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Induced seismicity and hydraulic fracturing insights from a fracture survey of an analogous Duvernay outcrop

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Introduction

Unconventional reservoirs are defined by their low matrix permeability and the need for horizontal wells and hydraulic stimulation to produce economically. The volume of fluid and proppant that is currently injected in unconventional reservoirs exacerbates several geomechanical problems (Smith and Montgomery, 2015). One of these problems is interwell connectivity, or frac hits, where completions in adjacent wells interfere with production and stimulations in adjacent wells (Ajani and Kelkar, 2012). Another problem is induced seismicity, where completions trigger the slip of pre-existing faults and generate moderate size earthquakes that can halt operations and pose a risk to surface infrastructure (Ellsworth, 2013). Both of these problems can be linked to the presence of a discrete fracture network (DFN), which is necessary for explaining the transmission of fluid pressures hundreds of meters farther than the planned simulation zone (Warpinski and Teufel, 1987).

Constraining a DFN in the subsurface is difficult due to a scarcity of information. This is especially true in the Duvernay formation, where the majority of large-scale faults and fractures have high dip angles that are unlikely to be identified by vertical wellbores. This means that analogous information is required to characterize the nature of subvertical faulting. This analogous evidence can include microseismic data from previous completion programs, kicks and inflows during drilling of horizontal wells, production analysis, and geological studies of outcrops. This study uses the later to constrain a DFN and discusses the implications of this DFN on induced seismicity and hydraulic fracturing.

Workflow

A well-exposed outcrop analogue of the Duvernay Formation near Cline River, Alberta was studies. This outcrop of the Perdrix formation, shown in Figure 1A and hereafter referred to as the Allstone's Creek outcrop, is unique in that it provides two orthogonal windows to study fractures – a bedding parallel outcrop of the Beaverhill formation and a bedding perpendicular outcrop of the Duvernay formation. Both exposures are located on the far limb of a tight fold, which reduces structural deformation. The Beaverhill formation abuts the lower portion of the Duvernay outcrop and provides an erosionally resistive and laterally extensive bed parallel expression of tectonic fracturing. The Duvernay outcrop was oblique to bedding and relatively well exposed due to it being located in an alpine avalanche chute and creek. The outcrop provided a vertical section of the lower Duvernay formation in two locations – the well exposed but laterally constrained creek bed and the less exposed but laterally continuous avalanche chute.

Figure 1. A photograph of the three exposures in the fracture study. The yellow region is the bed-parallel exposure of the Beaverhill formation. The red region is the bed-perpendicular exposure of the Duvernay formation along the avalanche path. The blue region is the Duvernay formation exposure along the creek.

The fracture study included unmanned aerial vehicle (UAV) photogrammetry, three lateral scanlines, thirteen 1m2 fracture windows in the Duvernay formation, and a larger (4 m2) fracture window in the Beaverhill formation. This study was also part of a larger effort that included compositional evaluation, stratigraphy, characterization of geomechanical heterogeneity, geomechanical testing, and photogrammetric structure mapping. This information was integrated with the fracture study to identify geomechanical facies and flow units and their effect on hydraulic fracturing and induced seismicity.

The scanlines were used to identify fracture frequency (P10) and measured in three separate facies – the interbedded shale and limestone facies, a predominantly carbonate facies, and a shale rich facies. The fracture windows and two orthomosaics were used to identify dominant joint sets and fracture intensity (P21). The orientation of fractures were determined using cleavage planes in the fracture windows to provide the strike and dip of the dominant joint sets and correct the spacing of the P10 and P21 measurements. The orthomosaics were also used to investigate scale-dependence and the fractal distribution of fracture spacing.

Results

Four joint sets were identified in the Beaverhill formation using an orthomosaic from the photogrammetry data and the fracture spacing quantified. Two joint sets represented shear failure under tectonic loading whereas another two sets represented extensional fractures due to deposition and/or diagenesis. The fracture window displayed a wide range of fracture orientations, with a mean plane of 161°N/86° after rotating the bedding to vertical. The fracture intensity was measured in the window and orthomosaics, as illustrated by an example section from the Beaverhill photomosaic in Figure 2.

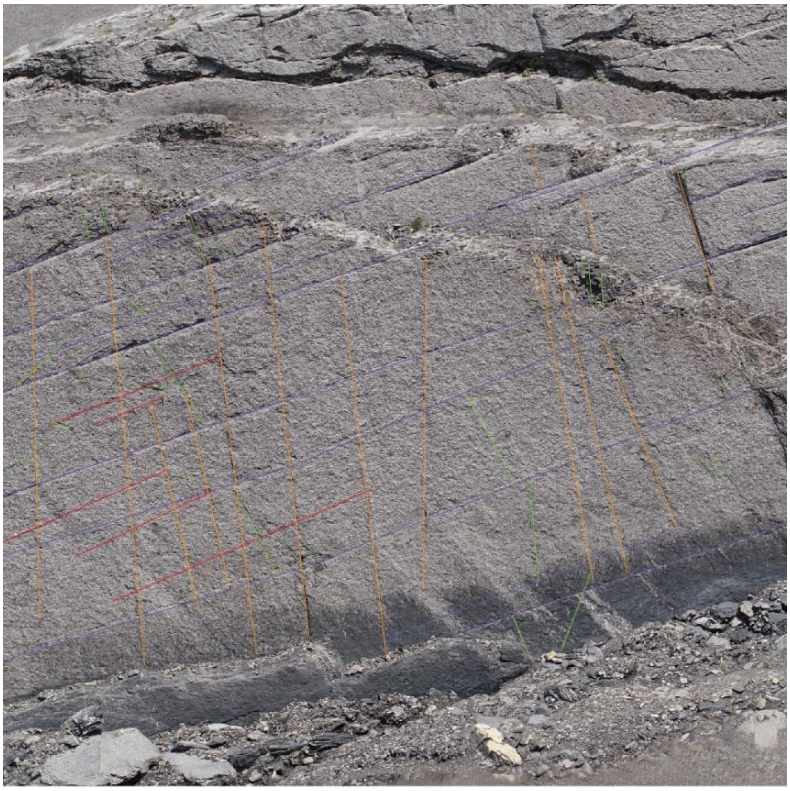

Figure 2. An excerpt from the photomosaic of the Beaverhill formation. Four joint sets are illustrated – two orthogonal joint sets (orange and purple) that are likely a result of diagenesis and two joint sets that are likely a result of deformation and occurred after the orthogonal joint sets (red and green).

The larger tectonic fractures continued into the lower Duvernay formation, albeit at a lower intensity and spacing. The orthomosaic showed the dominance of the two tectonic fracture sets observed in the Beaverhill and the near absence of the orthogonal extensional fractures. The fracture intensity was measured in the three scanlines, the fracture windows, and the orthomosaics. The fracture windows displayed tightly grouped bedding planes with a mean orientation of 128°N/70°. Two orthogonal joint sets were also identified at 162°N/87° and 246°N/89°, which may correlate with the tectonic deformation. Stereonets from the Duvernay and Beaverhill exposures are illustrated in Figure 3.

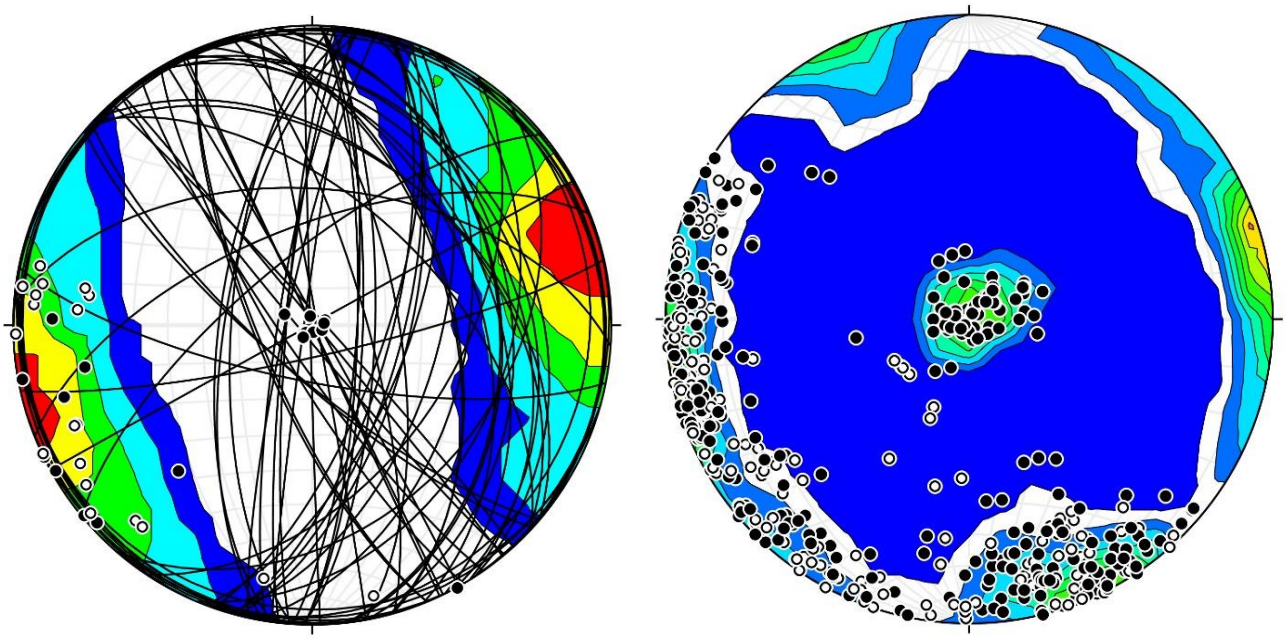

Figure 3. Equal-area stereographic projections of the fracture window mapping of the Beaverhill (left) and Duvernay formation exposures (right). Planes have been rotated to make bedding horizontal.

Discussion

A combination of geomechanical heterogeneity, detailed stratigraphy, and a discrete fracture model can inform hydraulic fracture models and help mitigate induced seismicity and interwell connectivity. In addition to providing an analogous characterization of fracture intensity and orientation in both the Beaverhill and Duvernay formations, this study showed several features that are important when conceptualizing geomechanical and reservoir models.

Bed-bound fractures were observed in numerous units, suggesting that smaller, stiffer lithofacies units may act as flow units when perturbed by diagenesis, tectonic loading, or hydraulic fracturing (if the fracturing can shear and dilate these pre-existing discontinuities). The bed bound fractures also show the influence of small weak shale layers for increasing fracture complexity due to jogging of hydraulic fractures and bed terminations. Extensive bedding parallel fractures were observed in both the fracture windows and orthomosaics of the Duvernay. These fractures support subsurface observations of “rogue fracs”, or fractures that propagate along bedding planes and promote casing deformation due to bedding plane slip. The presence of healed bedding plane fractures that are perpendicular to the inferred maximum horizontal stress direction in this study provides evidence that this process is not only possible, but commonplace in the geological record. A fracture window from the lower portion of the Duvernay illustrates both these principles in Figure 4.

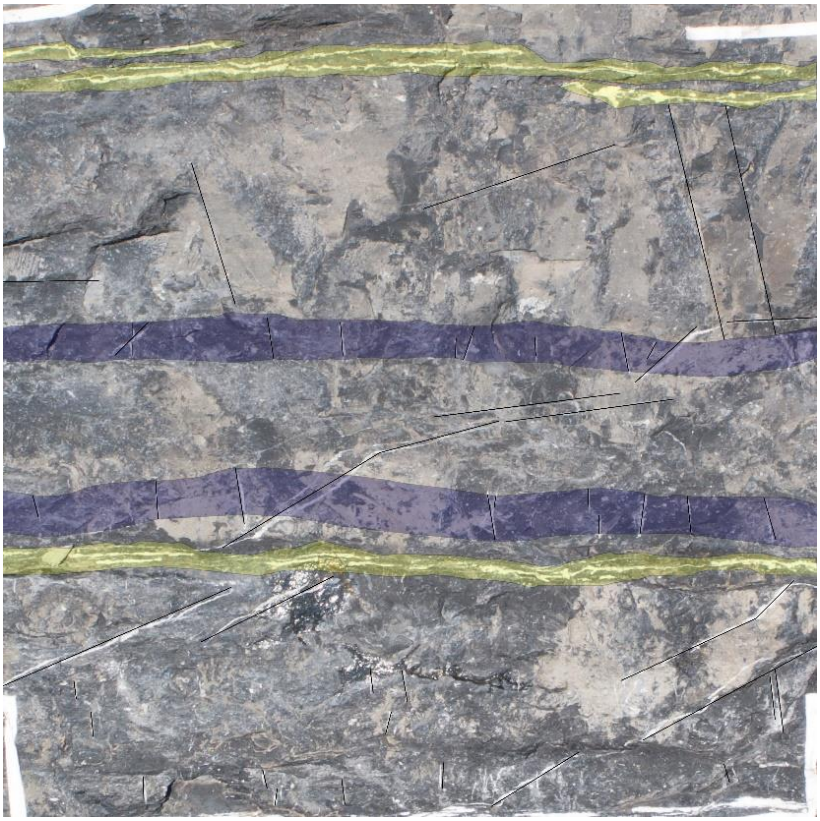

Figure 4. Fracture window of the Duvernay formation outcrop from 1 m to 2 m above the Beaverhill contact. The yellow regions highlight bed parallel slip and fluid flow. The purple regions illustrate bed bound fractures that may serve as anisotropic flow units.

The observed tectonic scale fractures in the Duvernay formation showed how rock properties and heterogeneity influence the geomechanical response of a formation to fracturing and strain. The lower section of the Duvernay (0 – 10 m), directly above the Beaverhill formation displayed large displacements along tightly constrained shear zones. These tectonic fractures changed character in the interbedded shale and siltstone facies that were directly above the lower section. The interbedded section (14 – 20 m) showed echelon fractures along larger damage zones, which is indicative of plastic deformation. Shear displacement was muted in the interbedded facies, indicating that these units can accommodate significant pore pressures and tectonic strains without brittle failure. Figure 5 compares faults from the the lower and upper sections to illustrate this principle.

Figure 5. Photographic illustration of the variable response of different geomechanical facies to tectonic strain. The lower unit (left) shows significant shear displacement and brittle expressions of failure. The upper unit (right) shows muted displacements and plastic expressions of failure shown by echelon shear fractures over a large damage zone.

Acknowledgements

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