Beneath the Oil Sands: Stratigraphy and Structural Features of the Devonian of Northeast Alberta, Canada*

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Abstract

Devonian limestone and shale subcrops beneath the McMurray Formation oil sand in northeastern Alberta. The Beaverhill Lake Group and the Watt Mountain Formation of the Elk Point Group underwent structural deformation and karstification related to the dissolution of subsurface Prairie Formation halite. We reconstructed four scales of folds, ranging from a wavelength of 50 m to the width of the study area, and encountered small normal faults in outcrops and abundant offset fractures in cores. Throughout the area, karst is a common feature, primarily occurring as active and relict sinkholes, enlarged joints and to a lesser extent, caves.

Our reconstruction of the pre-Cretaceous unconformity surface reveals a channel system roughly paralleling the present-day Athabasca River north of Fort McMurray. Abundant lineaments related to erosional and salt dissolution processes and circular structures attributed to sinkholes or other collapse from halite dissolution occur on the Devonian surface.

Introduction

In much of northeastern Alberta, the bitumen-bearing McMurray Formation unconformably overlies Devonian limestone and shale. The structure of Devonian rock is further complicated by deformation and collapse arising from the dissolution of the subsurface Prairie Formation halite. Furthermore, post-Devonian erosion resulted in complex pre-McMurray topography. Structural features of Devonian strata and the complexity of the Devonian surface (the pre-Cretaceous unconformity) in the region of salt dissolution have significant bearing on resource development in northeastern Alberta, because of their influence on the thickness distribution of the lower McMurray Formation, the connectivity of saline and freshwater aquifers, and their potential effect on the mechanical integrity of caprock overlying oil sands deposits in the in-situ area. Herein, we present results from our investigation of Devonian stratigraphy and structure, part of the AGS' Oil Sands Caprock Integrity Project to characterize the stratigraphic units above and below bitumen resources in order to determine the geological factors affecting caprock quality.

Methods

The study area extends from township 87, south of the Clearwater and Athabasca rivers, to township 99 in the north, and from range 1W4 along the Alberta-Saskatchewan border to range 13W4, west of the Athabasca River. Strata included in this study extend from the Early Devonian La Loche Formation (granite wash) to the Late Devonian Woodbend Group.

To reconstruct Devonian stratigraphy and structure, we picked formation and member tops in every available well log. However, most wells only penetrated the top of Devonian strata to a maximum depth of 15 m. To facilitate correlation between short Devonian logs, we picked additional marker beds that were consistent throughout at least a quarter of the study area. Marker beds in the Waterways Formation occur at 2 m to 5 m vertical intervals. We supported our picks with examination of representative cores. Outcrops were investigated for detailed lithology, correlation and structural features that could not be captured by the subsurface study.

To reconstruct the surface of Devonian subcrop, we first used pre-Cretaceous unconformity picks to model a smooth surface to account for the basinal dip trend and regional erosion effect, using the methodology described by Mei (2009a, 2009b). Then, this trend surface was removed from the data points and a residual map was created to accentuate the local structural features.

Results and Discussion

Devonian Stratigraphy

Most wells penetrated Devonian strata insufficiently to recover correlative relationships deeper than the upper few metres of limestone and shale. Cross-sections reconstructed from deep wells and cores indicate (1) a complex basement surface with topographic highs and lows; (2) thinning and eventual disappearance from west to east of Prairie Formation halite, including at least one salt scarp; (3) a variably thick Keg River Formation, resulting from localized biohermal and biostromal development in the upper half of the formation; (4) thin Watt Mountain through Slave Point formations; (5) consistently thick (except where eroded) Waterways Formation members; and (6) consistent regional lithology of Devonian formations (Figure 1). Marker beds within the Waterways Formation can be traced across most of the region.

Eastward, Devonian strata erosionally pinch out against the pre-Cretaceous unconformity. In the eastern-most portion of the study area, the Beaverhill Lake Group was completely eroded, leaving only the siliciclastics of a combined Watt Mountain/Prairie Formation remnant or the Keg River Formation dolostone to subcrop at the unconformity. At the southwestern-most limit of the study area, basal Cooking Lake Formation limestone subcrops beneath the McMurray Formation.

Structure

Throughout the area, Devonian strata are folded and faulted. Deformation is most obvious in the folded limestone that sporadically outcrops along river valleys. We noted several scales of fold wavelengths in this study: (a) 50 m, seen only in outcrop; (b) several hundred metres, also

seen only in outcrop; (c) 2 or more km, reconstructed from outcrops and seen in cross-sections; and (d) a study area-wide, salt scarp-related warping, seen only in cross-section. Smaller folds occurred as parasitic folds on the limbs of larger folds. Normal faults seen in outcrop display offsets from 10 to 50 cm. In core, many fractures show offsets of 1 to 3 mm and are most frequent in the Firebag and Christina members of the Waterways Formation.

In the southwest portion of the study area, where the thickness of the Prairie Formation is greater than 300 m, Devonian strata dip to the west. Where the Prairie Formation is thinner than 300 m but still west of the salt scarp, Devonian strata younger than the Prairie Formation are nearly flat-lying. East of the salt scarp, post-Prairie strata dip resume a westward dip, albeit at a shallower angle than in the southwest portion of the study area.

Karst

Karst is common throughout the study area. Caves and enlarged joints can be observed in many limestone outcrops. Sinkholes sporadically occur throughout the region. Subsurface picks reveal potential pre-Cretaceous collapse features and/or sinkholes, particularly east of the salt scarp where most or all of Prairie Formation halite has been dissolved.

Major joint trends are northeast-southwest, northwest-southeast, and north-south. Along the Athabasca River, north of Fort McMurray, the northeast-southwest and northwest-southeast joints are most commonly observed. Along the same river to the west of Fort McMurray, we also observed the north-south joint trend. Where joints along the river have been widened by subsequent karst, joints are open, but often contain "melted" oil sand along their sides or at their junction with the outcrop surface. All joint trends were observed at Hammerstone Quarry trend, where joints are enlarged and are filled with a mixture of oil sand, green clay and limestone breccia and are pervasive into the upper Christina Member (Kozdial and DePaoli, pers comm).

The pre-Cretaceous Unconformity

The pre-Cretaceous unconformity in the study area represents a time gap of approximately 250 Ma and a long history of erosion, non-deposition and karstification, which resulted in an ancient and mature erosional paleotopograhic surface containing high reliefs and a river valley-dissected landscape (Figure 2). Linear features include escarpments, surface elevation offsets, possible faults and linear erosion of "weak" zones, such as subcropping shale. Circular features include present-day and relict sinkholes and other salt dissolution-related collapse structures. A channel roughly parallels the present-day Athabasca River, best seen in the northern portion of the study area. A tributary channel joins the main channel north of Fort McKay.

Conclusions

Collapse of Devonian strata in the Prairie Formation salt dissolution zone in northeast Alberta was, for the most part, gradual enough to maintain consistent stratigraphic relationships, but resulted in a regional series of 2+ km diameter domes and saddles containing smaller

parasitic folds. Small faults occur in outcrops; mm-scale offsets are common in cores throughout the study area. Karst features, such as sinkholes, enlarged joints and caves are common in the salt dissolution zone.

Our reconstruction of the pre-Cretaceous unconformity surface includes both erosional features (channels, highlands) and salt dissolution related structures, such as sinkholes and possible faults. Some portion of the current westward dip of Devonian strata may have been in place before the pre-Cretaceous unconformity and the present-day Prairie Formation salt scarp. Most of the collapse of strata east of the salt scarp took place after tilting and before deposition of the McMurray Formation.

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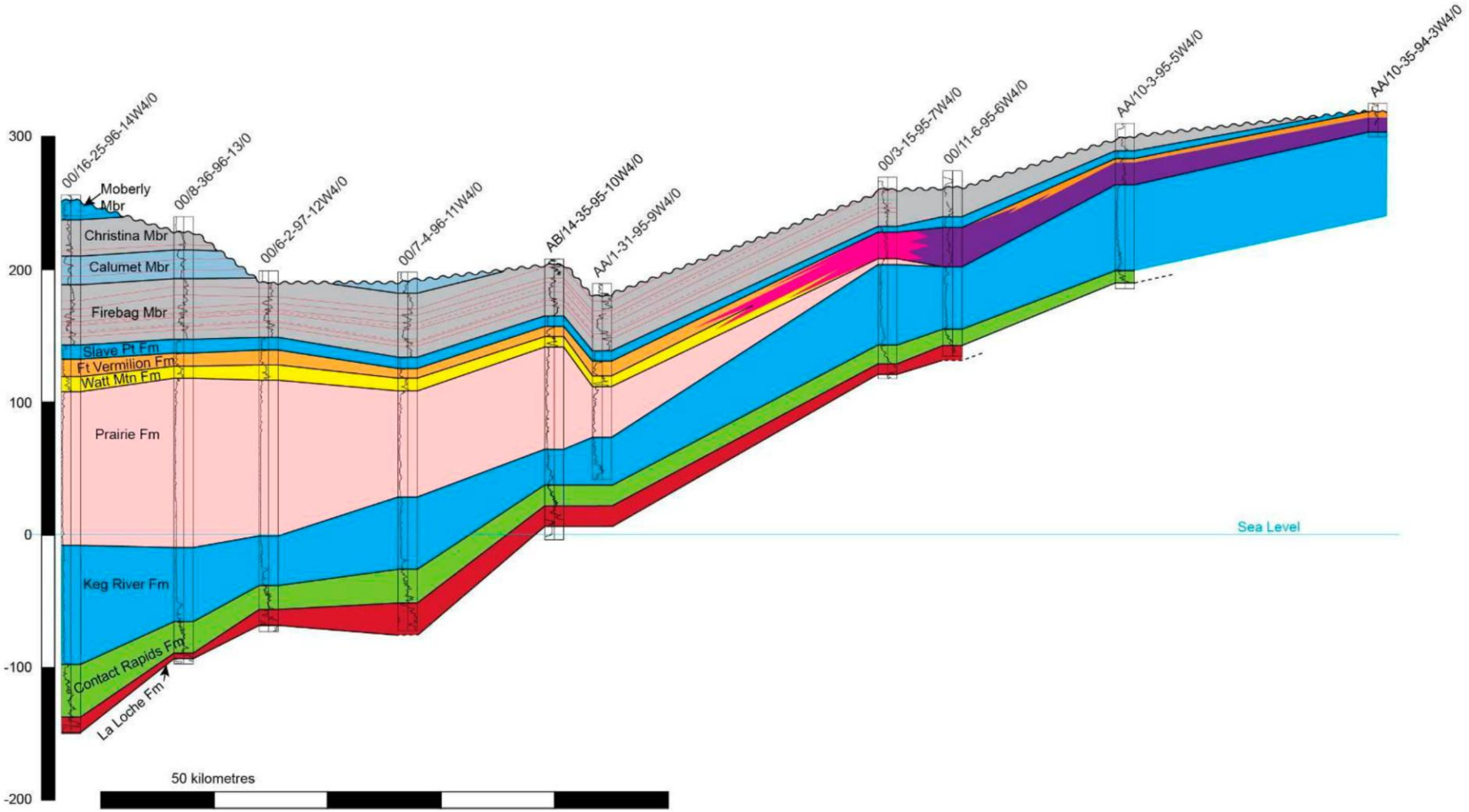

Figure 1. Cross-section of Devonian strata in deep wells through the northern portion of the study area.

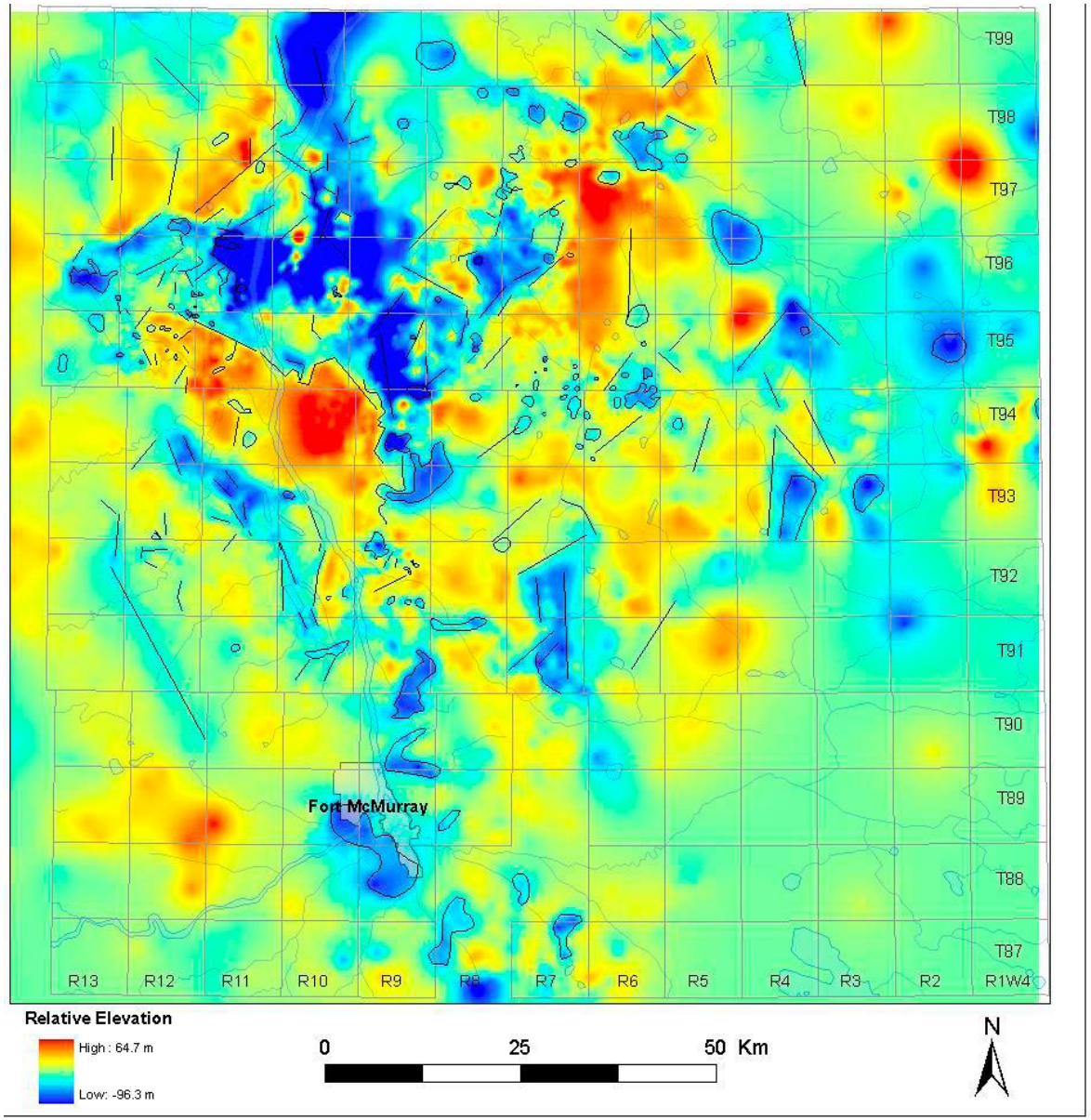

Figure 2. Residual map showing local structural features highlighted by removing the regional effect (regional dip, regional erosion and regional salt-dissolution collapsing) using the methodology described by Mei (2009a).