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Sedimentary processes and depositional environments of the gas-bearing Horn River Shale in British Columbia, Canada

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ABSTRACT: The Horn River Basin in the northeastern British Columbia, Canada, is one of the largest unconventional gas-bearing basins in North America. The main reservoir of this gas accumulation is the Devonian Horn River Formation that is stratigraphically divided into three members, the Evie, Otterpark and Muskwa in ascending order. This study focuses on sedimentary processes and depositional environments of the Horn River Formation based on sedimentary facies analysis by the aid of well-log mineralogy (ECS) and total organic carbon (TOC) data from the Kiwigana well. The shales of the formation consist dominantly of silicate minerals (quartz, feldspar and mica) and subordinate clay mineral and carbonate materials, with TOC ranging from 0.3 to 7.6%. Three sedimentary facies were identified on the basis of centimeter-scale description of sedimentary structures and texture in borehole cores: homogeneous mudstone (HM), indistinctly laminated mudstone (ILM), and planar laminated mudstone (PLM). Integration of sedimentary facies, lithology and TOC suggests that the Horn River shale was primarily deposited in overall distal marine setting deeper than shelf or marginal slope, possibly base-of-slope to deeper basin plain off the carbonate reef (or shelf). Facies HM is siliceous and organic-rich, and dominant in the Evie and the overlying lowermost Otterpark members. It is interpreted as a pelagic to hemipelagic deposit formed mainly by suspension fall-out in an anoxic setting below maximum storm wave base. Likewise, facies ILM shows relatively high proportion of silicate minerals and TOC. This facies is identified frequently in the Muskwa and rarely in the Otterpark; it reflects a deposition from hemipelagic settling with an influence of persistent and weak bottom currents or nepheloid flows. Facies PLM, dominant in the large part of the Otterpark, is relatively depleted in silicate minerals and TOC. This facies indicates more frequent inflow of episodic turbidity currents punctuating the hemipelagic settling of the background sedimentation process. During the deposition of the Horn River Formation, the depositional site has experienced an earlier relative sea-level fall changing from a deep basin (Evie) to shallower marginal slope (middle Otterpark), and subsequent relative sea-level rise turning back to a deeper marine environment (Muskwa).

Key words: shale gas, laminated mudstone, sedimentary process, depositional environment, Horn River Formation

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1. INTRODUCTION

Shale gas refers to natural gas trapped within organic-rich shale formation with very low porosity and permeability (Curtis, 2002). Although exploration and development of shale gas began as early as 200 years ago, it is not until recent years that shale gas becomes one of the most promising unconventional hydrocarbon resources by virtue of continued technological advances such as horizontal well drilling and large-scale hydrofracturing (Zou et al., 2013). The most successful area for shale gas exploration and development is North America (Fig. 1), where the gas-bearing shale has been found from Paleozoic and Mesozoic strata in about 50 basins, and shale gas production has been achieved in about 10 basins (Zou et al., 2013). The Horn River Basin (HRB) in the northeastern British Columbia (BC), Canada, is one of these largest unconventional shale gas accumulation areas in North America (Figs. 1 and 2). One of main reservoirs of the HRB is the Middle Devonian Horn River Formation which consists of fine-grained, organic-rich strata formed in an open marine environment, much like the Barnett

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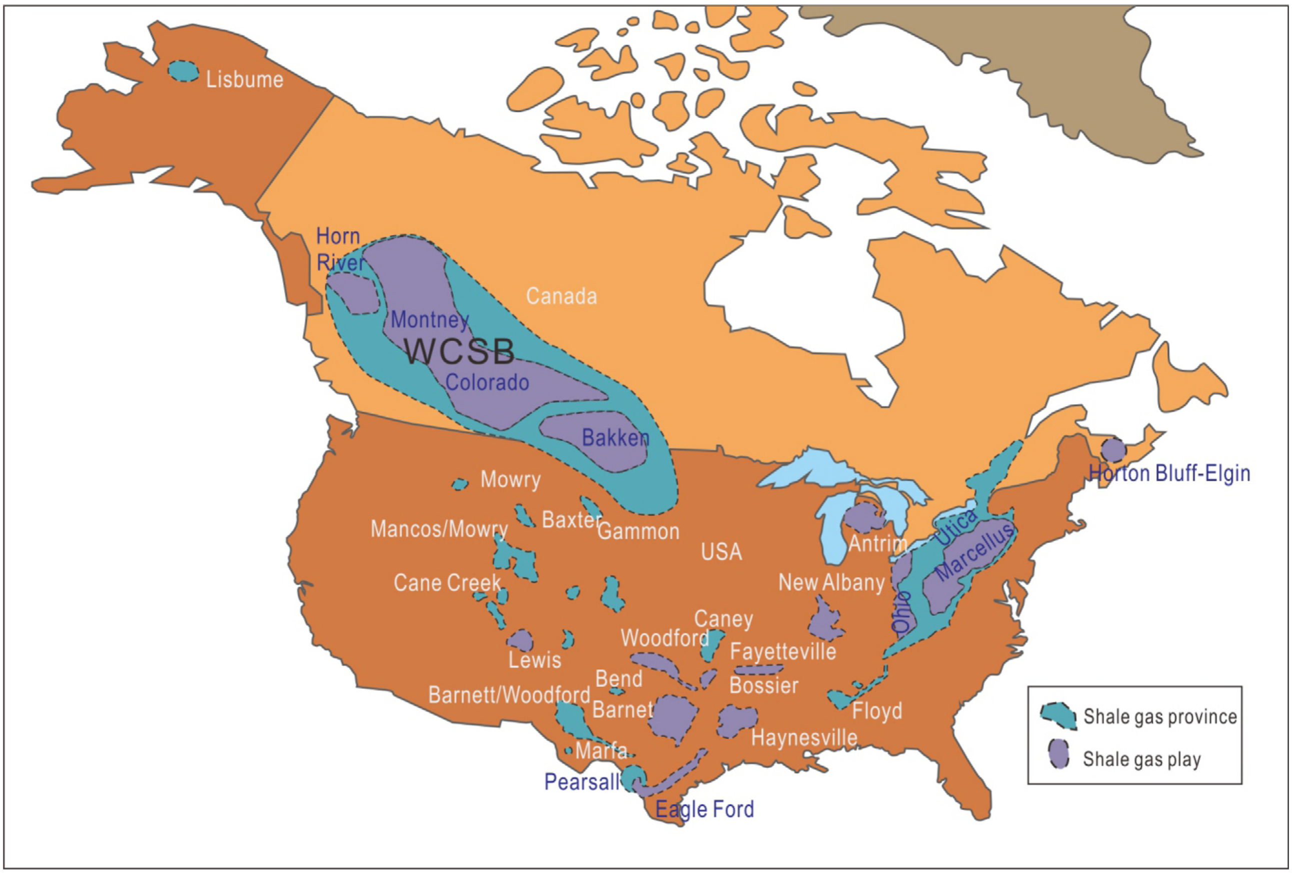

Fig. 1. Distribution of major gas-bearing shale in North America. WCSB: Western Canada Sedimentary Basin. After U.S. Energy Information Administration (2011).

shale formation, a classic example of shale gas reservoir in United States. (Oldale and Munday, 1994; Nieto et al., 2009). Stratigraphically, Horn River Formation is divided into three members, Evie, Otterpark and Muskwa in ascending order, showing subtle variations in lithology, grain size and organic matter content (Ness et al., 2010; Dong et al., 2013). In this study, we have undertaken a sedimentological characterization of these stratigraphic units based on sedimentological and geochemical analyses of borehole cores by the aid of well-log mineralogical data. The main objectives of these analyses are to define and describe the lithology and sedimentary facies at centimeter scale, and eventually to decipher the sedimentary processes and depositional setting of the stratigraphic members in the Horn River Formation. The sedimentological case study in prolific shale gas reservoirs such as the Horn River Formation may provide an insight into environmental condition favorable for generation and preservation of the shale gas.

2. GEOLOGIC SETTING

The HRB is one of the Devonian (Givetian and Frasnian stages) depocenters in the northwestern corner of the Western Canada Sedimentary Basin (WCSB) (Mossop and Shetson, 1994), and occurs in the northern British Columbia (BC) and the Northwest Territories covering an area of 18,400 km^2 (Fig. 2). The eastern and southern boundaries of the basin are constrained by Devonian carbonate platforms of the Keg River, Sulphur Point, and Slave Point formations, and the northern border, in Northwest Territories, is defined by the thinning of the basin-fill strata (Oldale and Munday, 1994). On the other hand, the basin is bounded on the west by the Bovie Fault Zone which is a major structural feature separating the Horn River Basin from the Carboniferous (Mississippian) Liard Basin (MacLean and Morrow, 2004) (Fig. 3).

The Horn River Formation within the HRB mainly consists of siliceous, organic-rich shales with minor matrix-supported carbonate rocks (wackestones) in the lowermost part, that are typically at a depth of 2,200–2,700 m and usually thicker than 200 m as a complete section (Kennedy et al., 2013). Stratigraphically, this shale section is subdivided into three members by lithofacies and mineralogical characteristics in conjunction with detailed well log correlation: Middle Devonian Evie and Otterpark members, and Upper Devonian Muskwa Member, in ascending order (Oldale and Munday, 1994) (Fig. 3). The Horn River

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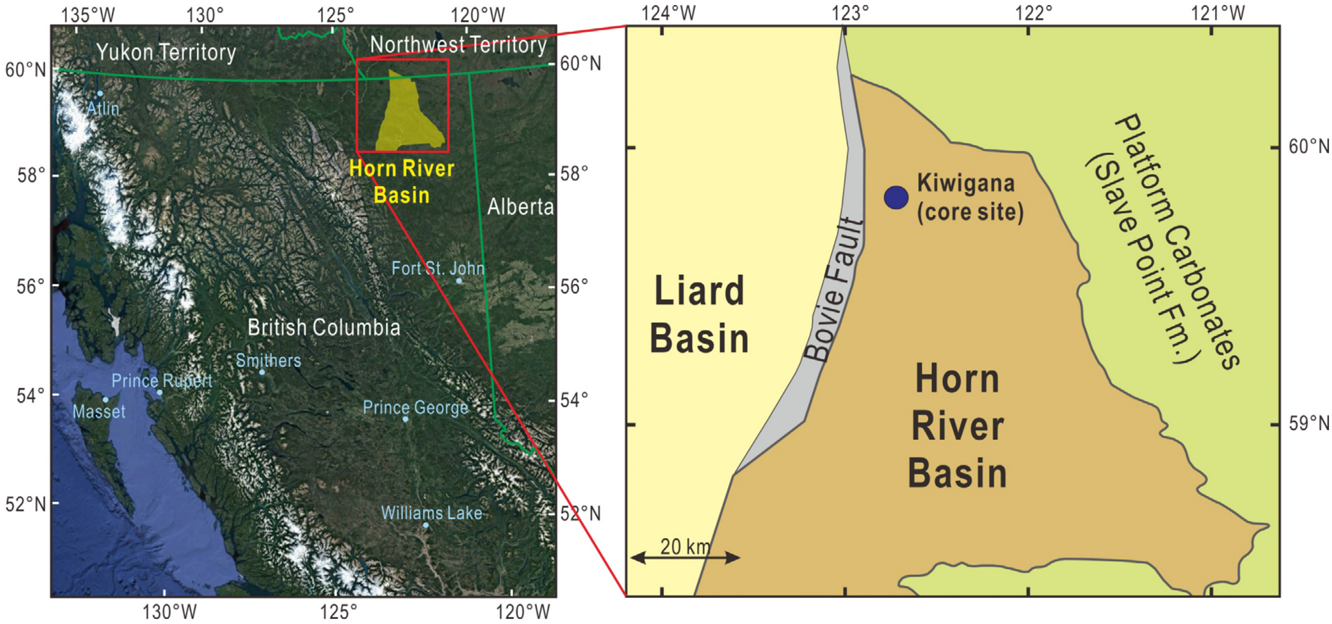

Fig. 2. Distribution of the Horn River Basin and location of the borehole core for this study.

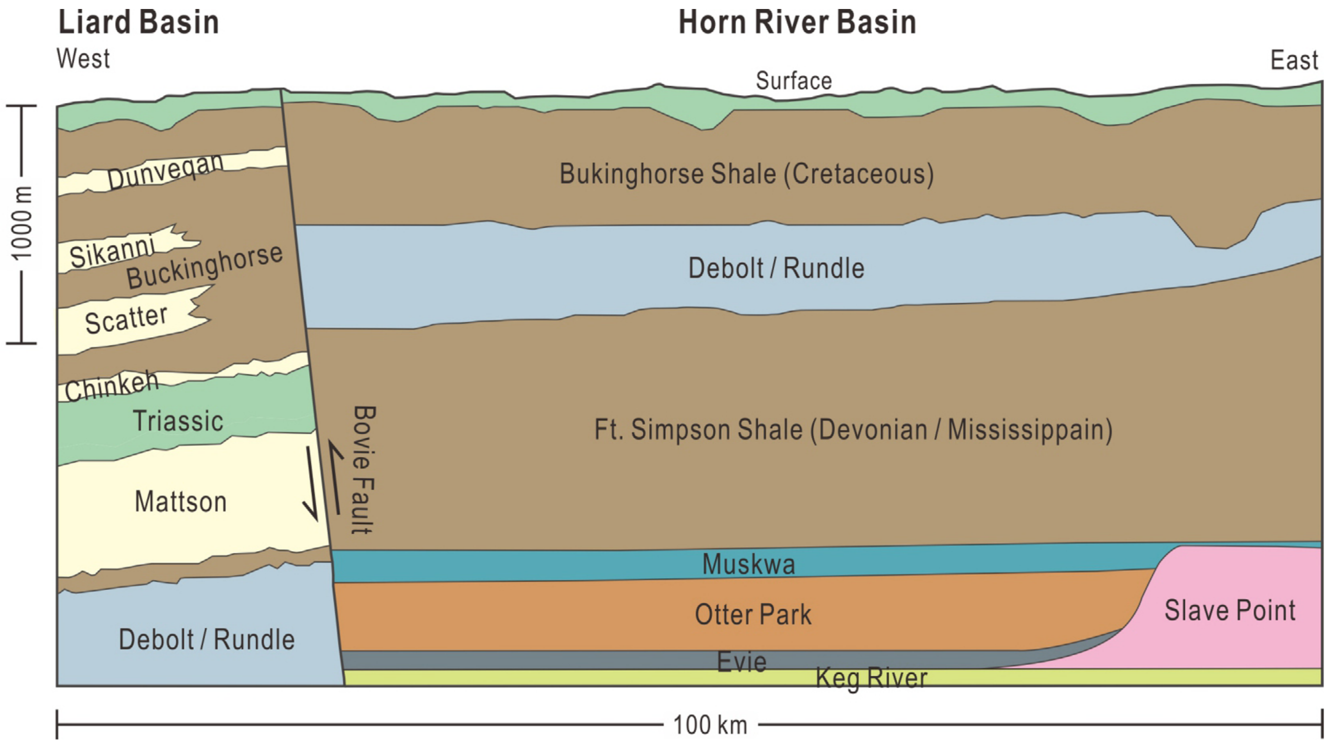

Fig. 3. Stratigraphic cross-section of the Horn River Basin and adjacent Liard Basin. After BC Oil and Gas Commission (2010).

shales are underlain by limestones and dolomites of the Lower Keg River Formation, and overlain by the younger shales of the Fort Simpson Formation.

3. MATERIALS AND METHODS

The main material of this study is a 160 m long, subsurface borehole cores recovered from depths of 2307.6-2470.0 m (95.7% of core recovery) in the Kiwigana Field, the middle western part of the HRB (Fig. 2). The core analysis focused on the description of lithology, texture, primary and secondary sedimentary structures, bedding contacts, and character of bedding. In addition, analysis of total organic carbon (TOC) was carried out on 101 rock samples by the Rock-Eval 6 Turbo

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instrument. Thin-section examination as well as X-ray diffraction (XRD) analysis on 45 selected rock samples were also carried out by TerraTek for rock fabric, texture, biotic content, and mineralogy. For more detailed lithological classification of Horn River shale, we also analyzed well-logging data by Elemental Capture Spectroscopy Sonde (ECS) which provide nearly continuous (10 to 20 cm interval) mineralogical composition including total clay, total carbonate, and QFM (quartz, feldspar, and mica).

4. LITHOLOGY

In this section, the mineralogical and lithological characters of three members (Evie, Otterpark and Muskwa in ascending order) are presented based on the technical report by TerraTek (2010). Due to lithological heterogeneity, the Otterpark Member is further divided into 4 submembers (lower, middle, upper and lowermost) (Fig. 4).

4.1. Evie

In the core, the Evie Member occurs deeper than 2442 m (Fig. 4). It consists of a dark grey to black siliceous and calcareous laminated mudstone (Fig. 5) that is punctuated with thin beds of very fine grained skeletal material. The siliceous mudstone in the upper part of the member gradually changes into a wackestone and calcareous mudstone with depth. On thin sections, moderate to high amounts of detrital silts (15–30%) are recognized, whereas clay proportions are relatively low. The ECS logging data show that QFM (quartz, feldspar and mica) is the most prominent (average 61%) mineral group in this member with minor amounts of calcite (22%) and clay (17%) (Table 1; Fig. 4). Fractures are only observed in rare thick carbonate beds and are filled with calcite. The TOC in the Evie is high (average 3.9%) and ranges from 1.45 to 6.26% (Table 1). Fossil types in limestone and calcareous mudstone comprise shell fragments of mainly styliolinids with fewer bivalves and brachiopods (Fig. 6a).

4.2. Otterpark

4.2.1. Lowermost Otterpark

The lowermost part of the Otterpark Member between 2,434 m and 2,442 m (Fig. 4) consists of light gray to black siliceous mudstone and argillaceous mudstone (Fig. 5). According to the technical report by TerraTek (2010), this interval is suggested to be correlated with the Middle Devonian Carbonate to the east of the Horn River Basin, where it is characterized by a light grey calcareous mudstone interbedded with dark grey, calcareous,

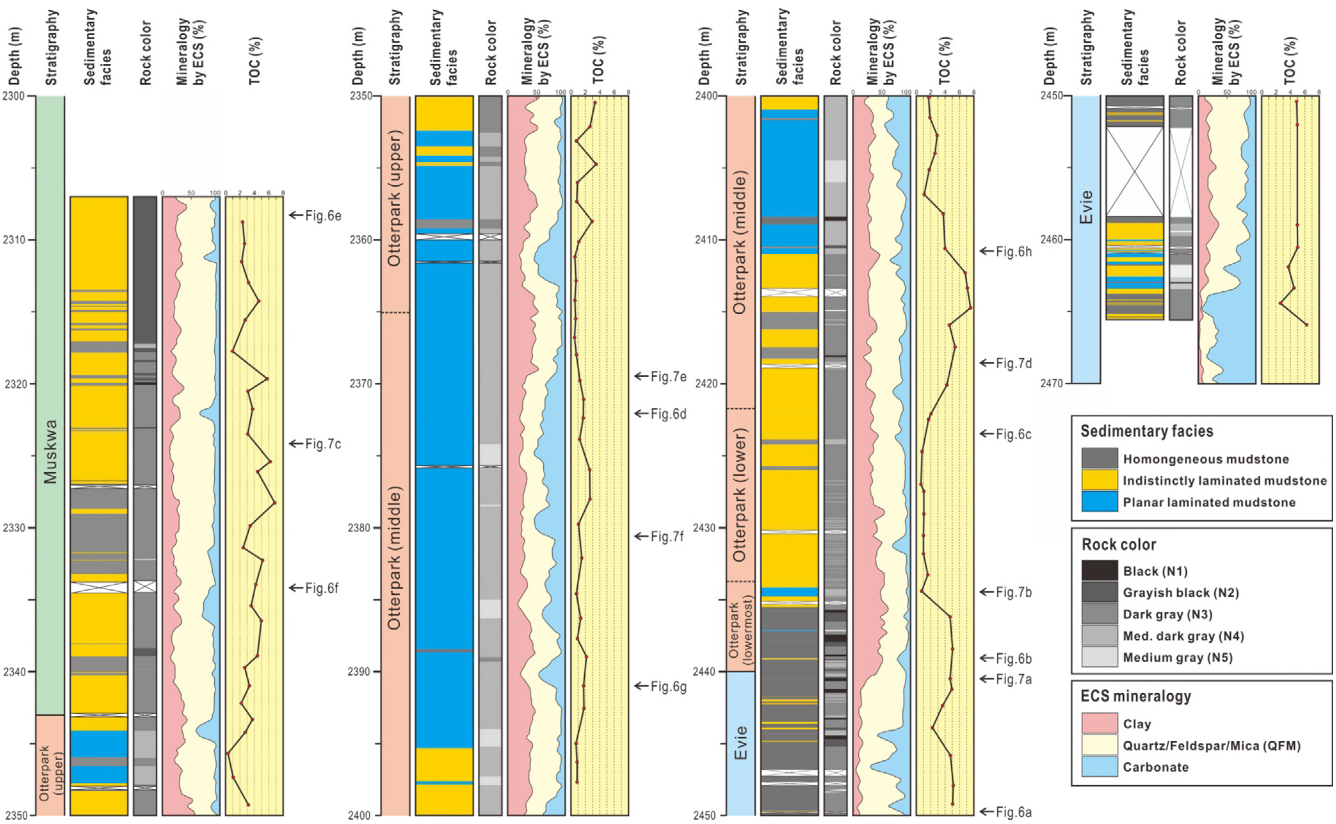

Fig. 4. Summarized borehole depth plots of stratigraphy, sedimentary facies, rock color, mineralogy and TOC.

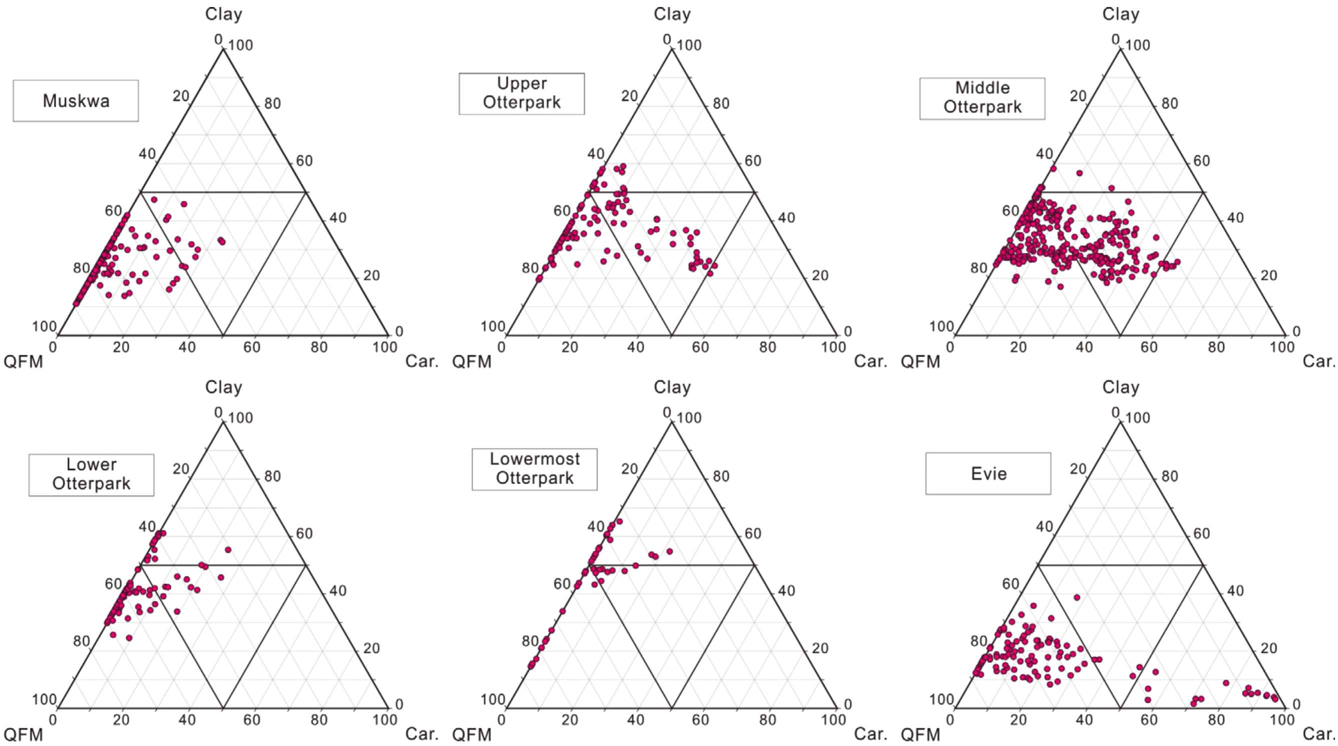

Fig. 5. Lithology of stratigraphic units based on mineral composition of total clay, total carbonate, and QFM (quartz, feldspar, and mica) from the ECS logging data (Fig. 4). Interval of sampling depth is about 15 cm. For nomenclature of lithology, see Figure 8.

Table 1. Summary of geological characteristics in stratigraphic units of the Horn River shale

Stratigraphic units	Facies occurrence[(a)] (%)			Mineral composition by ECS (%)			TOC (%)	Detrital silt content[(c)]
	HM	ILM	PLM	QFM[(b)]	Clay	Carbonate		
Muskwa	26.4	**73.6**	0.0	71.9	24.9	3.2	3.68 (n = 25) (0.96–6.84)	Low (15–20%)
Upper Otterpark	6.1	29.7	**64.2**	52.0	36.9	11.2	1.67 (n = 15) (0.34–3.49)	High (20–30%)
Middle Otterpark	5.4	23.7	**70.9**	48.7	33.4	17.9	2.36 (n = 33) (0.52–7.57)	Moderate to high (15–30%)
Lower Otterpark	5.1	**94.9**	0.0	53.7	41.8	4.7	1.44 (n = 11) (0.65–4.25)	Moderate to high (15–30%)
Lowermost Otterpark	**72.6**	16.6	10.8	52.0	44.7	3.3	4.85 (n = 4) (4.68–5.06)	Moderate to high (15–30%)
Evie	**68.3**	24.1	7.6	61.0	17.4	21.6	3.90 (n = 13) (1.45–6.26)	Moderate to high (15–30%)

[(a)]Occurrence percentage along the core depth in each stratigraphic unit; for facies codes, see Table 2.
[(b)]QFM denotes quartz, feldspar and mica.
[(c)]On thin section samples (TerraTek, 2010).

siliceous mudstone. Compared with the underlying Evie Member, there is a significant change in mineralogy. In particular, the clay content remarkably increases up to 44%, whereas the carbonate content decreases less than 5% (Table 1; Fig. 4). It is also noticeable that the lowermost Otterpark shows the highest TOC (average 4.85%) in Horn River Formation. The detrital silt content of this unit is moderate to high, quite similar to that of the Evie (Table 1). On the other hand, the XRD analysis shows that quartz is major component of matrix or cement ranging from 31 to 57% (average 39%) due to diagenetic overprint. On thin sections, a few micro fossils occur as indistinct siliceous forms and reworked calcareous fossil hash (Fig. 6b).

4.2.2. Lower Otterpark

The lower part of the Otterpark occurs as relatively thin interval of the core from 2,421 m to 2,434 m in depth (Fig. 4). This submember consists dominantly of gray to black siliceous mudstone, argillaceous mudstone and mixed (siliceous-argillaceous) mudstone (Fig. 5). Considering the mineralogy by the ECS, it is quite similar to the lowermost Otterpark: 54% of quartz, 42% of clay and 5% of carbonate (Table 1). Minor fossil types are also recognized as more or less indistinct siliceous forms and reworked calcareous fossil hash on thin sections (Fig. 6c). However, the average TOC from 11 samples of this interval is the lowest (1.44%) among the Horn River shale (Table 1).

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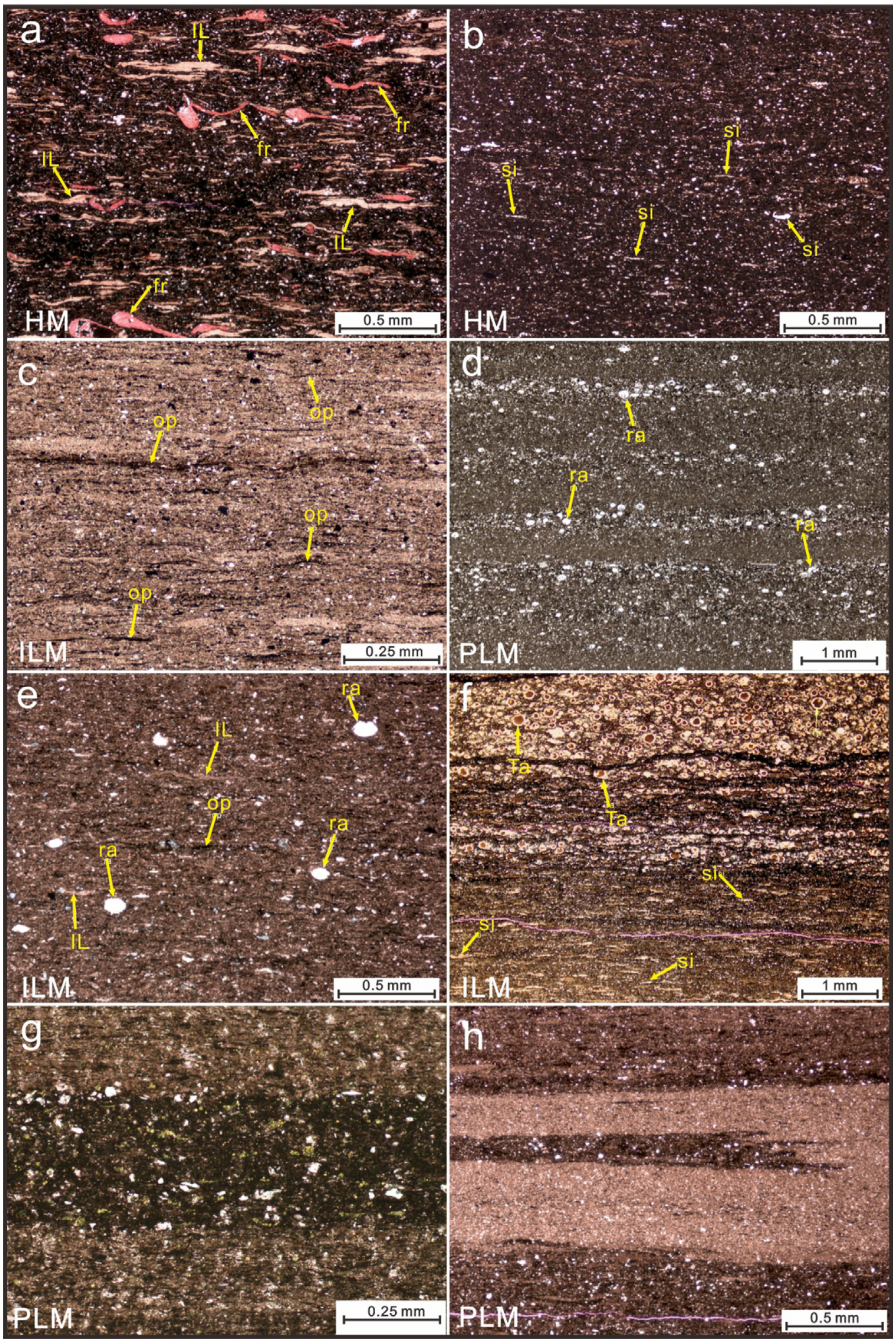

Fig. 6. Photos of thin section samples. (a) Dolomitic mudstone from Evie, showing finely crystalline dolomite crystals in an opaque matrix of clays and organic matter. Rare calcareous shell fragments of bivalve (fr). (b) Siliceous mudstone from the lowermost Otterpark, characterized by overall homogeneous texture with some compacted siliceous forms (si). (c) Argillaceous mudstone from the lower Otterpark, showing indistinct lamination by aligned organic particles (op) and clay-rich laminae. (d) Siliceous mudstone from middle Otterpark, showing well-developed laminations defined by organic particle-rich laminae alternating with clay-rich laminae. (e) Siliceous mudstone from Muskwa showing indistinct lamination from aligned organic particles (op) and lenses of illitic clays (IL); quartz-replaced radiolarian microfossils (ra) and moderate amounts of detrital silt grains (white) are scattered in the matrix. (f) Siliceous mudstone from Muskwa, showing laminae of *Tasmanites* algal cysts (Ta) and compacted siliceous forms (si). (g) Calcareous mudstone from middle Otterpark, characterized by distinct laminations by concentrated radiolarians (ra) and opaque organic particles. (h) Siliceous/argillaceous mudstone from middle Otterpark, showing well-developed lamination by alternation of clayey laminae and organic-rich lamaine; a dark flake within organic-poor laminae at center is rip-up clast from lower organic-rich laminae. For sampling location see Figure 4. By courtesy of Encana. HM: homogeneous mudstone, ILM: indistinctly laminated mudstone, PLM: planar laminated mudstone.

4.2.3. Middle Otterpark

The middle submember of the Otterpark Member (2,365–2,421 m interval) shows wide variety of lithotypes dominated by argillaceous mudstone intercalated with siliceous mudstone and dolomitic mudstone (Fig. 5). Micro burrows are common at base of the submember. The matrix quartz content by the XRD analysis ranges from 6 to 39% (average 18%) and QFM amount by ECS averages 49% (Table 1). These represent overall less siliceous feature of the middle Otterpark compared with the other stratigraphic units in the Horn River Formation. Moreover, the clay proportion (average 33%) is less than those of the other part of the Otterpark Member. On the other hand, the carbonate content of the middle Otterpark is the highest among the whole Otterpark Member ranging from 5 to 51% (average 18%). Detrital silt content in this interval is moderate to high (15–30%). The TOC contents of 33 samples range from 0.52 to 7.57% (average 2.36%) (Table 1). Fossils are commonly recognized from this interval, dominated by silicified forms, calcareous fossil hash and minor radiolaria (Fig. 6d)

4.2.4. Upper Otterpark

The upper part of the Otterpark occurs in depth from 2,343.5 m to 2,365 m (Fig. 4). Various lithotypes including argillaceous mudstone, siliceous mudstone, mixed siliceous-argillaceous mudstone, and calcareous-dolomitic mudstone occur in this interval (Fig. 5). All of these mudstones commonly show weak to distinct lamination, and dominantly contain numerous pyrite nodules and fractures filled with fine quartz. The upper part of the Otterpark is characterized by high amount of detrital silt (mainly 20–30%) and increase in degree of bioturbation. According to the ECS data, QFM and clay in this submember are also slightly enriched, but carbonate is somewhat depleted compared with the middle part of the Otterpark (Table 1; Fig. 4). The TOC contents of 15 samples are relatively low ranging from 0.34 to 3.49% (average 1.67%) (Table 1; Fig. 4). Fossils recognized on thin sections include silicified forms, calcareous fossil hash, conodonts, styliolinids, and minor radiolaria.

4.3. Muskwa

In the core, the Muskwa Member occurs between 2,308 m and 2,343.5 m in depth (Fig. 4). It consists mainly of light gray, siliceous mudstone with minor interbeds of argillaceous mudstone and dolomitic mudstone (Fig. 5). These fine-grained rocks are commonly characterized by faint lamination, occasionally exhibiting homogeneous texture. Bioturbation is very rare except for few traces of micro burrows near the uppermost part of the member. According to ECS data, this member dominantly comprises quartz (average 72% including feldspar and mica) with subordinate amounts of clay and carbonate (Table 1; Fig. 4). The XRD analysis suggests that quartz is mainly concentrated in siliceous matrix ranging from 26 to 70% (average 53%), while detrital quartz (silt size) content measured on thin sections is relatively low (15–20%) (Fig. 6e). The TOC of 25 samples ranges from 0.96 to 6.84% (average 3.7%) (Table 1). Fossils are dominated by radiolarian, replaced with dolomite or ferroan dolomite; other types include a thin bed of *Tasmanites* sp. algal cysts, common indistinct siliceous forms, and conodonts (Fig. 6f).

5. SEDIMENTARY FACIES

In sedimentary successions, sedimentary facies provide an insight into mechanism and environmental setting of sediment transport and deposition processes that were responsible for their formation (Stow, 2005; Dalrymple, 2010). In case of outcrops and cores, one of the most widely adopted attributes for sedimentary facies analysis is primary sedimentary structures along with sediment texture. This attribute reflects environmental conditions that prevailed at the time of deposition (Boggs, Jr., 2006). Thus the sedimentary structures are of special interest as

Table 2. Summary of sedimentary facies from the Horn River shale

Sedimentary facies	Characteristics	Interpretation
Homogeneous mudstone (HM)	Absence of primary structures including bioturbation; occasional intercalation of laminae, layers or lenses of pyritized materials; boundaries transitional, but some thin units showing a sharp lower boundary and a more or less transitional upper boundary	Deposition mainly by suspension fallout below maximum storm wave base, in the quiescent setting of an anoxic water; some thin units indicative of fine-grained turbidity currents or or nepheloid flows
Indistinctly laminated mudstone (ILM)	Thinly laminated with discontinuous or indistinct laminae; laminae mostly less than 0.5 mm thick; lamination identified by a repetition of very thin streaks of lighter color; lamination dominantly planar and parallel, but locally curved (wavy) and pinching out; occasional intercalation of laminae, layers or lenses of pyritized materials; boundaries of individual deposition unit mostly indistinct of gradational	Continuous sediment accumulation by suspension settling under relatively weak and slow flow under anoxic bottom-water deposition conditions
Planar laminated mudstone (PLM)	Well-developed lamination by alternation of light-colored, clay-rich laminae and dark-colored, organic-rich laminae; thickness or vertical spacing of individual lamina 0.5~a few mm, but nonsystematic vertical change (thickness of vertical spacing in a unit is variable or irregular); lamination dominantly planar and parallel; light lamina sometimes graded and/or having a distinct base and a diffuse top; rare rip-up clasts	Persistent hemipelagic settling as a background sedimentation process with occasional events of rapid and episodic sediment influx by turbidity currents, muddy plumes, nepheloid layers and planktonic blooms

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a tool for interpreting ancient sedimentary environments. In this study, we define three sedimentary facies on the basis of primary sedimentary structure and texture qualitatively examined in the borehole core at centimeter scale (Fig. 4). They are (1) homogeneous mudstone, (2) indistinctly laminated mudstone, and (3) planar laminated mudstone (Table 2; Fig. 7).

5.1. Facies HM: Homogeneous Mudstone

Facies HM is characterized by overall absence of primary sedimentary structures except occasional weak grading and intercalation of faint or diminishing laminae in some units (Figs. 7a and b). In microscopic observation, faintly developed laminations are defined by compacted siliceous forms (particles) and organic particles aligned parallel to the laminae (Figs. 6a and b). Compacted siliceous forms are likely organic macerals replaced with quartz and pyrite. Degree of bioturbation is estimated as 0 to 1 in bioturbation index (BI) (see Lazar et al., 2015), which means well preserved original sedimentary structures with no or a few visible burrows. In microscopic observation, however, silt-filled micro-burrows are sometimes recognized. Overall rock color of this facies is black to gray (N1 to N5). Thickness of individual facies unit varies significantly from a few centimeters to more than a meter. Facies boundaries are generally transitional, but some thin units show relatively sharp and distinct upper and lower boundaries (Fig. 7b). In ternary

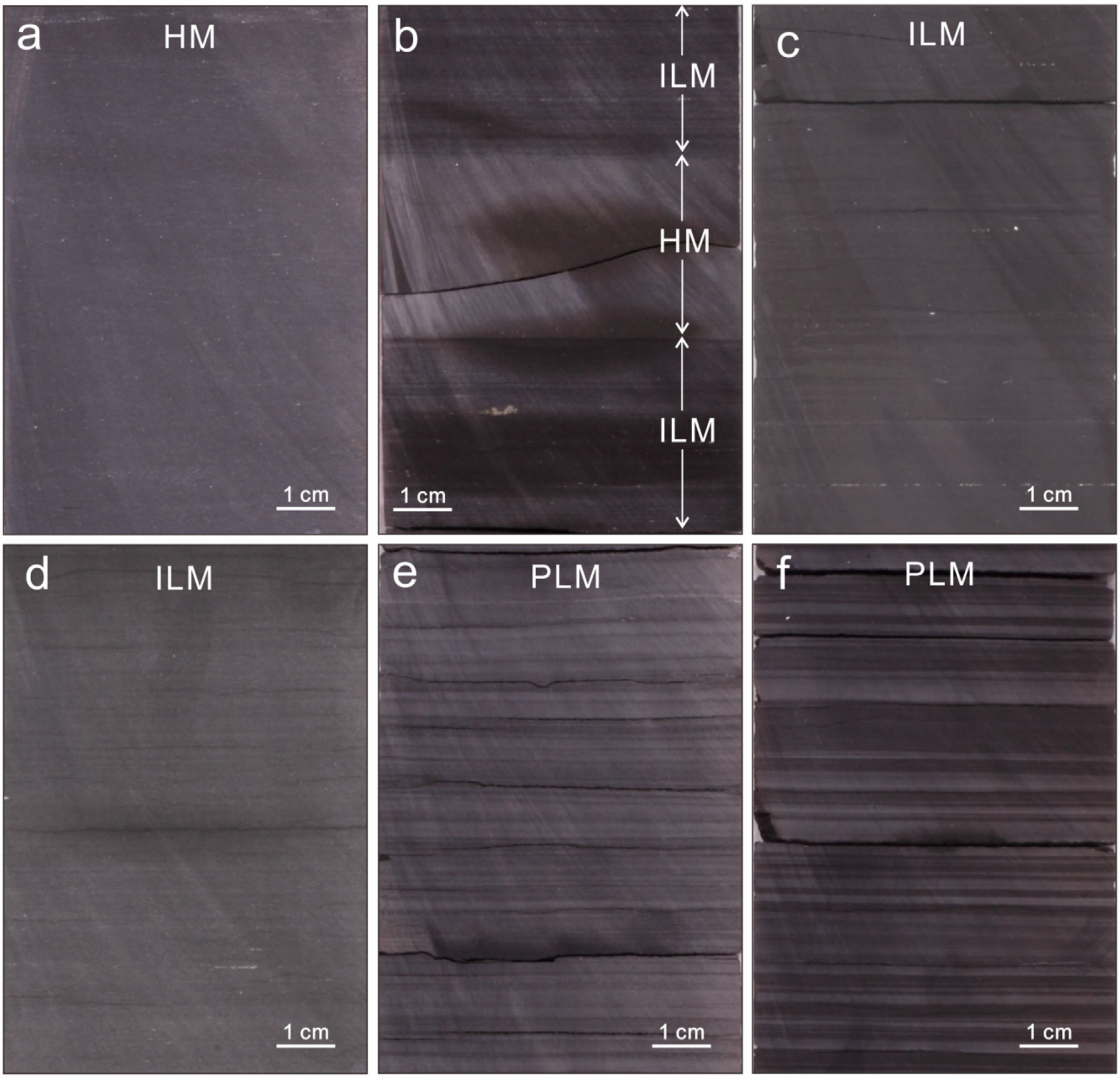

Fig. 7. Photos of sedimentary facies: homogeneous mudstone (a and b), indistinctly laminated mudstone (c and d), and planar laminated mudstone (e and f). For location of photos, see Figure 4. HM: homogeneous mudstone, ILM: indistinctly laminated mudstone, PLM: planar laminated mudstone.

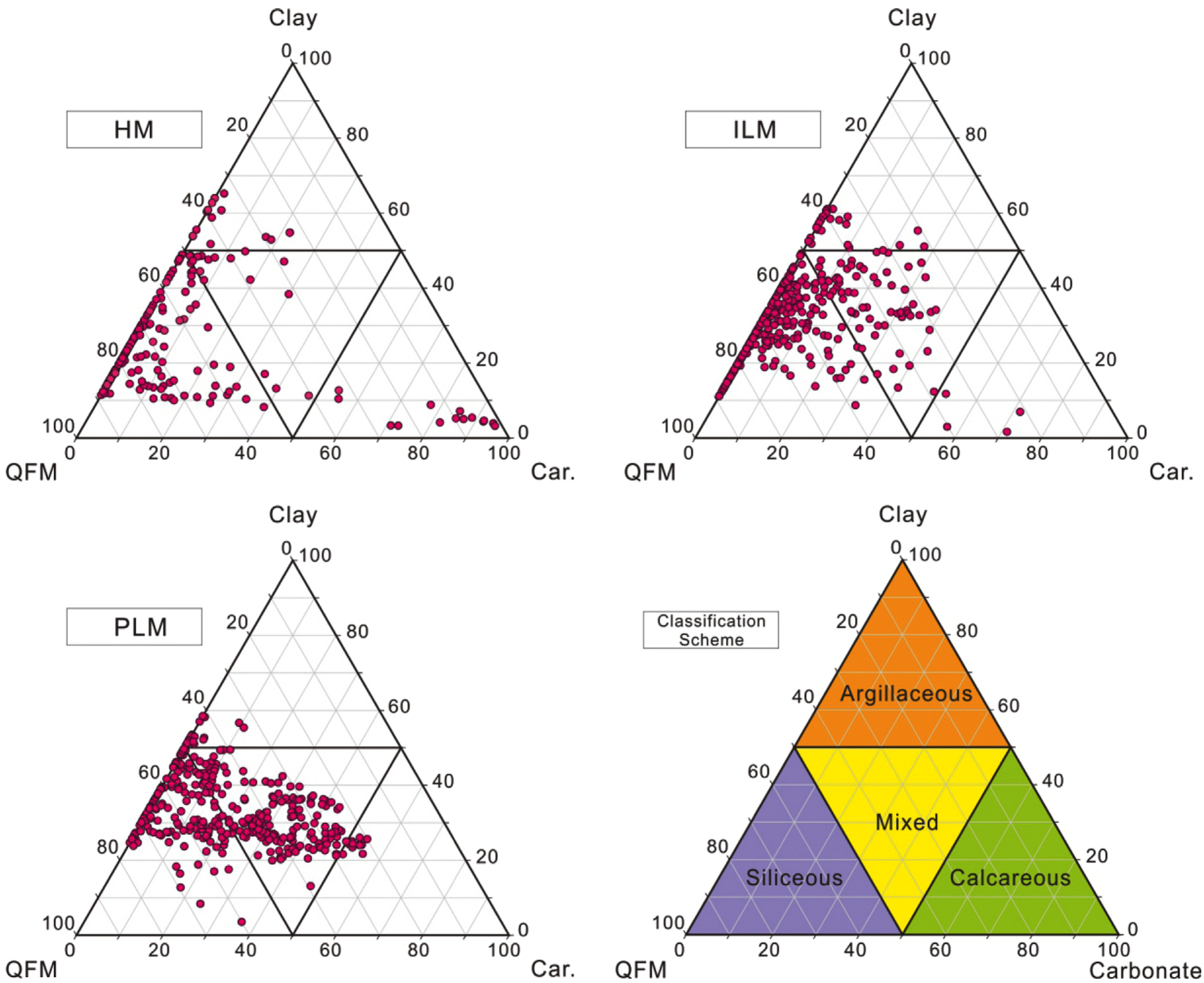

Fig. 8. Lithology of sedimentary facies based on mineral composition of total clay, total carbonate (Car), and group of quartz, feldspar, and mica (QFM) from the ECS logging data. Interval of sampling depth is about 15 cm. Classification scheme and nomenclature of lithology are modified from Lazar et al. (2015).

compositional diagram based on ECS data, units of facies HM dominantly fall into siliceous mudstone category (60–70%) and infrequently into argillaceous or calcareous mudstone (Fig. 8). TOC content measured in 25 samples from this facies is relatively high ranging from 0.78% to 6.84% (average 4.0%). This facies is dominantly encountered in the upper part of the Evie through the lowermost part of the Otterpark, and some stacked and thicker facies units occasionally occur in the Muskwa (Fig. 4).

5.2. Facies ILM: Indistinctly (Streaky) Laminated Mudstone

This facies is characterized by indistinct and very thin (< 1 mm) lamination identified by frequent intercalation of very thin streaks of light-colored dolomite (or radiolarian) and pyrite crystals (dominantly silt to very fine sand size) within dark background materials (Figs. 7c and d). Lamination is dominantly planar and parallel, but locally are gently curved (wavy) and pinch out. Individual lamina is generally poorly defined and laterally discontinuous. Clarity and thickness of lamination vertically change, but it is more or less random or unsystematic. Rarely, light-colored units vertically grade into homogeneous mudstone facies. Thin section analysis confirms that moderate textural laminations are recognized by aligned organic particles, lenses of illitic clay, and indistinct siliceous forms (perhaps compacted agglutinated forams or silicified algal mats) (Figs. 6c, e, and f). In some cases, elongate calcareous styliolinids shell fragments define the laminations (Fig. 6h). In units with higher detrital silt content, detrital silt grains are randomly disseminated (scattered) in the matrix of illitic clays and quartz cements.

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Degree of bioturbation is less than 10%. Facies boundaries (top and bottom) of individual deposition unit are mostly indistinct or gradational (Figs. 7c and d). In ternary compositional diagram based on ECS data, units of facies ILM dominantly fall into siliceous mudstone category and infrequently into argillaceous or mixed (siliceous and argillaceous) mudstone (Fig. 8). The TOC content measured in 39 samples ranges from 0.65% to 7.57% (average 3.20%). Facies ILM is the most common facies in the Horn River Formation, but it is more frequently encountered in whole interval of the Muskwa Member as well as the lower and middle lower parts (core depth of 2,411–2,434 m) of the Otterpark Member (Fig. 4).

5.3. Facies PLM: Parallel (Planar) Laminated Mudstone

This facies is composed of gray (N3–N5) mudstone, characterized by relatively conformable succession or repetition of planar laminae (a few millimeters thick) or occasionally thin beds (> 1 cm thick) that exhibit subtle color difference, dark gray and light gray (Figs. 7e and f). Individual lamina is generally thicker and more continuously defined than in facies ILM. Thickness of individual lamina generally ranges from 0.5 mm to a few millimeters, but some units are more than a few centimeters. Clarity and thickness of laminae are more or less persistent laterally, but vertically they are not consistent exhibiting nonsystematic change. Light-colored laminae or beds are rarely graded and/or have a distinct base and a diffuse top. Bioturbation is common, especially in the upper part of the Otterpark.

Under the petrographic microscope, well developed laminations in facies PLM of argillaceous mudstone are defined by alternating dark, organic-rich laminae with lighter clay-rich laminae (Figs. 6d, g, and h). In calcareous/dolomitic mudstone, parallel laminations are developed by thin micro-laminae of concentrated radiolaria replaced with calcite cement (Fig. 6d). Opaque organic particles are also concentrated in the thin micro-laminae and contribute to the distinct lamination. Detrital silts are commonly concentrated in organic-rich laminae (Fig. 6g). But in some units, detrital silt grains are randomly or uniformly scattered throughout the facies rather than concentrated either in clay-rich or organic-rich lamina similar to the facies ILM. The boundary of individual lamina generally exhibits conformable and non-erosive contact with adjacent lamina. In some units, however, organic-rich lamina shows jagged-edged feature suggesting a rip-up intraclast hosted within organic-poor lamina (Fig. 6h).

In ternary compositional diagram based on ECS (Elemental Capture Spectroscopy) data, facies PLM dominantly fall into categories of siliceous mudstone and mixed mudstone (Fig. 8). The TOC content of this facies (measured from 37 samples) is relatively low ranging from 0.34% to 4.51% (average 1.51%). This facies is quite common in the upper and middle intervals of the Otterpark Member (Fig. 4).

6. DISCUSSION

6.1. Depositional Setting

During the Devonian time, numerous reef complexes developed within the WCSB (Western Canada Sedimentary Basin) (Mossop and Shetson, 1994; Oldale and Munday, 1994). The HRB (Horn River Basin) was situated seaward (westward) of the barrier-reef complex along the western margin of the WCSB (Ness et al., 2010). The Horn River Formation is stratigraphically equivalent to reefal carbonates of the Slave Point Formation to the east (Fig. 3). In the initial stage of deposition in HRB, relative sea-level rise allowed seas to transgress the older basin margins dividing the interior basin into several bank complexes and intra-platform basins (Oldale and Munday, 1994).

As described in the previous section, the Horn River shale in Kiwigana area is characterized by fine grain size of sediments, absence of wave-induced sedimentary structures such as ripples and hummocky laminations, and lack (scarcity) of larger skeletal debris. These characteristics suggest that the Horn River shale most likely has formed in a deep-water depositional setting, possibly below the storm wave base. Moreover, bioturbation indicative of benthic biota living in the seafloor occurs very rarely throughout the core except for limited interval of the upper Otterpark. The overall lack of bioturbation in Horn River strata suggests that the deep-water condition was generally antagonistic to the benthic organisms, possibly an anoxic condition resulting from the active consumption of dissolved oxygen in the process of bacterial degradation of the abundant organic matter in the substrate (Loucks and Ruppel, 2007; Potter et al., 2010).

In spite of restricted bioturbation, the Horn River shale contains relatively abundant biogenic materials which generally occur as an admixture of radiolarians, indistinct siliceous forms, *Tasmanites sp.*, and other skeletal debris (mostly < 1 mm size) of bivalves, brachiopod, styliolinids and conodonts (Fig. 6). Considering the Horn River Formation was dominantly formed under the anoxic condition, the benthic fauna materials included in the formation may have been transported into the deeper anoxic sea floor, and the pelagic fauna settled on the sea floor after death. The paleontological interpretation of faunal and floral fossils in the Horn River Formation suggests that most benthic biota including mollusks, brachiopods, and agglutinating foraminifera was confined to the shallow-water shelf or to the marginal slope, and pelagic fauna such as radiolarians and *Tasmanites* also lived in the oxygenated interval of water column (TerraTek, 2010).

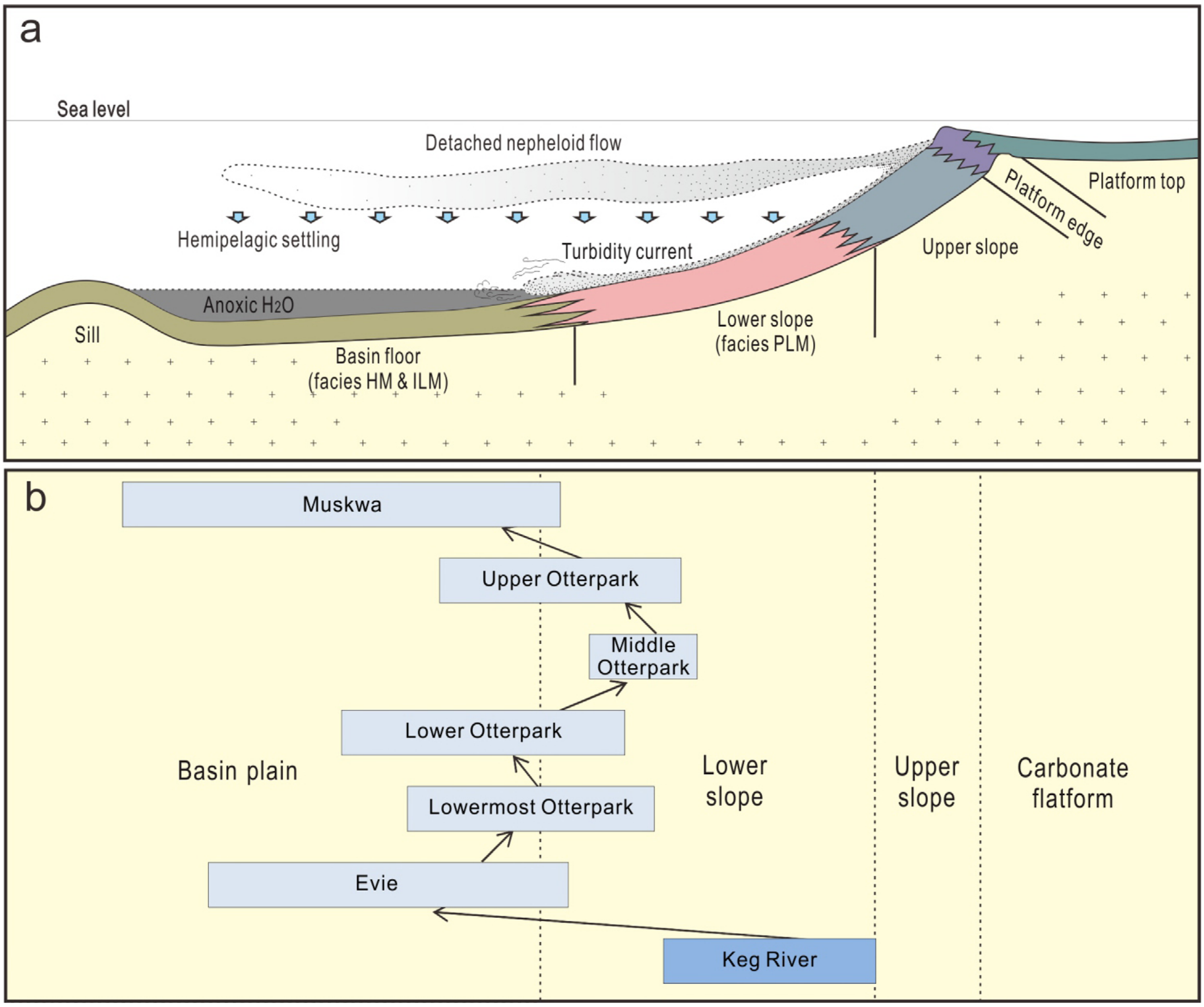

Fig. 9. Schematic diagram of depositional environments and sedimentary processes for the Devonian Horn River shale.

Thus, the Horn River shale is interpreted to have formed in overall distal marine setting deeper than shelf or marginal slope, possibly base-of-slope to deeper basin plain off the carbonate reef (or shelf) to the east (Fig. 9a).

6.2. Sedimentary Processes

In a deep-water setting like the Devonian HRB, sediments are deposited primarily the result of two sedimentation processes: persistent suspension settling from water column and episodic density currents from shallow marine (Loucks and Ruppel, 2007) (Fig. 9a). It is also possible that these end members are combined to a hybrid sedimentation process such as vertical settling from hemipelagic mud plumes transported from the shallow-water shelf (Fig. 9a). In Horn River strata, the homogeneous mudstone (facies HM) is characterized by lack of current-induced sedimentary structures, gradational unit boundaries and varying thickness of individual facies unit from a few centimeters to more than a meter. These characteristics suggest that deposition occurred mainly by suspension fall-out in a quiescent setting. The material in these suspension sediments most likely came from biogenic sediments of skeletal tests from the water column as well as hemipelagic mud plumes transported from the shallow-water shelf.

In an aerobic sea bottom condition, sediments are generally disturbed by benthic organisms obliterating primary sedimentary structures, which gives rise to common bioturbated facies in hemipelagic mudstones (Stanley and Maldonado, 1981; Chough et al., 1984). However, the homogeneous facies of the Horn River shale is characterized by overall lack of bioturbation except rare micro-burrows. As mentioned earlier, this reflects the paleoenvironmental condition is hostile to burrowing benthic

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organisms due to a lack of oxygen. Such anoxic bottom water condition resulted in preservation of homogeneous texture without an overprinting of post-depositional burrowing by benthic animals. The TOC content of facies HM is highest (average 4.0%) in the Horn River shale. The abundance of organic matter indicates that the sea bottom during the deposition of homogeneous mudstones was generally anoxic because bacteria would have consumed much of the organic material if the sea bottom had been aerobic. Collectively, the physical and biogenic structures that characterize the homogeneous mudstone of the Horn River shale are indicative of deposition mainly by suspension fall-out in the quiescent deep marine setting with an anoxic condition below maximum storm wave base.

However, some homogeneous mudstone beds exceptionally show sharp to distinct basal boundary and weak grading even though its fine-grained texture. The dominantly fine grain size in the homogeneous mudstones is suggestive of deposition at great distances from the sediment source. This homogeneous mudstone may be the result of relatively rapid settling from fine-grained turbidity currents or long-running nepheloid flows, which can carry fine-grained sediments into a deep basin. Before the turbidity currents reached the study area, most of the coarser sediments had settled from the flow, leaving only fine-grained sediments to be deposited in further deep and distal part of the basin (Loucks and Ruppel, 2007).

The texture of facies ILM is very similar to that of facies HM, except for subtle to moderately developed textural laminations that are defined by aligned organic particles, compacted siliceous forms, and thin lenses of illitic clays. Such indistinctly laminated beds with gradational boundaries are interpreted to have formed by hemipelagic settling with an influence of more or less persistent and weak bottom currents or nepheloid flows (Yoon and Chough, 1993; Lazar, 2015). The weak but persistent lateral movement of bottom waters made settling particles to lie parallel to bedding plane, producing pronounced lamination. The indistinct lamination may also have been enhanced by elongation of particles during post-depositional compaction. Discontinuous, but more distinct grain horizons or silty streaks found in some ILM units may be indicative of intermittent accumulations of coarser grains from stronger bottom currents or die-out events of waning turbidity currents (Kennedy et al., 2013).

Sedimentary structure typifying facies PLM of the Horn River shale is well-developed lamination which is defined by alternating dark, organic-rich laminae with light gray, clay-rich laminae or thin beds. Laminated and thin-bedded mudstones commonly suggest discontinuous sediment accumulation by lateral transport in bed load or dense suspension, under intermittent energetic flows (Lazar, 2015). The Horn River shale contains commonly 15–30% of detrital silt grains, which are randomly scattered in cases of hemipelagic facies HM and ILM. In facies PLM, however, detrital grains are usually depleted in clay-rich, organic-poor laminae. This textural character is indicative of relatively rapid sedimentation for the clay-rich laminae or thin beds. The clay-rich, organic-poor laminae or thin beds are interpreted as event beds emplaced by rapid and episodic flux of sediments, while the organic-rich laminae are interpreted to have been formed by slower hemipelagic settling as a background sedimentation process.

Clay-rich and organic-depleted laminae are most likely associated with resuspension or reworking of marine sediments in oxygenated zones by bottom currents, storm waves or gravity flows rather than riverine input of organic-rich continental muds (Kennedy et al., 2013). On thin sections, many of clay-rich laminae or beds exhibit non-erosive and conformable boundaries. A likely mechanism for these non-erosive sedimentation units is heavy rain of various sediment sources including muddy plumes, nepheloid layers and planktonic blooms. On the other hand, clay-rich laminae or beds sometimes exhibit erosive lower boundaries and rarely contain sharp rip-up intraclasts (Fig. 6h). These are indicative of intermittent inflow of stronger bottom-hugging turbidity currents. Such physical processes most likely enhanced mixing of deep water, which results in relatively low TOC content in facies PLM.

6.3. Change of Depositional Environments

As mentioned in section 6.1, deposition of the lower strata (Evie) in HRB was associated with relative sea-level rise onto the older basin margins (Oldale and Munday, 1994). According to regional stacking pattern of mudstone lithofacies in HRB, the Evie Member is interpreted as transgressive-highstand systems tract (Potma et al., 2012). Such sequence stratigraphic interpretation is supported by dominance of homogeneous mudstone facies (HM) and high TOC content (3.9%) in the Evie (Table 1). Based on geochemical analysis on Horn River shale, Dong et al. (2013) suggest that TOC is richest in the late stage transgressive systems tract and early stage of highstand systems tract (maximum flooding surface). Consequently, the Evie Member may represent a deep basinal setting (Fig. 9b).

The overlying Otterpark Member is characterized by darker and more bituminous mudstones with only local calcareous-rich laminations in the lower part, and by less bituminous (low TOC), predominantly medium grey calcareous mudstones in the upper part. In the core, the lower part of the member generally shows sedimentological characteristics similar to that of the Muskwa (dominantly ILM). On the other hand, the upper part of Otterpark predominantly consists of parallel laminated light grey mudstone (PLM) beds in which laminae are generally

0.5–a few mm thick, but their vertical change of lamina spacing is more or less nonsystematic or irregular. Therefore, this member reflects an overall upward shallowing environmental change from a deep basin to shallower marginal slope most likely due to progressive sea-level fall (Fig. 9b).

The uppermost member, Muskwa is a dark grey to black, siliceous mudstones with high TOC content and low detrital silt amounts. In the core, it predominantly consists of indistinctly laminated dark grey mudstone (ILM) beds with subordinate intercalating thin beds of homogeneous light grey mudstone (HM). Facies ILM is characterized by indistinct lamination mostly less than 0.5 mm thick, and also by indistinct or gradational boundaries of facies units. Facies HM shows no primary structures except occasional intercalation of laminae, layers or lenses and spots of pyritized materials, and its unit boundaries are transitional. This member is interpreted to represent a pelagic environment in a deep basin to lower marginal slope setting (Fig. 9b).

7. CONCLUSIONS

The mineralogical examinations by ECS, XRD and thin sections reveal that the Horn River shale is composed of abundant silicate minerals (quartz, feldspar and mica) and subordinate clay minerals and carbonate materials. Lithologically, the Evie and Muskwa members are commonly dominated by siliceous mudstones, whereas in the Otterpark Member, mixed type mudstones such as siliceous-argillaceous or siliceous-carbonate mudstone frequently occur along with siliceous mudstone. The TOC content, varying from 0.3 to 7.6%, is relatively high (more than 3.5%) in Muskwa, Evie and the lowermost part of the Otterpark. Based on sedimentary structures and texture, three facies were classified: homogeneous mudstone (HM), indistinctly laminated mudstone (ILM), and planar laminated mudstone (PLM). Comprehensive interpretation of the sedimentary facies, lithology and TOC suggests that the Horn River shale was primarily deposited in an anoxic quiescent basin plain and base-of-slope off carbonate platform or reef to the east. In this deep marine setting, facies HM and ILM, dominant in the Evie (the lower part of the Horn River Formation) and the Muskwa (the upper part of the Horn River Formation) members respectively, may have been emplaced on the anoxic sea floor by pelagic to hemipelagic sedimentation with infrequent effects of low-density gravity flows (turbidity currents or nepheloid flows). On the other hand, facies PLM, typifying the large part of the Otterpark Member (the middle part of the Horn River Formation), suggests more frequent inflow of bottom-hugging turbidity currents punctuating the hemipelagic settling of the background sedimentation. The stratigraphic change of sedimentary facies and TOC content in the Horn River Formation can be interpreted to have been caused by the relative sea-level change: initial sea-level fall resulting in progressive shallowing from a deep basin (Evie) to shallower marginal slope (middle Otterpark), and subsequent sea-level rise causing deeper marine environment (Muskwa). This is indicative of overall regression-lowstand-transgression of the sea-level change.

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