Impact of Inclined Heterolithic Stratification on Oil Sands Reservoir Delineation and Management: An Outcrop Analog from the Late Cretaceous Horseshoe Canyon Formation, Willow Creek, Alberta

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Inclined heterolithic strata (IHS) formed by laterally-accreting, fluvial-estuarine point-bars are economically important deposits of the lower Cretaceous McMurray Formation, which hosts the Athabasca Oil Sands (AOS) in Northern Alberta. Stratigraphic and lithologic heterogeneities occur at various scales and orientations throughout IHS, rendering interpretation and modeling of their 3-dimensional stratigraphic architecture, aimed at better estimation and extraction or resources/reserves, a serious challenge. An exceptional 3-dimensional exposure of a laterally-accreting, fluvial-estuarine point-bar deposit occurs at Willow Creek, in the Badlands of central Alberta, approximately two hours northeast of Calgary. This exposure serves as an ancient analogue to the IHS point-bar deposits commonly observed in the subsurface at the AOS (Figure 1). The Willow Creek deposits, from the Late Cretaceous Horseshoe Canyon Formation, were studied in order to better understand the stratigraphic architecture of a point-bar deposit.

Figure 1. An exceptional 3-dimensional exposure of a laterally-accreting, fluvial-estuarine point-bar deposit occurs at Willow Creek. The alternating units of darker (mud-rich) and lighter (sand-rich) commonly observed in this type of deposit is known as inclined heterolithic stratification (IHS).

Detailed sedimentology and interpretations of photomosaics suggest that point-bar evolution is characterized by constant adjustment. Evidence for various sedimentary processes active on the point-bar can be observed, including erosion (scours and mudstone rip-up clasts), traction (cross-stratification and planar lamination), tides (double mud drapes), and soft sediment deformation (loading features, including flame structures). Lags are common along the major erosion surfaces, implying bank erosion and rapid deposition. Minor adjustments are characterized by on-lapping bedding geometry. From analysis of the Willow Creek point-bar, the stratigraphic complexity of IHS is apparent (Figure 2). Analysis of a high-resolution digital model

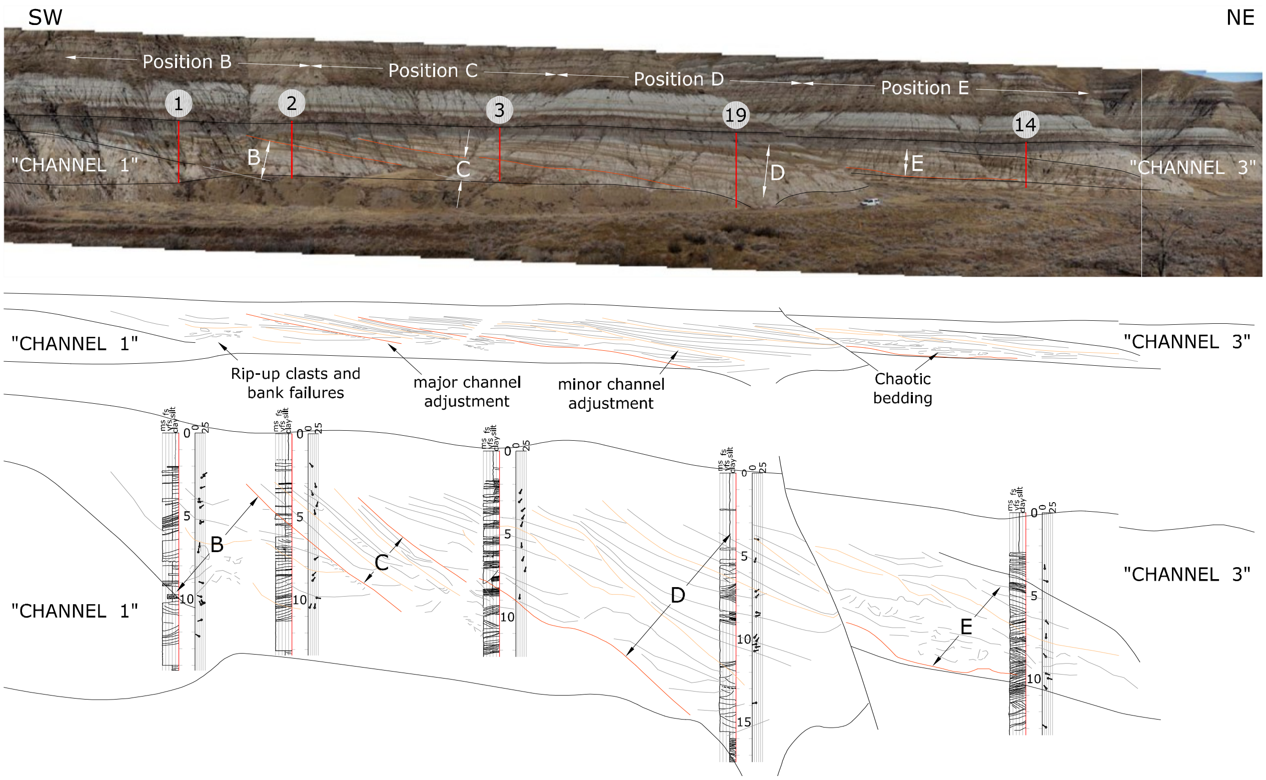

Figure 2. Photomosaic and line drawing traces (no vertical exaggeration and 3x vertical exaggeration) of main IHS transect at Willow Creek.

acquired by ground-based LIDAR (Figure 3) allow for a quantitative reconstruction of the stratigraphic architecture and paleohydrology of the exposure. The LIDAR data, once rendered in a 3-dimensional model, can remove the perspective uncertainty induced by the vagaries of outcrop geometries and exposures, and allows for direct measurement of dimensions and orientations of outcrop features. By recording the orientation of stratigraphic surfaces in 3-dimensional space, the changing dip inclination and azimuth of accretion surfaces enables the evolution of the channel meander to be charted, improving the usefulness of the analog and helping to improve existing AOS interpretations.

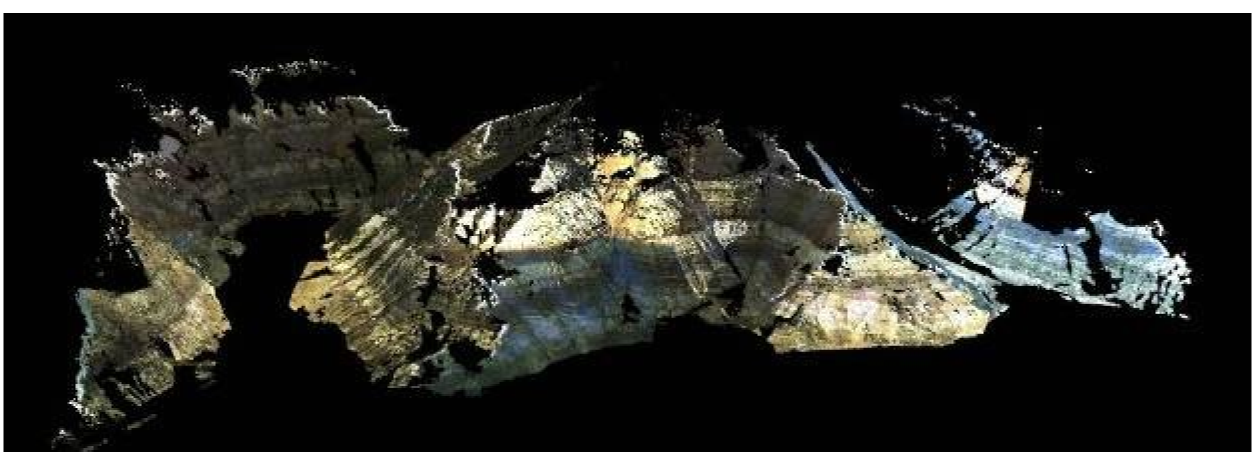

Figure 3. Ground-based LIDAR data of Willow Creek point-bar deposit.

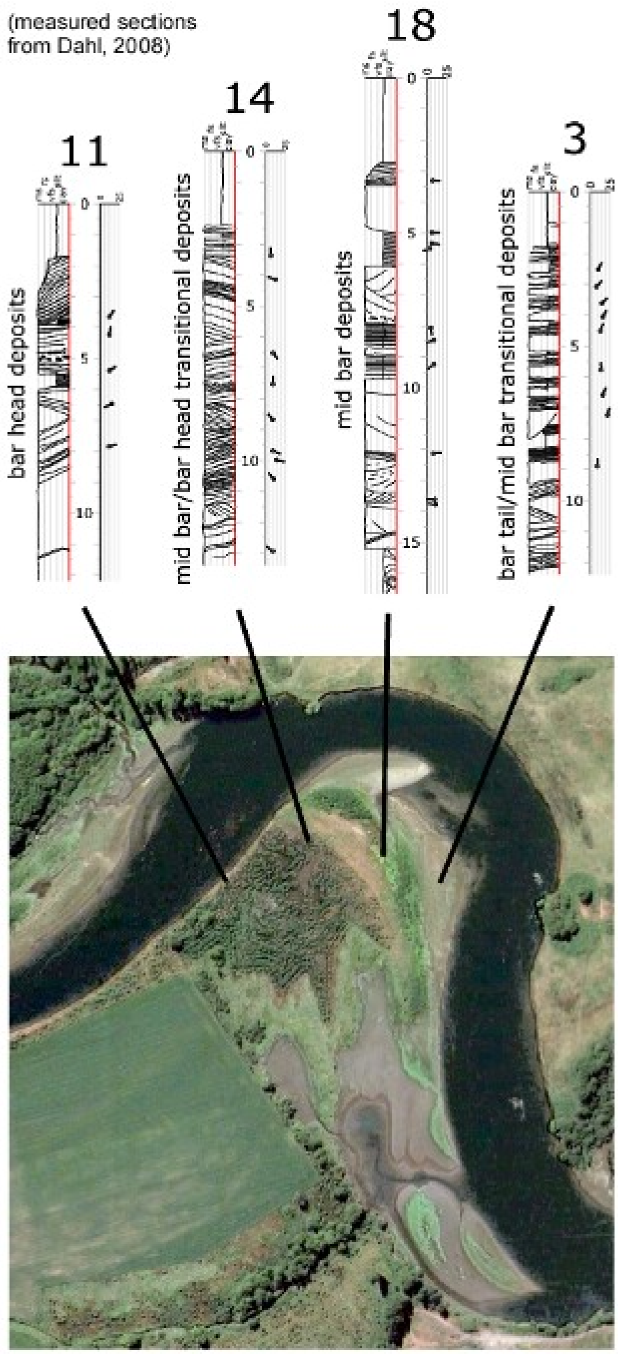

Figure 4 (left). A modern tidally-influenced point-bar from the Chehalis River, near Montesano, Washington. The systematic shift in sedimentation observed across the Willow Creek outcrop might be explained by the tendency of a point-bar deposit to fine in the downstream direction.

The rhythmic heterolithic deposits characteristic of the tidally-influenced point-bar at Willow Creek accompanies another systematic shift in sedimentation preserved in the outcrop. In modern point bars, the coarsest deposits typically occur along the upstream portion of the bar, the “bar-head,” while increasingly fine deposits tend to be preserved along the downstream reaches at the “bar-tail.” Deposits at Willow Creek display a systematic coarse-fine/sandy-muddier from west to east, which allows the deposit to be interpreted as the reorganization of an individual point-bar rather than an amalgamation of several (cf. Figure 4). In profile, the outcrop is dominated by laterally-accreting scours filled by sequences of heterolithic fining-upwards strata. Fill strata are typically truncated by erosion surfaces. A similar depositional motif is often interpreted as stacked channels in wireline well log.

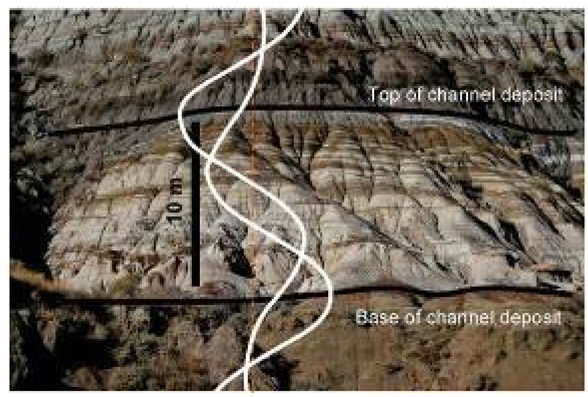

Figure 5. Hypothetical seismic response to the top and base of the Willow Creek channel deposit is illustrated. Parameters of typical high-quality seismic data acquisition allow for channels as thin as 6 metres to be imaged, resolving thick point bar deposits common to the upper portion of the McMurray deposit. However, thinner and more homogeneous beds found near the base of the Oil Sands deposit are poorly resolved and, while much of the deposit is imaged vividly in plan view (with time slices), it is imaged rather poorly in sectional view.

The variable scales of heterogeneity that occur in the Willow Creek point-bar deposit highlights some of the difficulty associated with interpreting AOS IHS deposits found in the subsurface. 3-dimesional seismic imaging is commonly used for interpretation of AOS deposits; however, direct comparison with the Willow Creek outcrop analog suggests that many important architectural elements of AOS deposits, particularly those at the sub-channel scale, cannot be resolved seismically (Figure 5). Conversely, many wireline logging tools have a limited depth of investigation and provide too fine a resolution to capture the larger-scale architectural complexities demonstrated by heterogeneities in the Willow Creek point-bar deposit (Figure 6).

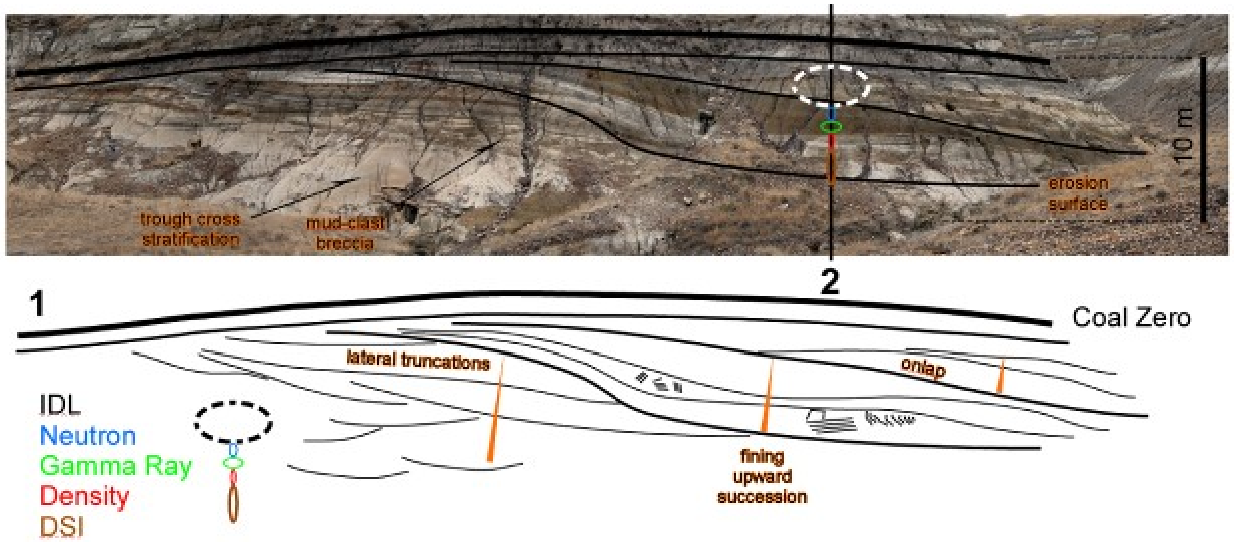

Figure 6. 1) Photomosaic and line-drawing trace of key architectural elements at the Willow Creek point-bar outcrop. Note the hierarchy of scales observed. 2) Wireline logging tools commonly used to delineate Oil Sands deposits have a very limited depth of investigation, as shown above. A well drilled through this deposit at bore location (2) would suggest the presence of a flat-lying laterally-continuous mud. Similarly, delineation wells drilled 50 metres apart on either side of the inclined muddy bed may lead to erroneous correlation between sand- and mudstone across these IHS.

These and other comparisons of the Willow Creek point-bar outcrop analyses with examples from the Athabasca Oil Sands allow for a better consideration of the effects of vertical and lateral heterogeneities associated with IHS on reservoir modeling, SAGD well placement, and steam chamber development.

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