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# Quantification of geological and geomechanical heterogeneity of the Duvernay shale through integration of outcrop and subsurface data and its application to unconventional exploration

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## Summary

Organic-rich mudstone deposits have generally been considered homogeneous. In the last 10-15 years, with hydrocarbon exploration of organic-rich shale reservoirs becoming economically viable, we have appreciated their extremely high degree of heterogeneity (Jarvie et al., 2007; Hart et al, 2013; Sone & Zoback, 2013). The heterogeneity in reservoir properties is in part responsible for the significant changes in gas and liquids production seen in horizontal wells, even over short lateral distances. Lateral variation within shale reservoirs is usually extremely difficult to quantify in the early stages of exploration, because the density of drilled wells is not enough to allow detailed quantification of heterogeneity within the reservoir. To attain a more detailed understanding of the lateral and vertical facies changes and relations, outcrops provide an important dataset of the 3-D architecture of the reservoir. Outcrop observations can be used as analogues for the subsurface and become a critical dataset for accurate identification of reservoir mineralogy, sedimentary facies and geomechanical properties. These can be used to calibrate well log-derived reservoir properties, thus allowing for improved mapping and interpretation of the subsurface.
The late Devonian Duvernay Formation has been targeted for shale oil, gas and condensate for nearly a decade. In the Kaybob area more than 550 horizontal wells are currently producing from the organic-rich shales, and more than 500 vertical wells have logs within the Duvernay interval. 48 Duvernay cores have been taken in a 8000 km$^2$ area, but this still leaves wide regions without any core coverage. Well logs can be used for subsurface facies mapping as discussed in Venieri & Pedersen (2018) and Venieri et al. (2018), but they need to be tied to physical rock observations in cores or outcrops to capture the heterogeneity of the formation at different scales. In this study we integrate geological and geomechanical properties of the Duvernay Formation in the Allstones Creek outcrop exposure to well log and core data in the subsurface of the Kaybob region. This allows a better understanding of the 3-D Duvernay reservoir and its vertical and lateral sedimentological, mineralogical and geomechanical heterogeneity, and how this may affect completion and reservoir performance.

## Dataset and Workflow

This study uses data from outcrop and the subsurface. For the subsurface part, 500 vertical wells of which 48 cored and 550 horizontal wells have been used for the mineralogical and stratigraphical framework of the Duvernay Formation in the Kaybob area. The workflow used to interpret mineralogy of the shales is described in detail in Venieri et al. (2018) and consists of integration of core analyses and

multiple well logs, among which Spectral Gamma Ray and Elemental Capture Spectroscopy. These logs are present in just 24 out of 550 vertical wells in the Kaybob region, adding high degree of uncertainty to the geological and geomechanical characterization of the Duvernay Formation due to the relative far spacing of these wells. This uncertainty significantly decreases when the interpretation is guided by outcrop data and observations.
For this purpose, we used the Allstones Creek Duvernay outcrop as natural laboratory to investigate the 3-D geological and geomechanical characteristics of the reservoir.
Three vertical stratigraphic sections - respectively 30m, 23m and 25m high - were logged, with hand samples collected every 0.5-1m and 25-50kg boulders every 3-4m. For each sample, 2 faces were cut at 90 degrees to bedding to describe the specimen and, using a 1cm x 1 cm grid, measure microhardness and elemental composition using an Equotip piccolo and XRF gun tools respectively. To measure the static mechanical properties of the Duvernay outcrop samples, drill plugs were taken from the boulders and the hand samples for Triaxial, UCS, Brazilian and Point Load tests. Drilling chips from the same samples have been for analyzed for RockEval at the Geological Survey of Canada.
To compare lithostratigraphy with mechanical stratigraphy, 4 scanlines of fracture orientations and intensities were taken. Additionally, rock stiffness measurements using a Schmidt Hammer and fracture orientations have been performed in 13 windows each one having an area of $1m^2$. Finally, heterogeneity in outcrop-derived geological and geomechanical properties has been compared to what observed in the subsurface in the Kaybob area. This aims at providing detailed info on how to quantify heterogeneity in the subsurface using outcrops as an analogue.

## Results

The Duvernay is characterized by a high degree of geological and geomechanical heterogeneity in both the subsurface (from core, Spectral Gamma Ray, Elemental Capture Spectroscopy and Dipole Sonic logs), and in outcrop (from XRF, Schmidt Hammer and microhardness measurements).
Outcrop data show a relationship between mineralogy and geomechanics, similar to what demonstrated in the subsurface in previous studies of the Duvernay Formation (e.g. Dong et al., 2018; Venieri et al., 2018). Mechanical hardness is directly proportional to biogenic silica and carbonate content, whereas it decreases with increasing clay content. The extremely complex depositional architecture seen in outcrop reflects the high heterogeneity in sedimentary facies, mineralogy, fabric, organic content and mechanical properties visible in subsurface data within the Kaybob region. Outcrop observations help assess lateral and vertical continuity of Duvernay lithofacies for improved core-to-well log tie and subsurface mapping of depositional features. High degree of geological and geomechanical heterogeneity within the Duvernay Formation is also reflected by highly variable completion data and reservoir performance across the Kaybob region.

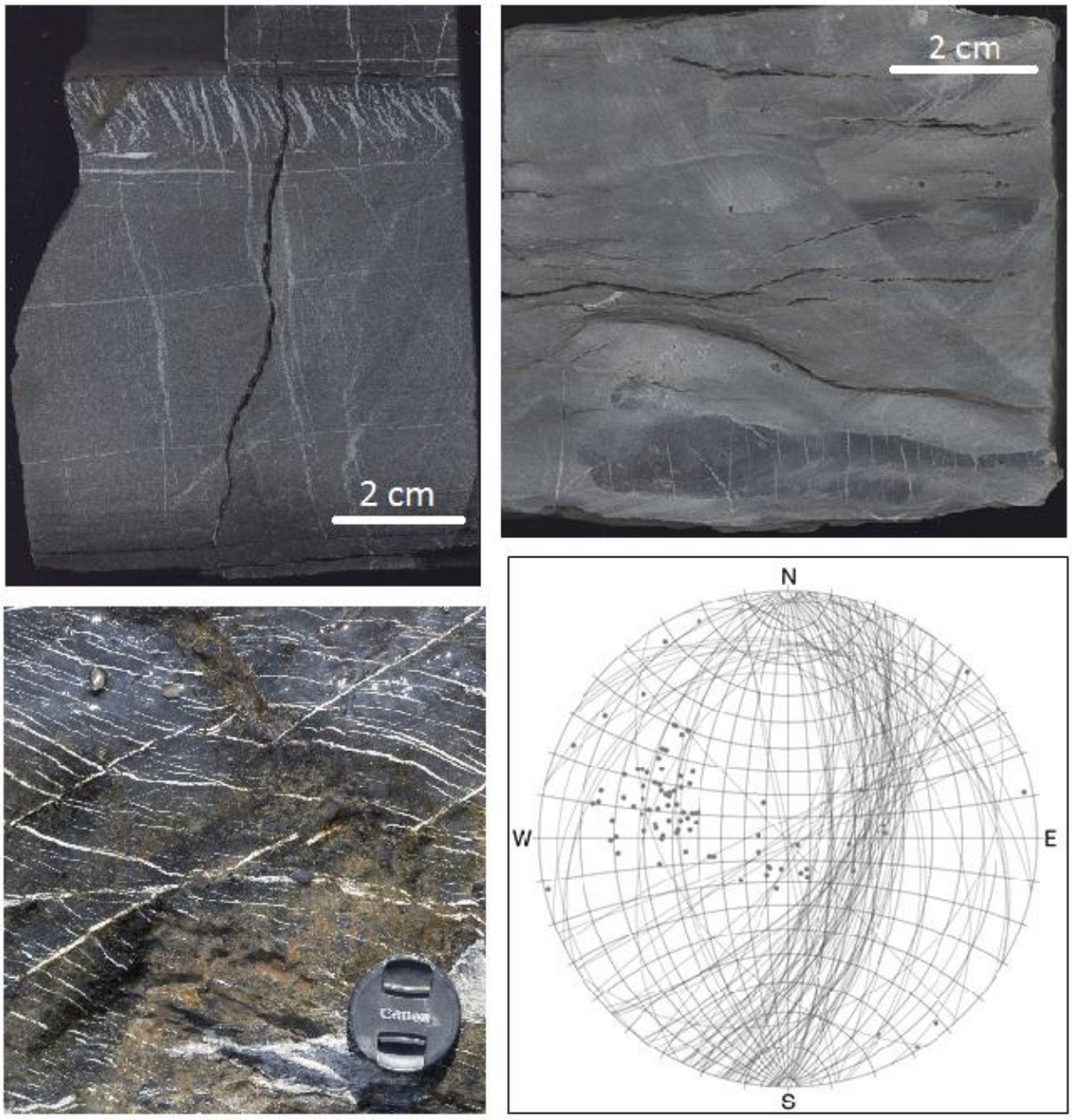


Fig.1: Example of geological and geomechanical heterogeneity of the Duvernay Formation from outcrop samples

## Conclusions

This research integrates outcrop to subsurface observations and measurements to understand the 3-D variability of the Duvernay Formation in the Kaybob area. Characterization of geological and geomechanical heterogeneity within the Duvernay reservoir in outcrop has been tied to subsurface observations in cores, well logs, completion data and production data.

This research suggests that outcrops are highly valuable datasets to assess the variability in geological and geomechanical properties in unconventional shale plays, and this workflow comes crucial when interpreting reservoir properties in case of sparse subsurface datasets.

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