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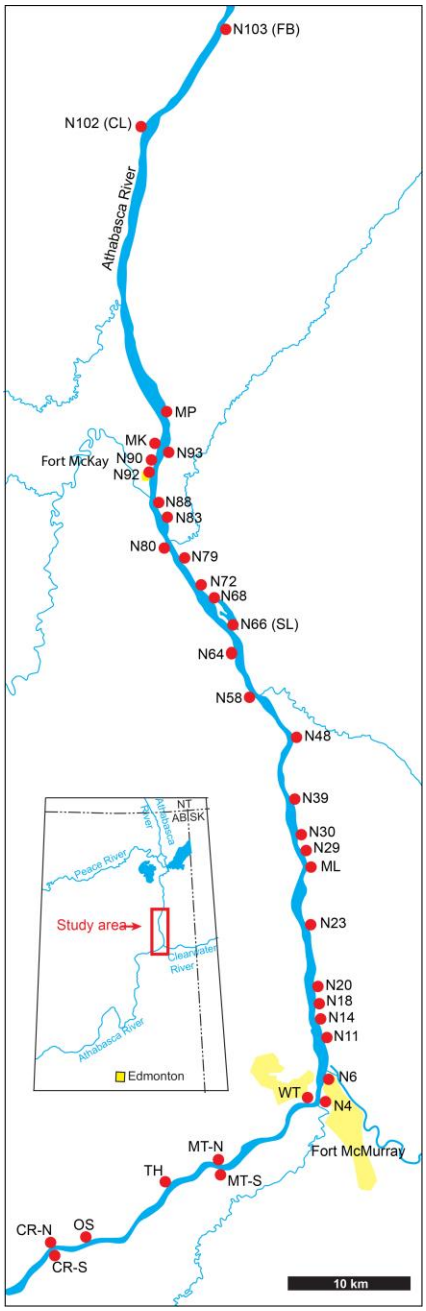
Structural Deformation and Karst in the Devonian Waterways Formation: Examples from Outcrops along the Athabasca River

Chris L. Schneider
University of Alberta and Devonian Solutions Geological Consulting
Matthias Grobe
Alberta Energy Regulator, Alberta Geological Survey



Summary

Structural deformation and karst are frequent phenomena of Devonian outcrops along the Athabasca River in northeastern Alberta. Folds, joints, and, less so, evidence of movement along fractures are ubiquitous; karst features are less common and often subtle. Evidence of paleokarst includes green clay, breccia, and sandstone fill, often in fractures, and less commonly, caves and solution-enlarged joints.

Introduction

In the last few decades, structural deformation and karst in Devonian rocks has become an important topic for oil sands production. Fractures, joints, faults, karst, and collapse features can become discharge or recharge zones where exposed by mining operations, creating potential hazards to mining operations. Thus, a better understanding of karst and structural features in the Devonian rock underlying the Cretaceous McMurray Formation is essential to efficient production and environmental stewardship.

We encountered many examples of structural deformation and karst during our fieldwork from 2010 to 2013. Here, we present an overview of these features found in outcrops along the Athabasca River.

Fieldwork: Methods and Protocols

Several outcrops along the Athabasca River were visited in late summer from 2010 to 2013 (Figure 1). Exposures changed little from 2010 to 2012, but floods in June of 2013 washed rock debris from several outcrops, exposing new features while covering other outcrops with new layers of mud and debris.

Figure 1. A map of outcrops visited along the Athabasca River. Outcrops at all localities fall within the Moberly Member, except N102, which is Calumet Member and N103, which is Firebag Member middle limestone. Locality numbers refer to the station numbers in Norris (1963) (N = Norris). Other abbreviations are for outcrops not included in Norris (1963).

We collected stratigraphic (measurements, lithology) and structural data (strikes and dips of beds, fold wavelengths, joint and fracture strikes, fault strikes and dips, slickenside presence) at each outcrop. We noted karst features, such as joint expansion, breccias, and green clay. Other features we noted involve evidence of fluid flow along fractures (iron-staining, pyritization, calcite spar, bitumen staining).

Stratigraphy

Devonian outcrops along the Athabasca River fall within the Waterways Formation of the Beaverhill Lake Group. Most outcrops fall within the Moberly Member except for two outcrops at the northern end of the Waterways Formation outcrop belt, which feature the Firebag and Calumet members, respectively. The Christina and Mildred members do not outcrop along the Athabasca River. We used lithological and paleontological characteristics of measured sections to correlate the outcrops and constructed a composite section of the Moberly Member, consisting of 14 informal units (Figure 2).

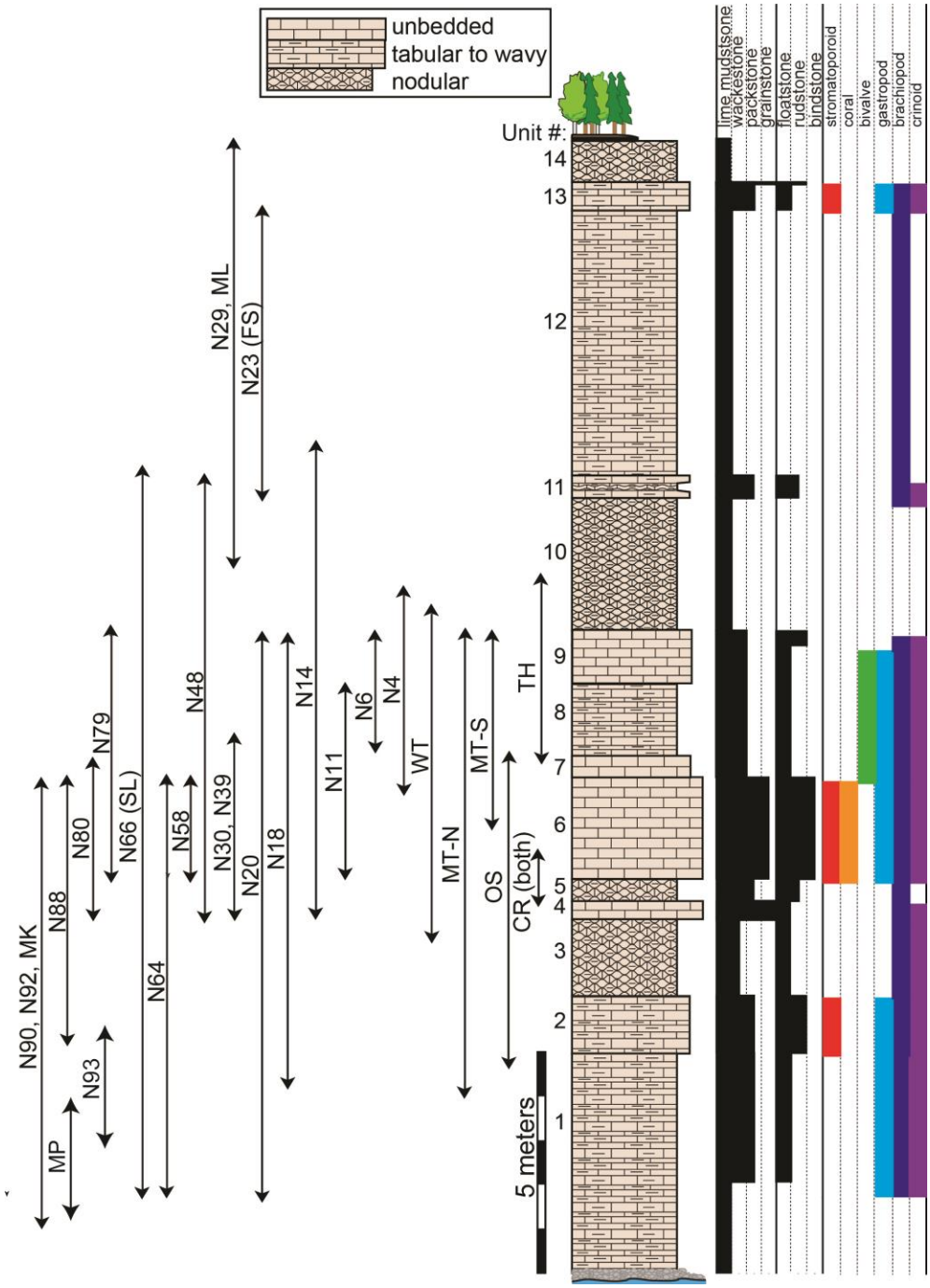


Figure 2.Composite section of the Moberly Member, Waterways Formation from outcrops along the Athabasca River. “Clean” limestone units are 4 and 6; all of the other units are argillaceous to some degree.

Folds

Almost all outcrops visited contain folds or dipping beds. Erosion and exposure along river banks create the impression that fold axes strike perpendicular to the orientation of the river, but closer examination indicates that deformation in the Waterways Formation resulted in a “dome-and-basin” structure rather than simple anticlines and synclines. Four scales of folds occur in the study area:

1. the regional anticline-like structure formed by eastward subsidence and collapse of post-Prairie Evaporite Formation strata dip eastward because of evaporite dissolution, compared to the tectonically-induced westward tilting that was initiated in the Mesozoic;

2. kilometre-scale domes and basins;

3 and 4. Parasitic folds on the scales of hundreds of metres (Figure 3) and 50 to 100 m, respectively.

Beds on the limbs of folds rarely dip more steeply than 10 degrees, which agrees with dips reported in Norris (1963). Only locality N103 along the Athabasca River contained beds with dips greater than 20 degrees along the limbs of a complex series of folds in the Firebag Member middle limestone.

Figure 3. The northern limb of a 150+ metre fold at locality N88. Note the solution-enlarged joints in the outcrop. Unit 6 forms the 2.5 metre-thick resistant bed along the top of the outcrop.

Fractures, Joints, and Faults

Outcrop-pervasive fractures and joints are common at every locality and most are nearly vertical. Of the measured joints, 20% have dips between 60 and 85 degrees. None are shallower than 60 degrees.

Our results are consistent with those reported by Babcock (1975), Babcock and Sheldon (1976) and Nichols (1996). Analysis of orientation data from joint and fracture measurements (Figure 4) identified System I (NE-SW and NW-SE) and System II (N-S and E-W) trends of Babcock (1975). However, our dataset is noisier, which we attribute to the fact that Babcock collected joint data from nearly flat-lying outcrops, whereas our joint measurements were taken from outcrops where joints were present and easily measurable, regardless of the orientation of beds.

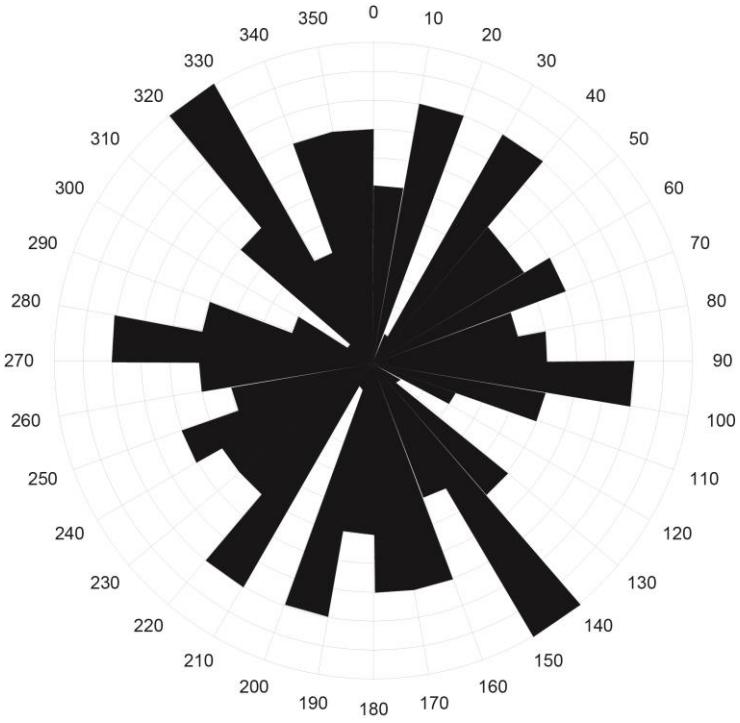


Figure 4. A rose diagram of fracture and joint orientations in outcrops along the Athabasca River that were examined in this study.

Most outcrops contain evidence of normal faulting with vertical offsets of 10 cm or less. Slickensides are common on limestone surfaces, most frequently in unit 6. Many fractures are orange with iron-staining or contain pyrite crystals. Calcite spar fills some fractures with clusters of crystals up to 1 cm in length. Calcite crystals rarely contain petroleum inclusions.

Karst

Most evidence of paleokarst is subtle, such as fractures containing green clay, breccia, or sandstone. Large, conspicuous features such as solution-enlarged joints are rare in outcrops. Several fractures at the locality N48 contain green clay, associated with carbonate breccia and oil sand. Green clay was not encountered at the other outcrops visited, but may have been washed from fractures; fractures bearing green clay at N48 were newly exposed by the June 2013 flood.

Sandstone, presumably from the same source as the McMurray Formation, fills fractures at two outcrops. Sandstone in locality N48 fractures contains bitumen; fracture-filling sandstone at locality N93 is well-cemented, but contains no bitumen.

Conclusions

Among structural features in Devonian outcrops along the Athabasca River, folds are most conspicuous. Evidence for movement along vertical fractures is also common, but most offsets are 10 cm or less. Outcrop-pervasive joints occur at all localities and are usually near-vertical. Joint trends follow those reported in Babcock (1975), but data reported herein contains a wider distribution of orientations than those of Babcock. Karst features are usually subtle, such as green clay, sandstone, and breccia in fractures. Large features such as caves and enlarged joints are rare.

This study area falls within an intermediate zone where the Prairie Evaporite Formation is reduced in thickness and still dissolving. Thus, these features may not be representative of areas that may have more extensive karst and collapse in the Waterways Formation, such as zones of increased to complete evaporite dissolution further to the east. However, these outcrops, being a sub-sample of all Devonian outcrops along the Athabasca River, may represent the relative frequency and distribution of karst and structural features within this zone of partial evaporite dissolution.

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