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Recognition of Wave-Influenced Deltaic and Bay-Margin Sedimentation, Bluesky Formation, Alberta

Scott E. Botterill[1], S. Gordon Campbell[2], and Murray K. Gingras[2]
[1]Murphy Oil Company, [2]Ichnology Research Group, University of Alberta

Summary

The combination of sedimentology and ichnology provides for more refined facies identification, and in turn allows for more robust palaeoenvironmental interpretations (e.g. Seilacher, 1978; Pemberton et al., 1982; MacEachern et al., 2010). In order to identify the palaeodepositional affinity and better understand reservoir architecture within a region of the Peace River oil sands, detailed facies analysis focusing on lithology, process sedimentology, and ichnology was performed on a 40 core dataset (Fig. 1). This analysis led to the identification of sixteen distinct facies, five facies associations (FA1-FA5), and a complex vertical and lateral preservation of sedimentation. Importantly, the presence of sediments possessing a wave-dominated character with associated marine-indicative ichnological assemblages led to the identification of previously un-recognized wave-dominated, marine-embayment to open marine deltaic and shoreface deposition.

Introduction

The Early Cretaceous Bluesky Formation is comprised of marginal-marine to marine siliciclastic sediments, and is the primary host to substantial subsurface bitumen deposits of the Peace River oil sands (~70 billion barrels in place, Energy and Resources conservation board, 2013). The preserved record of sedimentation is characterized by a complex vertical and lateral architecture, making lithostratigraphic subsurface correlation impractical. With respect to depositional affinity, a range of environments have been recognized within close proximity to this study, including wave-dominated estuary (Hubbard et al., 1999; 2004), tide-dominated estuary to deltaic (Caplan et al., 2007; Mackay and Dalrymple, 2005; 2011), and wave-dominated deltaic (Botterill et al., 2015; Campbell et al., in-press). The objective of this research was to enhance the understanding of facies distribution, and identify the palaeodepositional setting within the project area (Fig. 1). This was done through: 1) high-resolution (cm scale) documentation of lithological, sedimentological, and ichnological characteristics on a 40 core dataset; 2) combination of these properties into distinct facies; 3) combination of individual facies into facies associations, and; 4) reconstruction of the depositional architecture and depositional environment based on facies association distributions and process sedimentological and ichnological characteristics.

Methods

The dataset for this study consisted of 40 cored wells, with an additional 21 wells for which wireline logs were available (Fig. 1). All 40 core were logged at the individual box scale (1.5 m per core box), with detailed documentation of: lithology, sedimentary structures, lithological accessories, grain-size, trace fossils, and bitumen saturation. Detailed ichnological observations consisted of BI (bioturbation intensity) following Taylor and Goldring (1993), taken at every 37.5 cm (2 measurements per core sleeve). Maximum burrow diameter and ichnological diversity were taken every 75 cm (1 measurement per core sleeve), and used to calculate SDI (Size Diversity Index, *sensu* Hauck et al., 2009). To aid in the identification of primary, secondary and tertiary physical processes affecting sedimentation, the ternary framework of Ainsworth et al., (2011) was utilized. This methodology provides a framework in which the effects of waves, tides, and fluvial processes are plotted based upon their normalized abundance. Wave-

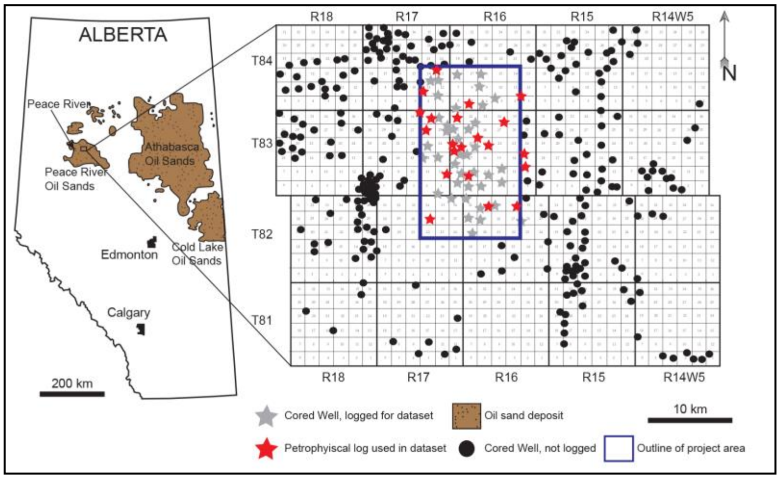

Figure 1. Location map of project area with respect to oil sand deposits of Alberta.

influenced sedimentation was inferred from amalgamated parallel-planar bedding (interpreted as hummocky cross-stratification), quasi-planar lamination (*sensu* Arnott, 1993), and oscillation ripple cross-lamination. Tidally-influenced sedimentation was inferred from the presence of double mud drapes, well-developed grain-size striping, and apparent bi-directional cross-bedding and lamination. Finally, fluvially-influenced sedimentation was inferred from the presence of persistent high-angle cross-bedding in association with abundant granule-pebble lags and abundant organic material (i.e. coal fragments, wood debris, “coffee grounds”).

Results

Sixteen distinct facies were recognized within the dataset and are summarized in Table 1. Facies were separated primarily by lithology, with a sub-script abbreviation given to each facies that characterizes the primary sedimentologic or ichnologic feature of that particular sediment (e.g. SS_{PL} = parallel-planar bedded sandstone). These facies were then combined to identify five facies associations (FA1-FA5, Table 2). These include: FA1-Wave-dominated, fluvially-influenced deltaic sedimentation, FA2-Fluvially-dominated, tidally-influenced distributary channel, FA3-Fluvially- and tidally-influenced deltaic sedimentation, FA4-Wave/storm-dominated embayment shoreface to offshore, and FA5-Mixed-energy estuary. Sequence stratigraphic surfaces observed include marine flooding surfaces, transgressive ravinement surfaces (WRS with local tidal modification), ?regressive surface of marine erosion, and *Glossifungites*-demarcated surface of erosion. Within the project area, only the *Glossifungites* surface is present in every well, and marks the contact between the Bluesky Formation and overlying Wilrich Member. The contact between the Bluesky and underlying Gething Formation is erosional, and appears to represent a compound transgressive ravinement surface and regressive surface of marine erosion depending on the geographical location and nature of Bluesky sediments directly above the contact.

Discussion

The distribution of facies associations and their contrasting nature suggest a complex depositional history recording periodic regressive events within an overall transgressive system. These facies associations, their stratigraphic relationships, and contact types suggest a five-stage evolution from base to top of the Bluesky Formation within the project extents (Fig. 2). Initial Bluesky deposition consisted of wave-dominated, fluvially-influenced sedimentation within an open marine-embayment setting (FA1, lower stratigraphic expression). The contact between FA1 and the underlying Gething Formation is interpreted to represent a transgressive ravinement surface (WRS with local tidal modification). This inference is based upon 2 main criteria: 1) FA1 sediments display a strongly wave-reworked sedimentary character (underlying Gething sediments do not), and 2) a marine-indicative ichnological assemblage, compared to the predominantly brackish-water assemblage common to the Gething Formation. FA2 and FA3 are interpreted to represent a regressive episode, where current-dominated channel and deltaic

Facies	SS HAP	SS PL	SS RL	SS BB	SS MB	SS BC	HET HAP	HET PL	HET WP	HET BB
Typical Core Expression										
Sedimentary Characteristics	HAP, LAP, TxB, GS, RxL, RS, TRhy	LAP, PL, HoWP, RxL, HCS, QPL,	RxL, OsR, HoWP, LAP, PL	HoWP, Bio.Bdd	LAP, HCS, HoWP, RxL, PL	HeWP, HoWP, LAP, PL, Cnvlt, L.C, Lent	LAP, HAP, TxB, RxL, HeWp, Sc.Surf, HBxL, G.S	LAP, HAP, TxB, HCS, RxL, HeWp, Sc.Surf	HeWP, RxL, OsR, LAP, HAP, TxB, Sc.Surf, SSD.	HeWp, FL, Bio.Bdd, Cnvt, LAP
Ichnogenera	*Cy, Di, Ma, Pa, Pl, Sk, Te*	*Ma, Pa, Pl, Te*	*As, Cy, Di, Pa, Pl, Sc, Te, fu*	*Pl, Sk*	*As, Di, Ma, Ro, Sc,*	*Di, Pl, Sk, Th*	*Pl, Sk*	*As, Cy, Di, Ma, Pa, Pl, Ro, Si, Sk, Te, Th*	*Ar, As, Cy, Di, Pa, Pl, Sc, Sk, Te, Th*	*Ar, Cy, Pl, Te*
Ichnological Characteristics	Low diversity, Sporadic Dist, BI 0-1	Low diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic Dist, BI 0-6	Low diversity, Homogeneous Dist, BI 4-6	Low-mod diversity, Sporadic Dist, BI 0-2	Low diversity, Sporadic to Homogeneous Dist, BI 0-6	Low diversity, Sporadic Dist, BI 0-1	Low-mod diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic Dist, BI 0-3	Low-mod diversity, Sporadic-Homogeneous Dist, BI 2-5
Accessory Features	MClst, MBrec, Py/C, G-PLg, Bio.Clst, MDrps	MDrps, Py/C, MClst, C.Frag,	C.Lam, C.Frag, Py, Bio.Clst, Org.Lam	C.Lam, C.Frag, Py, Bio.Clst	C.Lam, C.Frag, Py	Abnt Gastropods, Bivalves, Bio.Clst, Py, C.Frag, Calc.Cmt	M.Clst, Bio.Clst, Py/C, C.Lam	M.Clst, Bio.Clst, Py/C, C.Lam	M.Clst, C.Frag, Bio.Clst, Py, Sh.Lam	Py, Bio.Clst, C.Frag, G-PLag

Facies	HET MB	HET GL	MD RL	MD LM	MD BB	MD MB
Typical Core Expression						
Sedimentary Characteristics	HeWp, FL, Bio.Bdd, Cnvt, LAP	PL, Bio.Bdd	Lent, HeWP, OsR, CuR	Lent, HeWP, PL	PL, LAP, RxL,Fl, Lent,	Lent, HeWP, Bio.Bdd
Ichnogenera	*Ar, As, Cy, Pa, Pl, Ph, Ro, Rz, Sc, Sk, Te, Th, Zo*	*As, Di, Pl, Sk, Th*	*As, Pl, Si, Sk, Th, Zo*	*Pl, Sk, Th*	*Cy, Pl, Po, Sk, Te, Th, Tr*	*As, Ch, Cy, Di, Pa, Ph, Pl, Ro, Rh, Si, Sc, Sk, Te, Th, Zo,*
Ichnological Characteristics	Mod-high diversity, Sporadic-Homogeneous Dist, BI 3-5	Mod diversity, Homogeneous Dist, BI 3-6	Low-mod diversity, Sporadic Dist, BI 0-3	Low diversity, Sporadic Dist, BI 0-2	Low-mod diversity, Sporadic Dist, BI 0-6	Mod-high diversity, Homogeneous Dist, BI 3-6
Accessory Features	Py, Bio.Clst, C.Frag, G-PLag	Abnt Gl, Py, M.Clst	Sd.Lam, Py, Bio.Clst, C.Frag	Py, Bio.Clst	Bio.Clst, C.Frag, C.Lam, Py	Sd.Lam, Py, Bio.Clst

Abbreviation Key

Sedimentary Structures

TxB-Trough Cross-Bedding
HAP-High Angle Planar Bedding
LAP-Low Angle Planar Bedding
PL-Planar Bedding
HCS-Hummocky Cross-Stratification
QPL-Quasi-Planar Lamination
HoWP-Homogeneous Wavy Bedding
HeWP-Heterogeneous Wavy Bedding
RxL-Ripple Cross-Lamination
OsR-Oscillation Ripple
CuR-Current Ripple
G.S. Grain Striping
Lent-Lenticular Bedding
FL-Flaser Bedding
TRhy-Tidal Rhythmite
Sc.Surf-Scour Surface
HBxL-Herringbone Cross-Lamination
SSD-Soft Sediment Deformation
Cnvlt-Convolute Bedding
L.C.-Load Cast
Bio.Bdd-Bioturbated Bedding

Ichnogenera

Ar-Arenicolites
As-Asterosoma
Ch-Chondrites
Cy-Cylindrichnus
Di-Diplocraterion
Ma-Macaronichnus
Pa-Palaeophycus
Ph-Phycosiphon
Pl-Planolites
Po-Polykladichnus
Rz-Rhizocorallium
Ro-Rosselia
Sc-Scolicia
Si-Siphonichnus
Sk-Skolithos
Te-Teichichnus
Th-Thalssinoides
Tr-Trichichnus
Zo-Zoophycos
fu-fugichnia

Accessory Features

Abnt-Abundant
Bio.Clst-Bioclastic Debris
C.Frag-Coal Fragments
C.Lam-Coal Lamina
Calc.Cmt-Calcite Cement
Gl-Glauconite
G-PLag-Granule/Pebble Lag
MBrec-Mudstone Breccia
MClst-Mudstone Clast
MDrps-Mudstone Drapes
Org.Lam-Organic Rich Laminae
Py-Pyrite
Py/C-Pyritic Coal laminae
Sd.Lam-Sand Laminae
Sh.Lam-Shale Laminae
Sid-Siderite Nodule

Facies

SS-Sandstone
HET-Heterolithic
MD-Mudstone
BC-Bioclastic
HAP-High-Angle Planrar
PL-Planar laminated
BB-Brackish Bioturbation
MB-Marine Bioturbation
RL-Ripple Laminated
LM-Laminated
GL-Glauconitic

Table 1. Summary of facies and their sedimentary, ichnologic and lithologic characteristics.

FACIES ASSOCIATION	DESCRIPTION	CONSTITUENT FACIES																SUB-ENVIRONMENTS
		SS HAP	SS PL	SS RL	SS BB	SS MB	SS BC	HET HAP	HET PL	HET WP	HET BB	HET MB	HET GL	MD RL	MD LM	MD BB	MD MB	
FA1	Wave-Dominated, Fluvially-Influenced Embayment Delta	Minor	Major	Minor	Absent	Minor	Absent	Absent	Major	Absent	Absent	Minor	Absent	Absent	Absent	Absent	Absent	Proximal to distal delta front
FA2	Fluvially-Dominated, Tidally-Influenced Distributary Channel	Major	Minor	Minor	Absent	Absent	Minor	Major	Absent	Minor	Absent	Absent	Absent	Absent	Absent	Absent	Absent	Distributary channel
FA3	Fluvial- and Tidally-Influenced Delta	Major	Minor	Minor	Absent	Absent	Minor	Minor	Minor	Major	Major	Absent	Absent	Minor	Minor	Minor	Absent	Proximal to distal delta front, prodelta, ?tidal flat
FA4	Marine-Embayment Shoreface to Offshore	Absent	Minor	Minor	Absent	Major	Absent	Absent	Absent	Absent	Absent	Major	Minor	Absent	Absent	Absent	Major	Middle-lower shoreface, offshore
FA5	Mixed-Energy Estuary	Absent	Minor	Minor	Major	Absent	Major	Absent	Absent	Minor	Minor	Absent	Absent	Absent	Minor	Minor	Absent	Bayhead delta, tidal creek, tidal flat, lagoon

MAJOR CONSTITUENT — MINOR CONSTITUENT — ABSENT

Table 2. Summary of Facies Associations, relative abundance of constituent facies and sub-environments within each FA.

sediments appear to cut wave-dominated facies of FA1 and the Gething Formation. The surface demarcating this regression appears erosive, and is often characterized by a coarse granule-pebble lag. The exact nature of this contact is uncertain, but may represent a regressive surface of marine erosion (RSME). FA4, and the upper stratigraphic expression of FA1 are interpreted to represent a transgressive phase, placing open-marine embayment shoreface (FA4) and open-marine deltaic (FA1) above previously deposited facies. Transgression is inferred through the juxtaposition of marine-indicative ichnological assemblages (robust *Asterosoma,* with *Rosselia, Rhizocorallium, Scolicia, Zoophycos*) directly above highly-stressed, diminutive, low-diversity assemblages in FA2 and FA3, with the contact representing a marine flooding surface. Prior to complete transgression and deposition of the Wilrich Member shale, a second regressive event resulting in the incision and subsequent deposition of FA5 is observed (Figure 2, wells 03-06, 10-23 and 16-25). This is evidenced by the sharp change in ichnological character from fully-marine (upper FA1, FA4) to brackish (FA5), and the contrast in depositional processes from wave- and storm-dominated in FA4 and upper FA1 to sheltered, mixed process, lower energy conditions in FA5.

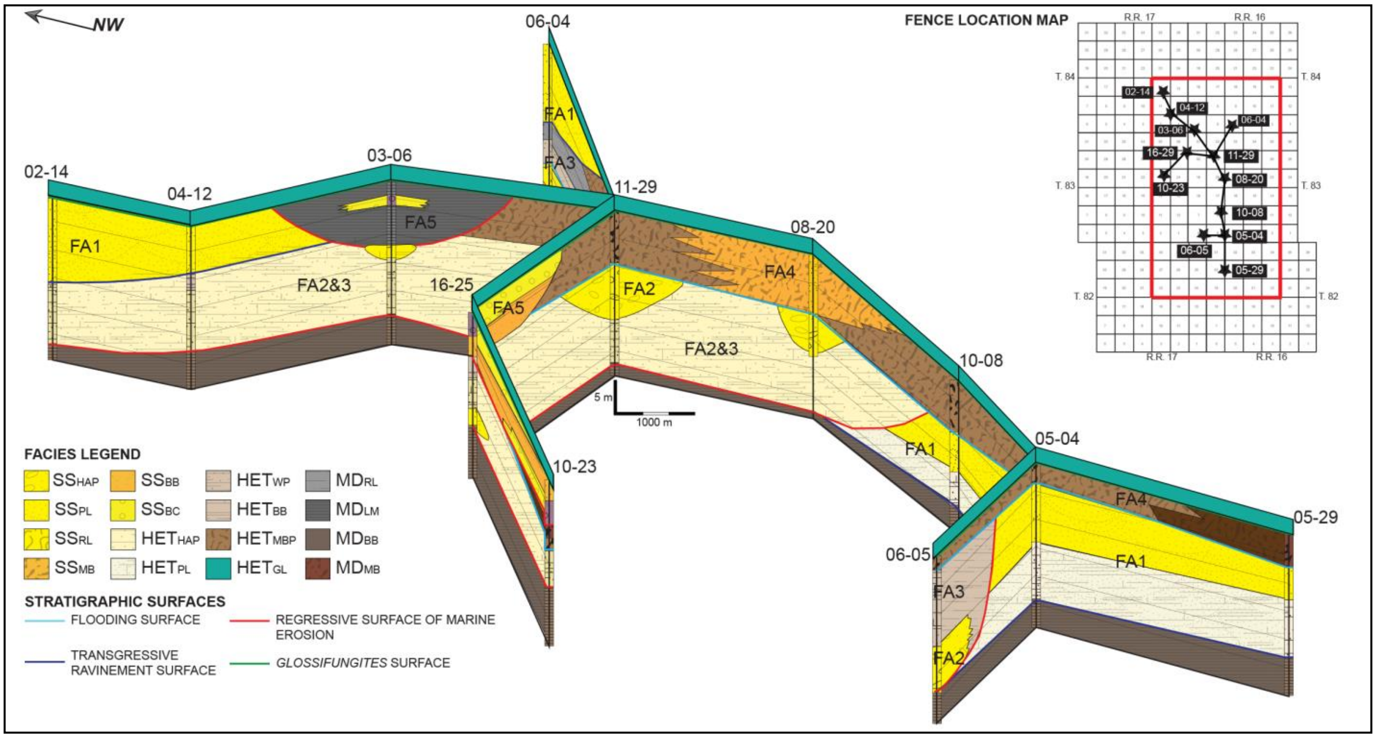

Figure 2. Stratigraphic architecture and relationship of facies associations within the project area.

Conclusions

Bluesky sedimentation within the project area is characterized by a complex vertical and lateral architecture, and diversity of facies suggesting periodic regressive events within an overall transgressive system. The depositional affinity ranges from fully-marine, wave- and storm-dominated deltaic and embayment to highly-stressed, fluvially-dominated channel, deltaic and estuary environments. The combination of sedimentology and ichnology was essential in the identification of this variability, and resulted in the recognition of previously undocumented wave-dominated marine conditions within the confines of the project area.

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