[PS]Detailed Lithofacies Analysis and High Resolution Sequence Stratigraphy of the Horn River Group, British Columbia, Canada*

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Search and Discovery Article #51324 (2016)**
Posted October 31, 2016

*Adapted from poster presentation given at AAPG 2016 Annual Convention and Exhibition, Calgary, Alberta, Canada, June 19-22, 2016

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Abstract

The Devonian Horn River Basin shales have been a target for gas exploration for the past decade in northeast British Columbia, Canada. The reservoir quality of these shales is highly variable due to the complex nature of the depositional setting and physical processes. Detailed sedimentological, ichnological, geochemical and stratigraphic analysis of nine Horn River cores indicated that depositional conditions range between anoxic conditions to oxygenated conditions. Integration of lithologic data, physical sedimentary structures, and geochemical signatures lets us better understand the fundamental architecture of the reservoir qualities. The Horn River Group consists of three formations: Evie, Otter Park, and Muskwa, which are relatively carbonate-rich, clay-rich and silica-rich, respectively. Ten lithofacies and three lithofacies associations were identified based on the sedimentological and ichnological observations. Massive and pyrite-rich mudstones show very rare current-generated structures and sparse bioturbation. These mudstones also show the highest total organic carbon (TOC) values and have been interpreted to represent anoxic deep-water (ADW) conditions. Heterolithic and laminated units show well-preserved physical sedimentary structures, and they are typically moderately to intensely bioturbated. They show the lowest TOC values and have been interpreted to represent oxygenated deep-water (ODW) conditions. An additional facies association, representing transitional conditions, has been assigned to facies showing intense or sparse bioturbation (BI 0-1 or BI 4-6) depending on the core location, possibly indicating local changes in the energy conditions. Transitional facies generally show moderate TOC values. The Evie Member and Muskwa Formation are dominantly represented by ADW while Otter Park Member is represented by both ODW and transitional conditions. Changes in the lithofacies distributions and distinct geochemical signatures in space and time resulted in recognition of nine depositional sequences (3rd order) and eight major surfaces. The sequence boundaries are marked by noticeable changes in the sedimentological and ichnological signatures. The Evie Member and the Muskwa Formation are mainly represented by high-stand and transgressive system tracts while the Otter Park Member is mainly represented by low-stand and falling-stage system tracts.

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ABSTRACT

The Devonian Horn River Basin shales have been a target for gas exploration for the past decade in northeast British Columbia, Canada. The reservoir quality of these shales is highly variable due to the complex nature of the depositional setting and physical processes.

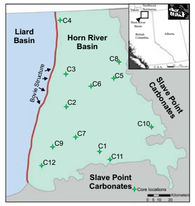
The Horn River Group consist of three formations: Evie, Otter Park, and Muskwa, which are relatively carbonate-rich, clay-rich and silica-rich, respectively. Ten lithofacies and three lithofacies associations were identified based on the sedimentological and ichnological observations. Massive and pyrite-rich mudstones show very rare current-generated structures and sparse bioturbation. These mudstones also show the highest total organic carbon (TOC) values and have been interpreted to represent anoxic deep-water (ADW) conditions. Heterolithic and laminated units show well preserved physical sedimentary structures, and they are typically moderately to intensely bioturbated. They show the lowest TOC values and have been interpreted to represent oxygenated deep-water (ODW) conditions. An additional facies association, representing transitional conditions, has been assigned to facies showing intense or sparse bioturbation (BI 0-1 or BI 4-6) depending on the core location, possibly indicating local changes in the energy conditions. Transitional facies generally show moderate TOC values. The Evie Member and Muskwa Formation are dominantly represented by ADW while Otter Park Member is represented by both ODW and transitional conditions.

Changes in the lithofacies distributions and distinct geochemical signatures in space and time resulted in recognition of nine depositional sequences (3rd order) and eight major surfaces. The sequence boundaries are marked by noticeable changes in the sedimentological and ichnological signatures. The Evie Member and the Muskwa Formation are mainly represented by high-stand and transgressive system tracts while the Otter Park Member is mainly represented by low-stand and falling-stage system tracts.

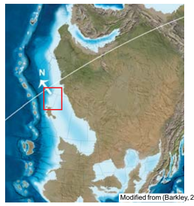
OBJECTIVES

- **Provide a detailed lithofacies analysis.**
- **Identify and map the 3D distribution of lithofacies.**
- **Determine the main paleo-hydrodynamic processes that contributed to mud transportation into the basin.**
- **Reveal potential major surfaces (e.g., discontinuities) and propose a sequence stratigraphic framework for the Horn River Basin.**

BACKGROUND

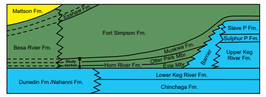


Study area and core locations.

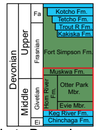


Modified from (Barkley, 2010)

Paleogeographic map.



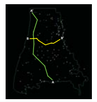
Modified from (Ferri et al. 2011)



Horn River Group shales were deposited during Middle to Late Devonian period. The group represents a relatively deep-water embayment setting surrounded by shallow water carbonate platforms. This group includes Evie Member (E), Otter Park Member (OP), and Muskwa Formation (M).
Area: 1.3 million hectares Estimated gas resource: 78 tcf (MEM, 2011; BCOGC, 2010)

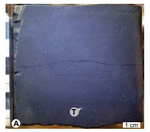
METHODOLOGY

- Detailed sedimentological and ichnological descriptions of 12 cores, each up to 175 m long.
- 25 thin section analysis to reveal micro-structures.
- Geochemical analysis to support depositional history.
- Correlation of lithofacies distributions with wireline logs and geochemical analysis.
- 135 wireline logs were used for subsurface correlation.



LITHOFACIES ANALYSIS

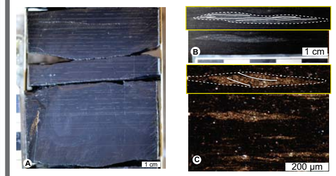
Anoxic relatively deep-water conditions



Massive mudstone:
- Siliceous to calcareous, dark grey color massive mudstones (A-B).
- Sedimentary structures: rare parallel laminations, thin carbonate-rich layers, and micro-scale starved ripples.
- Fossils: Siliceous, calcareous or pyritic radiolarians, sponge spicules, and tentaculites (B), as well as rare conodonts.
- Trace fossils: sparse bioturbation (BI 0–1), *Planolites*.

Depositional environment: **Anoxic deep-marine**
- Lack of bioturbation and lack of bentic and epifaunal fossils suggest that the habitat was not favourable for the organisms due to stressed conditions such as oxygen depletion.
- Depositional processes include suspension settling with minor or no traction currents.

Abundant in the Muskwa Fm. and the Evie Mbr, and to a lesser extend the Otter Park Mbr. Within the Otter Park Mbr., this lithofacies becomes more abundant from south (proximal) to north (distal).

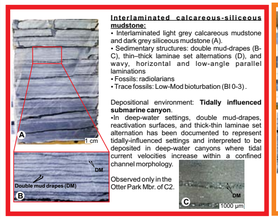


Pyritic mudstone:
- Dark grey massive mudstone with dominant pyrite-rich laminae or lenses, and rare pyritized grains (A).
- Sedimentary structures: rare organic-rich beds, siliceous fossil-rich laminae and micro-scale starved ripples (B and C).
- Fossils: Pyritic radiolarians, sponge spicules (), and tentaculites, as well as rare conodonts, fish scale, plant material, agglutinated foram. Trace fossils: sparsely bioturbated (BI 0–2) and is dominated by low diversity trace assemblages of *Thalassinoides*, *Planolites*, rare *Teichichnus*, as well as bio-deformation and mantle-swirl structures.

Depositional environment: **Anoxic deep-marine**.
- Little or no current generated structures
- Very sparse bioturbation.
- Lack of bentic and epifaunal fossils
- Depositional processes include suspension settling with minor traction currents.

Abundant in the Muskwa Fm. and the Evie Mbr.

Oxygenated relatively shallow-water conditions



Interlaminated calcareous-siliceous mudstone:
- Interlaminated light grey calcareous mudstone and dark grey siliceous mudstone (A).
- Sedimentary structures: double mud-drapes (B-C), thin–thick laminae set alternations (D), and wavy, horizontal and low-angle parallel laminations
- Fossils: radiolarians
- Trace fossils: Low-Mod bioturbation (BI 0-3) .

Depositional environment: **Tidally influenced submarine canyon.**
- In deep-water settings, double mud-drapes, reactivation surfaces, and thick-thin laminae set alternation has been documented to represent tidally-influenced settings and interpreted to be deposited in deep-water canyons where tidal current velocities increase within a confined channel morphology.

Observed only in the Otter Park Mbr. of C2.

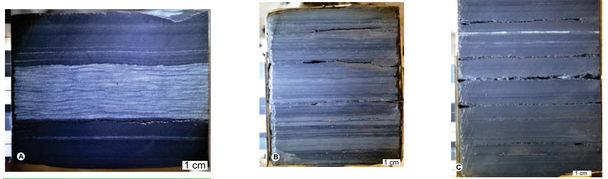
Intensely bioturbated pinstripe mudstone. :
- Intensely bioturbated (BI 4–6) dark-light grey mudstone lamination (A-B).
- Sedimentary structures: parallel to irregular horizontal laminations (B) and unbioturbated massive light grey mudstone intervals (A).
- Fossils: soft bodied vermiform worm-like fossils (D), and transported fossils.
- Trace fossils: *Thalassinoides*, *Planolites*, diminutive *Helmindhopsis* (B), and *Phycosiphon* (C) and laminae disruption (E).

Depositional environment: **Offshore or distal prodelta deposits**.
- Increased bioturbation.
- Unbioturbated light grey beds are indicative of event beds, such as hyper-concentrated flow deposits or turbidites, because the bottom of these beds are erosive and show mud clasts, and the top of them show opportunist colonization behaviour.
- Depositional processes include possible suspension settling and traction currents.

He : *Helmindhopsis*
Phy : *Phycosiphon*

(Dykstra, 2012; Rebesco et al., 2014; Shanmugam, 2003, 2008; Shanmugam et al., 2009)

Transitional conditions



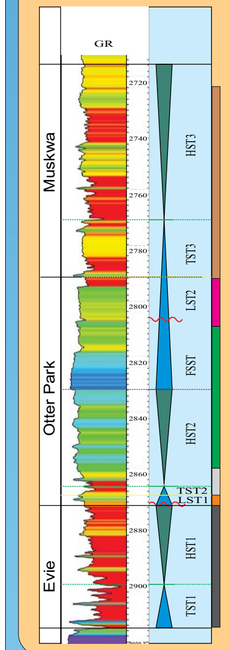
A) Calcareous siltstone and massive mudstone bed/bed sets alternation.
- Flaser bedding, silty current ripples, climbing ripples, normal graded beds, soft-sediment deformations

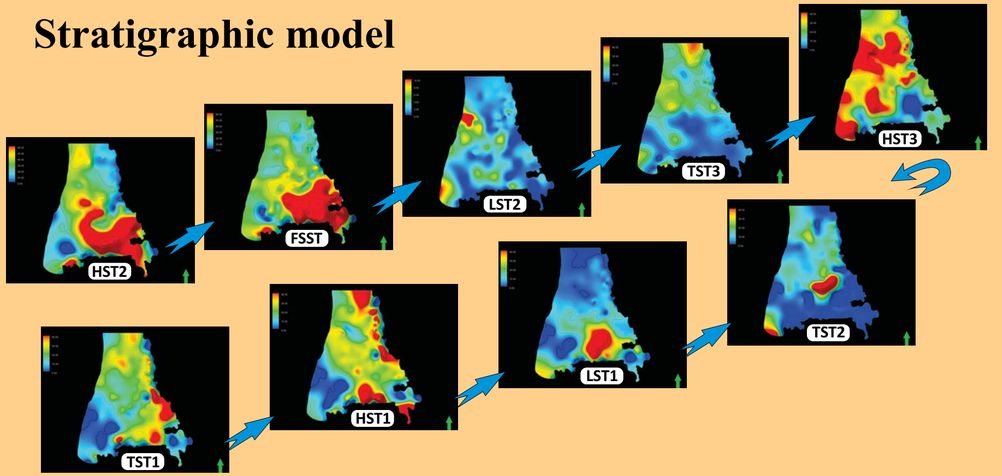
B) Siliceous to calcareous light and dark grey massive mudstones alternation.
- Normal grading and low angle parallel lamination

C) Faintly laminated dark to light grey mudstone lamination.
- Horizontal parallel lamination

Transitional conditions were mainly determined based on bioturbation or whether a lithofacies is found closely associated with both anoxic as well as oxygenated lithofacies. For example, if one lithofacies shows moderate bioturbation in one core while the same unit shows lack of bioturbation in another core that lithofacies is attributed to represent transitional conditions. These lithofacies represent relatively energetic conditions (e.g., contourites) due to the presence of current-generates structures, increased bioturbation, and event beds. They are abundant in the Otter Park Mbr, but also present in the Muskwa Fm. and the Evie Mbr.

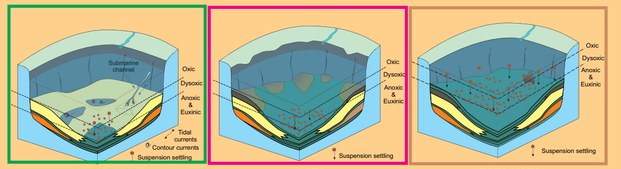
Stratigraphic model

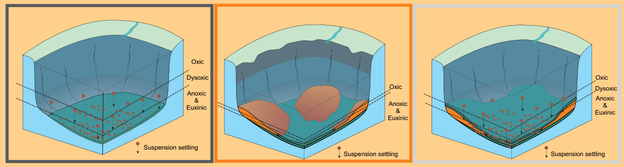




The LST1, HST1-2, and FSST show thick sequences at the south and south east of the Horn River Basin suggesting a major sediment input. Although it is not very close to the HRB the Peace River Arch is a possible source for this input. The LST2 indicates another potential source on the west side of the basin which is probably eroded completely, because there is no documented source in the west.
TST1 and 3, and HST3 suggests transgressive deposit developments.
The thick sequence in the middle of the TST2 isopach map is interpreted to represent erosion then deposition of older sediments (there is no core recovery at this location, but it may represent a transgressive lag deposit).

Depositional model





Conclusions

- In this study, we have analyzed extensive core data that led us to create a better depositional history for a shale basin. Both sedimentological and geochemical analysis suggest that the Horn River Gorup show significant variability in terms of lithofacies distribution and depositional conditions in both spatially and stratigraphically.

- The percentage of sediments representing oxygenated and anoxic deep-water conditions vary significantly; however, proximal (south) cores include more oxygenated units compared to those of the distal (north) cores. Moreover, among the Horn River Group, the Otter Park Mbr. is represented by less anoxic conditions than the Muskwa Fm. and the Evie Mbr. This indicates that at the time of the Otter Park deposition, the relative sea level was probably lower than the Muskwa Fm. and the Evie Mbr. The presence of lithofacies showing energetic conditions and higher bioturbation in the Otter Park Mbr. strongly support this conclusion.

- Integration of detailed sedimentological and geochemical analysis of multiple cores allowed us to construct sequence stratigraphic framework of a deep-water mudstone setting as detailed as a shallow water coarser grained setting. Four different system tracts were determined in our study, as opposed to simple T-R cycles. This allows us to better understand the reservoir quality, and to better display their heterogeneity in space and time.

We thank the British Columbia Ministry of Energy and Mines in Victoria for the access to core data and well files. We are grateful for the funding support provided by the Nexen-CNOOC, Imperial, Husky Energy, Devon Canada, Shell Canada, NSERC, and ConocoPhillips Canada.

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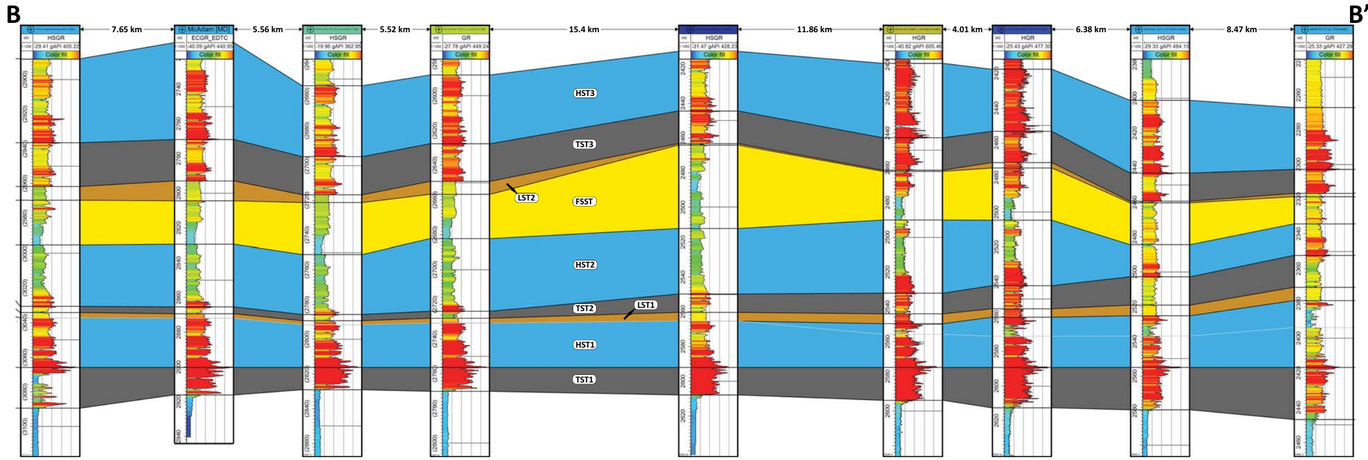
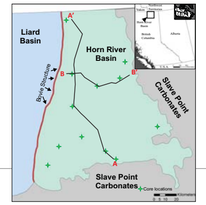
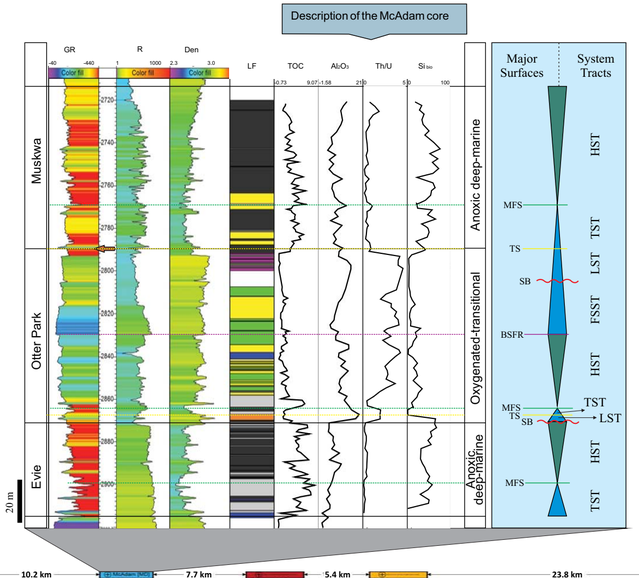
SEQUENCE STRATIGRAPHY





TST: Transgressive System Tract
HST: High Stand System Tract
LST: Low Stand System Tract
FSST: Falling-Stage Systems Tract

MFS: Maximum flooding surface
SB: Sequence boundary
BSFR: Basal forced regression surface
TS: Transgressive surface



System tracts and major surfaces are identified using gamma ray logs (e.g., decreasing- and increasing-upward pattern), and sedimentological and ichnological characteristics. Geochemical analysis were also integrated to identify changes in the terrestrial clay input. This multidisciplinary approach allowed us to construct a detailed sequence stratigraphic framework for the Horn River Basin.

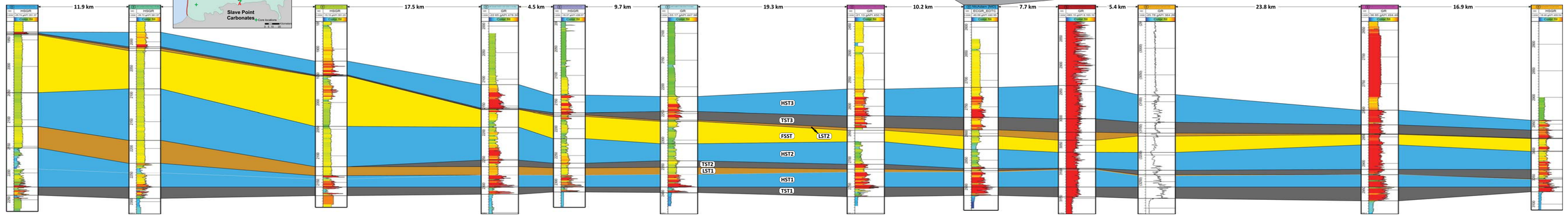
TSTs are distinguished by increasing GR patterns along with massive-pyritic lithofacies and increasing U and TOC values.

HSTs are characterized by decreasing GR patterns following a maximum flooding surface. Other characteristics such as lithofacies or mineral composition vary depending on the formation.

LSTs typically show sudden changes in the lithofacies and intensity of bioturbation. These include changes from massive to laminated lithofaices, and from low bioturbation intensities to moderate or intense bioturbation. Low TOC and U values along with high Al and Zr are also typical for LSTs. In the Lower Otter Park Mbr. the LST1 shows a typical constant GR.

FSSTs are distinguished by increasing GR patterns corresponding an increase in the terrestrial clay input (i.e., Al and Zr) and low U values. Contourite-like deep-water current deposits are common in the FSSTs.

- Calcareous-Siliceous Mudstone
- Pinstripe Mudstone
- Calcareous mudstone (BI3-5)
- Sandy Siltstone
- Fissile Shale (1-3 cm)
- Massive Mudstone
- Pyritic Mudstone
- Siltstone-Mudstone alternation
- L/D grey massive mudstone alter.
- Faintly laminated mudstone



Cross section through the Horn River Basin to correlate the identified sequence stratigraphic intervals using sedimentological, ichnological and geochemical characteristics, as well as wireline logs.