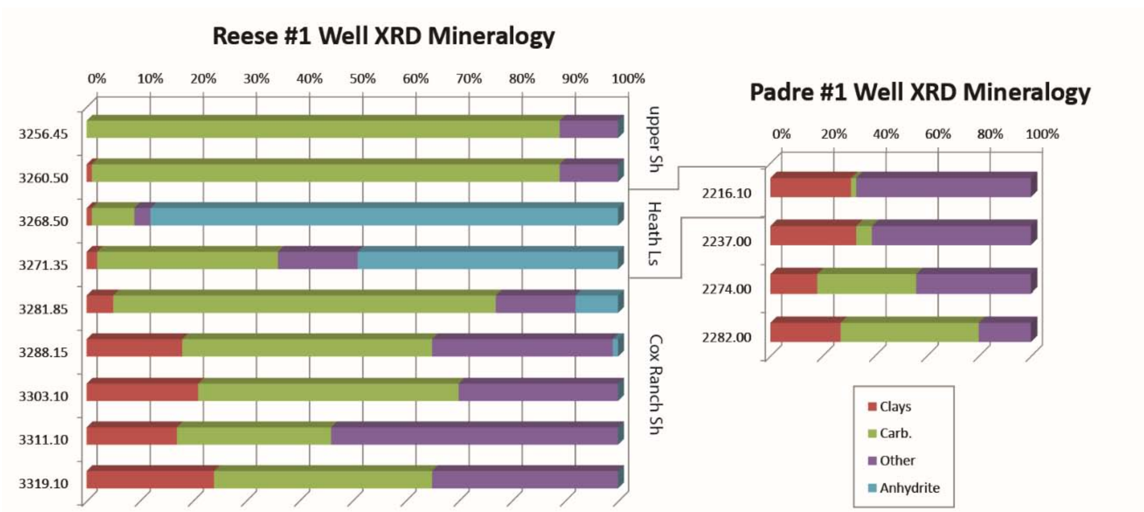

Figure 3. XRD mineralogy (total clay, total carbonates, anhydrite, and other (including quartz) for samples in the Reese 1 and Padre 1A wells. Not to scale.

DISCUSSION

A distinct fracture stratigraphy exists within the Heath Formation. Fractures within each interval (listed in stratigraphic order) are: 1) Potter Creek coal — closely spaced cleats; 2) lower Cox Ranch shale — mostly planar, vertical, mineralized joints; 3) upper Cox Ranch shale — mostly shear fractures and bed-parallel shears; 4) Heath limestone —

variable but prominent bed-limited fractures, mostly within thin, dolostone beds and laminations; and 5) upper shale member — mixed, highly variable fractures including bed-parallel shears, shear fractures, short, mineralized and unmineralized joints, and beef.

Densely-spaced cleats are expected in coals such as the Potter Creek. The presence of mostly planar joints in the lower Cox Ranch shale may be related to the calcareous nature (possibly increased due to the presence of calcareous bioclasts as a source of carbonate) of the marlstones and limestones, raising the shear strength of the interval, and inhibiting the development of shears. Conversely, the lower carbonate percentage (also lower calcareous bioclast concentration) within the upper Cox Ranch likely promoted development of shear fractures and bed-parallel shears. Both the thinly-bedded nature of the Heath limestone, and the alternating layers of ductile anhydrite with the more brittle dolostone, promoted the development of closely-spaced, bed-limited fractures. The argillaceous and laminated character of the mudstone facies in the upper shale may explain the presence of beef and dense shears. These changes show that facies and diagenesis, control the distinct differences in fracture characteristics including fracture mode (opening, shearing, etc) and geometry.

CONCLUSION

Data from two heterogeneous “shale” cores from the Heath Formation in Montana provided an opportunity to better understand fracture stratigraphy. Clear correlations exist between stratigraphy, texture, mineralogy, diagenesis, and fracturing. Ultimately, this and similar studies will make natural fracture prediction models more geologically accurate, increasing production in fractured shale plays.

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