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The interaction between cm- and m-scale heterogeneity of the Duvernay Formation based on an outcrop case study: implications for 3-D reservoir modeling

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Summary

Understanding geologic heterogeneity within shale rocks is critical to optimize hydraulic fracturing and enhance unconventional hydrocarbon recovery. In early development, it was thought that shale plays were dominantly homogenous with little geologic variation. More recent work (Hart et al., 2013; Sone and Zoback, 2013) has demonstrated an extremely high degree of geological and geomechanical variability within shale plays. Geologic and geomechanical heterogeneity within an unconventional reservoir are commonly evaluated using well log analysis and core measurements, both of which give 1-dimensional data. The limited dimensionality of this data cannot fully resolve the lateral heterogeneity of the reservoir. In addition, core plugs and well logs represent average measurements and not discrete points. Therefore, the cm-scale variability within many shale reservoirs remains unresolved. It is crucial to know if small scale heterogeneity reflects the variability observed at a meter scale to better understand the interaction between the two. This information is important in horizontal well completion design for wells targeting organic-rich shales. In this study, we investigate the vertical and lateral heterogeneity of the Duvernay shale play of Western-Central Alberta (Canada) at two different scales: meter and centimeter using an outcrop-based approach.

The outcrop analyzed in this study is the Allstones Creek outcrop, near Cline River, Alberta (Canada). This location hosts one of the few Duvernay equivalent outcrops which is unique in its lateral extent, lack of weathering, and access. Hand samples and blocks were collected along three vertical stratigraphic sections that were analyzed for sedimentary facies, elemental composition, TOC, static mechanical properties, and handheld hardness. This study shows how mechanical rock properties are strongly influenced by variations in elemental composition and lithofacies within the reservoir at both meter-scale and centimeter-scale, suggesting similar reservoir behavior likely occurs in the subsurface at the reservoir scale. This understanding can be applied to improve 3-D subsurface models, where upscaling often oversimplifies the reservoir and is unable to properly resolve the reservoir heterogeneity.

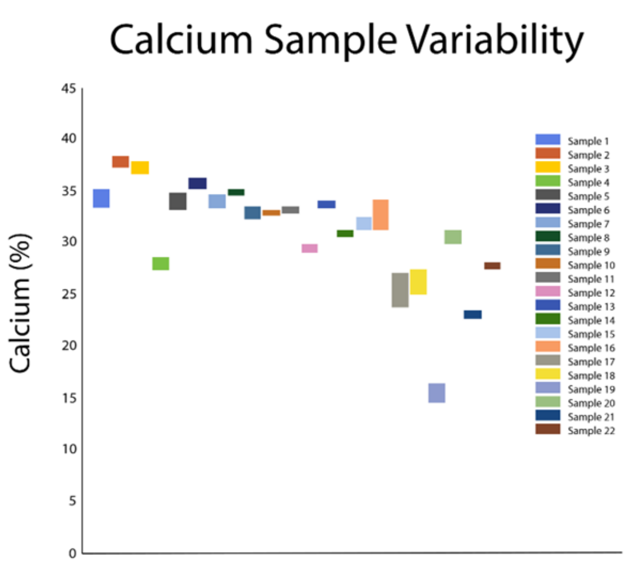
Workflow

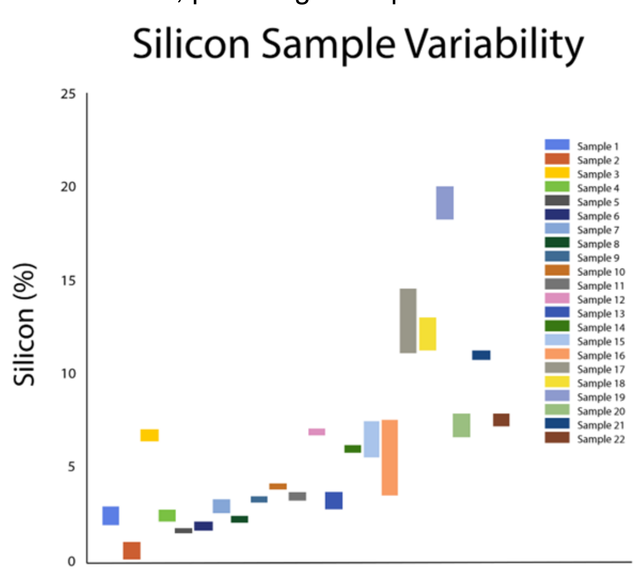
This study uses outcrop data from three vertical stratigraphic sections; 30m, 23m, and 25m in height. These sections were logged in detail and sampled at two scales: hand samples collected every 0.5-1m and blocks collected every 3-4m. Additionally, 13 windows of $1m^2$ were selected along the stratigraphic sections and Schmidt hammer measurements were taken on clean surfaces at a 10cm grid, yielding 1300 stiffness data points.

Hand samples and blocks were then cut perpendicular to bedding, creating two 90-degree flat surfaces which were then described for sedimentary facies. Microhardness and XRF data were collected from the sample's cut faces using a $1cm^2$ grid, yielding over 3500 data points. Drill plugs were then taken from the samples to attain static geomechanical properties by performing Triaxial, Point Load, Brazilian, and UCS testing. The samples were sent for RockEval analysis at the Geological Survey of Canada, Calgary. This gives information on TOC content and thermal maturity of the organic-rich shales. This data will be integrated with the elemental composition and mechanical dataset. The integration of these data suits allows for an understanding of the Duvernay Formation at different scales of investigation.

Results

This outcrop-based study demonstrates that geological and geomechanical heterogeneity is present in the Duvernay Formation at both meter scale, from plotting average measurements along a depth axis and centimeter scale by observing variability from different measurements within a single sample. The detail acquired from the centimeter scale cannot be resolved with well log analysis or core plug testing. Results show compositional and mechanical coefficients of variation within a single sample at the centimeter scale can exceed 20% in relative magnitude (Figure 1). This study also highlights the large variation at the meter scale, which can have coefficients of variation exceeding 70% (Figure 1). This study also confirms the close relationship between the composition and mechanical properties of the reservoir. A direct relationship is observed between mechanical hardness and carbonate as well as biogenic silica content. As the clay content increases, hardness generally decreases. This result is consistent with observations of the subsurface Duvernay Formation from analysis of drill cores (Dong et al., 2018). Our work extends this research by addressing small-scale heterogeneity of the organic-rich shales. In addition, the lateral continuity of the Allstones Creek outcrop offers a 2-D overview of the complex depositional architecture of the shales, providing an explanation for the





geological heterogeneity of the subsurface Duvernay Formation.

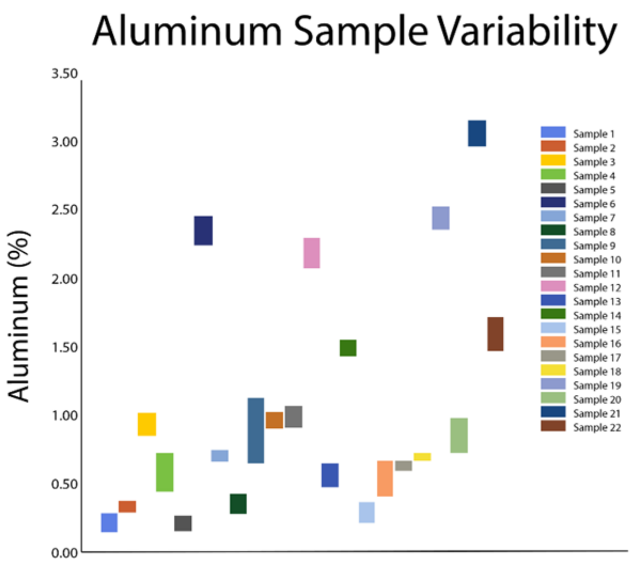


Figure 1: Box plots showing the variability of elemental composition within individual hand samples from the Duvernay Formation outcrop. This study shows a range of data exceeding 20% in coefficient of variation in elemental composition within individual samples, highlighting the centimeter scale heterogeneity within the Duvernay Formation. The data also highlights the meter scale heterogeneity of the Duvernay Formation as a single stratigraphic section can exceed 70% coefficients of variation.

Conclusions

This research suggests a close relationship between compositional and mechanical properties of the Duvernay shale from outcrop samples. Multi-scale observations and analysis of the outcrop samples display the presence of geological and geomechanical heterogeneity at both centimeter and meter-scale. The centimeter scale variations cannot be resolved with standard subsurface data and testing, making it difficult to accurately quantify in subsurface reservoir models.

Outcrop data is a valuable dataset in assessing geologic variability and geomechanical properties in unconventional shale plays. Outcrop data is valuable in allowing for broad-scale characterization of the mechanical and fracture properties of the Duvernay Formation. Once centimeter-scale variability within the Duvernay is quantified, this value can be implemented in pre-existing 3D subsurface models to resolve the reservoir complexity with more accuracy. This study reveals variation within a single Duvernay hand sample can reach values higher than 20% on a relative scale, which may significantly impact the mechanical behavior of the reservoir when undergoing hydraulic fracturing treatment.

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