

**Sedimentological and Ichnological Characterization  
of Small- and Large-Scale Channel IHS in the  
Middle McMurray Formation of the Central-C area,  
McMurray Sub-Basin, Alberta**

by  
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characterization of Small- versus Large-Scale  
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## **Abstract**

The Lower Cretaceous McMurray Formation is interpreted as a brackish-water, tidally influenced estuarine complex. The study area encompasses Townships 90-95, Ranges 10-14W4 in northeast Alberta. Facies analysis of 41 cored wells led to the identification and differentiation of large- and small-scale lateral accretion IHS associated with tidal-fluvial channels. Five sedimentary facies are assembled into four recurring facies associations to characterize these channel systems. Sedimentological and ichnological characteristics point to elevated physico-chemical stress in most large-scale channel successions, interpreted to be the consequence of carrying the bulk of the fluvial discharge through these trunk channel systems. By contrast, small-scale channels display less evidence of physico-chemical stress indicating they carried little fluvial flow. Abandoned channel deposits likewise show reduced paleoenvironmental stress. This study suggests that the deposits of small-scale channels and abandoned channels are the most suitable for assessing the degree of marine influence in the study area.

**Keywords:** Sedimentology; Ichnology; Large-scale Channels; Small-scale Channels; Marine Influence; Tidal-fluvial.

## **Dedication**

To my beloved son who means the world to me and to my dear wife that helped me and supported me in every moment of this stage of our lives.

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I would like to thank God for providing me this great opportunity to grow in many aspects of my life and to my family for all their encouragement and positive vibes.

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# **Chapter 1. Generalities**

## **1.1. Introduction**

The Canadian Oil Sands are contained within three main deposits: Cold Lake, Peace River and Athabasca, covering a total area of more than 140,000 km<sup>2</sup> (Hein, 2008). The McMurray Formation represents the most important deposit of bitumen-bearing strata within the Athabasca Oil Sands, and it is one of the largest bitumen reservoirs in the world. In central Alberta, the McMurray Fm directly overlies the Sub-Cretaceous Unconformity (SCU), which was created by long-term exposure and erosion of Paleozoic strata (Flach and Mossop, 1985; Ranger and Pemberton, 1997). McMurray Fm deposition occurred during a period of relative sea level rise, which progressively changed the characteristics of sedimentation from predominantly fluvial to marginal marine and marine (Carrigy, 1971). Overlying the McMurray Formation are the marine sand and shales of the Clearwater Formation, which accumulated during transgression of the Boreal Sea (Carrigy, 1967).

The bulk of the bitumen contained in the McMurray Formation is found in channel (large and small scale) and their point bar deposits (e.g., Brooks et al., 1988; Creaney and Allan, 1992; Ranger and Pemberton, 1997; Adams et al., 2013; Tozer et al., 2014, Findlay, 2014). It is crucial to conduct in-depth research of channel systems in order to more accurately predict the geometry of these subsurface bodies, as well as the distribution of high-quality bitumen deposits. Such data provides more accurate predictions of optimal drilling locations for exploration and development.

## **1.2. Data Base and Methods**

The study area is located within east-central Alberta from Township 95, Range 14W4 to Township 90, Range 10W4. The study area encompasses 30 townships (2797 km<sup>2</sup>), and is located in the central part of the research area of the McMurray Geology Consortium referred to as the Central-C area (Fig. 1.1).

The area is well drilled and 872 wells with LAS files were used in this study. As well, cores from 41 wells (located at the Alberta Energy Regulator's Core Research,

Calgary, Alberta) (Fig. 1.2) were logged at a centimetre scale in order to identify and describe the trace fossil suites, bioturbation intensities, and physical sedimentology of both small-scale and large-scale channel deposits.

Well selection was done following the thickness and sand trends in the area with the aim of assessing the degree of marine influence in the main (large-scale) channels. The cores selected intersect the base and the top of the Middle McMurray Fm. in the Central-C area. These observations are compared with those obtained from secondary, smaller-scale channels. The goal of this thesis is to evaluate the degree of marine influence operating in the study area by evaluating these two scales of channel deposit. In order to differentiate large-scale channels from small-scale channels, it is important to consider characteristics such as: thickness of the cross-bedded sands, cross-bed thickness, grain size, thickness of the inclined heterolithic stratification (IHS), diversity of trace fossils, and intensity of bioturbation. Also, in order to identify important characteristics within large-scale vs. small-scale channels and to discern the main differences and similarities between these channel types, core data, well logs and software (Geoscout and Accumap) data are used to analyze and discern these characteristics. These data are intended to assist future detailed studies planned in the Central-C area. With these data, it also will be possible to create a facies model in the future to visualize the distribution of sediments in the area. Thickness and Net Sand maps were created by correlating 913 wells (872 wells with LAS files and 41 wells with core interpretation) (Table 1.1) using the core wells as the main input to identify the top and the base of the Middle McMurray Fm.

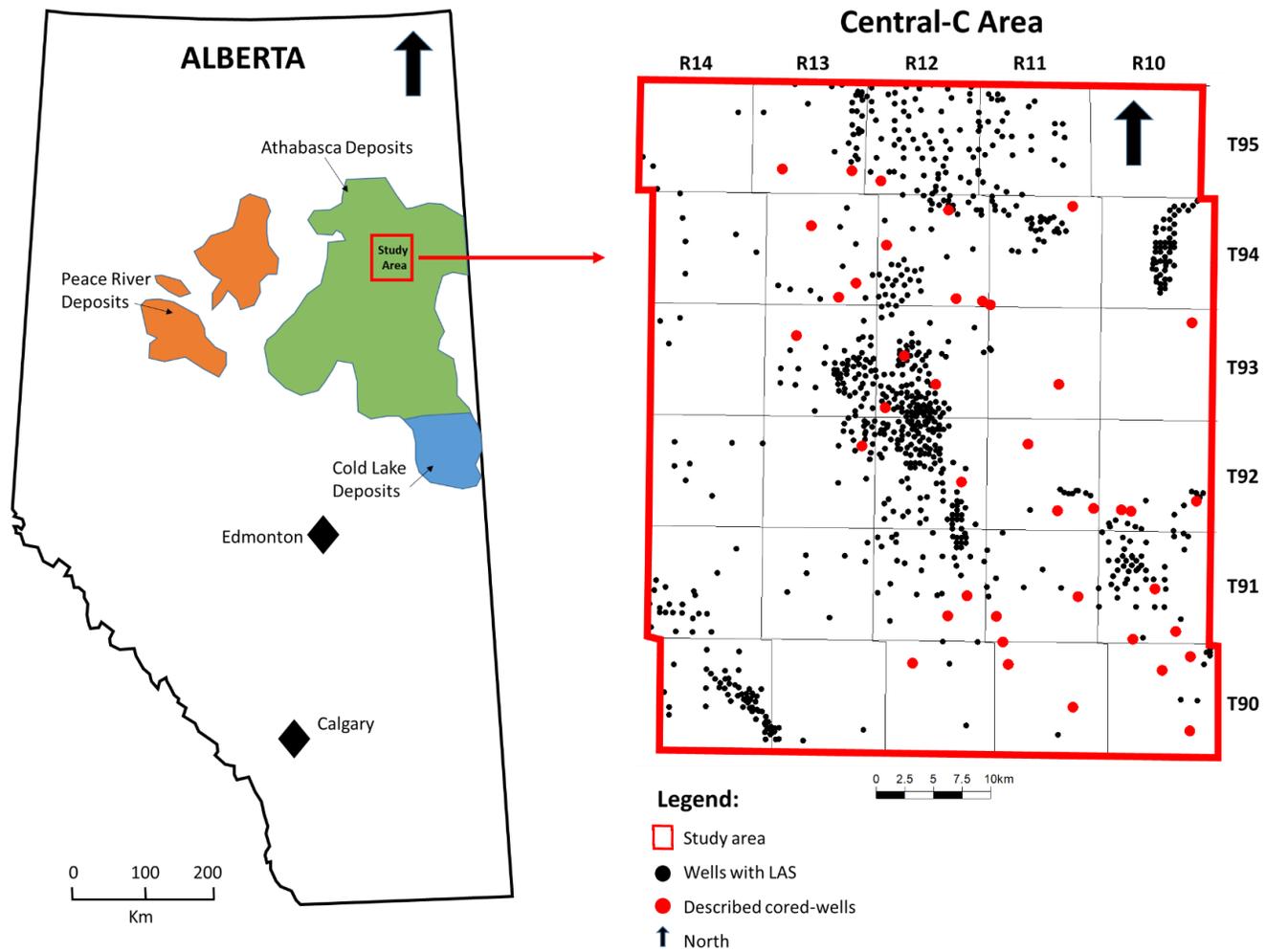


Figure 1.1 Map of Alberta on the left, showing the Canadian Oil Sands producing areas (modified from Alberta Geological Survey, 2013). Study area map in the Athabasca Oil Sands Region on the right, showing the wells used in this research.

Table 1.1 List of logged cores intersecting the McMurray Formation.

CORE	COMPANY	INTERVAL
06-11-090-10W4	IMPERIAL OIL	56.39-113.34m
06-35-090-10W4	IMPERIAL OIL	46.02-1047.59m
09-28-090-10W4	IMPERIAL OIL	39.93-102.72m
12-14-090-11W4	SUNCOR	120.7-167.5m
15-30-090-11W4	SUNCOR	171.80-218.50m
14-29-090-12W4	SUNCOR	68m
16-16-091-10W4	CHEVRON	35-102.1m
08-05-091-10W4	SUNCOR	99.7m
12-02-091-10W4	SUNCOR	83.2m
07-07-091-11W4	SUNCOR	144.40-194.80m
09-14-091-11W4	SUNCOR	85.80-122.20m
01-06-091-11W4	SUNCOR	69.6m
08-10-091-12W4	SUNCOR	158.30-213.55m
09-14-091-12W4	SUNCOR	72.7m
12-12-092-10W4	SUNCOR	45.15-94.40m
02-08-092-10W4	SUNCOR	77.1m
01-10-092-11W4	SUNCOR	46.20-86.7m
07-12-092-11W4	SUNCOR	28.96-73.96m
12-28-092-11W4	SYNCRUDE	45-84.80m
04-08-092-12W4	SYNCRUDE	13.60-76.60m
10-14-092-12W4	SUNCOR	75.20-123.4m
11-25-092-13W4	DEVON	57.4m
08-35-093-10W4	SYNCRUDE	6.68-52m
16-10-093-11W4	SYNCRUDE	44-90.90m
06-20-093-12W4	SUNCOR	86.5-129.95m
11-06-093-12W4	DEVON	127.25-165.60m
06-24-093-12W4	SYNCRUDE	86.6m
13-10-093-12W4	SUNCOR	72.3m
07-29-093-13W4	DEVON	65-102.90m
04-06-094-11W4	SYNCRUDE	52.3-109.3m
11-35-094-11W4	TOTAL	14.5-48.90m
05-02-094-12W4	SYNCRUDE	50.40-102.60m
07-01-094-12W4	SYNCRUDE	44.80-109.95m
07-34-094-12W4	TOTAL	49.80-97m
06-19-094-12W4	DEVON	53.1m
06-28-094-13W4	IMPERIAL OIL	100.60-132m
08-03-094-13W4	DEVON	56.50-102.50m
08-11-094-13W4	DEVON	50.20-94.20m
05-12-095-12W4	TOTAL	69.45-119.10m
16-06-095-12W4	TOTAL	60-106.70m
07-08-095-13W4	BP	87.9m

### **1.3. General Geology and Stratigraphic Overview**

The McMurray Formation is a succession of largely unconsolidated sands and mudstones, and represents the lowermost formation of the Mannville Group in the Western Canada Sedimentary Basin (WCSB) of Alberta (Fig. 1.3) (Keith et al., 1988). There are two main tectono-stratigraphic events that controlled the distribution of sediments in the Alberta Basin: a passive continental margin that endured from the Proterozoic to middle Jurassic, and sediment deposition into a developing foreland basin from the Middle Jurassic to Early Neogene. The Alberta Basin represents the foreland basin of the Canadian Rockies and is constrained between the Rocky Mountains (West) and the Canadian Shield (East). The first stage of foreland basin creation was during the Early Jurassic to Early Cretaceous (Columbian Orogeny) with the accretion of allochthonous terranes, which persisted until the Late Cretaceous to Paleocene during the Laramide Orogeny. Basin infill was derived mostly from Middle Jurassic and Cretaceous siliciclastics shed from the rising Cordillera (Leckie, 1986; Cant, 1988; Pana et al., 2001). Many authors, however, have documented that minor amounts of sediment also came from the eastern craton (Leckie and Smith, 1992, Morshedian, 2012). In an east-west section, the basin was asymmetric, such that sedimentation rates were more significant adjacent to the Cordillera, causing a distinctive eastward-thinning clastic wedge (Leckie and Smith, 1992).

The stratigraphy of the McMurray Formation is considered to be one of the most complex systems in the Canadian Basin (Ranger and Pemberton, 1997). Numerous authors have documented the lithostratigraphy of the McMurray Formation in Alberta (e.g., Carrigy, 1959; Flach, 1977; Mossop and Flach, 1983; Strobl et al., 1997; Wightman and Pemberton, 1997; Ranger and Pemberton, 1997; Hein and Cotterill, 2006; Labreque, 2011; etc.). It is recognized that the McMurray Formation rests unconformably over Paleozoic (Middle to Upper Devonian) carbonates (Nelson and Glaister, 1978; Flach and Mossop, 1985; Wightman and Pemberton, 1997; Hein and Cotterill, 2006) and this surface is referred to as the Sub-Cretaceous Unconformity (SCU). Paleotopographic relief on the SCU was probably caused by karstification of underlying carbonates as well as dissolution of salt in the Prairie Evaporite Formation. SCU relief represents a dominant control on the sedimentary environments and deposition of facies during the early part of McMurray Formation (Flach and Mossop,

1985; Wightman and Pemberton, 1997; Hein and Cotterill, 2006; Broughton, 2013). In the Early Cretaceous, the system is widely considered to have been fluvial to brackish-water (estuarine), and it is thought that this fluvio-estuarine system caused partial dissolution of the Paleozoic carbonates and evaporites during McMurray deposition. Correspondingly, syndepositional development of accommodation space is believed to have also served as an important control in the development of the McMurray Sub-Basin (e.g., Flach and Mossop, 1985; Wightman and Pemberton, 1997; Hein and Cotterill, 2000; Broughton, 2013) (Fig 3). At the end, the McMurray Fm was overlain by the Wabiskaw Member of the Albian Clearwater Fm, representing widespread sea level rise inundated the region from the north, resulting in the deposition of marine sands and shale of the Clearwater Fm on top of the of the McMurray Fm (Carrigy, 1967; Wightman et al., 1989, 1995; Wightman and Pemberton, 1993, 1997; Labreque, 2011; Broughton, 2013).

The Lower Cretaceous McMurray Formation is generally subdivided into three units – Lower McMurray, Middle McMurray and Upper McMurray (Carrigy, 1959). The Lower McMurray is interpreted as fluvially dominated unit (Carrigy, 1973; Flach, 1977; Steward and MacCallum, 1978; Falch and Mossop, 1985; Labreque, 2011; etc.), and is preserved only in the deepest valleys on the SCU surface (Flach and Mossop, 1985). The Middle McMurray is commonly interpreted as a brackish-water, tidally influenced estuarine complex, characterized by inclined heterolithic stratification (IHS), typical of point bar related deposits (Pemberton et al., 1982; Mossop and Flach, 1985; Thomas et al., 1987; Wightman and Pemberton, 1997; Smith, 2009; Labreque, 2011). Finally, the Upper McMurray reflects more marine influenced deposits (Carrigy, 1959; Mossop and Flach, 1983; Flach and Mossop, 1985; Ranger and Pemberton, 1997).

Several authors have undertaken studies in the McMurray Formation, and a vast amount of them have focused their research in the Middle McMurray unit. The principal reason is because the main reservoir facies are hosted by the channel and sandy IHS related deposits within the Middle McMurray. One of the first studies evaluating the stratigraphy and lithology of the McMurray Fm was carried by Carrigy (1959) who interpreted the succession as deltaic environment. Steward and MacCallum (1978), however, proposed an estuarine environment with significant tidal influence. Important ichnological analysis was first performed by Pemberton et al. (1982), who provided the first detailed description of ichnological features within the Middle McMurray, identifying

a brackish-water (estuarine) trace fossil suite. This lent greater credence to the Steward and MacCallum (1978) interpretation. Additional research followed Pemberton's ichnological assessment, and showed a consistent record of impoverished bioturbation in a brackish-water, tidally influenced system (e.g., Flach and Mossop, 1985; Ranger and Pemberton, 1992; MacEachern and Gingras, 2007; cf. Gingras et al., 2016 for a review.). Thomas et al. (1987) introduced a new concept of Inclined Heterolithic Stratification (IHS), defining low-angle dipping heterolithic bedsets made up of sands and muds, were interpreted as the lateral accretion point bars of the channel systems. This model is widely accepted and constitutes a main focus within this research.

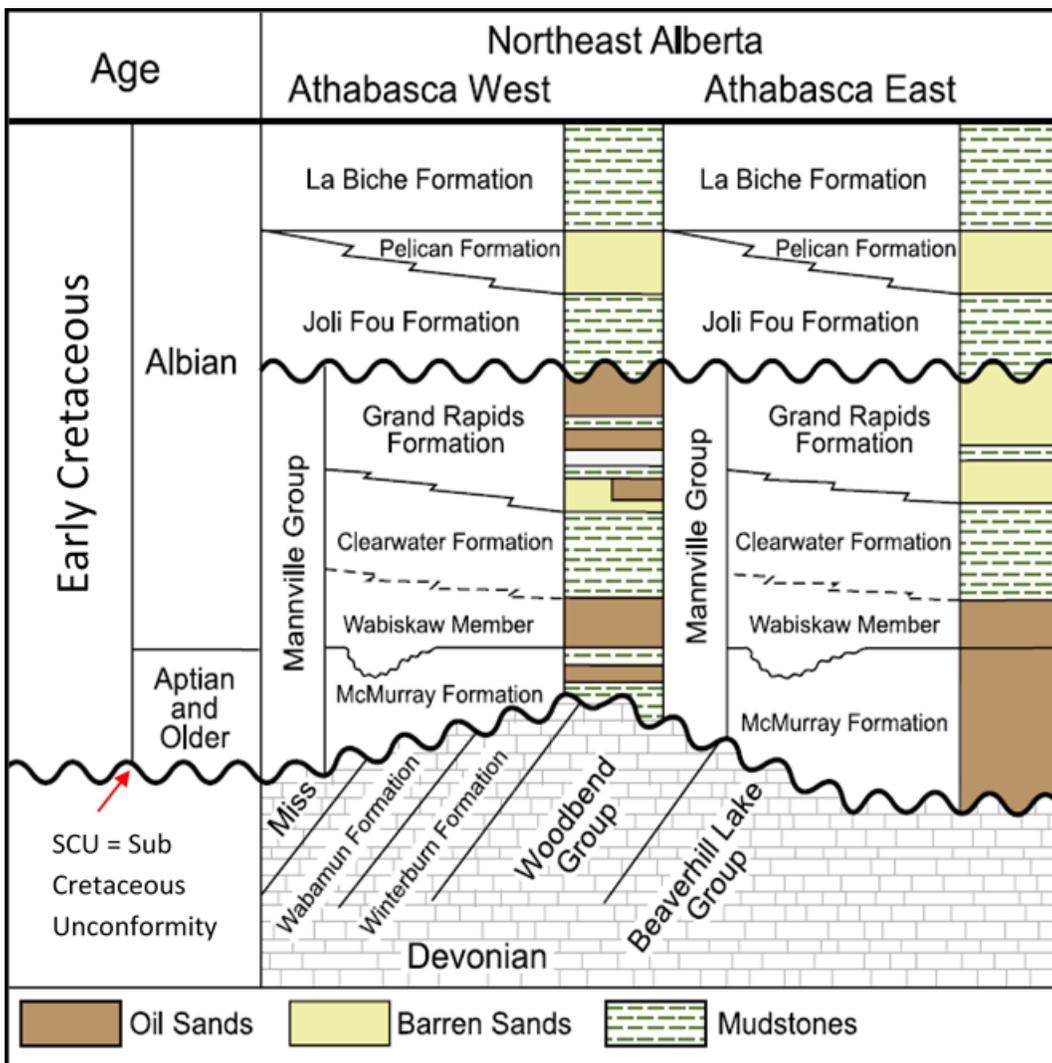


Figure 1.2 Stratigraphic chart of Lower Cretaceous strata in northeast Alberta (modified from Hein et al., 2013).

## 1.4. Research Objectives

The purpose of this research is to provide an integrated sedimentological and ichnological characterization of the Middle McMurray Formation in the Central-C area (Fig. 1.1). This study focuses on facies characterization of successions recording the different scales of channels. Detailed sedimentology and ichnology will be employed to discern subtle differences between these channel types. The thesis seeks to address two pivotal questions. 1) Is it appropriate to use the deposits of large-scale, trunk channel systems as the basis for assessing the degree of marine influence of a coastal margin area, given that they likely carry the bulk of the river discharge? 2) Do smaller-scale channel deposits and off-channel deposits show greater degrees of marine influence than do the large-scale channel systems, and if so, are these a better proxy for assessing a setting's proximity to the paleocoast?

These questions are investigated by defining facies and facies associations within 41 cored wells that were logged within the study area. Ichnological characterization focused on BI (bioturbation index) values and their distributions, trace fossil diversities, and paleoecological assessments of the trace fossil suites. Sedimentological characterization focused on the lithologies, textures, primary and syndepositional sedimentary structures, and bed / bedset thicknesses and their variations. Additionally, mapping of the distribution of the facies association thicknesses and net-sand trends in the area were undertaken to facilitate visualization of the channel complexes.

The integration of the trace fossil suites and sedimentary structures allow an approach for assessing the degree of salinity-induced physico-chemical stresses that operated in the area. The goal then is to evaluate the apparent degree of marine influence that operated in the study area by comparing what is expressed in the large-scale trunk channel systems with that of the small-scale channel complexes. This will serve to assist additional future studies planned in the Central-C area.

## **Chapter 2. Facies Descriptions and Interpretations**

A detailed facies analysis of 41 cored intervals, totaling 2223 m in thickness was undertaken, focusing on their sedimentological and ichnological attributes. Specifically, the sedimentary characteristics focused on lithology, grain size, color, lithological accessories, and primary sedimentary structures. The ichnological descriptions include bioturbation intensity (using the Bioturbation Index or BI), ichnogenera identification, characterization of trace fossil diversity, and burrow distributions. Through this detailed analysis, twelve distinct and recurring facies are identified within the McMurray Formation of the study area (Table 2.1). The aforementioned data have been integrated with geophysical well log signatures in order to discern facies associations and interpret sedimentary environments in locations without core.

Bioturbation intensities are identified using the Bioturbation Index (BI), originally proposed as grades of bioturbation by Reineck (1963) and later modified by Taylor and Goldring (1993). This index helps to assess the intensity of bioturbation within a rock interval using a scale from 0 to 6, wherein BI 0 value represents no visible bioturbation and BI 6 represents a completely (100%) bioturbated interval (Fig. 2.1).

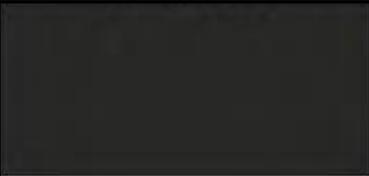
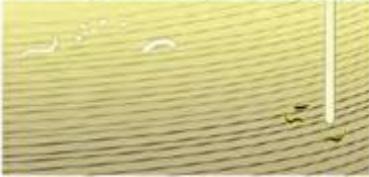
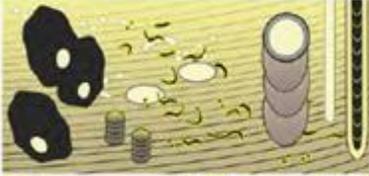
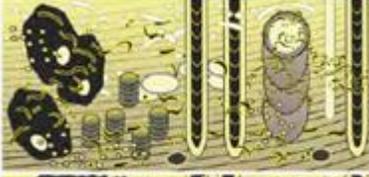
BI	Mudstone Facies	Sandstone Facies	Characteristics
0			No bioturbation
1			Sporadic bioturbation, bedding distinct, few discrete facies
2			Low bioturbation, bedding distinct, low trace density
3			Moderate bioturbation, bedding boundaries sharp, traces discrete, overlap rare
4			Common bioturbation, boundaries indistinct, high trace density with common overlap
5			Abundant bioturbation, bedding completely disturbed
6			Complete bioturbation Total biogenic homogenization of sediments

Figure 2.1 Bioturbation Index (BI). These indices represent grades of bioturbation expressed as relative distribution of original primary sedimentary fabric overprinted by biogenic structures. Modified after Bann et al. 2004 and MacEachern and Bann (2008).

Table 2.1 Facies described within the McMurray Formation in the Central-C area.

FACIES	TEXTURE	THICKNESS	SEDIMENTOLOGY	TRACE FOSSILS	BI	ENVIRONMENT/ PROCESSES
F1	Silt/clay to fine-grained sand	<2m	Sporadically distributed, very fine-grained sand, intercalated silt laminae, organic mud, pyrite, siderite, isolated roots.	Not observed	0	Continental or coastal swamp
F2	Silt/clay	<4.5m	Light gray to white mud, with soft, chalk-like texture, fractured. Roots and coal fragments. Spherules and nodules of pyrite and siderite.	Not observed	0	Pedogenically modified mud
F3	Medium- to fine-grained sand.	Decimetres to metres	High-angle, small- to medium-scale cross-stratification, inclined lamination, current ripples, and thin mud draped bundles. Mud clasts and mudstone layers are sporadically distributed. Coal laminae.	<i>Cylindrichnus</i> , <i>Palaeophycus</i> and <i>Planolites</i> .	0-2	Tidal-fluvial channel deposits
F4	Chaotically distributed mud clasts within a fine-grained sand matrix.	<6.5m	Sedimentary structures difficult to identify due to bitumen staining. Randomly oriented, angular rip-up clasts of mudstone.	Not observed	0-1	Channel and channel margin deposits
F5A	Fine- to medium grained sand interbedded with mud.	< 1.5m	Sand: current ripples, soft-sediment deformation, mud flasers and some mud laminae. Mud: current ripples, undulatory parallel laminae, planar parallel lamination, and rare normal grading.	Sand: <i>Cylindrichnus</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Thalassinoides</i> and <i>Fugichnia</i> . Mud: <i>Planolites</i>	Sand: 1-4 Mud:0-2	Counter point bar/ channel-related deposits of tidal-fluvial channels

FACIES	TEXTURE	THICKNESS	SEDIMENTOLOGY	TRACE FOSSILS	BI	ENVIRONMENT/ PROCESSES
F5B	Fine- to medium-grained sand interbedded with mud.	< 4.5m	Sand: current ripples, combined flow ripples, and small-scale planar parallel lamination, rare wavy parallel lamination. Carbonaceous detritus, siderite nodules and siderite cement locally present. Mud: planar parallel lamination, irregular parallel lamination, soft-sediment deformation, lenticular bedding, intercalated parallel laminae of silt, and syneresis cracks.	Sand: <i>Cylindrichnus</i> , <i>Gyrolithes</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Thalassinoides</i> and <i>Fugichnia</i> . Mud: diminutive <i>Planolites</i> with rare <i>Gyrolithes</i> and diminutive <i>Skolithos</i>	Sand: 1-3 Mud: 0-2	Counter point bar/ channel-related deposits of tidal-fluvial channels
F6A	Fine- to medium-grained sand interbedded with mud.	Decimetres to metres	Sand: high- to low-angle cross-stratification, current ripple cross-lamination, and planar parallel lamination. Mud couplets and organic matter as lamina-scale drapes marking stratification. Mud: Mud beds display parallel laminae of carbonaceous debris with normal grading.	Rare <i>Cylindrichnus</i> , <i>Planolites</i> and <i>Skolithos</i> in both sand and muds.	0-1	Point bar/ channel-related deposits of tidal-fluvial channels
F6B	Fine- to medium-grained sand interbedded with mud.	Decimetres to metres	Sand: high- to low-angle cross-stratification, planar parallel lamination and rare current ripple cross-laminae in sand beds. Parallel laminae and current ripples dominate. Mud: horizontal and inclined parallel laminae of carbonaceous detritus. Normal grading common.	<i>Cylindrichnus</i> and <i>Planolites</i> in both muds and sands	0-1	Point bar/ channel-related deposits of tidal-fluvial channels

FACIES	TEXTURE	THICKNESS	SEDIMENTOLOGY	TRACE FOSSILS	BI	ENVIRONMENT/ PROCESSES
F7A	Fine- to medium-grained, silty sand interbedded with mud.	Decimetres to metres	Sand: small-scale, planar tabular and trough cross-stratification, current ripple cross-lamination, oscillation ripple, horizontal planar parallel and low-angle planar stratification, locally with mud flasers. Mud: layers contain thin internal current ripple cross laminae and parallel laminae of silt and sand.	<i>Sand: Cylindrichnus</i> , diminutive <i>Palaeophycus</i> , <i>Conichnus</i> , sporadically distributed <i>Gyrolithes</i> , <i>Skolithos</i> , <i>Spirasensus</i> , <i>Thalassinoides</i> and <i>Teichichnus</i> . <i>Mud: Planolites</i> , <i>Teichichnus</i> , <i>Skolithos</i> and <i>Gyrolithes</i> .	Sand: 1-3 Mud: 2-4	Point bar/ channel abandoned - related deposits of tidal-fluvial channels
F7B	Fine- to medium-grain, silty sand interbedded with mud.	Decimeters to meters	Sand: planar parallel lamination, current ripple cross-lamination and aggradational current ripple cross-lamination. Mud: commonly fractured, normally graded and with intercalated sand laminae. Locally, sand disseminated as individual grains within the mud rather than as laminae. Rare syneresis cracks.	<i>Sand: Cylindrichnus</i> , <i>Palaeophycus</i> , <i>Planolites</i> , <i>Gyrolithes</i> , and diminutive <i>Skolithos</i> , <i>Thalassinoides</i> and <i>Teichichnus</i> . <i>Mud: Planolites</i> , <i>Teichichnus</i> , and <i>Gyrolithes</i> .	Sand: 1-3 Mud: 2-5	Point bar/ channel abandoned - related deposits of tidal-fluvial channels
F8A	Sandy mud to mud.	Decimetres to metres	Sand: low-angle, undulatory parallel lamination, oscillation ripple lamination, and soft-sediment deformation. Mud: predominantly structureless, but locally contains internal parallel laminae of silt and very fine-grained sand, and very rare syneresis cracks.	<i>Asterosoma</i> , <i>Conichnus</i> , <i>Diplocraterion</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Taenidium</i> , <i>Teichichnus</i> and <i>Thalassinoides</i> .	1-5	Shoreface to delta

FACIES	TEXTURE	THICKNESS	SEDIMENTOLOGY	TRACE FOSSILS	BI	ENVIRONMENT/ PROCES
F8B	Mud-dominated heterolithic bedsets, intercalated with fine- to medium-grained sand beds.	Mud beds 5-10 cm thick. Sand beds 2-5cm thick	Sand: low-angle, undulatory parallel lamination, with rare combined flow and oscillation ripple lamination. Soft-sediment deformation is common. Mud: fractured with internal undulatory and parallel laminae of silt and sand. Rare oscillation ripple lamination.	<i>Asterosoma, Planolites, Skolithos, Taenidium, Teichichnus</i> and <i>Thalassinoides</i> .	2-5	Open embayment
F9	Dark coloured, fine- to medium-grained sand with rare, bluish/gray mud interbeds	up to 5m	Horizontal planar parallel lamination, wavy parallel lamination (micro-HCS), HCS, and oscillation ripple lamination.	<i>Palaeophycus, Planolites, Rosselia</i> and <i>Skolithos</i> .	0-2	Shoreface to delta
F10	Dark grey mud with intercalated lenses of very fine-grained sand	decimetresto metres	Lenticular bedding, soft-sediment deformation, wavy parallel lamination, and starved oscillation ripples within the sand. Syneresis cracks, micro-faults and siderite are present locally.	<i>Asterosoma, Planolites, Schaubcylindrichnus freyi, Thalassinoides</i> and <i>Zoophycos</i> .	1-3	Open embayment/bay margin
F11	Green, glauconitic, fine- to medium-grained sand to muddy sand.	metres	Parallel lamination in the mud and local remnants of wave ripple cross-lamination in the sand.	<i>Asterosoma, Chondrites, Diplocraterion, Ophiomorpha, Palaeophycus, Phycosiphon, Planolites, Rosselia, Skolithos, Teichichnus, Taenidium, Thalassinoides, and Zoophycos</i> .	2-5	Open marine conditions associated with transgression

FACIES	TEXTURE	THICKNESS	SEDIMENTOLOGY	TRACE FOSSILS	BI	ENVIRONMENT/ PROCES
F12	Very fine-grained sand lenses intercalated with mud.	metres	Sand: starved oscillation ripples or apparently structureless lenses within the muds. Mud: fractured with internal parallel laminae of silt and sand, locally showing normal grading.	<i>Asterosoma</i> , <i>Chondrites</i> , <i>Planolites</i> , <i>Phycosiphon</i> , very rare <i>Rosselia</i> , <i>Skolithos</i> , <i>Thalassinoides</i> and <i>Zoophycos</i> .	1-4	Overall lower energy, fully marine setting above fairweather wave base

## **2.1. FACIES 1 – Coal and carbonaceous mud.**

### *Description:*

Facies 1 is very uncommon in the study area, and is present only at the base of the succession where the informally named “Lower McMurray member” is preserved. The facies comprises deposits of black coal and organic-rich mud (Fig. 2.2A, B). Coal laminae (0.5cm) within the organic-rich mud is common. This facies is generally less than 2m thick. The contacts with the overlying and underlying facies are typically sharp. Sporadically distributed sand grains, intercalated silt laminae, presence of organic mud, pyrite, siderite, and carbonaceous detritus, as well as isolated roots are present locally. The coal is predominantly dull, although bands of bright, vitrinic coal macerals are also present. The coal is bedded, cleated, and fractured. Micro-faults are also observed. No trace fossils are present.

### *Interpretation:*

The presence of coal layers and carbonaceous mud suggest the presence of vegetation in a low-energy environment under reducing conditions at the time of deposition. The accumulation and preservation of coal and carbonaceous mud is interpreted to reflect continental or coastal swamp environments.



Figure 2.2 Facies 1: A) Coal bed. B) Carbonaceous mud with coal laminae and coal fragments.

## **2.2. FACIES 2 – Light grey / white mud with coal laminae**

### *Description:*

Facies 2 is present in only a few cores within the study area, where the lowermost deposits of the McMurray Formation are preserved. The thickness of the facies is generally less than 2.5m. The contacts with the overlying and underlying facies are typically sharp. The mud is light grey to white in colour, and possesses a soft, chalk-like texture, commonly fractured to form small, irregular blocks (Fig. 2.3A, B). Root traces and coal fragments are present locally. Spherules and nodules of pyrite and siderite are also present. No trace fossils are recognized.

### *Interpretation:*

Facies 2 is interpreted to represent the subaerial exposure of various fine-grained sedimentary units in a terrestrial environment, either during base level fall or following extensive periods of progradational regression. This is indicated by the presence of sideritized intervals, roots, and disseminated carbonaceous detritus. According to Leckie et al. (1990) and Kraus (1999), grey colored soils, spherulitic siderite and preserved organic matter are common in very paleosols recording poorly drained conditions. The presence of preserved organic matter and roots capping the pedogenically modified mud, which are characteristic of reducing conditions, suggests that the associated coals (Facies 1) are autochthonous (Collinson, 1996). According to Kraus and Hasiotis (2006), this type of sedimentation can occur away from channel margins where sediments are less permeable.

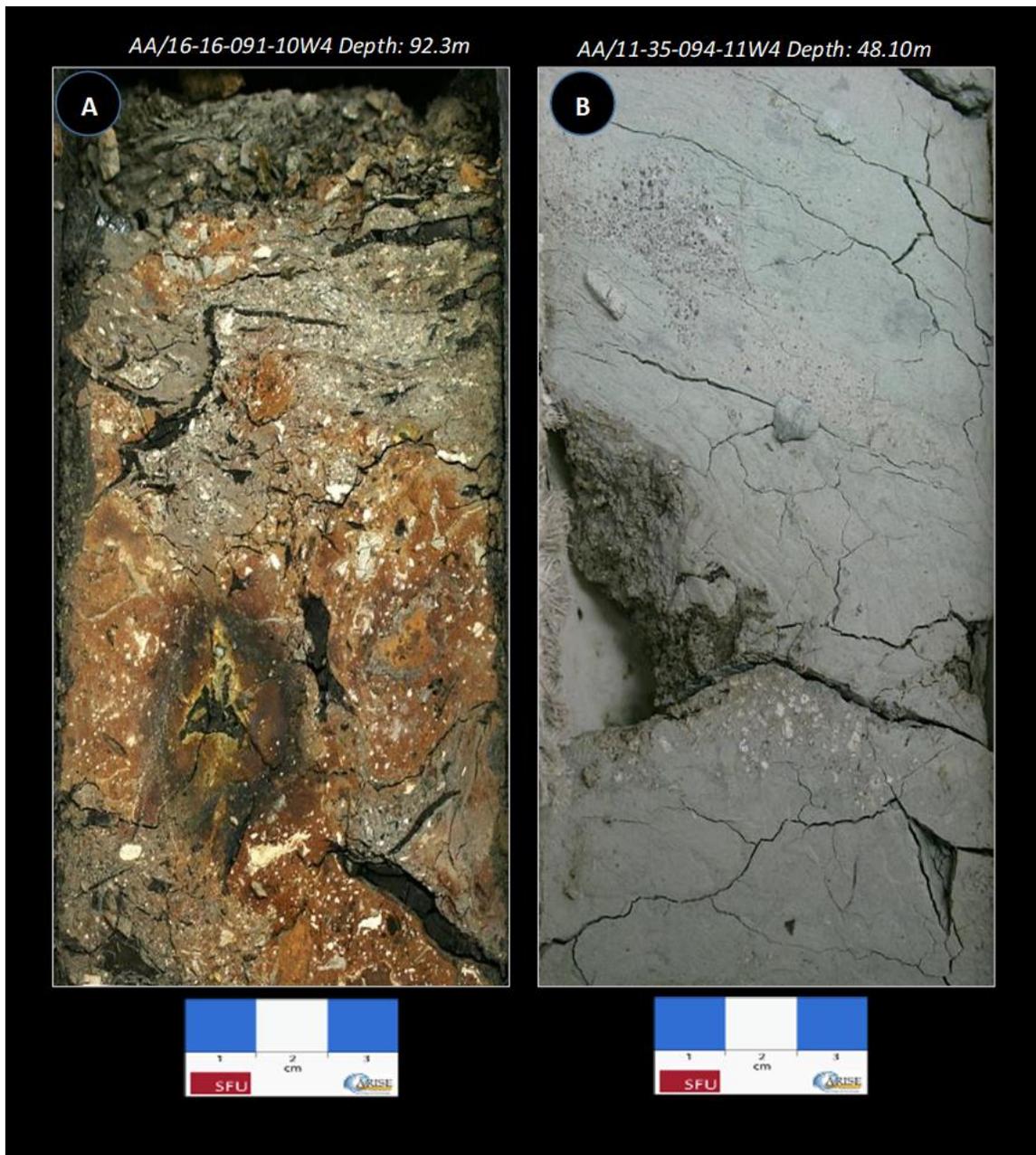


Figure 2.3 Facies 2: A): Pedogenically modified mud showing coal laminae, siderite, pyrite nodules and pedogenic mud. B) Pedogenic light gray/ white chalk-textured mud.

### **2.3. FACIES 3 – Medium- to fine-grained sand with low- to high-angle cross-stratification.**

#### *Description:*

Facies 3 comprises medium- to fine-grained sand with minor amounts of mud laminae (Fig. 2.4A, B: Fig. 2.5A, B). Coarse-grained sand and fine gravel can be found at the base of this facies, in erosive contact with Facies 1 and 2. Locally, the facies directly overlies the Sub-Cretaceous Unconformity (SCU), where it erosionally overlies Devonian-aged strata. Bitumen contents are highly variable, ranging from moderately bitumen stained (brown coloured) to bitumen saturated (black coloured). The facies ranges from decimetres to metres in thickness. Sporadically distributed mud beds and mud flasers are present. Due to bitumen staining, sedimentary structures are difficult to discern. Where primary structures are visible, they consist of high-angle, small- to medium-scale cross-stratification, and inclined lamination, forming cross-stratified beds of small scale (< 25cm thick) through to large scale (> 25cm thick) (Fig. 2.4A, B). Current ripples, and thin bundles of mud drapes are also present, but are rare. Mud clasts and thin intervals (up to 2cm in thickness) of light gray mud layers are sporadically distributed in the facies. Carbonaceous detritus concentrated into laminae are spatially limited, but occur in moderate abundances locally. Muds typically are caught up on the foresets, or in the troughs between ripples. Locally, they drape over ripples but they do not form continuous beds. Bioturbation intensities are low or absent (BI 0-2), with ichnogenera consisting of sporadically distributed *Cylindrichnus*, *Diplocraterion*, *Palaeophycus* and *Skolithos*. *Planolites* occurs locally within the mud layers. *Cylindrichnus* constitutes the dominant ichnogenus (Fig. 2.5B).

#### *Interpretation:*

The presence of high-angle (likely planar tabular) cross-stratification indicates deposition in a subaqueous environment subject to current transport in the upper part of lower flow regime. These bedforms represent subaqueous dunes, given the thickness of the individual beds, although rare zones of current ripple lamination are intercalated. The rare, thin mud intervals indicate that relatively small quantities of clay and silt were delivered and allowed to be deposited. The origin of the mud is unknown, but could possibly be the result of fluid mud deposition following higher energy events (e.g., river

floods), or from flocculation due to mixing within the turbidity maximum zone. The bundling of the mud drapes is a strong indicator of tidal processes (Fig. 2.4; *cf.* Smith, 1988; Wightman and Pemberton, 1997, Choi, 2004, Labrecque, 2011). The presence of carbonaceous detritus and coal laminae indicate transportation of allochthonous plant material into the system. Correspondingly, deposition is considered to have been affected, to some degree, by fluvial processes. The diversity of trace fossils is low, suggesting a very stressful but brackish-water environment, which was not favorable for infaunal colonization (*cf.* Beynon et al., 1988; see MacEachern and Gingras, 2007 for a summary). The low bioturbation intensities may also suggest that energy conditions and/or depositional rates were high, which helped to subdue substrate colonization and bioturbation.

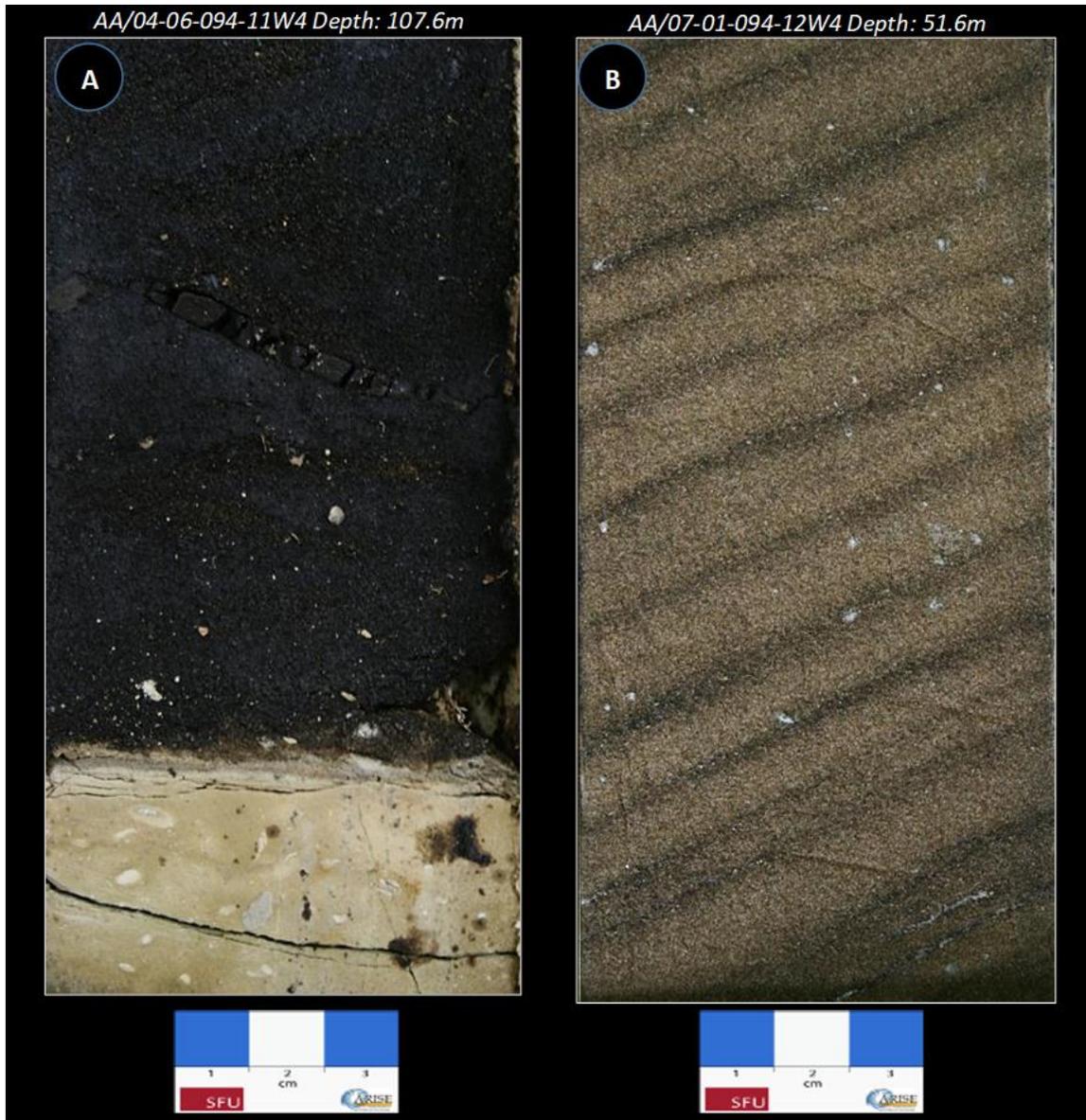


Figure 2.4 Facies 3: A) Unconformable contact between the underlying Devonian carbonates and oil-saturated Facies 3 of the Lower Cretaceous McMurray Formation, Note the coal laminae (5mm thick). B) Facies 3 showing cross-bed foresets.

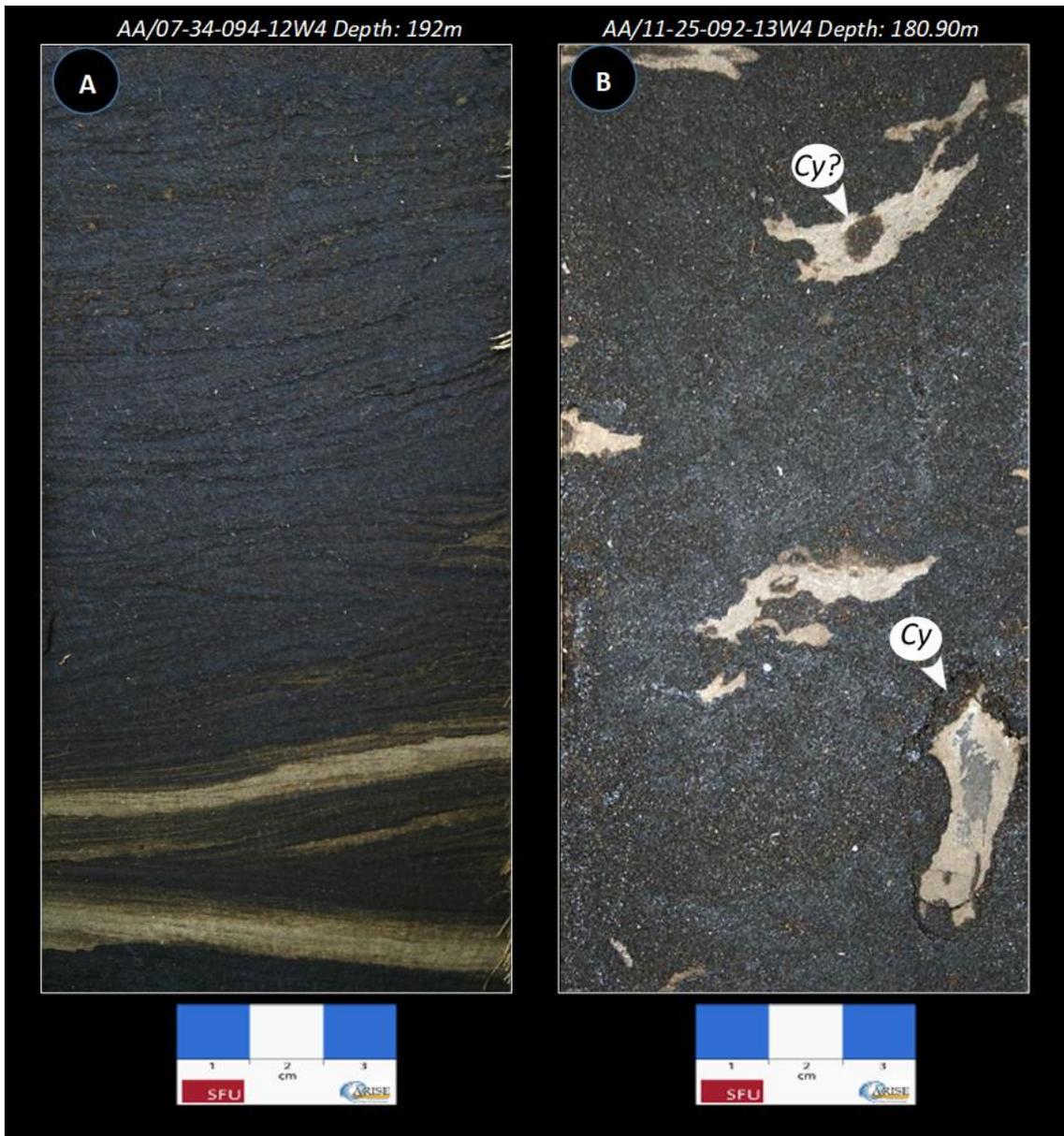


Figure 2.5 Facies 3: A) Oil-stained Facies 3, with current ripples and flasers of mud. B) Facies 3 showing *Cylindrichnus* (Cy).

## 2.4. FACIES 4 – Angular to subangular mud-clast breccia with sand matrix.

### *Description:*

Facies 4 is characterized by the presence of chaotic sedimentation, represented by fine- to medium-grained sand with rip-up clasts of mud (Fig. 2.6A, B). The upper and lower contacts are predominantly gradational, but can be sharp locally. Sedimentary structures, where present, are difficult to identify in the sand owing to bitumen staining. In the mud, parallel lamination can be observed rarely, as well as sideritized intervals. The rip-up clasts are commonly angular, vary in size, and are randomly oriented. The BI varies from 0 to 1 in the sand. The trace fossils comprise sporadically distributed *Cylindrichnus* and *Palaeophycus*. The mud clasts also possess burrows, but as they are allochthonous fragments, their ichnogenera do not constitute part of this suite.

### *Interpretation:*

The presence of chaotically distributed mud clasts within a sand matrix suggests that the environment of deposition for the facies was of high energy and erosional. The association of Facies 4 with Facies 3 (discussed above) suggests that deposition of the mud-clast breccia may have occurred along the margins of a channel or within a channel point bar. The presence of bioturbation with a low diversity of trace fossils suggests a stressed environment, possibly recording brackish-water conditions. High-energy scour events may have occurred at the base of the channel, causing the collapse of previously deposited mud beds along the channel margins (e.g., cut bank margins, flanks of straight channels). Alternatively, Facies 4, where associated with Facies 5 and 6 (discussed below), may indicate erosion of topset (vertical accretion) beds of point bars. The angularity of the clasts suggests that their transport distances were transported relatively short. The presence of rip-up clasts is evidence of possible autogenic erosion.

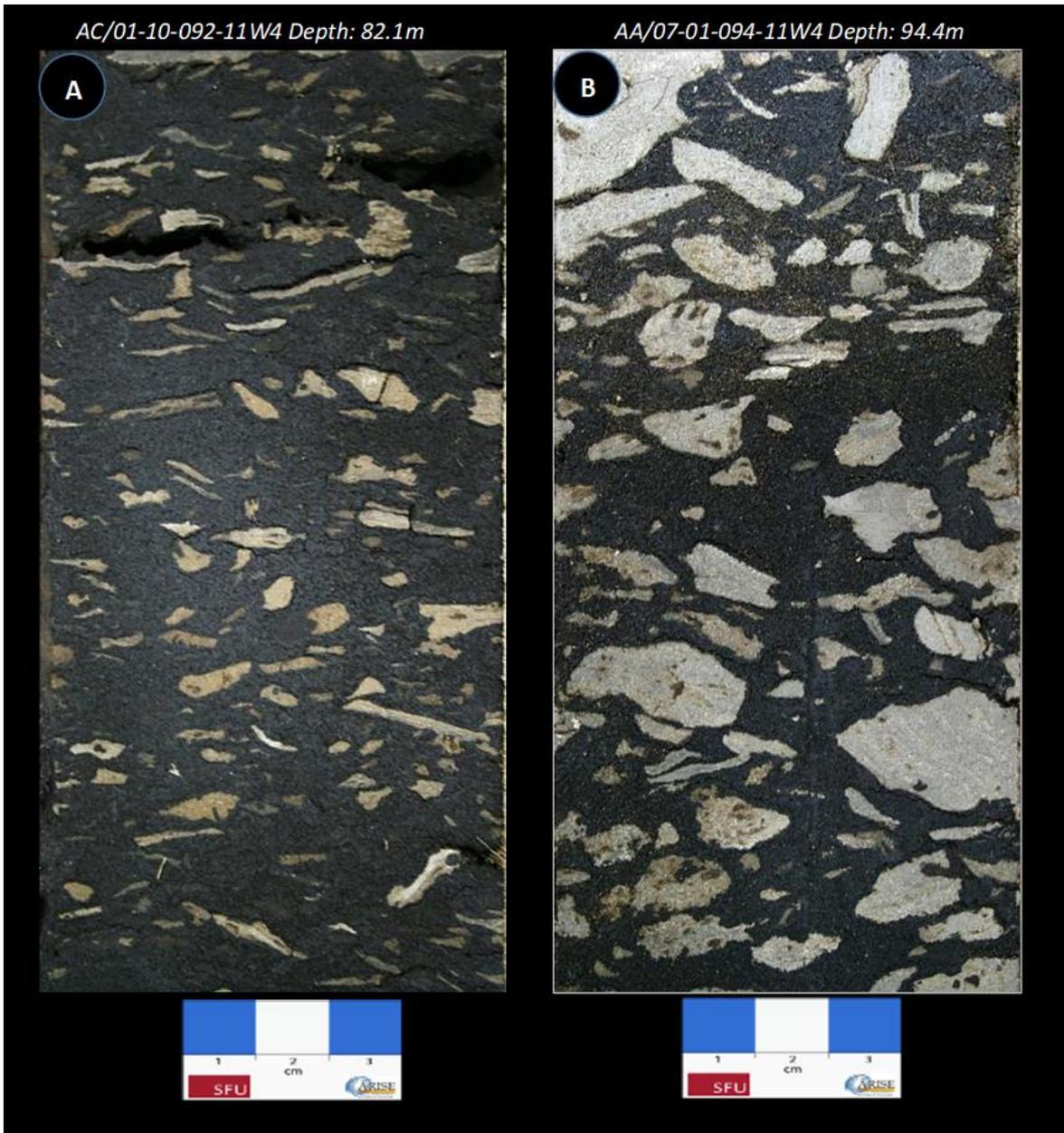


Figure 2.6 Facies 4: A and B: Chaotic arrangement of rip-up clasts in a mud-clast breccia, typical of Facies 4

## **2.5. FACIES 5 – Sporadically bioturbated massive to planar laminated mud and burrowed sand IHS composite bedsets.**

Facies 5 is a composite bedset, composed by discrete layers of sand and mud. The mud typically constitutes the dominant lithology. Nevertheless, there are intervals where sand proportions increase in respect to the mud. The muds are silt rich with intercalated sand laminae, and in some locations possess discernable current rippled or combined flow rippled tops. The sands locally contain mud and silt interlaminae. The bioturbation is more commonly preserved within the sandy intervals rather than in the muds. Facies 5 can be subdivided in two recurring subfacies: Facies 5A and Facies 5B.

### ***FACIES 5A – Sporadically bioturbated sandy IHS.***

#### *Description:*

Facies 5A (F5A) is characterized by light to dark gray, sporadically bioturbated mud interstratified with bioturbated, fine- to medium-grained sand beds. Bedset thicknesses are typically < 1.5m. The sand beds are of centimetre to decimetre scale. The mud beds are typically centimetre scale, with rare beds reaching decimetre scale. Sand bed proportions can vary from 60 to 80%. The contacts with overlying and underlying facies are generally sharp, but in rare locations can be gradational. The sands are well sorted, but can show mud and silt laminae locally. The sand layers possess current ripples, soft-sediment deformation, mud flasers and some mud laminae. In the muds, current ripples, undulatory parallel laminae, planar parallel lamination, and rare grading occur. Syneresis cracks are present, but rare. The BI in the sands varies from 1-4, this lithology being the most bioturbated. The BI in the muds is variable but overall is very low (BI 0-2), although there are rare exceptions where it reaches BI 4. The discernable trace fossils are *Cylindrichnus*, *Planolites*, *Skolithos*, *Thalassinoides*, and fugichnia.

#### *Interpretation:*

In this sandy expression of F5, the proportion of sand is greater. Overall, the thickness of the sand beds is relatively constant, suggesting that the scale of the events (energy and duration) that deposited the sand was more or less constant.

Correspondingly, it is interpreted that deposition of sand was associated with higher frequency events. Horizontal planar parallel lamination is consistent with sheet flow conditions; wherein fine-grained sands were deposited under relatively high velocity conditions. Current ripples record deposition during lower flow regime conditions. The presence of heterolithic bedsets are evidence of temporal changes in depositional energy. Fluctuations in physico-chemical conditions are supported by the presence of syneresis cracks, consistent with river-supplied freshwater interacting with tidally driven marine or brackish water (e.g., Donovan and Foster, 1972; Carmona et al., 2009). The mud in F5A (Fig. 2.7) was probably deposited by rapid flocculation (e.g., MacKay and Dalrymple, 2011). Rapidly deposited flocculated mud is commonly known as “fluid mud” or “dynamic mud”. Such mud accumulates during periods of elevated suspended sediment concentrations that are transported by physical processes (e.g., Mackay and Dalrymple, 2011). It is common to find fluid mud in tide-influenced systems in which fresh and brackish water mix (e.g., Ichaso, 2009; MacKay and Dalrymple, 2011; Sisulak and Dashtgard, 2012). The resulting brackish-water environment is subject to temporal fluctuations in salinity, induced by tidal-fluvial interactions, leading to a setting challenging for infaunal colonization. It is interesting that the mudstones generally show low to very low BI values, whereas the sand beds possess low to moderate bioturbation intensities of bioturbation with low-diversity trace fossil suites. The trace fossils within the sandy beds indicate the activity of organisms adapted to hostile or harsh environments (Beynon et al., 1988; Pemberton and Wightman, 1992; MacEachern and Pemberton, 1994; Gingras et al., 1999; MacEachern and Gingras, 2007; Gingras et al., 2011; Gingras et al., 2012; La Croix et al., 2015; Gingras et al., 2016).

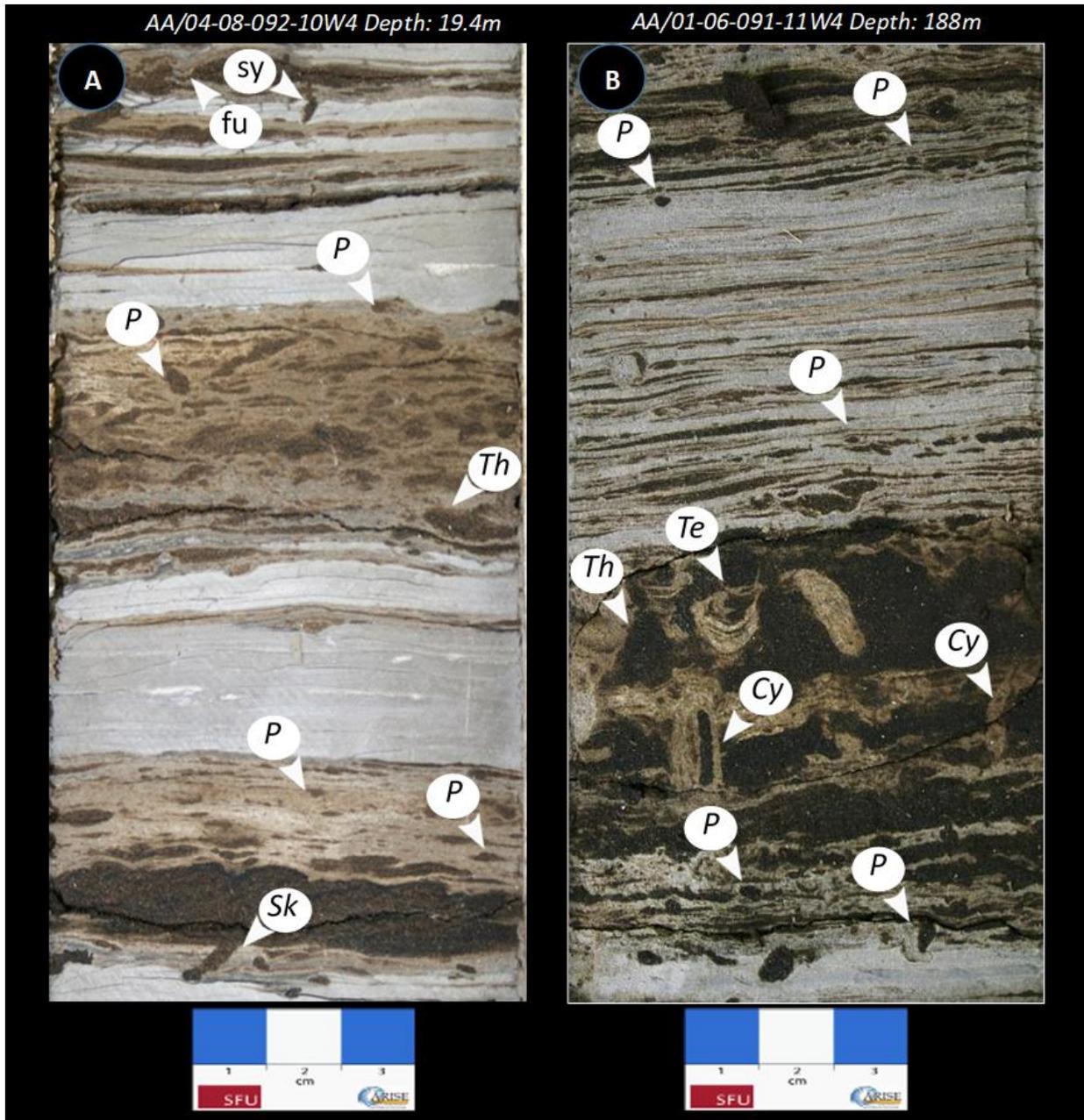


Figure 2.7 A) F5A showing unbioturbated and very weakly bioturbated mud with planar irregular lamination, intercalated with thin bioturbated sand beds containing *Planolites*, *Skolithos*, *Thalassinoides* and fugichnia (escape traces). B) Sandy expression of F5A showing very low bioturbation intensities in the mud (BI 1-2) and moderate bioturbation in the sand (BI 2-3). Trace fossils include *Cylindrichnus* (Cy), *Planolites* (P), *Thalassinoides* (Th) and *Teichichnus* (Te). Sand lenses, loading structures, parallel lamination and undulatory parallel lamination are also present.

## ***FACIES 5B – Sporadically bioturbated massive to planar laminated muddy IHS.***

### *Description:*

Facies 5B is composed by light to dark gray, weakly bioturbated mud interstratified with bioturbated sand beds. The sand is fine grained. The thickness of the bedsets is typically < 4.5m. The sand bed thicknesses are typically centimetre scale with rare occurrences of decimetre scale. The mud beds are typically decimetre scale in thickness. The contacts with overlying and underlying facies are generally sharp, but can be gradational locally. The mud is typically fractured. Mud constitutes approximately the 80% of this subfacies, and layers are typically silt rich and unburrowed. The main sedimentary structures present in the mud are planar parallel lamination, irregular parallel lamination, soft-sediment deformation, and rarely lenticular bedded. The mud may also show intercalated parallel laminae of silt and syneresis cracks. The muds appear to be normally graded. In places, thin beds of fine-grained sand occur. These sands show current ripples, combined flow ripples, and small-scale planar parallel lamination. In rare cases, wavy parallel lamination is present. Carbonaceous detritus and siderite nodules and cement are also present. The mud typically shows low BI values (BI 0-2) being diminutive *Planolites* the main trace fossil when this is the case; but in rare cases the BI can reach values of up to 3, presenting *Gyrolithes*, *Planolites* and diminutive *Skolithos* as the dominant trace fossils. Interstratified sand beds are uncommon, but where present display low BI values (BI 1-3), with suites consisting of diminutive and isolated *Cylindrichnus*, *fugichnia*, *Planolites*, *Skolithos* and *Thalassinoides*.

### *Interpretation:*

The mud in F5B (Fig. 2.8) is predominantly massive or possesses planar parallel lamination, interpreted to indicate deposition by dynamic processes in the turbidity maximum zone (TMZ) and/or by deposition due to rapid flocculation (e.g., MacKay and Dalrymple, 2011). The mud was deposited by either flocculation and settling, or by bedload remobilization of these flocculated muds or of mud already carried at the bed. Such mud is called fluid mud or dynamic mud, and occurs when suspended sediment concentrations greater than 10g/l are accumulated and mobilized by physical processes (Mackay and Dalrymple, 2011). Fluid mud can be readily found in tidal systems such as

tidal-fluvial channels and bars (e.g., Ichaso, 2009, MacKay and Dalrymple, 2011; Sisulak and Dashtgard, 2012). Normal grading in the muds probably implies deposition during periods of decelerating flow. Abundance of internally laminated mud suggests that some layers were transported as bedload. Nevertheless, mud deposition does not appear to have been driven solely by bedload transport. The presence of internal silt and sand laminae within the mud indicates fluctuating flow during the mud deposition. Such laminae indicate temporal variations in physical energy within the environment. Horizontal planar parallel lamination can be formed by grains rolling along the bed and mud laminae shifting as coherent masses. Current ripples record deposition during lower flow regime conditions. Rare presence of syneresis cracks implies that the depositional processes during the deposition of this subfacies were influenced by brackish-water conditions (e.g., Plummer and Gostin, 1972).

The low bioturbation within the mud is consistent with mobile mud, which didn't allow organisms colonize the substrate. However, another possibility could be environmental stresses owing to rapid deposition of the muds. Additionally, salinity fluctuations responsible for syneresis cracks may have contributed to physico-chemical stresses in the environment.

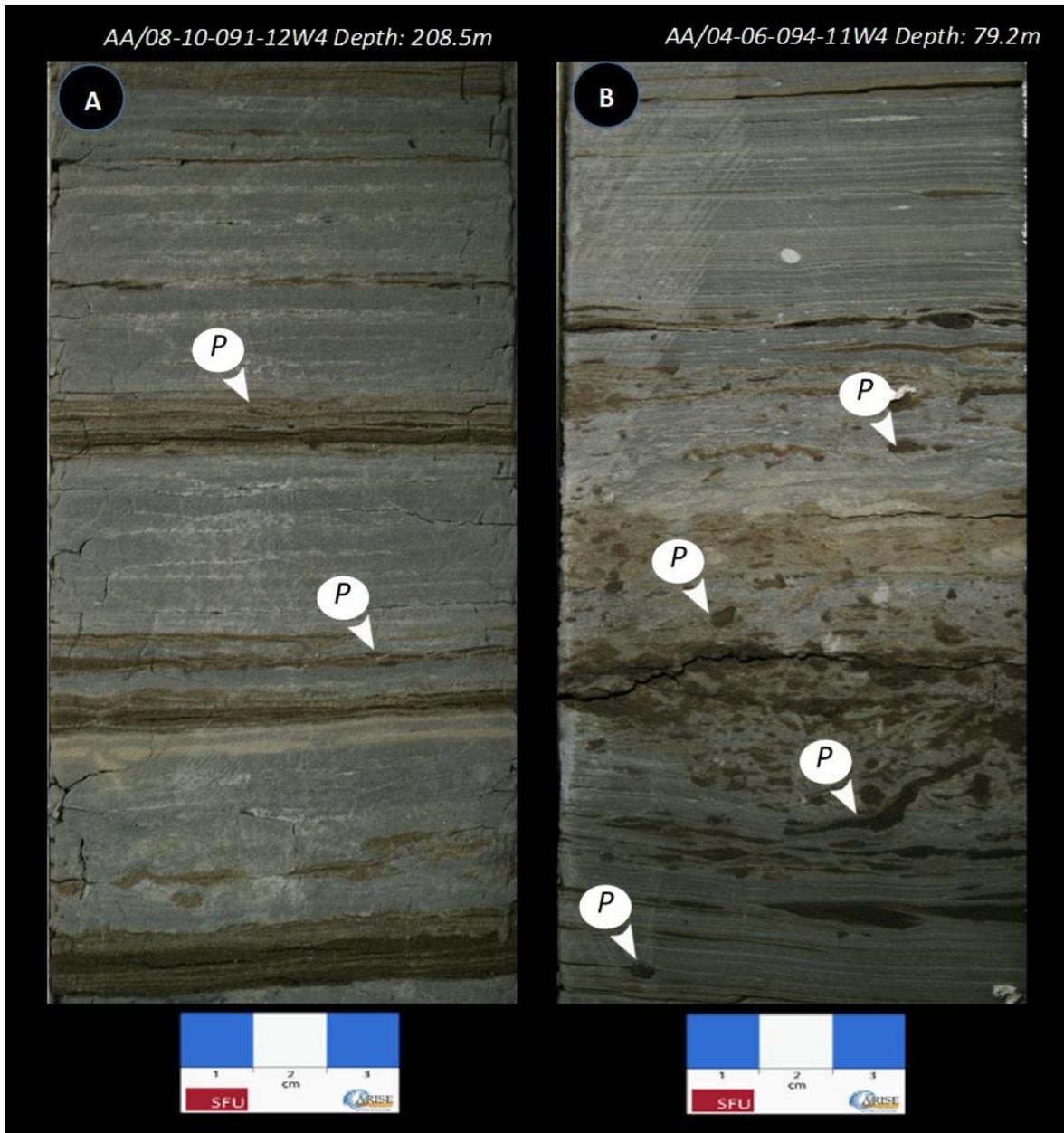


Figure 2.8 Facies 5B: A) Parallel lamination within the muds with little bioturbation (BI 0-1). The muds locally show grading. The sand laminae show small scale ripples and silt laminae. Low bioturbation occurs in the sandy intervals (BI 0-2). B) Mud, showing parallel laminae of silt, and bioturbation in both sandy and muddy intervals. Higher BI values (BI 1-3) occur in sandy intervals.

## **2.6. Facies 6 – Weakly Bioturbated, Current-Generated Inclined Heterolithic Stratification**

Facies 6 consists of composite bedsets of rhythmically bedded, dipping beds of fine-grained sand and light brown/gray mud. Characteristic of the facies is the presence of carbonaceous detritus or mud laminae. Facies 6 varies from mud-dominated to sand-dominated expressions. The trace fossils are sparsely present and are diminutive. Facies 6 is subdivided in two (2) subfacies, based on sand proportions and sedimentological characteristics.

### ***Facies 6A – Sand-Dominated Current-Generated IHS with Laminated and Carbonaceous Mud Interbeds***

#### *Description:*

Facies 6A is characterized by interstratified very fine- to fine-grained, oil-stained sand beds intercalated with light gray silty mud beds. Rhythmicity of the sand vs. the mud layers is characteristic of the facies. The beds within this composite bedset are typically inclined, and display rare horizontal to very low-angle parallel laminae (Fig. 2.9A, B). Bedset thicknesses range from decimetre to metre scale. Sand beds constitute 60-80% of the facies. Sand bed thicknesses range from 2cm up to decimeter scale. Mud bed thicknesses range from 1cm up to approximately 5cm. As the facies becomes sandier, sand bed thicknesses likewise increase. The contacts with the lower and upper facies are typically sharp (presence of scour surface), but can be gradational locally. Sedimentary structures are typically represented by high- to low-angle cross-stratification, current ripple cross-lamination, and planar parallel lamination. Mud couplets and organic matter are commonly present as lamina-scale drapes marking stratification. BI values are very low, ranging from 0-1 at the bed scale. The traces recognized consist of rare and sporadically distributed *Planolites* in both sand and mud.

#### *Interpretation:*

The sand-dominated inclined heterolithic stratification of Facies 6A displays predominantly current-generated structures in the sand alternating with periods of fluctuating and generally reduced energy, leading to the heterolithic character of the

composite bedset. The current-generated structures are generally associated with lower flow regime conditions. The rhythmicity pattern is well pronounced, and indicates a strong tidal influence on the system. The presence of mud drapes as well as mud couplets within the sand beds are interpreted to reflect tidal flux in the system, and is typically thought to record deposition from the fall out of suspended sediment during slack-water periods. Recent studies have shown that some mud can also accumulate dynamically from high suspended sediment concentrations near the bed, as well as when mud concentrations exceed 10 g/l (cf. MacKay and Dalrymple, 2011). This type of fluid mud is very common in channel settings with a strong tidal influence, particularly those that experience mixing of fluvial discharge and tidally driven saline water (e.g., MacKay and Dalrymple, 2011, Ichaso, 2009, La Croix, 2014). This style of accumulation is assigned to the thicker mud beds within the IHS. The IHS of F6A implies a tidal influence in a brackish-water setting associated with tidal-fluvial channels. These settings provide the cyclic characteristics and the fluctuating energy regime required to generate repetitive beds of mud and sand in a typical IHS succession (Thomas, 1987; Ranger and Pemberton, 1992; Gingras, et al., 1999; Sisulak and Dashtgard, 2012, Johnson and Dashtgard, 2014). A stressed brackish-water environment is inferred to predominate during the deposition of this facies, supported by the low-diversity trace fossil suites and low abundance of trace fossils. Such channels may correspond to tidal-fluvial estuaries or distributaries of tidally influenced deltas.

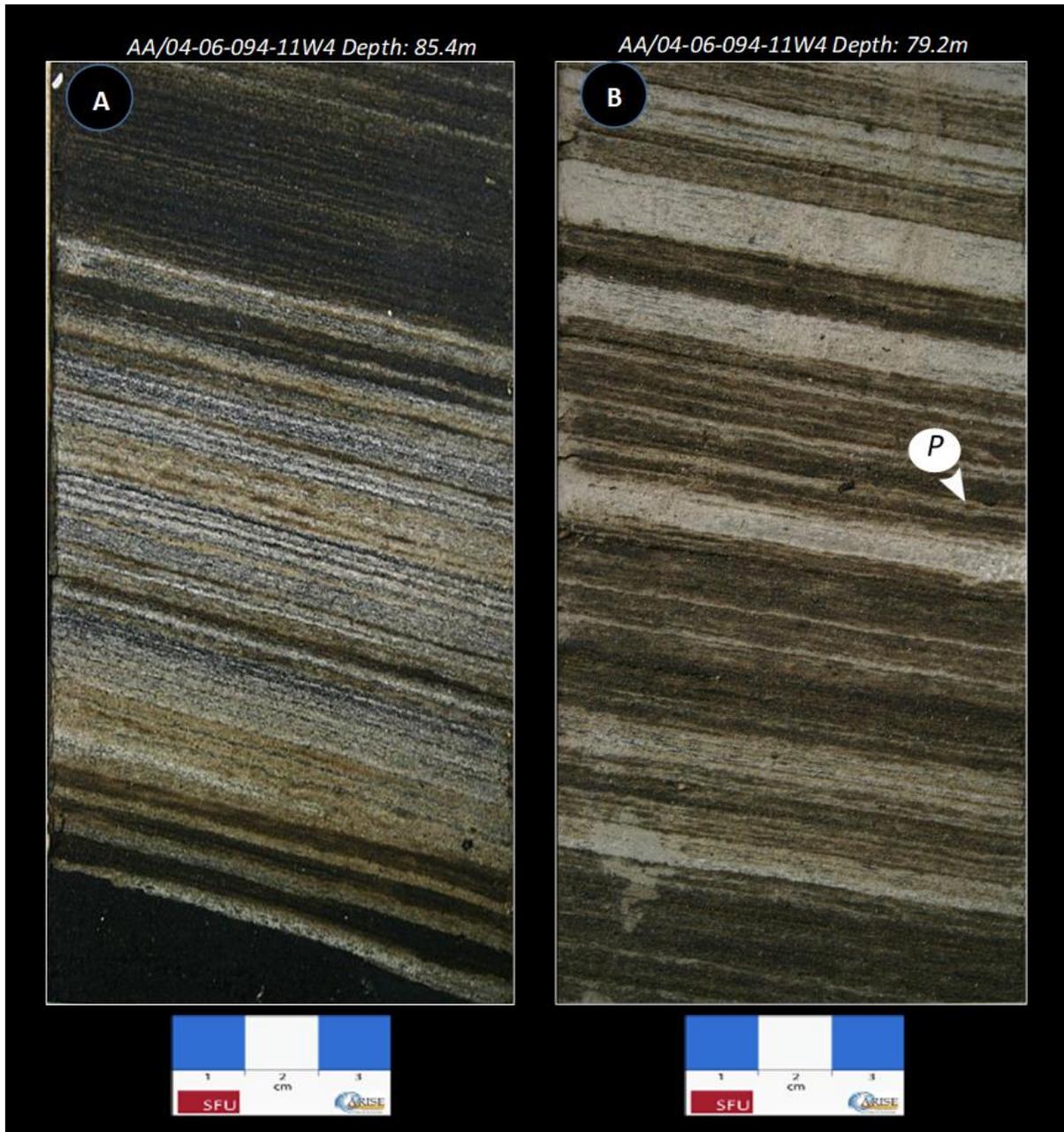


Figure 2.9 Facies 6A core examples. A) Inclined heterolithic stratification with mud drapes and abundant carbonaceous laminae. The unit shows BI 0. B) Rhythmicity in IHS, showing BI 0-1 with diminutive *Planolites* (P).

## ***Facies 6B – Mud-Dominated Current-Generated IHS with Laminated and Carbonaceous Mud Interbeds***

### *Description:*

Facies 6B is dominated by beds of light gray mud intercalated with very fine-grained sand. Mud beds constitute 60-70% of the facies. Thickness of the bedsets varies from centimetre scale up to metre scale. The thicknesses of individual mud beds vary from 2cm to 25cm. The sand beds are typically 1 to 6cm thick. The thickness of the sand beds decreases upwards in this subfacies. Contacts with the underlying and overlying facies vary from gradational to sharp. Sedimentologically, the unit is typically represented by high- to low-angle cross-stratification, planar parallel lamination and rare current ripple cross-laminae in the sand beds. As sand layers become thinner, parallel laminae and current ripples dominate. Mud beds also display horizontal and inclined parallel laminae of carbonaceous detritus. The bioturbation is very low in intensity (BI 0-1), with trace fossil suites consisting of rare and diminutive *Planolites* in both the sands and mud beds.

### *Interpretation:*

Facies 6B (Fig. 2.10) shows fluctuations in energy, which caused the deposition of a heterolithic composite bedset deposited as part of lateral accretion or channel margin accretion in a channel. Mud dominates this facies. It is likely that the deposition of the mud occurred as fluid mud, carried as bedload or by high-density flows near the bed (cf. MacKay and Dalrymple, 2011). Tidal influence in the system is indicated by the rhythmicity of the layers, and the presence of drapes of mud and carbonaceous detritus. Typically, tide-influenced channels and point bars show dynamic processes as the mechanism of mud deposition (Ichaso, 2009, La Croix, 2014). Inclined and low-angle parallel lamination may indicate that periods of lower flow regime conditions were dominant. Small-scale, current-generated structures are persistent in the facies, and are typically related to lower flow regime conditions. The low BI values indicate that the environment was physico-chemically stressful or not favorable for organism colonization of the substrate. This could have been caused by elevated sedimentation rates, high depositional energy, and/or fluctuations and general reduction of salinity.

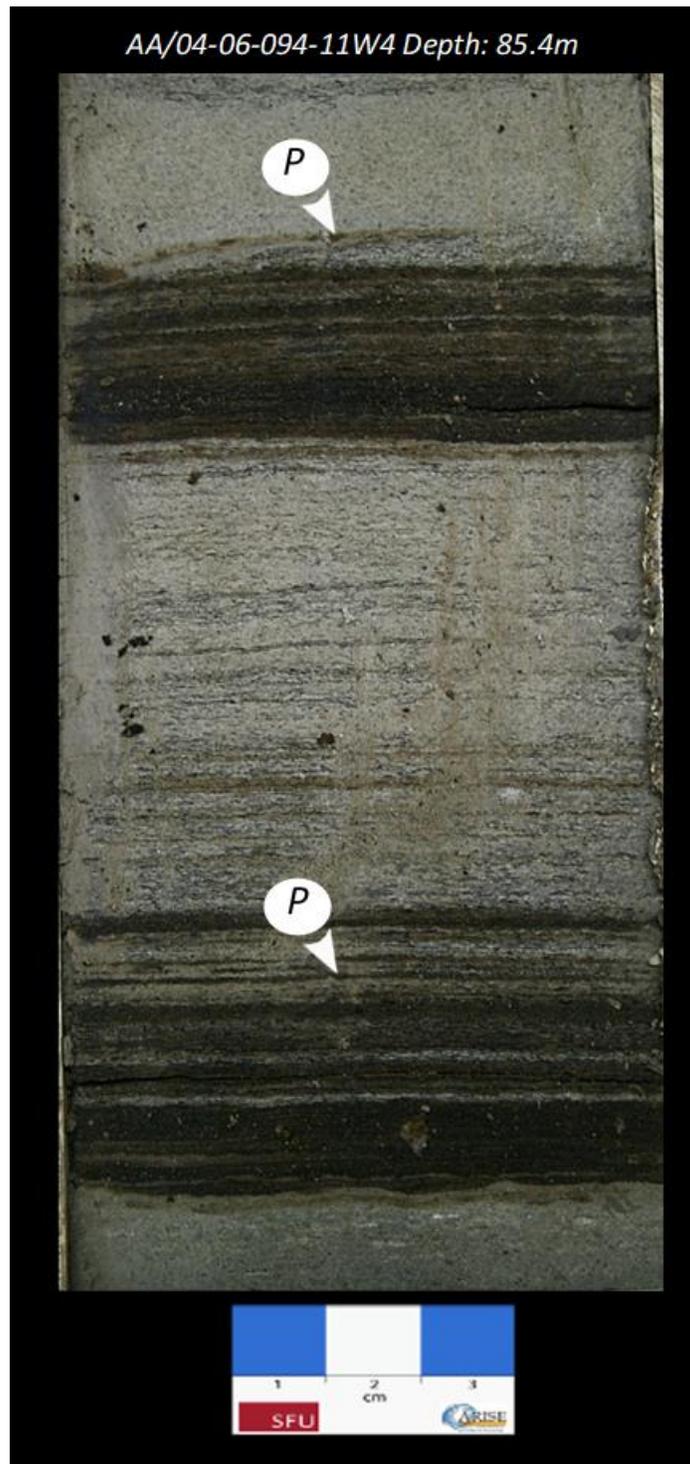


Figure 2.10 Muddy IHS of F6B, showing laminated and carbonaceous mud interbeds and diminutive *Planolites* (*P*).

## **2.7. FACIES 7 – Bioturbated, Current-Generated IHS Bedsets**

Facies 7 is characterized by composite bedsets consisting of intercalations of inclined, fine-grained sand and light brown/gray mud. The content of mud and sand are variable in the area, varying from sand dominated, mud dominated and subequal mixtures of these lithologies. Trace fossils are present in both bed types and are characterized by low diversity facies-crossing burrows occurring in low to high abundance. Facies 7 is subdivided in two (2) subfacies, based on sedimentological and ichnological characteristics.

### ***FACIES 7A – Bioturbated, Sand-Dominated, Current-Generated IHS Bedsets***

#### *Description:*

Facies 7A predominantly comprises low-angle, inclined, bitumen-stained, fine- to medium-grained sand interbedded with subordinate amounts of light gray to brown mud, forming a heterolithic composite bedset (Fig. 2.11A, B). The thickness of the bedset varies from decimetres to metres. The sand beds without mud interbeds range from decimetre scale up to 2 metres thick. Mud beds are typically centimetre scale in thickness. Sand generally constitutes 70 - 80 % of the facies. Most upper and lower contacts are gradational, although locally they can be sharp. Sedimentary structures in the sands are characterized by small-scale, planar tabular and trough cross-stratification, as well as current ripple cross-lamination, some of which are aggradational. More rarely, oscillation ripples are intercalated. Mud flasers occur within some sand beds. Horizontal planar parallel and low-angle cross stratification also occur locally throughout the facies. Mudstones layers contain thin internal cross laminae and parallel laminae of silt. The mud beds are sharp based and commonly show normal grading. Syneresis cracks are also present. Localized, inclined drapes of mud or carbonaceous detritus are present, but rare.

The BI ranges from 1-3 in the sands and 2-4 in the muds at the bed scale. The ichnological suite is of low diversity, and consists of *Cylindrichnus*, diminutive *Palaeophycus*, *Conichnus*, sporadically distributed *Gyrolithes*, *Skolithos*, *Spirasensus*,

*Thalassinoides* and *Teichichnus* in the sands. The muds are characterized by diminutive *Planolites*, *Teichichnus*, *Skolithos* and *Gyrolithes*.

*Interpretation:*

Facies 7A is dominated by current-generated structures formed in lower flow regime conditions. In some cases, the currents were accompanied by rapid sedimentation to produce aggradational current ripples, possibly related to rapidly decelerating river floods or tidal flow. The presence of low-angle inclined lamination suggests the presence of large, low-relief bedforms in fine-grained sand. The local presence of horizontal planar parallel lamination is consistent with periods of upper flow regime sheet flow conditions, allowing fine-grained sand and silt to be deposited under high velocity, shallow-water traction flow. The mudstones may record periods of low energy deposition, possibly due to rapid suspended sediment fall out. However, many of the mud beds contain internal laminae of sand and silt with current ripples, demonstrating possible periods of bedload transport rather than pure drape conditions (cf. MacKay and Dalrymple, 2011). Some tidal influence may be indicated by the presence of local drapes of mud or carbonaceous detritus, interpreted as tidal bundles (e.g., Smith, 1988). These mud drapes are not very common however. Syneresis cracks are interpreted as subaqueous shrinkage cracks produced by salinity changes, suggesting a brackish-water influence in the system (Burst, 1965; Plummer and Gostin, 1972). The association of *Planolites*, *Skolithos* and *Cylindrichnus* is consistent with a setting prone to reduced and fluctuating salinity (see MacEachern and Gingras, 2007; Gingras et al., 2016 for summaries).

The low-diversity suite identified from Facies 7A is consistent with physico-chemically stressed environments. The suite is characterized by marine-related but facies-crossing trace fossils (cf. Beynon et al., 1988; MacEachern and Pemberton, 1994; Butaiois et al., 2005; MacEachern and Gingras, 2007; Gingras et al., 2016). The variability in bioturbation intensity may indicate pronounced changes in the rate of deposition and/or other changes in physico-chemical stress (e.g, fluctuating salinities, markedly reduced salinity). Further, the high-energy conditions during the deposition of the sand and the lower energy and/or reduced/fluctuating salinity during mud deposition may also have affected the diversity of trace fossils. The presence of the structures created by mobile deposit feeders (e.g., *Planolites*), and dwellings of possible carnivores

or deposit feeders (e.g., *Palaeophycus* and *Teichichnus*) indicate communities of organisms that made their structures at or near the sediment-water interface. Dwelling structures (e.g., *Cylindrichnus*, *Gyrolithes* and *Skolithos*) indicate relatively permanent domiciles for organisms that penetrate deeper into the substrates, possibly in order to protect themselves from high-energy conditions (e.g., Wightman et al., 1987; Pemberton, 1992; Gingras et al., 2011), buffer or moderate salinity fluctuations (e.g., Beynon et al., 1988; MacEachern and Gingras, 2007), and/or facilitate surface detritus feeding (e.g., Gingras et al., 2011; Gingras and MacEachern, 2012; Gingras et al., 2016).

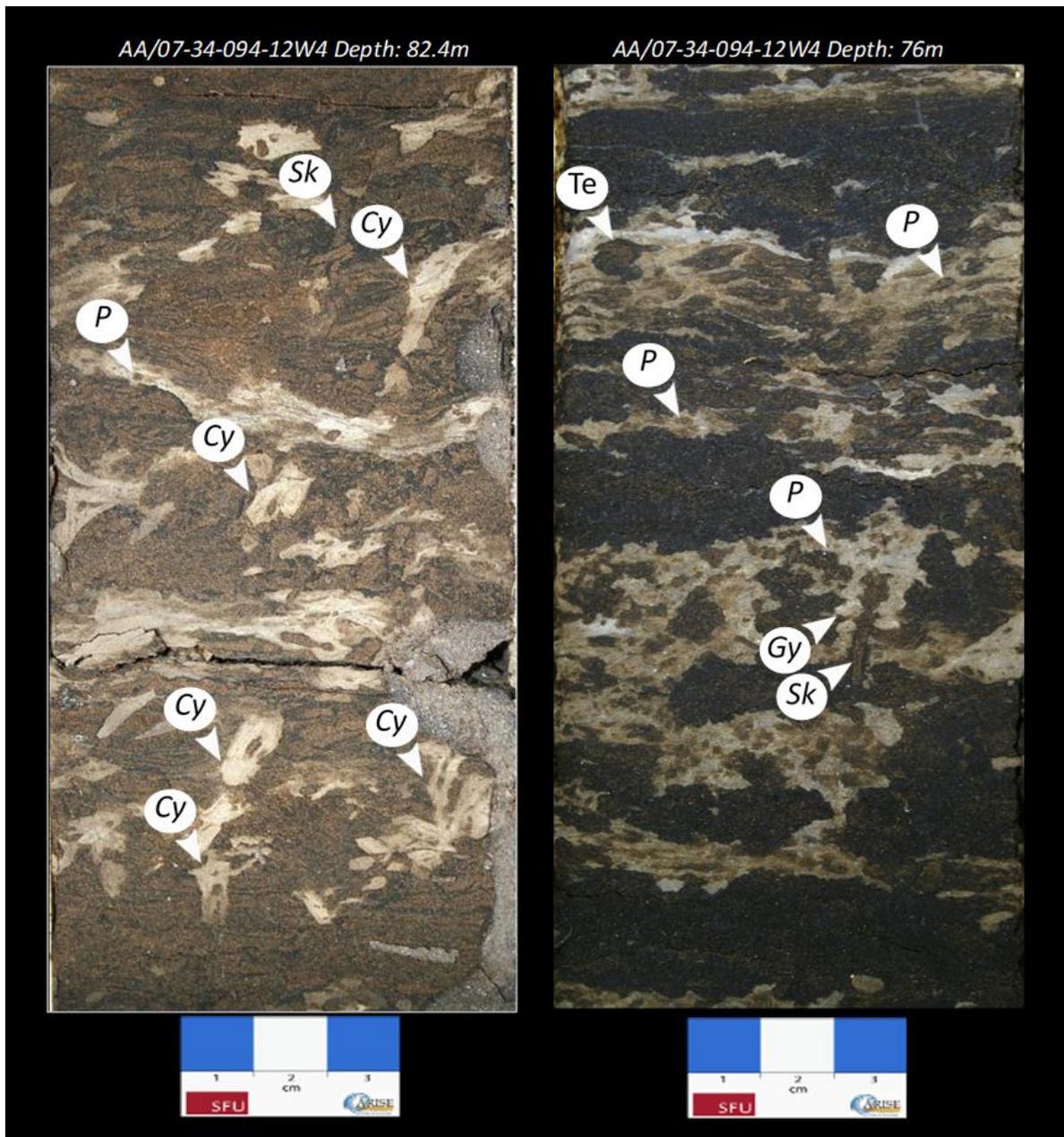


Figure 2.11 A) Fine- to medium-grained sand interbedded with mud, showing BI 3-4. Trace fossils include *Cylindrichnus* (Cy), *Skolithos*(Sk), and *Planolites* (P). B) Fine- to medium-grained sand with thin mud/silt laminae, showing BI 4. Trace fossils are *Gyrolithes* (Gy), *Planolites*(P), *Skolithos* (Sk) and *Teichichnus* (Te)

## ***FACIES 7B – Bioturbated, Mud-Dominated, Current-Generated IHS Bedset***

### *Description:*

Facies 7B comprises light gray/brown mud interstratified with subordinate proportions of bitumen-stained, fine-grained sand. Upper and lower facies contacts are typically gradational, but can be sharp locally. A depositional dip to the mud/sand layers is discernible. The bedding is typically gently inclined or horizontal, forming IHS bedsets (Fig. 2.12A, B). Bedset thicknesses range from decimetre to metre scale. Mud beds can vary from centimetre up to decimetre scale in thickness. Sand beds can vary from centimetres up to decimetres thick. Lenticular and wavy bedding are observed locally. The lenses of sand within the mud are apparently structureless. Loading structures are also present. Mud beds constitute 60 - 80 % of the facies. Sedimentary structures in the sands include planar parallel lamination, current ripple cross-lamination and aggradational current ripple cross-lamination. The mud is commonly fractured, but displays normal grading and intercalated sand laminae. Locally, sand is disseminated as individual grains within the mud rather than as laminae. Rare syneresis cracks are present.

The BI ranges from 2-5. The trace fossils are represented by a low to moderate diversity of ichnogenera, which mainly consist of *Cylindrichnus*, diminutive *Palaeophycus*, *Planolites*, robust *Gyrolithes*, and diminutive *Skolithos*, *Thalassinoides* and *Teichichnus*. Facies-crossing trace fossils are dominant.

### *Interpretation:*

The presence of aggradational current ripples, planar parallel lamination, and low-angle inclined parallel lamination suggests that deposition of the sand occurred under lower flow regime traction transport. Planar parallel lamination is more common in Facies 7B than in Facies 7A, which may indicate that periods of upper flow regime conditions were dominant. Given the prevalence of mudstone deposition, this may indicate generally shallower flow conditions with finer-grained sediment, rather than overall higher flow velocities. Historically, wavy bedding and lenticular bedding is regarded to be commonly associated with alternations from traction flow and standing water sedimentation (Reineck and Wunderlich, 1968; Martin, 2000). That said, such bedding styles can also occur in any depositional environment where higher velocity

flows occur and where mud is able to be deposited and drape the sandy bedforms. Such mud may also be of fluid mud origin and deposited by dynamic conditions (e.g., mixing in the turbidity maximum zone or from rapid flocculation; cf. MacKay and Dalrymple, 2011).

The presence of syneresis cracks indicates that there were salinity changes within the system, consistent with a brackish-water environment. The generally low-diversity suite of trace fossils indicates that the environment was physico-chemically stressful for organisms. The variation of BI is similar to that observed in Facies 7A, but intervals with higher bioturbation intensities are more common in Facies 7B. The variable intensity of bioturbation indicates that there were variations in the depositional rate and/or fluctuations in chemical conditions (e.g., salinity). The trace fossil suite comprises biogenic structures consistent with the activity of opportunistic trophic generalists, reflected by the dominance of trace fossils regarded as facies-crossing, deposit-feeding structures (e.g., *Planolites*), and dwelling structures of inferred deposit-feeding organisms (e.g., *Palaeophycus*, *Teichichnus*, and *Gyrolithes*) (see MacEachern and Gingras, 2007 for a summary). These indicate communities of organisms that construct structures below the sediment-water interface for the extraction of food resources from the sediment (Gingras et al., 1999; MacEachern et al., 2007; Gingras et al., 2011; Gingras et al., 2012b; Gingras and MacEachern, 2012; Gingras et al., 2016; Shchepetkina, 2016). Such tracemakers are likely adaptable to harsher environment conditions. Dwelling structures of inferred suspension feeders or detritus feeders (e.g., *Cylindrichnus* and *Skolithos*) are less common compared to Facies 7A. In general, the impoverished suite of marine trace fossils (e.g., *Cylindrichnus*, *Teichichnus*, *Palaeophycus*, *Planolites*, and *Skolithos*) fulfill the conditions proposed by the brackish-water model established by Pemberton (1982), Wightman et al. (1987), Beynon et al. (1988), and refined by Gingras et al. (1999), Buatois et al. (2005), and MacEachern and Gingras (2008).

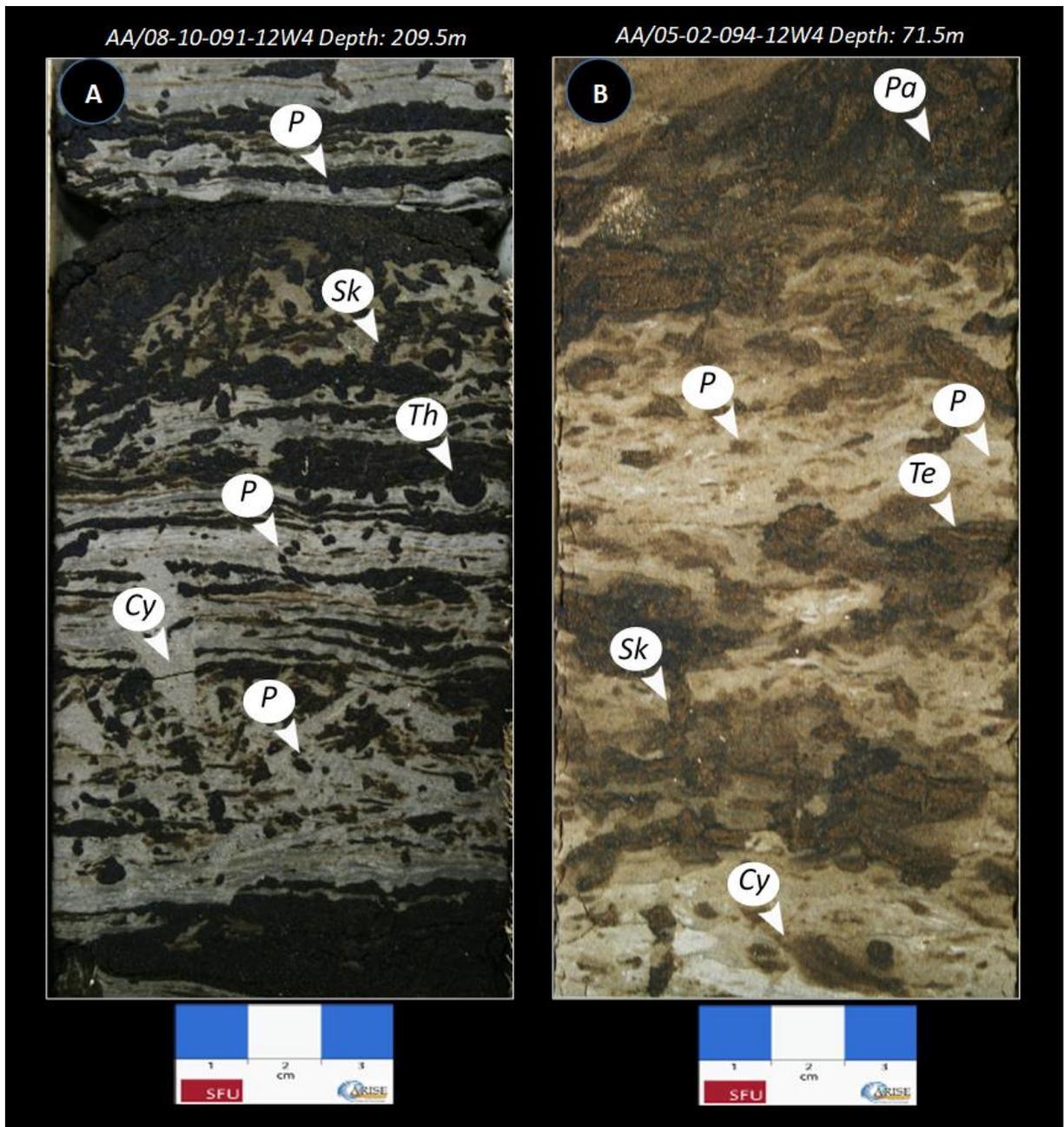


Figure 2.12- Mud-dominated bioturbated heterolithic units of Facies 7B, showing an impoverished marine trace fossil suite consisting of: A) *Skolithos* (*Sk*), *Planolites* (*P*), *Thalassinoides* (*Th*); and B) *Cylindrichnus* (*Cy*), *Planolites* (*P*), *Thalassinoides* (*Th*) and *Teichichnus* (*Te*). Sand lenses, loading structures, parallel lamination and undulatory parallel lamination are also present.

## 2.8. FACIES 8 – Bioturbated, Oscillatory-Generated Heterolithic Bedding

Facies 8 is characterized by composite bedsets of sand and dark gray/bluish mud beds. The proportions of sand vs mud content vary markedly. The trace fossils are present in both lithologies and are characterized by typically robust, facies-crossing elements. Facies 8 is subdivided in two (2) subfacies, primarily based on sedimentological characteristics.

### ***FACIES 8A – Bioturbated, sand-dominated heterolithic sand and dark grey/blue mud.***

#### *Description:*

Facies 8A displays heterolithic composite bedsets, consisting of sand beds intercalated with dark gray/bluish-colored mud beds (Fig. 2.13), forming wavy bedding. Bedset thicknesses vary from decimetre up to metre scale. The proportion of sand to mud also varies, but ranges from 50-70% sand. Sand grain sizes range from fine to medium. The sand beds range between 5 - 50cm thick and are in sharp contact with the blue mud layers. Mud bed thicknesses vary from 1 - 10 cm. Locally, F8A is in sharp contact with the underlying facies, particularly where such intervals are mud dominated. In other locations, the contact with the underlying facies is gradational. Facies 8A is sharply overlain by mud-dominated units of Facies 9 or 10. Bitumen-stained sand beds are common. Primary sedimentary structures in the sands include low-angle, undulatory parallel lamination, oscillation ripple lamination, and soft-sediment deformation. The mud beds are predominantly structureless, but locally contain internal parallel laminae of silt and very fine-grained sand, as well as very rare syneresis cracks. Locally, Facies 8A is thoroughly bioturbated, and sedimentary structures are difficult to discern. BI values range from 1 to 5, with the mud layers commonly more intensely bioturbated than the sand beds. The trace fossil suite consists of robust ichnogenera, and shows a mixture of facies-crossing elements with more typical marine forms. The suite consists of *Asterosoma*, *Conichnus*, *Diplocraterion*, *Planolites*, *Skolithos*, *Taenidium*, *Teichichnus* and *Thalassinoides*.

*Interpretation:*

Facies 8A is characterized by the presence of low-angle undulatory parallel lamination within wavy bedded composite bedsets, interpreted to represent micro-HCS and/or long-wavelength oscillation ripples draped with mud. The mud drapes may be indicative of either fluvial or tidal influence; however, the physical deposition of the sand is more consistent with waves and low-energy storms. While the mud may have been deposited initially either through suspension settling, tidal mixing or tidal-fluvial processes, it may have been mobilized subsequently as bedload fluid mud (or dynamic mud) by tides, longshore drift, and/or storm-driven currents. Oscillation ripples and micro-HCS demonstrate that wave influence was a persistent depositional process. Soft-sediment deformation records rapid emplacement of sand onto soft, cohesive muddy substrates.

The trace fossil diversity and bioturbation intensity in Facies 8A is higher compared to that of the previously described facies, indicating that the environment was probably less physico-chemically stressed. Zones of BI 5 reflect periods of slow, persistent deposition in a relatively sheltered marine setting. The trace fossil suite is characterized by a dominance of mobile and sessile deposit-feeding structures and very robust dwelling structures, suggesting a more stable marine environment. Forms such as *Asterosoma* and *Conichnus* are typically assigned to settings characterized by stable marine salinities (e.g., MacEachern et al., 2007; Gingras et al., 2011).

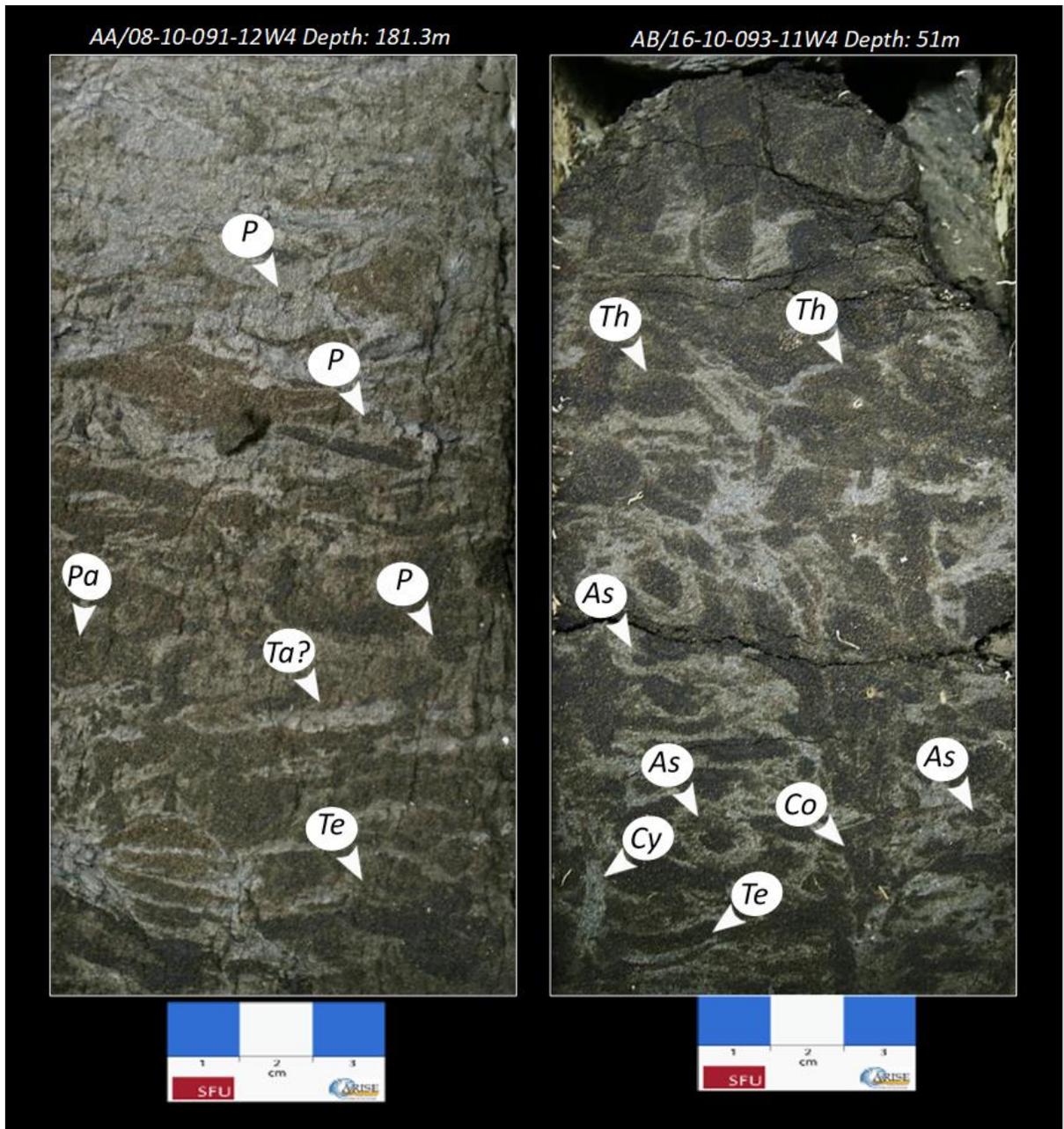


Figure 2.13 Facies 8A, showing higher BI values and more robust trace fossils, characterized by dwelling structures as well as mobile and sessile deposit-feeding structures. Identified trace fossils are *Asterosoma* (As), *Conichnus* (Co), *Palaeophycus* (Pa), *Planolites* (P), *Teichichnus* (Te) and *Thalassinoides* (Th).

***FACIES 8B – Bioturbated, mud-dominated heterolithic sand and dark grey/blue mud.***

*Description:*

Facies 8B consists of mud-dominated heterolithic bedsets characterized by dark grey/blueish-colored mud beds intercalated with fine- to medium-grained sand beds. The bedsets are characterized by wavy bedded intervals, which vary from decimetre to metre scale in thickness. The mud beds are in sharp contact with the sand beds. Mud beds comprise 60-80% of the bedset, and vary from 5-10 cm thick. The sand beds range between 2-5cm thick. The contact of this facies is gradational with Facies 8A, but sharp with all other facies. The main sedimentary structures in sand beds include low-angle, undulatory parallel lamination, with rare combined flow and oscillation ripple lamination. Soft-sediment deformation is common. The mud beds are commonly fractured and contain internal undulatory and parallel laminae of silt and sand, as well as rare oscillation ripple lamination. Many intervals are biogenically mottled as a result of intense bioturbation. The BI values range from 2-5. The trace fossils include *Asterosoma*, *Planolites*, *Skolithos*, *Taenidium*, *Teichichnus* and *Thalassinoides*.

*Interpretation:*

Facies 8B displays undulatory parallel lamination, associated with wavy bedded bedsets. The mud is interpreted to have been deposited by dynamic processes such as tides and/or fluvial discharge into saline water. Wave and storm influence are best reflected in the stratification of the sand beds (e.g., oscillation ripples and micro-HCS). Soft-sediment deformation indicates loading caused by rapid emplacement of sand onto muddy sediments. The locally high BI values and trace fossil diversity indicates that the environment was more suitable for organism colonization, suggesting less stressed environment (more ambient) conditions. Slow rates of deposition are evident through intervals displaying a BI of 5. The environment is interpreted to have been stable and more normal marine, due to the dominance of structures produced by mobile and sessile deposit feeders, and robust dwelling structures. Periods of physico-chemical stress, presumably from event style deposition and/or rapid deposition, are indicated by units showing low BI values and low diversity trace fossil suites. Most trace fossils in the facies are facies-crossing elements, with the exception of *Asterosoma*.

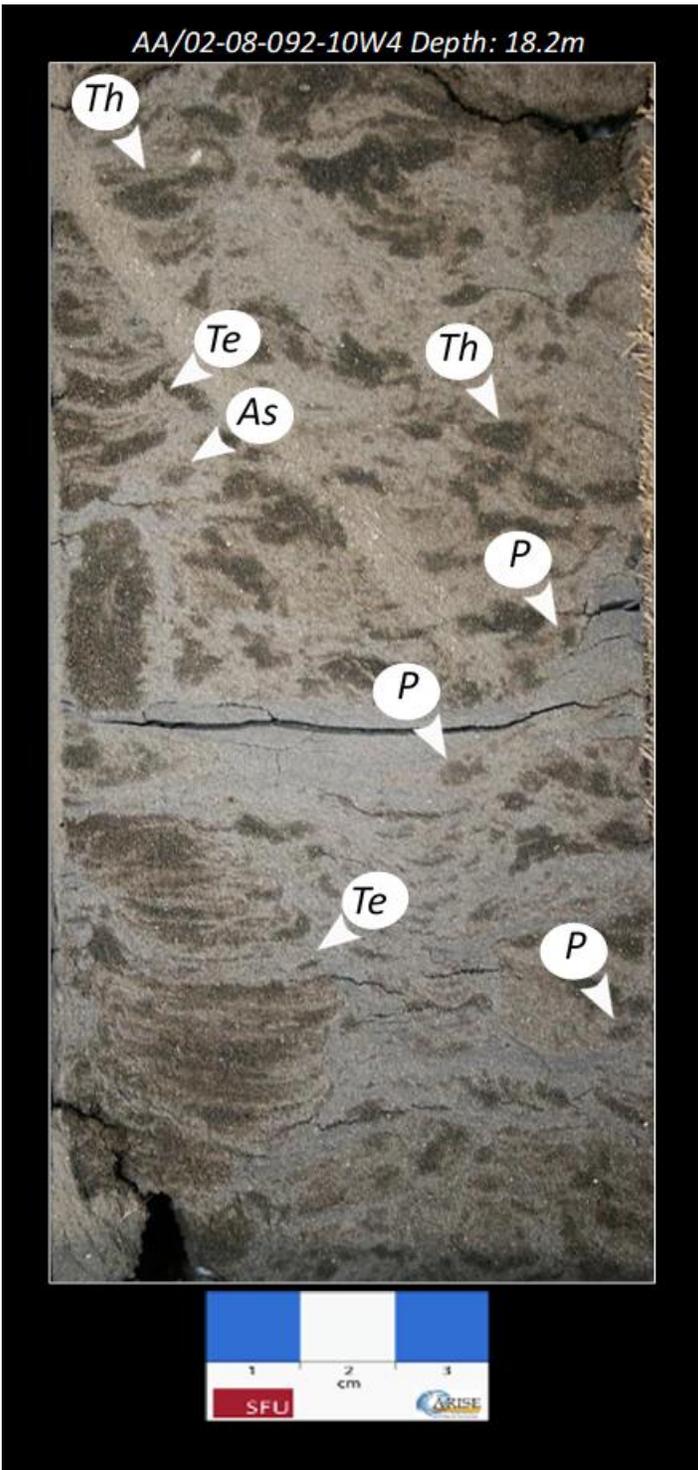


Figure 2.14 Facies 8B. Mottled mud-dominated heterolithic unit, showing *Asterosoma* (*As*), *Planolites* (*P*), *Teichichnus* (*Te*), and *Thalassinoides* (*Th*).

## 2.9. FACIES 9 – Weakly burrowed, wavy bedded, HCS-bearing sand.

### *Description:*

Facies 9 is characterized by dark coloured sand and rare, bluish/gray mud interbeds. The sand is fine to medium grained. The thickness of the bedsets is typically of metre scale (up to 5m). Some intervals may contain up to 20% mud beds, which are typically 1 to 2 cm thick. Contacts between the sand beds and mud beds are sharp. The facies contact can be gradational or sharp with underlying subfacies of F8. The contact with the overlying facies is typically sharp. Primary sedimentary structures are dominated by horizontal planar parallel lamination, wavy parallel lamination (micro-HCS), HCS, and oscillation ripple lamination. Locally, the sand appears massive (apparently structureless). Bioturbation intensities are generally low (BI 0-2). The trace fossil suite consists of *Palaeophycus*, *Planolites*, *Rosselia* and *Skolithos*. Bioturbation typically occurs in the mud beds; though locally, the sands are also burrowed.

### *Interpretation:*

Facies 9 is dominated by oscillatory-generated structures in the sands, indicative of fair weather waves and storms (Walker, 1983). The mud beds are believed to have been deposited as fluid mud, which may have been produced by rapid flocculation of large amounts of suspended sediments in buoyant plumes and/or by hyperpycnal bedload discharge (cf. MacEachern et al., 2005; Bhattacharya and MacEachern, 2009). The low bioturbation intensitivity may indicate a very stressful environment for the fauna. Fluid mud is very difficult to colonize because of its soupy characteristics. During burial and compaction, most of the burrows are likely obliterated (e.g., Lobza and Schieber, 1993).

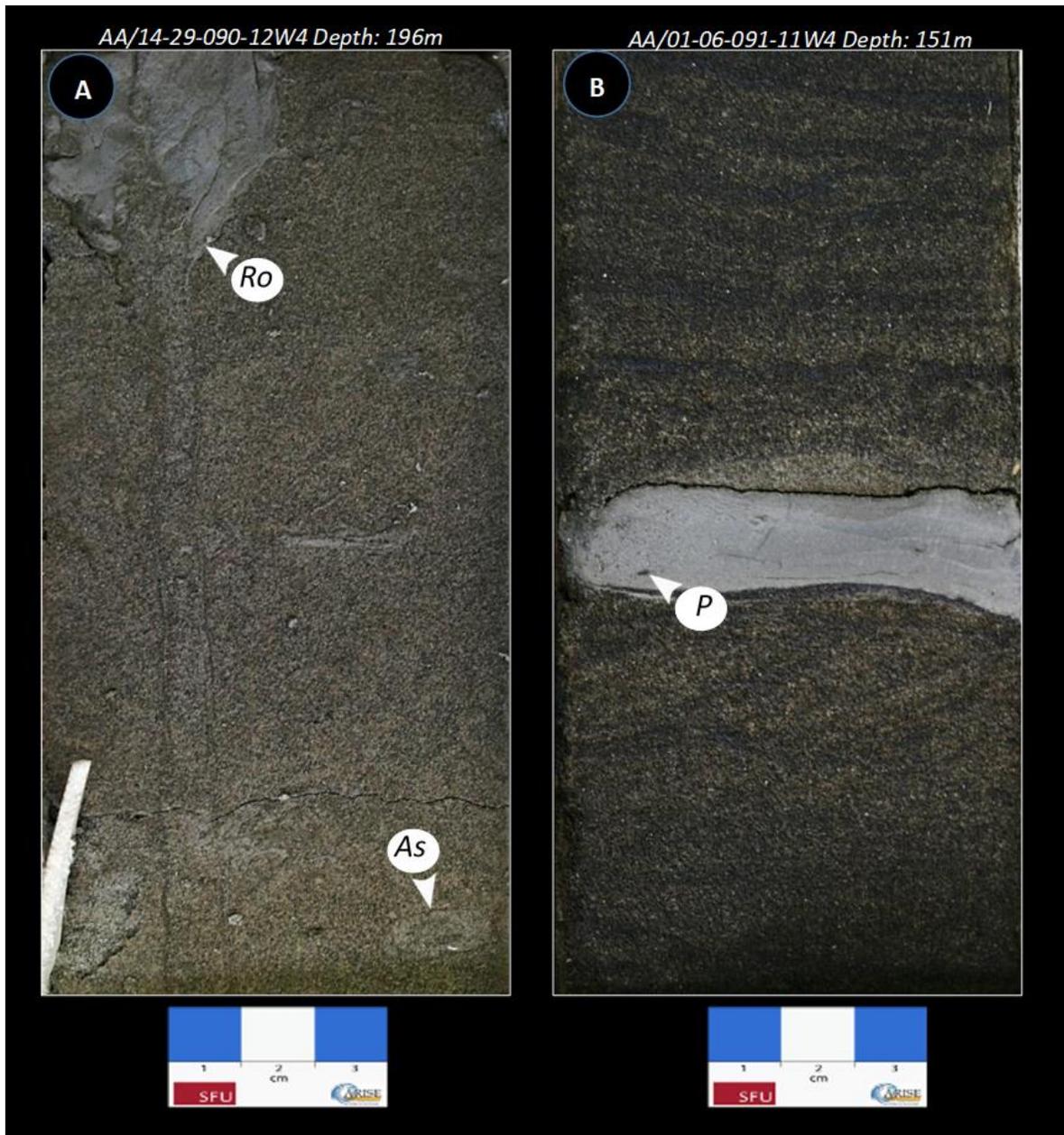


Figure 2.15 A) Apparently massive F9 with robust *Rosselia* (*Ro*) and *Asterosoma* (*As*). B) F9 with storm-generated structures and fluid mud bed. There are combined flow ripples as well as low-angle parallel laminae towards the top. The mud bed shows *Planolites* (*P*) and possibly some grazing structures near its upper margin

## **2.10. FACIES 10 - Bioturbated, dark grey mud with wavy lamination and very fine sand lenses.**

### *Description:*

Facies 10 consists of dark grey mud with intercalated lenses of very fine-grained sand. The facies is sporadically distributed across the study area. Where present, the thickness of the bedset varies from decimetre to metre scale. The proportion of mud ranges from 80-90% of the composite bedset. Primary sedimentary structures comprise lenticular bedding, soft-sediment deformation, wavy parallel lamination, and starved oscillation ripples within the sand. Syneresis cracks, micro-faults and siderite are present locally. The thickness of the sand lenses is typically millimetre scale, but it can reach centimetre scale locally. BI values vary from 1 to 3, and trace fossil suites include traces *Asterosoma*, *Planolites*, *Schaubcylindrichnus freyi*, *Thalassinoides* and *Zoophycos*.

### *Interpretation:*

Facies 10 (Fig. 2.16) largely records rapid mud accumulation as discrete layers, with variations in flow conditions that led to deposition of the isolated sand lenses. These lenses consist of starved oscillation ripples, consistent with subaqueous deposition in the presence of wave-induced orbital flow. The intercalated wavy parallel lamination within the mud is consistent with dynamic mud accumulation (e.g., MacKay and Dalrymple, 2011). The mud beds likely reflect fluid mud accumulation, although such layers could also be a combination of bedload (traction) transport and rapid (flocculated) suspended sediment settling from buoyant plumes. The presence of syneresis cracks indicates salinity fluctuations, probably caused by hyperpycnal bedload material carried by river influx or by storm processes bringing flood-induced fresh water into a more marine system or due to flocculation of mud carried in the fresh-water buoyant plume. Such high-energy periods of brackish-water conditions are not favorable for substrate colonization. Soft-sediment deformation is indicative of rapid deposition. The trace fossil suite indicates a fairly more marine setting, even though there are still physico-chemical stresses that influenced the system, reducing ichnological diversity as well as bioturbation intensity.

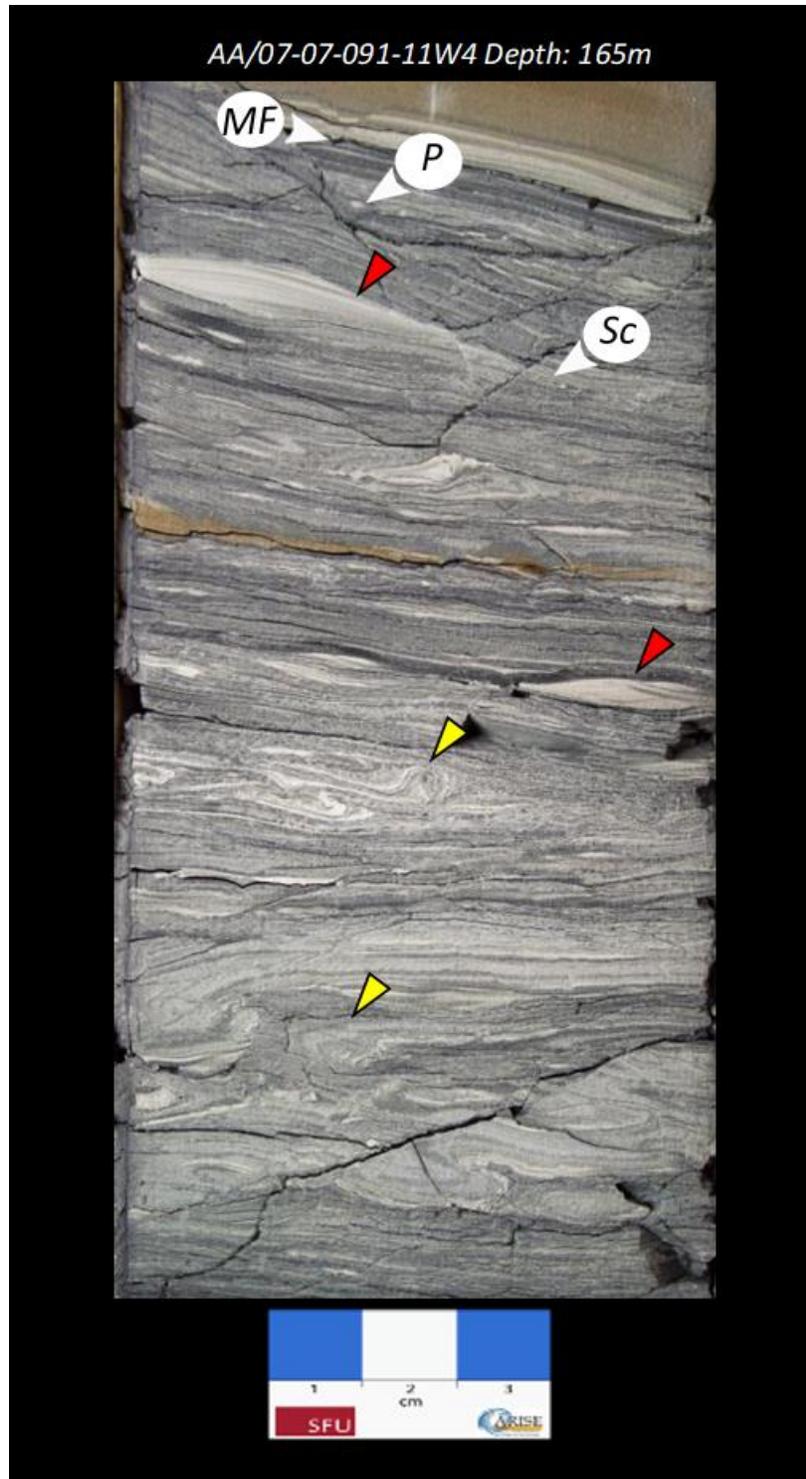


Figure 2.16 Facies 10 showing wavy lamination, and very fine-grained sand lenses recording starved oscillation ripples (red arrow). Micro-faults (MF), syneresis cracks (Sy), siderite, soft-sediment deformation (yellow arrows) is present. Trace fossils include *Planolites* (*P*) and *Schaubcylindrichnus freyi* (*Sc*).

## 2.11. FACIES 11- Bioturbated glauconitic sand to muddy sand.

### *Description:*

Facies 11 comprises a green, glauconitic, fine- to medium-grained sand to muddy sand (Fig. 2.17). The contact with the underlying facies is sharp and commonly erosional, and is characterized by an abrupt change from quartz sand to green, glauconitic quartz sand that typically has variable concentrations of interstitial silt and clay. Bitumen is patchily distributed and most intense in sandier intervals. Bedsets can be several metres thick. The sedimentary structures are mainly characterized by parallel lamination in the mud and local remnant wave ripple cross-lamination in the sand. The mud beds are fractured. Siderite is locally present, mainly associated with the mud beds. BI values range from 2-5, with the higher bioturbation indices more common. Burrow sizes are robust. Trace fossils include *Asterosoma*, *Chondrites*, *Diplocraterion*, *Ophiomorpha*, *Palaeophycus*, *Phycosiphon*, *Planolites*, *Rosselia*, *Skolithos*, *Teichichnus*, *Taenidium*, *Thalassinoides*, and *Zoophycos*.

### *Interpretation:*

Due to bioturbation, most primary sedimentary structures are obliterated. In zones of reduced bioturbation, the sand preserves oscillation ripples, indicative of wave-influenced conditions. Fractured intervals of gray mud are rare; muds are locally cemented with siderite. Facies 10 is characterized by fairly abundant glauconite. The glauconite content is believed to be *in situ*, because of its presence in the sand as well as in the interstitial mud. Preferential concentration in the sand is more typical of winnowing and mobilization of the glauconite as part of a transgressive lag. The trace fossil suite is manifest by a robust, fully marine assemblage, particularly expressed by the common presence of *Zoophycos*, *Phycosiphon* and *Asterosoma*. The *in situ* development glauconite within the sand is evidence of a change in the setting from brackish-water conditions to more open marine conditions associated with transgression of the Boreal (Clearwater) Sea (e.g., Keith, 1988).

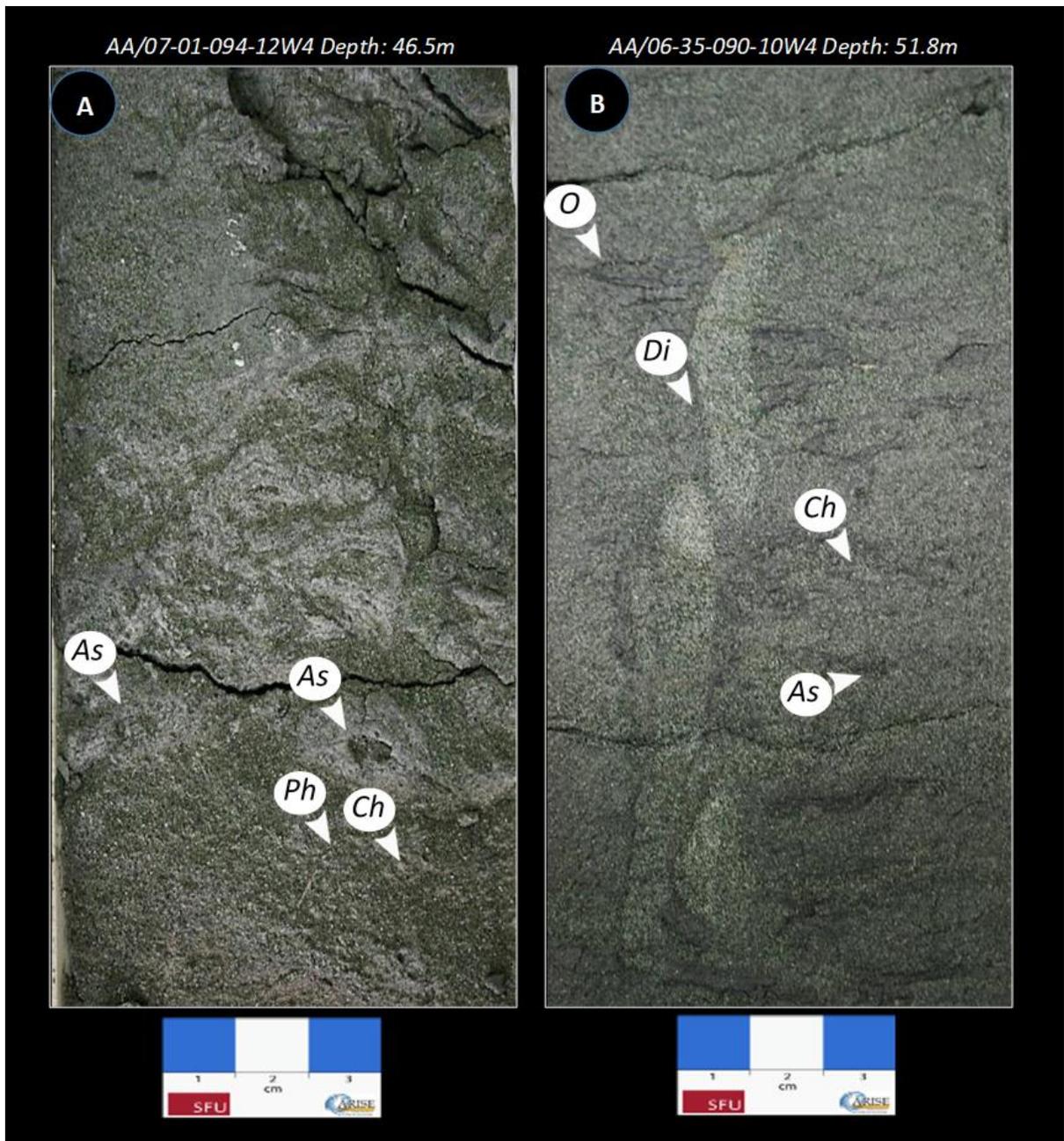


Figure 2.17 A and B: Glauconitic sand of Facies 11, with *Asterosoma* (As), *Chondrites* (Ch), robust *Diplocraterion* (Di), *Ophiomorpha* (O) and *Phycosiphon* (Ph).

## 2.12. FACIES 12 - Bioturbated, wavy and lenticular bedded dark grey/green sandy to silty mud

### *Description:*

Facies 12 (Fig. 2.18) is represented by dark grey/green, bioturbated sandy mud to silty mud. The contact with the underlying facies is gradational, but locally can be sharp. The facies is dominated by lenticular bedding, wherein very fine-grained sand lenses are intercalated within the mud. Mud constitutes 70-95% of the unit. Mud layers are commonly fractured but contain internal parallel laminae of silt and sand, locally showing normal grading. The sand lenses within the muds are characterized by starved oscillation ripples or are apparently structureless. The sand lenses can vary from few millimetres up to a centimetre in thickness. BI values range from 1-4, and is higher in the mud than in the sand. The trace fossils include *Asterosoma*, *Chondrites*, *Planolites*, *Phycosiphon*, very rare *Rosselia*, diminutive *Skolithos*, *Thalassinoides* and *Zoophycos*.

### *Interpretation:*

Lenticular bedding records short-lived periods of physical energy that produced starved ripples during the overall lower energy conditions that favored mud deposition. Internal parallel laminae within the mud also may be indicative of flow rather than suspended sediment settling. There are sharp contacts in the mud that could suggest bedload deposition, consistent with dynamic mud (e.g., MacKay and Dalrymple, 2011). These thin mud layers may have been deposited by rapid fallout of suspended sediment from fluvial plumes, and/or bedload transport of mud by physical processes such as longshore drift or tides. Bioturbation probably occurred during pauses in deposition. The low diversity of trace fossils in some intervals may be related to rapid deposition and/or to slightly reduced dissolved oxygen in a quiet-water, fully marine setting (e.g., Dashtgard et al., 2015; Dashtgard and MacEachern, 2016).

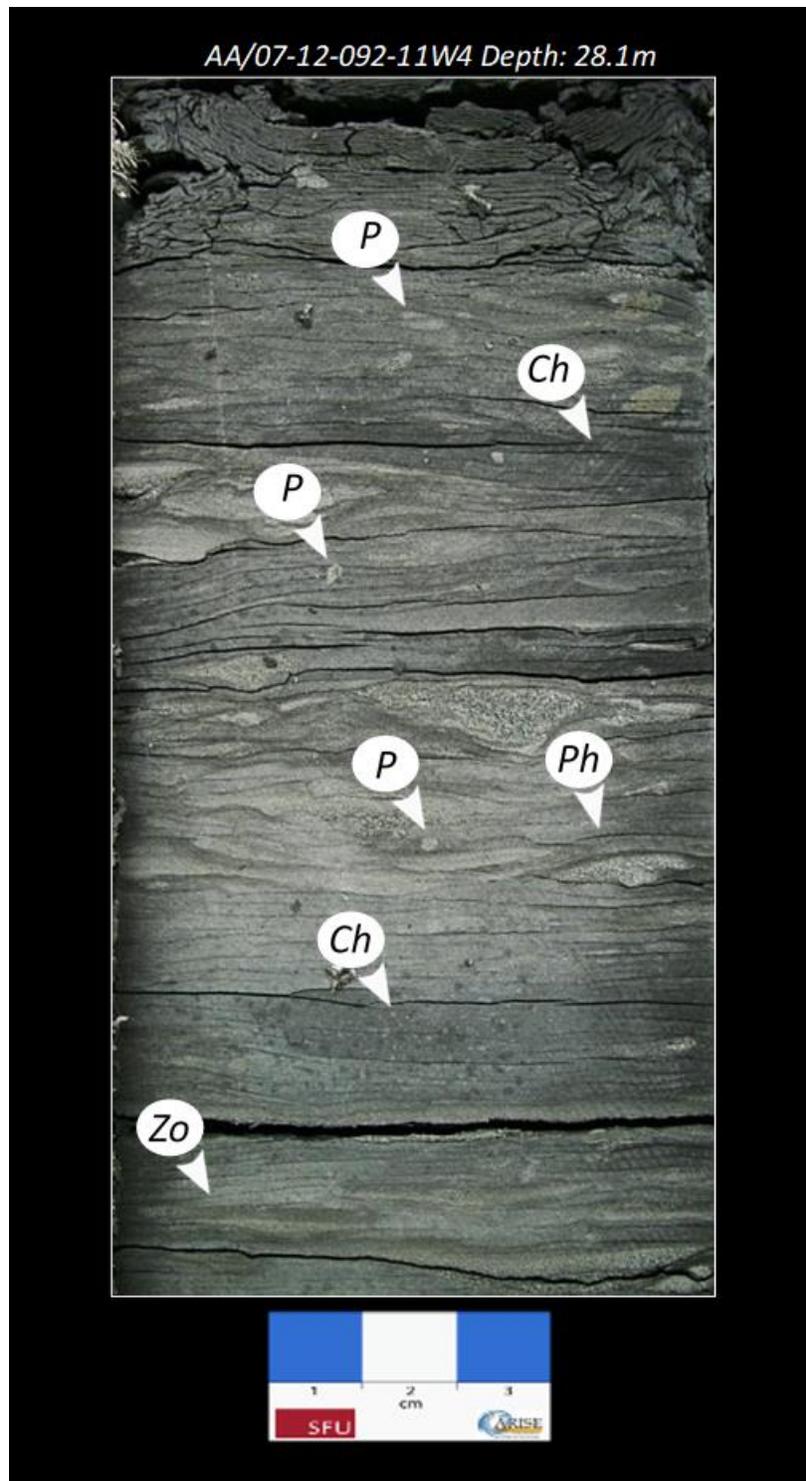


Figure 2.18 Facies 12 showing light grey to dark grey mud with lenticular bedding and parallel lamination. *Chondrites* (*Ch*), *Planolites* (*P*), *Phycosiphon* (*Ph*) and *Zoophycos* (*Zo*) are present.

## Chapter 3. Facies Associations

The main objective of this thesis is the analysis of different channel types and their IHS complexes within the middle part of the McMurray Formation. Based on the description of the facies (see Chapter 2), four recurring facies associations are identified from the middle McMurray succession in the Central-C study area. These facies associations were established by considering the genetic relationship(s) between facies, as well as the geometries of their stacking patterns. These variations are employed to characterize the channels and to differentiate them using cores and well logs. Facies associations represent tidal-fluvial channel deposits and tidally influenced IHS deposits. Within these FA there are distinctive features that will help to interpret the type of channel/IHS present in the area. These distinctive characteristics are: the thickness of cross-bed sets at the base of the succession, the thickness of the cross-bedded sands, thickness of breccia intervals and the sizes of mud clasts within it, the nature of the IHS intervals, colonization within IHS indicating if the colonization was higher in the sands or in the muds, the type of muds within the IHS and the rhythmicity and regularity of sand beds vs mud beds.

### 3.1. Facies Association 1: Counter Point Bar Deposits

Facies Association 1 (FA1) consists mostly of vertical and horizontal accretion of heterolithic bedsets of F5, which locally coarsen upwards and are capped by F7. FA1 directly overlies the sub-Cretaceous Unconformity, or erosionally overlies remnants of Lower McMurray fluvial deposits. The thickness of FA1 successions ranges between 11m and 28m in the study area. The FA1 succession comprises intercalated weakly bioturbated (BI 0-2) muds and weakly to moderately bioturbated (BI 1-3) sands (F5). The F5 muds in this FA are characterized by being interlaminated with silt and very fine sand. The interlaminae are locally irregular and discontinuous or parallel. It can also be massive in some intervals. BI values are very low (0-2), with *Planolites* the most common trace fossil. Trace fossils are diminutive and not much evidence of vertical burrows are observed. The F5 sand intervals within this style of IHS are characterized by current ripples, combined-flow ripples and parallel laminae (Table 3.1 and Chapter 2). These sandy interbeds show higher BI values than the mud, with a higher occurrence of vertical burrows such as *Cylindrichnus* and *Skolithos*, as well as the presence of

*Planolites*, *Gyrolithes* and *Palaeophycus*. Subfacies F5A and F5B are commonly interstratified in the interval, and pass abruptly upwards into other facies associations (e.g., FA3). In addition, the two subfacies locally pass gradationally into Facies 7. Abundant sideritized intervals are characteristic, particularly where F5 directly overlies the SCU. Locally, deposits of F5 are overlain by bioturbated heterolithic intervals of F7, characterized by composite heterolithic bedsets comprising intercalations of inclined, fine-grained sand and light brown/gray mud. Trace fossils are present within F7 in both bed types, but generally show higher BI levels in the mud beds. See Table 2.1 for a summary of facies characteristics.

### *Interpretation*

FA1 is interpreted to represent IHS associated with counter point bars at the margins of channel bodies, where water levels fluctuated between high and low tide. Counter point bars are characterized by a concave scroll pattern and high mud content (Fig. 3.1) (Smith, 2009). Preserved channel axes do not comprise IHS intervals, as they appear to have possessed the highest flow velocities and/or more persistent flows, and are dominated by sand intervals. By contrast, channel margins are more favorable to IHS development, because they are more susceptible to fluctuations in flow velocity and experience intermittent subaerial exposure (e.g., during low tide, neap-spring cycles, and base flow conditions).

The muds present in these IHS deposits are interpreted to have been transported and ultimately deposited by dynamic flow and as bedload, rather than from suspension sediment settling. Paucity of burrowing and the presence of interlaminae of sand within the muds, show evidence of dynamic mud deposition and bedload transport. One location for accumulation of such mud is the turbidity maximum zone (TMZ), where mixing of freshwater and salt water within the channel induces flocculation of the mud and its rapid deposition. The resulting fluid mud indicates significant environmental stress, particularly for organisms trying to colonize these soupy mud substrates.

F5 contains trace fossil suites that are made up of strongly facies-crossing elements, which are commonly interpreted to record brackish-water (salinity stressed) conditions (e.g., Pemberton et al., 1982; Beynon et al., 1988; MacEachern and Pemberton, 1994; Gingras et al., 1999; Bann et al., 2004; MacEachern and Gingras,

2008; Gingras et al., 2016). F5 mudstones generally display low BI values, consistent with physically and/or chemically stressed deposition. Such mud is interpreted to have been supplied during river floods into the TMZ (e.g., MacKay and Dalrymple, 2011; Sisulak and Dashtgard, 2012). BI values are higher in F5 mudstones where F7 is present, suggesting that mud deposition may have occurred under a wider range of conditions in this setting.

High BI values are observed in some sand-prone intervals of F5, interpreted to have been deposited during more uniform though still physico-chemically stressful conditions in a tidally influenced estuary. Infaunal colonization occurred after the deposition of the sand under elevated and more uniform salinities. The muddy intervals in bedsets of F5 with low BI values are also interpreted to have been colonized after its deposition, suggesting that it records a discrete sedimentation event. The colonization of the sand prior to being draped by the mud indicates that sand depositional events were not directly related to the flocculated mud depositional event. The low BI values are likely associated with high deposition rates, mixing of saline and freshwater, rapid mud flocculation, and/or bedload transport of this “dynamic” mud by currents in the channel. That said, it is notable that BI values tend to be higher in F5 mud beds, particularly in locations where F7 is present in the succession. Thus, this could suggest that some muds record slower, gradual suspension sediment settling under reduced energy, allowing opportunistic organisms sufficient time to colonize the substrate and deposit-feed in the mud. One setting favoring a slightly increased BI may be characterized by hypopycnal processes, where the mud settled from intermittent buoyant plumes. Another possibility is either positions upstream or downstream along the edges of the turbidity maximum zone (TMZ), where the interaction of salt water and freshwater generated persistently brackish-water conditions but with low overall depositional energies. A third possibility is that such deposition may have occurred in sheltered zones along the downstream positions of laterally accreting point bars.

Overall, FA1 is mud dominated (e.g., F5; Table 3.1). These muds (F5) are interpreted to represent deposition at the landward edge of the TMZ, wherein mud deposition tends to increase and mud beds thicken (e.g., Gingras et al., 1999; La Croix et al., 2014). However, where F7 overlies F5, FA1 is interpreted to represent vertical accretion, with higher bioturbation intensities (BI 1-3) recorded toward the top of the interval. Previous work from Willapa Bay, Washington, USA by Gingras et al. (1999)

shows that intertidal flats capping IHS tend to have higher BI values due to much slower rates of sedimentation, coupled with abundant and regularly replenished food. Identification of such occurrences is significant, as such scenarios tend to preserve the full thickness of the channel complex. Correspondingly, F7 is interpreted to represent the intertidal portions of FA1.

Siderite and/or Fe-rich precipitates increase in abundance where F5 directly overlies the SCU. This relationship has environmental implications, as it suggests a more continental/freshwater influence within the system (e.g., Postma, 1982). The abundance of siderite in FA1 is consistent with its depositional position along the landward edge of the turbidity maximum zone (TMZ).

High-resolution micro-resistivity image log (HMI) and/or dip-meter log data would be needed to identify and map the distribution of IHS dip angles within FA1 (cf. Brekke et al., 2017; Brekke and Roenitz, in review). Mere descriptions of cores are not sufficient to determine the maximum dip angles of the IHS. In general, cores through F5 never display apparent dip angles steeper than 10°. Image log analyses of the maximum dip angles and dip directions of the sand and mud interfaces would determine whether they preferentially dip into the channel, whether they are aligned parallel to the channel (cf. Sisulak and Dashtgard, 2012), or fan radially, as is typical of point bars (e.g., Brekke and Evoy, 2004; Brekke and Roenitz, in review). Furthermore, identification of any pronounced changes in dip angle or direction is compelling evidence of IHS sets from different stacked channel deposits (Brekke and Roenitz, in review), providing a clearer indication of channel dimensions and architectures.

Previous research on the Fraser River (Dashtgard, et al. 2012; La Croix, et al. 2014; La Croix et al., 2015) demonstrate that there is an increase in the proportion of mud layers and their thicknesses towards the landward edge of the TMZ. This seems to fit the muddy FA1 successions within the Central-C area. Nevertheless, in the Fraser River example, La Croix et al. (2014) showed that it is the muds that are preferentially bioturbated, whereas, in general, the sands are not. This is because the sand is transported by the Fraser River during floods or freshet, and therefore are deposited under both high energy and effectively freshwater conditions. In FA1 of the middle McMurray, however, the beds show an opposite relationship, with the muds displaying the lower BI values and most burrowing associated with the sands. This suggests that

the muds were rapidly deposited in the TMZ and possibly remobilized by the river as bedload mud. The sands, once deposited, were available for colonization. This means that there must have been a period of time available for substrate colonization after sand accumulation prior to mud deposition. This may suggest that these channels did not have a strong fluvial discharge and that the sands were largely introduced by tidal flux. Another possibility is that the TMZ was displaced further landward when the sand was colonized, and was displaced seaward during mud accumulation.

Table 3.1 Facies Associations

	Facies Succession	Lithologic Characteristics	Sedimentary Structures	Bioturbation	Trough-Cross Sets / Current Ripples	Depositional Interpretation
FA1	Devonian Deposits/ SCU/F5B/F5A/F5B/± F7	Aggradational successions of F5, locally coarsening upward where F7 caps the succession.	Planar parallel lamination, irregular parallel lamination, soft-sediment deformation, and rare lenticular bedding. The sand interbeds host current ripples and small-scale planar parallel lamination	Generally BI 0-2 <i>Cylindrichnus</i> (common), <i>Planolites</i> (common), <i>Skolithos</i> , <i>Thalassinoides</i> , and fugichnia	Not observed	Channel-related deposit (counter point bar) of tidal-fluvial channel
FA2	F3±F4/F5B/F5A	Fining-upward succession, generally represented by cross-bedded sands of F3 and chaotic mud-clast breccia of F4, overlain by weakly bioturbated muddy sediments of Facies 5B and/or 5A.	Low-angle, small- to medium-scale trough and planar tabular cross-stratification. Current ripples, soft-sediment deformation, mud flasers, parallel lamination, and some mud laminae are also present.	BI 0-2 <i>Cylindrichnus</i> (common), <i>Diplocraterion</i> , <i>Palaeophycus</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Thalassinoides</i> , and fugichnia	Trough cross-stratification (cm to m scale) and current ripples are present	Channel-related deposit (channel, point bar, counter point bar) of tidal-fluvial channel
FA3	F3±F4/F7A/F7B	Fining-upward succession, consisting of F3 with breccia of F4, passing gradationally into heterolithic deposits of F7A and F7B.	High-angle, small- to medium-scale cross-stratification. Small-scale planar tabular and trough cross-stratification, current ripple cross-lamination (locally aggradational). Mud flasers, horizontal planar parallel stratification and low-angle planar stratification.	BI 1-5 <i>Cylindrichnus</i> (common), diminutive <i>Palaeophycus</i> , <i>Planolites</i> (common), robust <i>Gyrolithes</i> , and diminutive <i>Skolithos</i> , <i>Spirasensus</i> , <i>Thalassinoides</i> and <i>Teichichnus</i>	Trough cross-stratification at the base (cm to m scale). Current ripples upwards in the succession	Channel-related deposits (point bar) of tidal-fluvial channel/ Abandoned large-scale channel
FA4	F3/F4/F6A/F6B	Fining-upward succession, consisting of F3, overlain by breccia of F4 and capped by rhythmic bedded sand and light brown to gray mud of F6.	High-angle, small- to medium-scale trough and planar tabular cross-stratification at the base. High-angle cross-stratification, current ripple cross-lamination, and horizontal planar parallel lamination. Mud couplets and organic detritus as lamina-scale drapes marking stratification.	BI 0-2 Diminutive <i>Skolithos</i> , <i>Planolites</i> and <i>Cylindrichnus</i>	Metre-scale cross stratification	Channel-related deposits closer to TMZ



Figure 3.1 Facies Association 1 in well 01-06-091-11W4- Succession of unburrowed F5B and common siderite (yellow arrows), overlain by F5A with noticeably higher BI within the sandy intervals and practically absent burrowing in the mud beds. Lastly, a repetition of F5B showing more silty/sandy intervals with higher BI values than those in the muds.

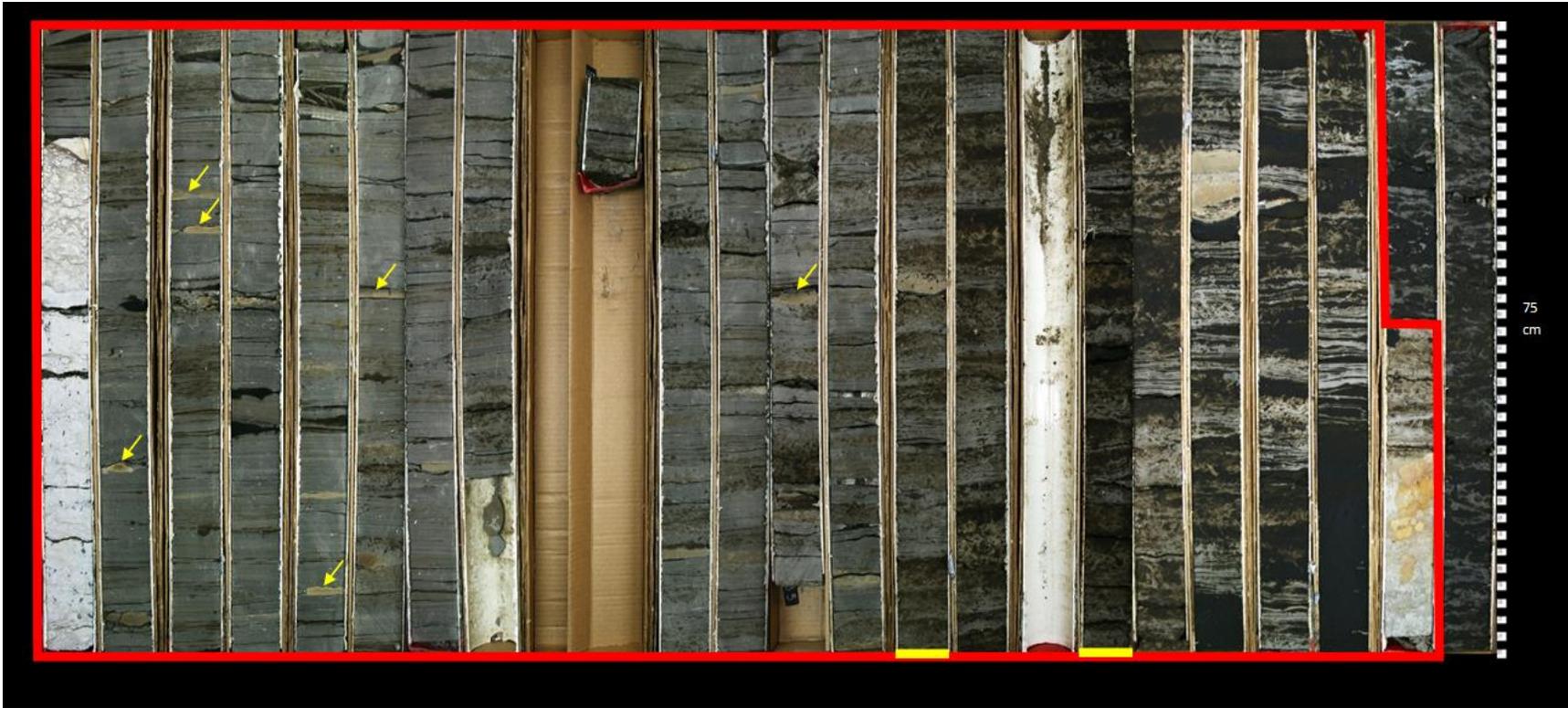


Figure 3.2 Facies Association 1 in well 07-29-093-13W4 - Succession of F5B with higher BI values in the sands and common siderite (yellow arrows) overlain by F5A. Note that the BI values are higher within the sandy intervals and are overlain by F7A, which shows elevated BI values in both the sand and mud beds.

### **3.2. Facies Association 2: Channel and Counter Point Bar Deposits.**

Facies Association 2 (FA2) typically erosively overlies underlying units and shows a fining-upward succession. It is generally represented at the base of the succession by cross-stratified sand and chaotically bedded mud-clast breccia deposits of Facies 3 and Facies 4, respectively, with overlying weakly bioturbated (BI 0-2) mud-dominated heterolithic bedsets of Facies 5 (see Table 3.1 and Table 2.1). The FA2 succession varies from 6 - 30 m thick. Facies 3 deposits are characterized by small- and large-scale cross-stratification associated with subaqueous dunes, with thin bundles of mud drapes and intercalated current ripples. The F3 units within FA2 show mostly small-scale cross stratification (<30cm thick) with only very few occurrences of large-scale cross-bed sets (>30cm). The BI values of F3 in this type of IHS are very low (0-1). Facies 4 comprises randomly oriented mudstone rip-up clasts that range from 1 cm to 5 cm in diameter, and occur in a relatively well-sorted sand matrix. The thickness of Facies 4 within FA2 is less than 2 metres, with the exception of the well 08-05-091-10W4 where F4 has a thickness of 8m. The sedimentological and ichnological features of Facies 5 are very similar to those observed in equivalent facies of FA1. F5 commonly displays interlaminae of silt and very fine-grained sand within the mud beds, characterized by planar parallel lamination, irregular parallel lamination, soft-sediment deformation and, less commonly, lenticular bedding. F5A shows a higher proportion of sand interbeds than does F5B. Sand beds are characterized by current ripples, combined flow ripples, and small-scale planar parallel lamination. The two expressions of F5 are commonly interstratified and may alternate with F3 and F4. The regular interstratification of Facies 3, 4 and 5 demonstrates that they are genetically related and part of the same sedimentary environment.

#### *Interpretation*

The deposits of FA2 are interpreted to have been deposited in a brackish-water environment towards the landward limits of tidal influence. These deposits represent fining-upwards successions associated with channel deposits and muddy point bar/counter point bar deposits.

In contrast to the successions of FA1, the cross-bedded sands of F3 and the mud-clast breccia of F4 are present at the base of the succession. Cross-bedded sediments of Facies 3 can be related to stacked dunes within the same sedimentary body (e.g., mesoforms, macroforms or geobodies; Miall, 1985). This is inferred through the lack of any marked changes in grain size or the presence of mudstone rip-up clasts, suggesting that the different dune sets may actually correspond to bedforms within the same channel. However, to confirm whether such stacked beds were derived from different stacked channels, dipmeter or image log data are essential. Rip-up clasts can be related to either cut-bank deposits or to scour across point bar deposits (e.g., Brekke et al., 2017). Such mud-clasts can be formed in point bar deposits if elevated discharge during floods, for example, allowed erosion of heterolithic lateral accretion bedsets (e.g., Sisulak and Dashtgard, 2012; Choi et al., 2013; Jablonski et al., 2016; Brekke et al., 2017).

Cross-bed thicknesses present at the base of FA2 may be a useful indicator for estimating the scale of the channel. Such cross-beds are, of course, the erosional remnants of stacked bedforms and so give a minimum height of the dunes. Leclair and Bridge (2001) provide a means to calculate the height of dunes by analyzing the preserved cross-set thicknesses. However, such measurements presuppose that the stacked cross-beds record bedforms within the same channel. Dipmeter or image log data are needed in order to confirm that the erosionally stacked cross-bed sets record bedform migration within the same channel, if one wishes to predict original channel scale. As well, the LeClaire and Bridge (2001) calculation is based on the analysis of fluvial channels lacking tidal influence. It has not been confirmed that this relationship persists in tidal-fluvial systems and is a possible direction of future research. The LeClaire and Bridge calculations are related to the size scaling of the dune to water depth, and to the degree of preservation of the bedform during amalgamation. The degree of potential aggradation due to tidal variances in flow depth and flow direction generates uncertainties, as is the case within the McMurray Fm. Nevertheless, by determining potential bedform size, based on stratification thicknesses, may be useful for predicting how deep the producing channel may have been.

Even though it is difficult to apply the methodology proposed by LeClaire and Bridge (2001) to the middle McMurray, owing to the uncertainties associated with tidal influence, what is possible is to compare the general thickness of a complete FA (i.e.,

FA2 cycles with preserved F7; cf. Chapter 2), and to assess its relationship with respect to channel size (cf. Chapter 4). The scale of those FA coupled with the scale of the cross-bed thicknesses will be used in tandem, in order to further develop the hypothesis of this research.

The upper portion of FA2 is interpreted as muddy deposits related to counter point bars within the same channel, which were deposited as concave-shaped deposits caused by a separation zone and eddy currents that were directed upstream (cf. Smith, 2009). These deposits correspond to the previously described F5 (see Chapter 2 or Table 2.1 for details), interpreted as the lateral accretion IHS deposits of counter point bars. Counter point bars can have a similar thickness as their adjacent point bars (Smith, 2009), but the mud contents are noticeably higher. The process of formation of the counter point bars is related to reverse eddy currents that move along the channel in an upstream direction, owing to a hydraulic separation zone formed by the collision of the channel against an erosionally resistant rock (Smith, 2009).

The low levels of bioturbation associated with F3, F4, and F5 correspond to an environment that was less favorable to substrate colonization by opportunistic organisms, such as those exposed to high energy levels. The capping of the succession by units with a high intensity of bioturbation may be an indicator that a more complete succession has been preserved.



Figure 3.3 Facies Association 2 in well 16-06-095-12W4, displaying F3 at the base followed by the muddy expression of the weakly bioturbated F5B and F5A. Notice the very low BI values in the muds and the higher BI values in the sandy beds.

### **3.3. Facies Association 3: Abandoned channels and Point Bar Deposits.**

Facies Association 3 (FA3) comprises a fining-upward succession characterized by F4/F3 at the base, overlain gradationally by F7A and F7B. Locally, thin intervals of F5 cap F7, but these occurrences are only sporadically distributed and uncommon (see Table 3.1). The succession varies from 6 to 45m thick. At the base of FA3, F3 consists of inclined stratification, developing <30cm thick cross-bed sets that in some wells can get up to 1m scale. Current ripples and mud clasts are also present, commonly increasing towards the upper part of the succession. Mud beds are universally discontinuous. The BI values of F3 in this facies association are low to absent; however, where overlain by heterolithic successions of F7, bioturbation intensities within F3 can vary from BI 2-3, especially towards its top. F3 passes gradationally into F7, first through Subfacies F7A and into Subfacies F7B. Nevertheless, exceptions occur locally where the opposite occurs (e.g., in well 12-14-090-11W4, where F3 is overlain by F7B and passes upwards into F7A), or where Subfacies F7A simply is not present (e.g., 05-12-095-13W4). Typical sedimentary structures in sand beds of F7A and F7B are current ripples, aggradational current ripples, and rare oscillation ripples. By contrast, the muds consist of inclined and planar parallel laminae, and locally are normally graded. Bioturbation can be intense and pervasive, reaching BI 4-5. See Table 2.1 for a summary of the facies characteristics.

#### *Interpretation*

FA3 is interpreted as channel-related IHS point bar deposits and abandoned channel deposits. The transition from F3 to F7 may represent progressive lateral accretion IHS produced during channel migration, such that channel floor and channel margin deposits are ultimately overlain by tidal flat deposits. This is consistent with the high BI values, reflecting reduced sedimentation rates towards the middle/upper part of the succession. The sand is interpreted to have accumulated as discrete event beds and actively migrating bedforms, which were bioturbated afterwards. The sand appears to have been abruptly buried by the mud, and then cross-cut by burrows associated with post-depositional colonization of the mud layers. This indicates that the intervening muds also record episodic accumulation and their colonization later.

F4 is less common in FA3 successions compared to FA2. This could indicate that the energy within the FA3 system was lower and, therefore, less collapse of muddy sediments along the channel margins occurred. F3 intervals show higher BI values towards the top of the interval when genetically related to F7. In the upper part of FA3 successions, the proportion of mud beds increases, showing a contrast with the stratigraphically lower, sandy expressions of F3. This might suggest deposition a greater distance from the active channel and associated mud deposition affected by greater tidal influence. Additionally, the higher BI values may indicate that there was more time between depositional events and/or overall lower energy conditions, either of which may have facilitated substrate colonization by opportunistic organisms. Interstratification of F7 and F3 could represent the zone of the channel where the mixing between freshwater and saltwater tended to shift markedly on a seasonal basis, causing more interstratification of rapidly deposited mud from suspension (hypopycnal mud), bedload deposited mud, and beds of sand. Higher intensities of bioturbation may reflect periods of time when the environment became less physico-chemically stressed (e.g., elevated or more uniform salinities), leading to a more stable environment for substrate colonization. This process could have been caused due to abandonment of the channel due to a cutting-off process from the main channel. Therefore, more marine saline water was brought to the system by the effect of high tides, allowing the pervasively colonization of the sediments.

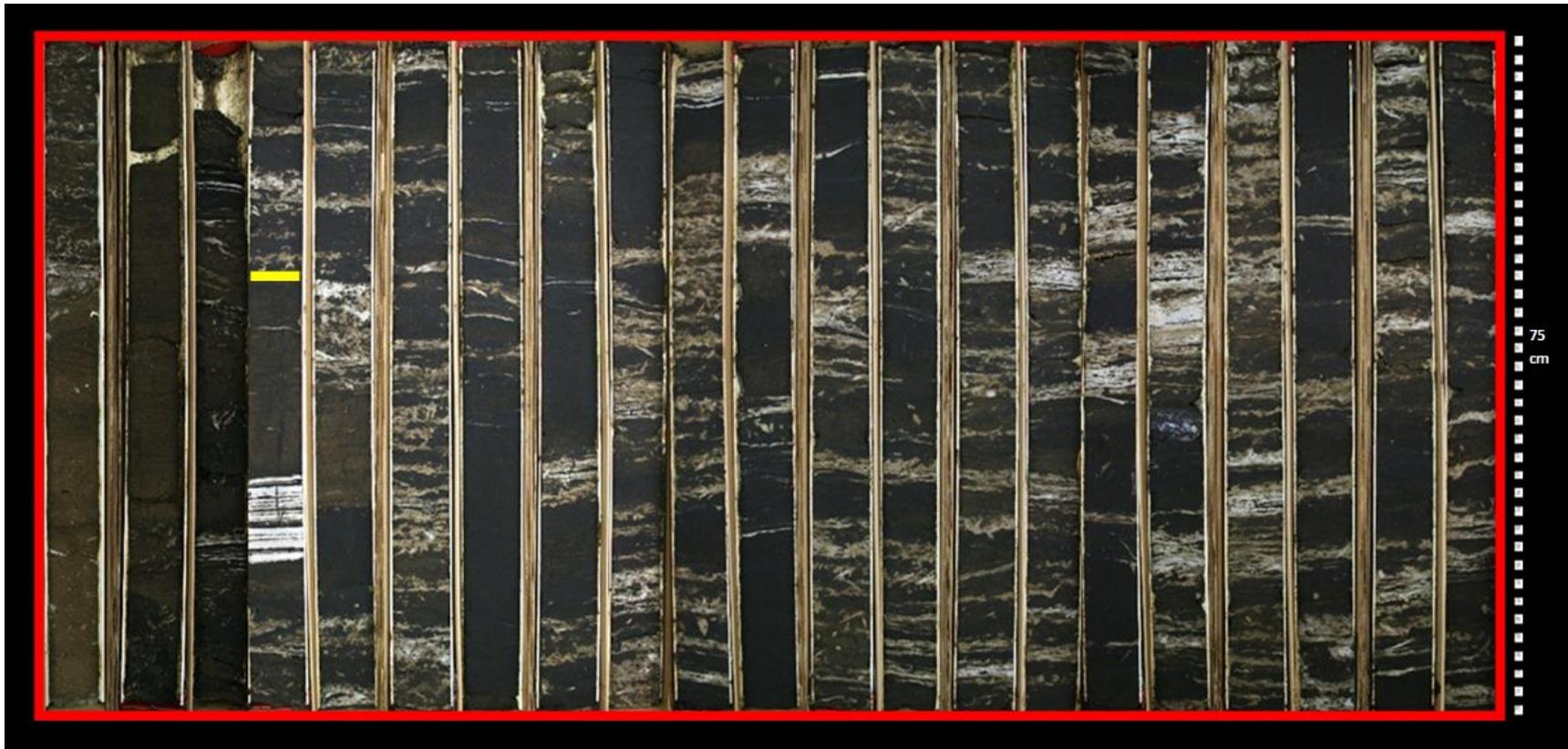


Figure 3.4 Facies Association 3 in well 05-02-094-12W4, showing F3 at the base overlain by a bioturbated heterolithic interval of F7. Note that in this example, the higher intensity of bioturbation is associated with the muds and reduced bioturbation occurs in the sands.

### 3.4. Facies Association 4: Strongly Tidally Influenced Channel Deposits

Facies Association 4 (FA4) is characterized by a fining-upward succession consisting of mud-clast breccias (F4) at the base, overlain by cross-bedded sand (F3), and capped by composite bedsets of rhythmically bedded sand and light brown/gray mud (F6) (see Table 3.1 and 2.1). The typical thickness of the FA4 succession is approximately 28m. The F4 units show chaotically distributed mud clasts with a sand matrix, are generally unburrowed, and locally form thick intervals (6.5m). Sandy cross-stratified intervals of F3 overlie the mud-clast breccias, and generally show BI 0-1. Thin mud laminae are present, as well as carbonaceous laminae and current ripples. F3 is overlain by bedsets of F6, which is characterized by rhythmically bedded, fine-grained sand and light brown/gray mud. Carbonaceous detritus and mud laminae are common. The trace fossils are sparsely distributed and diminutive in size. See Table 2.1 for a summary of the facies characteristics.

Facies Association 4 was only observed in one core (i.e., 04-06-094-11W4) in the Central C study area. It is also the only well that contains Facies 6. Additionally, this succession is also unique, as it is the only core showing a pronounced rhythmic pattern to the sand and mud beds. The expressions of F3 and F4 are very different where they are intercalated with F6, compared to their occurrences in association with F5 and F7. In FA4, the F4 breccias are also noticeably thicker (> 7m) and the sizes of the mud clasts increase significantly as well. The expression of F3 is also unique, displaying several large-scale cross-beds (>75cm thick) with abundant muddy drapes within the cross-beds. The bioturbation is very low (BI 0-1) with mostly absent to very rare occurrences of diminutive *Cylindrichnus*, *Planolites* and *Skolithos*.

#### *Interpretation*

Facies Association 4 is interpreted to represent main tidal-fluvial channel-related IHS showing a strong tidal influence, which induced rhythmicity in the deposition of sands and muds. Low diversity trace fossil associations and reduced BI values suggest a depositional position that was closer to the TMZ but residing on the fluvial (landward) side (e.g., Archer and Hubbard, 2003, Hovikoski et al, 2005; La Croix and Dashtgard, 2014).

Breccia thicknesses are especially great in FA4 (7.5m), indicating very high flow velocities in the system and their ability to erode previously deposited muddy sediments at the channel base and cut-bank margins. The mud clasts within the breccia are large (pebble to cobble sized) and angular to sub-angular in shape, indicating proximity to source and limited transport.

Bioturbation intensities are very low, indicating pronounced physico-chemical stress in the environment. The reduced bioturbation is consistent with being closely related to the transition from fluvial-dominated to tide-influenced environments. As a consequence of this high energy and physico-chemical stress, organisms were largely unable to colonize the strata. The restriction of the trace fossil suite supports the interpretation of proximity to the TMZ, but still residing on the fluvial (landward) side despite the evidence of pronounced tidal rhythmicity.



Figure 3.5 Facies Association 4.in well 04-06-094-11W4 Thick F4 interval with large mud clasts (yellow arrows), overlain by F3 with metre-scale cross stratification (green arrow) capped by IHS showing rhythmic expressions of F6B and F6A.

## Chapter 4. Results and Discussion

The sedimentological and ichnological analysis of the middle McMurray in the Central-C area has led to the identification and differentiation of both large-scale and small-scale channels, each recording deposition in tidal-fluvial environments. In this study, the recognition and analysis of trace fossil suites, sedimentary structures, bed thicknesses of the cross-bedded sands, brecciated intervals at the bases of successions, variations in mud clast sizes in breccia zones, and variations in the characteristics of IHS (bed thickness, bioturbation intensity and burrow distributions) were essential for the differentiating large-scale from small-scale channels (Table 4.1). The relative percentage of mud vs. sand within complete large-scale channel and small-scale channel successions also led to the differentiation of two main subcategories in each: 1) sand-dominated channels, and 2) mud-dominated channels (Table 4.1).

Previous studies have successfully shown that dune size can be estimated, based on the thickness of preserved cross-bed sets (e.g., Bridge and Tye, 2000; Leclair and Bridge, 2001). Dunes typically scale to channel depth, where flow depth is approximately 8 to 10 times the dune height (Leclair and Bridge, 2001; Bhattacharya and Tye, 2004). Bridge and Leclair's equation to calculate the dune height is  $H_m = 5.3\beta + 0.001\beta^2$ , where  $\beta = S_m/1.8$  and  $S_m$  is the mean cross-bed thickness (Bridge and Tye, 2000; Leclair and Bridge, 2001; Bhattacharya and Tye, 2004). However, these studies were carried out using bedform data from fluvial settings and not from tidally influenced systems. The Leclair and Bridge (2001) equation has not been proven to apply to tidally modified bedforms, leading to some uncertainty as to its applicability to successions of the McMurray Formation. As such, the equation is employed as simply one line of investigation into the facies characteristics of large- vs. small-scale channels.

Facies in the middle McMurray Formation in the study area are characterized by the interplay between fluvial and tidal processes, which impacts the size as well as degree of erosional amalgamation of the cross beds. Thus, the tidal influence in the sediments of the McMurray Formation makes it difficult to recognize whether the cross beds of F3 at the bases of channels represent the bulk of the bedform or only a small erosional remnant. In a high accommodation setting, thicker and more complete bedforms might be expected to be preserved. In low-accommodation settings, owing to

erosional amalgamation, large-scale dunes may be strongly eroded, leading to marked underestimation of original dune heights. Finally, tidal environments are prone to marked complexity of their architectures due to stacking of successive channels, making it difficult to recognize the actual dimensions of the original channels (e.g., Dalrymple and Choi, 2005). In order to be more certain about the cross-bed sizes and their dimensions relative to channel succession thickness, one needs image logs and/or dipmeter data. Unfortunately, those data were not available in this study.

The transition zone between purely fluvial and marine environments can be challenging to characterize, owing to the multiple processes operating and their corresponding physico-chemical stresses. These are the result of complex interactions associated with fluvial-sediment input, tidal fluctuation, flocculation of mud in the TMZ, etc. It is hypothesized that small-scale channels preserve facies that are a better indication of the degree of marine influence in the area, because the channels would have carried much less of the fluvial discharge. By contrast, the time-equivalent large-scale channel complexes are interpreted to be the trunk systems that carried the bulk of river flow, and therefore would appear to be more fluvial dominated, show higher energy deposition, and generally display a lower degree of marine influence. In the transition zone, the range of tidal influence increases landward (Dalrymple and Choi, 2005), but that tidal influence is weak; thus, one can hypothesize that a record of tidal influence in an area is more likely to be expressed in facies where the fluvial influence is weaker (e.g., small-scale channels) than those subjected to higher fluvial sediment input (e.g., large-scale (trunk) channels).

A thickness map and net-sand map were generated in Petrel in order to display the distribution of the sand-dominated geobodies. The resulting map shows the general distribution of large-scale channels versus small-scale channels in the study area (Fig. 4.13 and 4.14).

Table 4.1 Characteristics of the different types of channels. Dominant trace fossils indicated by (d).

Type Of Channel Deposit		Facies	F3/F4 Combined Total Thickness	Dune-Scale Cross-Bed Thickness	Breccia Thickness And Size Of Mud Clasts	l/s Thickness	Trace Fossil Suite	Bi	Distribution Of Bioturbation	Average Total Thickness	Maximum Channel Depth Using Leclair & Bridge (2001) Equation
SMALL-SCALE	SANDY	F3, F5	75cm -5m	5-25cm	N/A	6.5m	Sand: <i>Cylindrichnus</i> (d), <i>Palaeophycus</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Teichichnus</i> , <i>Thalassinoides</i> with rare <i>Diplocraterion</i> , <i>Gyrolithes</i> and <i>fugichnia</i> . Traces fossils are robust. Mud: diminutive <i>Planolites</i> (d), <i>Gyrolithes</i> and rare <i>Teichichnus</i> .	Sand: 3-4 Mud: 1-2	Sands and muds are bioturbated, but the sand is more intensely bioturbated than the mud	<15m	Approx. 7m
	MUDDY	F3, F5	75cm -5m	5-25cm	Breccia interval: 20cm-3.5m Clast size: 2mm-6cm	4.5 to 12m	Sand: <i>Cylindrichnus</i> (d), <i>Palaeophycus</i> , <i>Planolites</i> , <i>Skolithos</i> , <i>Teichichnus</i> , and <i>Thalassinoides</i> , with rare <i>Diplocraterion</i> , <i>Gyrolithes</i> and <i>fugichnia</i> . Mud: <i>Planolites</i> (d), <i>Gyrolithes</i> , and rare <i>Teichichnus</i> .	Sand: 3-4 Mud: 1-3	Sands and muds are bioturbated, but the sand is more intensely bioturbated than the mud	<15m	Approx. 7m
LARGE-SCALE	SANDY	Not F7 bearing	F3, +/-F4, +/-F6, +/-F5	7.5-30m	50cm-1.3m	5m to 9.5m	Sand: <i>Cylindrichnus</i> Mud: <i>Planolites</i>	Sand: 0-2 Mud: 1-2	Bioturbation very low, variable, slightly higher in the mud. Generally, BI slightly increases towards the upper part of the succession.	30-45m	Approx. 39m
		F7 bearing	F3, F7, +/-F5	3-8m	Where present, up to 30cm	N/A	15 to 35m	Sand: <i>Cylindrichnus</i> , <i>Skolithos</i> , <i>Thalassinoides</i> , <i>Teichichnus</i> , <i>Palaeophycus</i> , <i>Diplocraterion</i> Mud: <i>Planolites</i> , <i>Cylindrichnus</i> , <i>Skolithos</i> , <i>Teichichnus</i> , <i>Gyrolithes</i>	Sand: 2-4 Mud: 3-5	Sand and mud pervasively bioturbated with irregular distribution of BI	30-40m
	MUDDY	F5 dominated	F3, +/-F4, +/-F5	1-5m	Where present, up to 50cm	14 to 34m	Sand: <i>Cylindrichnus</i> (d), <i>Planolites</i> , <i>Gyrolithes</i> , <i>Skolithos</i> . Mud: <i>Planolites</i> (d), <i>Gyrolithes</i> , <i>Cylindrichnus</i> . Both robust and diminutive elements.	Sand: 1-3 Mud: 1-2	Irregular distribution of BI. Higher BI commonly in sand and lower in mud. Pervasively bioturbated. Intervals of both also present.	25-40m	Approx. 15m

## 4.1. Small-Scale Channel Deposits

Small-scale channel successions display unburrowed to very weakly burrowed cross-stratified sands that pass into weakly to thoroughly bioturbated IHS intervals. The vertical successions in this type of channel are mainly composed of FA1 and FA2, which are associated either with sandy or muddy IHS deposits. Nevertheless, it is more common to find them related to muddier IHS deposits (6 cored wells out of 7). Small-scale channel intervals are represented by 3 or 4 recurring sedimentary facies (Table 2.1 and Table 3.1). Commonly, relatively thin expressions of individual cross-stratified sand beds (5-25 cm) within F3/F4 occur at the base of the succession, forming a stacked bedset ranging from 15cm up to 2m thick. The total facies interval of combined F3 and F4 is also thin, ranging from 75cm to 5m thick, which indicates small- to modest-sized bedforms in the channel with less erosion of the channel margins and possibly greater aggradational fill. In this study, the combined F3/F4 total facies interval thickness falls into the classification as “small-scale” channels. These sandy F3/F4 intervals are interpreted as the basal portion of a tidally dominated channel, showing the migration of small subaqueous dunes, as evidenced by the small-scale cross-bed sets. Applying the Leclair and Bridge (2001) equation, cross-beds of 5 to 25cm thick would suggest channel depths of about 2 to 7m.

The thickness of the cross-stratification within F3 of small-scale channel deposits ranges from ripple scale (1-5cm) up to small dunes (max. preserved thickness of 25cm), indicating that the energy was generally low (Pettijohn, 1987; Glover, 2007). This also implies that the water depths were not great at the time of deposition. The progressive reduction of water depth can also be inferred by the upward diminishment of cross-bed thicknesses from the base to top of the succession (e.g., Jablonski, 2016).

The breccia interval thicknesses and mud clast sizes present in F4 are also generally smaller, compared to those in large-scale channels. The thicknesses of the brecciated intervals range from 20 cm to 3.5 m, with mud clasts that vary from 2 mm up to 6 cm in diameter. The thinness of this facies within deposits of small-scale channels suggests that current flow was insufficient for creating steeply undercut outer margins, also suggesting that the channels were somewhat more aggradational and that the lateral migration was not rapid.

IHS intervals overlying the cross-stratified sands of F3 also vary in thickness, showing an average of 7m. The thickness of individual beds of sand and mud within the IHS are quite variable and unpredictable with moderate to high BI values. IHS deposits of the small-scale channels, whether sand-dominated (Fig 4.1) or mud-dominated (Fig. 4.2), are generally bioturbated, showing BI 3-4 in the sand beds and BI 1-3 in the muds (Fig. 4.4). In the sand beds, suites are dominated by facies-crossing elements, characterized by relatively robust *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus*, *Thalassinoides*, with low numbers of *Diplocraterion*, and *Gyrolithes*, and rare fugichnia (Fig. 4.3). Mud beds contain low numbers of diminutive *Planolites*, *Gyrolithes*, and sporadic occurrences of *Teichichnus*. The facies also contains rare and sporadically distributed syneresis cracks. Small-scale, channel-related muddy IHS are interpreted to have been deposited by channel migration during seasonal variations in discharge. The sand was deposited during relatively high energy and rapid periods of sedimentation. This could have been caused by the draining of the flats caused by the saline water invading the area during high tides. Also, the sands might have been deposited by river discharge and then colonized later when more saline conditions existed in the channel, but before mud deposition. The mud is interpreted to have been rapidly deposited, but following an extended period of time so that the sand was available to be colonized by the opportunistic fauna. The BI values in the small-scale channels are similar whether the channel succession is sandy or muddy. The lower BI in the mud beds may support greater physico-chemical stress.

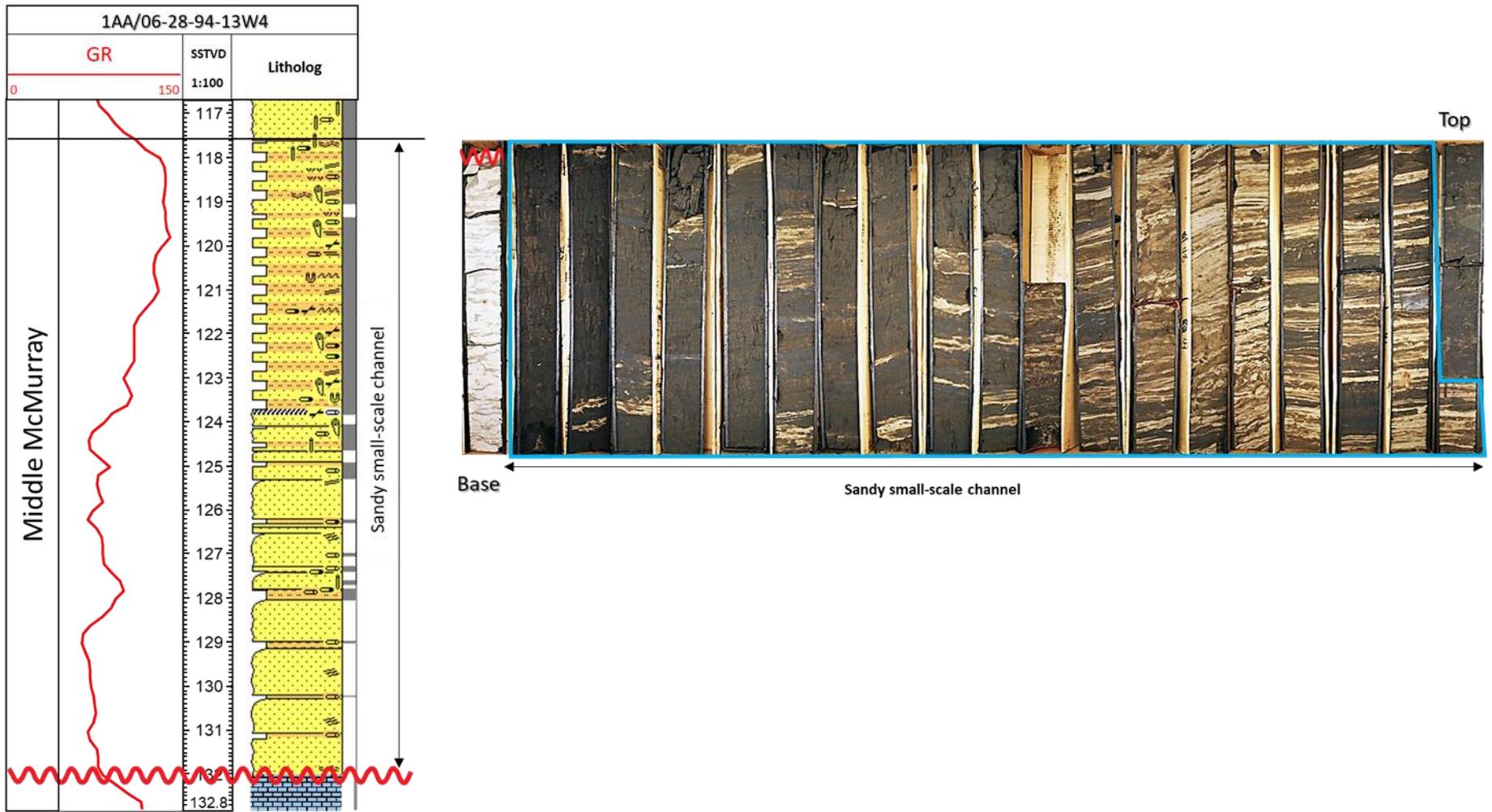


Figure 4.1 Vertical succession of a sandy, small-scale channel in the middle McMurray Fm.

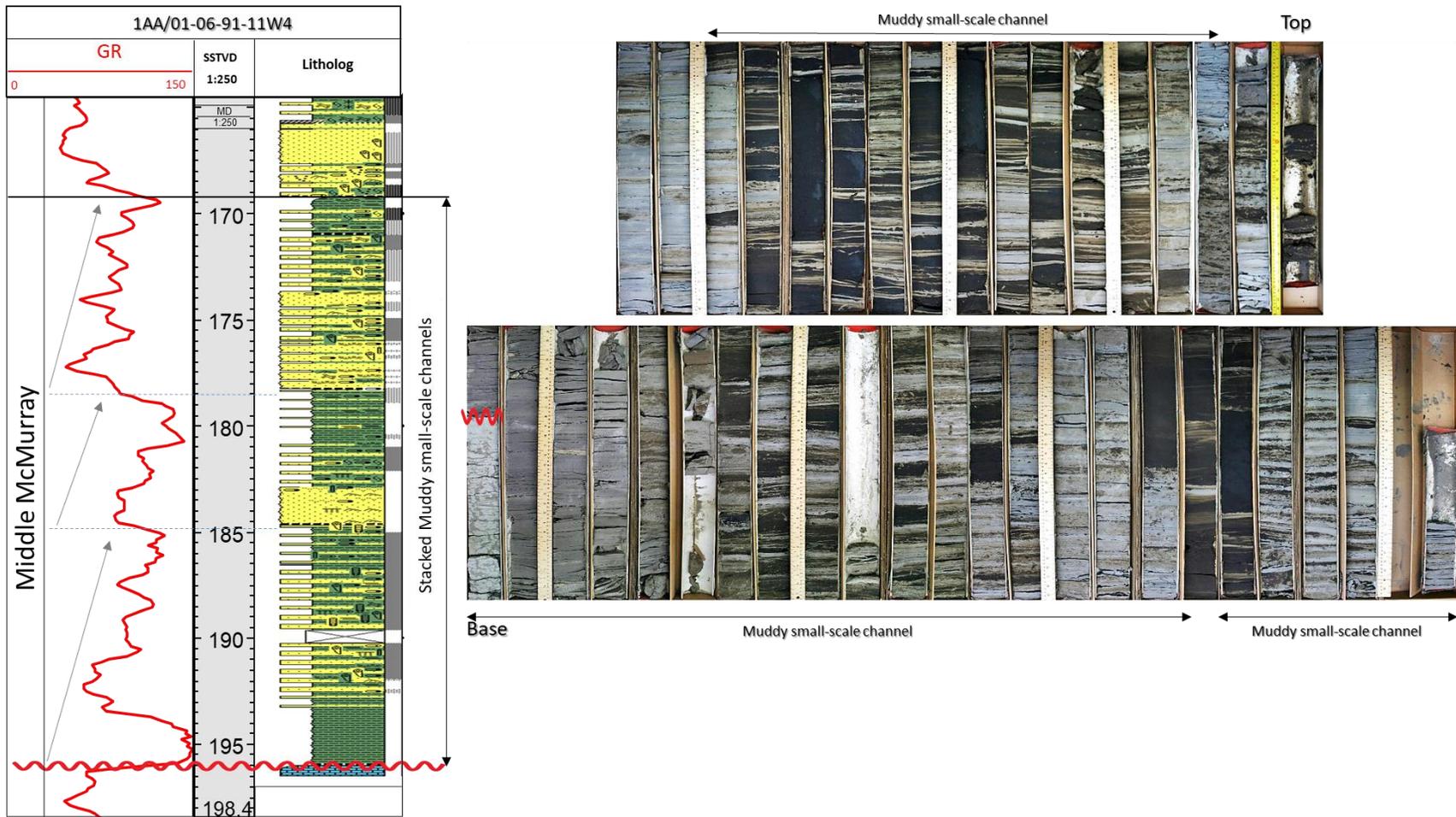


Figure 4.2 Vertical succession of stacked muddy small-scale channels in the middle McMurray Fm.

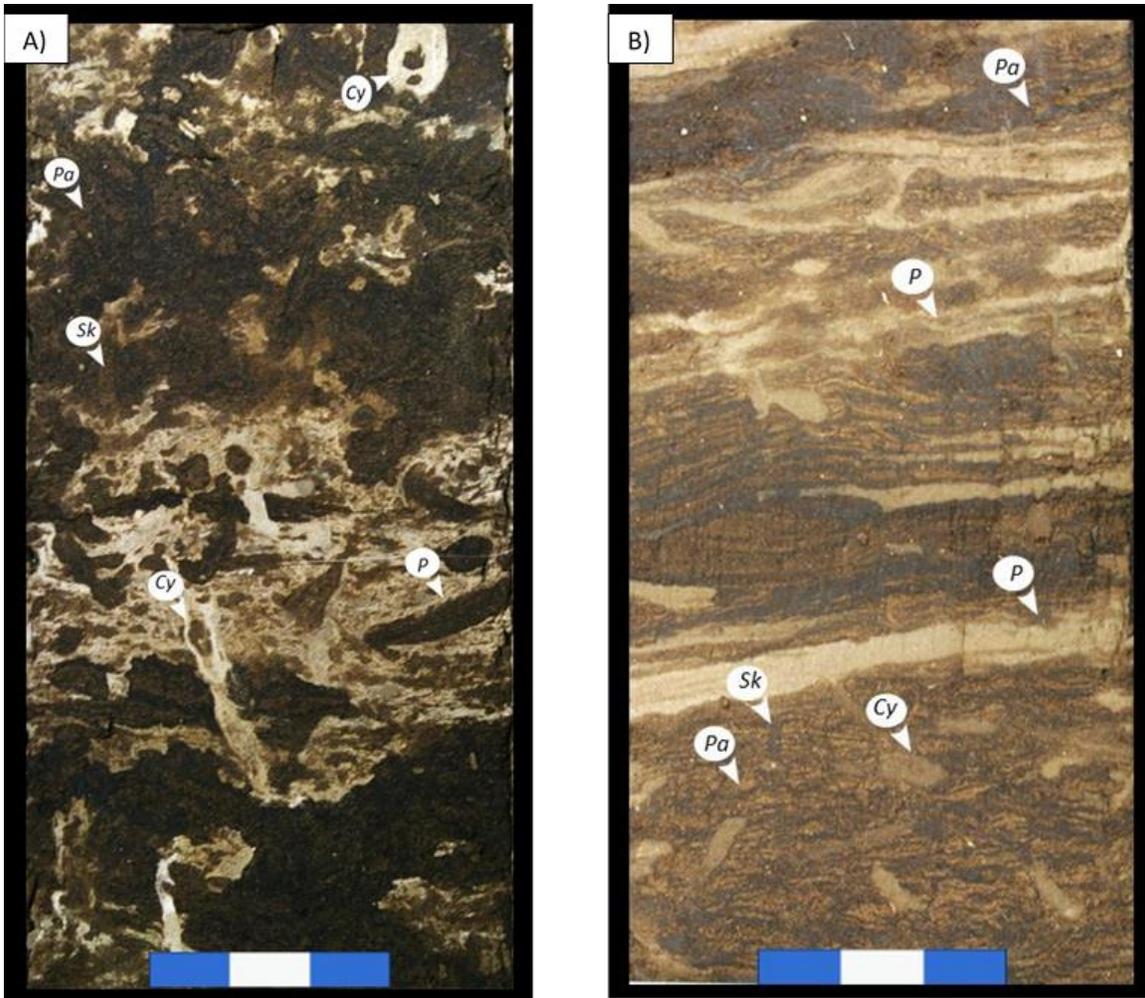


Figure 4.3 Bioturbation in small-scale sandy channels. BI 3-4 in the sand beds and BI 2-3 in the muds. *Cylindrichnus* (Cy), *Palaeophycus* (Pa), *Planolites* (P) and *Skolithos* (Sk).

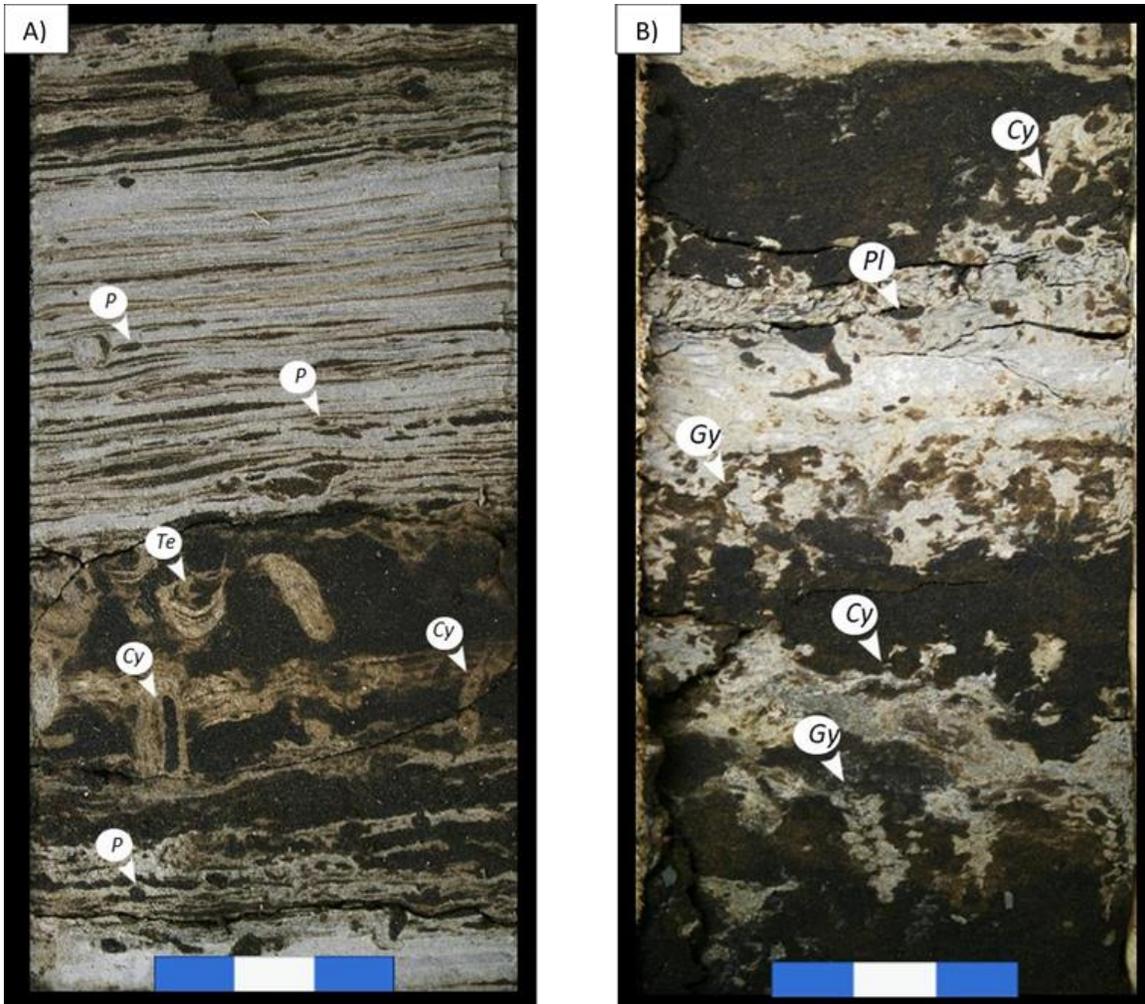


Figure 4.4 Bioturbation in small-scale muddy channels. BI 3-4 in the sand beds and BI 1-2 in the muds. *Cylindrichnus* (Cy), *Gyrolithes* (Gy), *Planolites* (P), *Teichichnus* (Te) and *Skolithos* (Sk).

## 4.2. Large-Scale Channel Deposits

Large-scale channels are represented by a fining-upward succession that encompasses unburrowed cross-stratified sandstones that pass into thoroughly to weakly bioturbated heterolithic IHS intervals. This type of channel is believed to represent the main conduits of fluvial sediment influx into the system in the study area. Such large-scale trunk channel systems are interpreted to have carried a high volume of sediment with high energy levels. Large-scale channels are generally represented by 4 or 5 recurring sedimentary facies: F4, F3, F5, F6 and F7, and by facies associations FA2, FA3 and FA4. F4 may be or may not be present in the succession. The IHS deposits in the large-scale channels can be differentiated into two main subcategories – sand dominated and mud dominated.

### ***Large-scale channels with sand-dominated IHS:***

Large-scale channels with sand-dominated IHS are believed to represent the main conduits of fluvial discharge into the Central-C area. These sand-dominated large-scale channels are characterized by thick intervals of F3 and F4 at the base of the succession, followed by heterolithic intervals of F5/F6 that extend to the top (Fig. 4.5). The thicknesses of the individual sand beds vary from 20cm up to 1.5m, with bedsets ranging from 1.9 to 2.8m thick. The F3 total interval ranges from 7.5m up to 30m thick. F4, where present, reaches 6.5m in thickness. Cross-bedded sands are interpreted to record deposition in the deeper parts of the channel. The cross-beds within the sand-dominated large-scale channels range from 20cm up to 1.3m thick, indicating that the channels carried enough sediment with sufficient energy to induce the migration of fairly large dunes. This, in turn, suggests that the water depths were significant (Pettijohn, 1987; Glover, 2007; Jablonski, 2012, 2016). The Leclair and Bridge (2001) equation would suggest flow depths of up to 39m (Table 4.1). Where F4 is present at the base of the succession, there is a general lack of large-scale cross-bed sets. This is because the chaotic accumulation of the breccia interval from bank collapse created irregular turbulence at the bed and inhibited dune formation. These basal mud-clast breccia intervals are interpreted to record close proximity to the cutbank margin of the channel.

Sand-dominated large-scale channels tend to encompass very thick mud-clast breccia intervals (F4) at the base of the succession, which range from 2m up to 4.5 m thick. Mud clasts range in size from 0.1-20 cm in diameter. An anomalously thick breccia

interval occurs in well 04-06-094-11W4, reaching 6.5m. Individual mud clasts reach approximately 60cm in diameter. Sizes larger than the core barrel diameter were identified by the angular discordance between the clasts' internal stratification and the bedding contacts in the interval. The transport distances of the individual large mud clasts within the breccia are believed to have been short, due to their angular shapes and poor sorting. The thick intervals of breccia within the large-scale channel successions are interpreted to represent higher energy conditions within the tidal-fluvial system, and marked undercutting of the channel cutbank margins. Additionally, there are some wells that display thick intervals of breccia, but the clasts within it are small and more rounded. This suggests that they experienced some transportation from their source, indicating a position down-drift of and at some distance from the cutbank margin. However, the best way to prove this is by analyzing image logs and dip-meter logs.

The IHS in the sand-dominated large-scale channels range from 5m to 9.5m thick (Table 4.1), and individual beds of mud and sand show variable thicknesses. This suggest a more fluvial-dominated tidal-fluvial setting. An important exception to this occurs in well 04-06-094-11W4, where even though the thicknesses of the sand vs mud beds vary, their distribution appears quite rhythmic. This constant depositional pattern is interpreted to record a stronger tidal influence (e.g., Sisulak and Dashtgard, 2011). In general, the IHS present in the large-scale sandy channels of the Central-C area are interpreted to have been deposited due to seasonal influence by the effects of strong but short-lived fluvial discharge in an otherwise tidally influenced setting.

Sand-dominated large-scale channels characteristically display low bioturbation intensities. At the base of the succession, F3 and F4 are only weakly and sporadically bioturbated (BI 0-1), and this only increases slightly towards the top of the succession (BI 1-2). Bioturbation intensities in the upper part of the IHS interval are very low (BI 1-2) in both the sand and mud beds (Fig. 4.6). The ichnological suite is of low diversity, and trace fossils mostly include *Cylindrichnus* in the sand and *Planolites* in the mud, consistent with deposition on the landward side and in close proximity to the TMZ. Such positions are characterized by elevated physico-chemical stresses and generally high energy (e.g., Archer and Hubbard, 2003; Hovikoski et al., 2005; La Croix and Dashtgard, 2014).

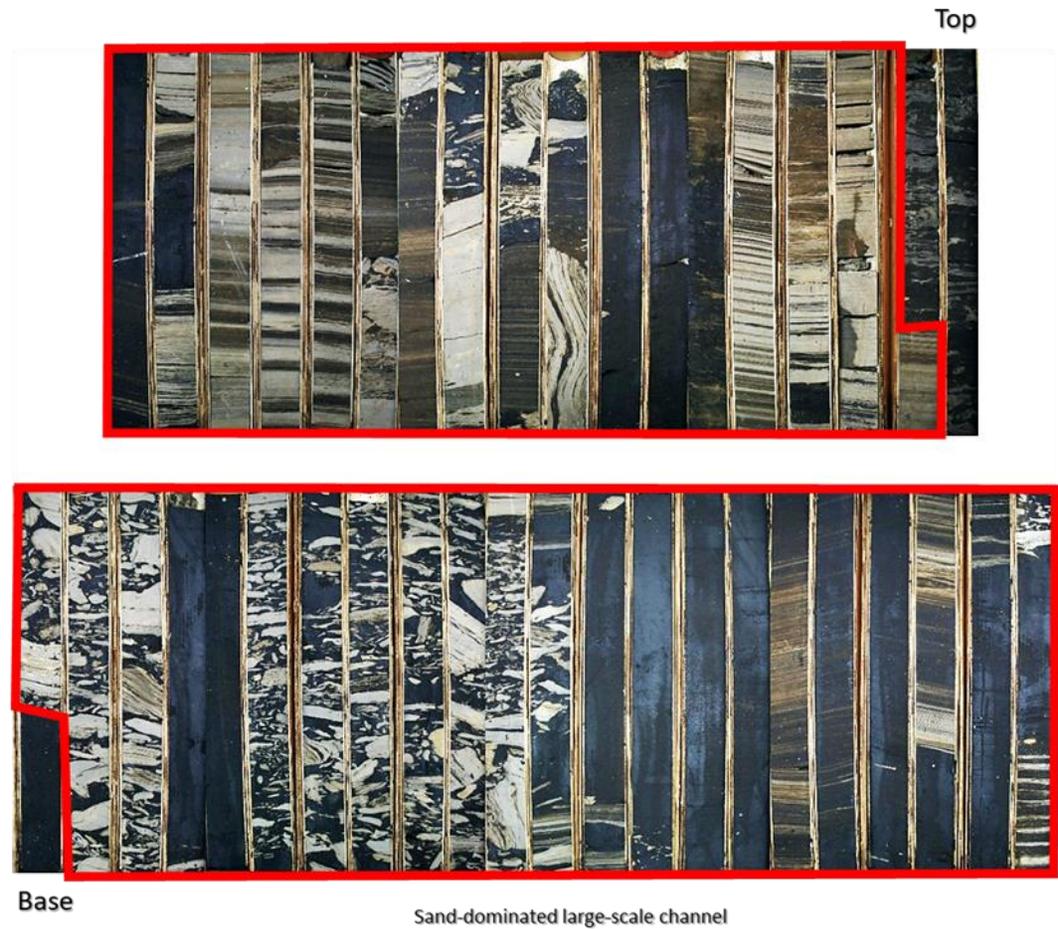
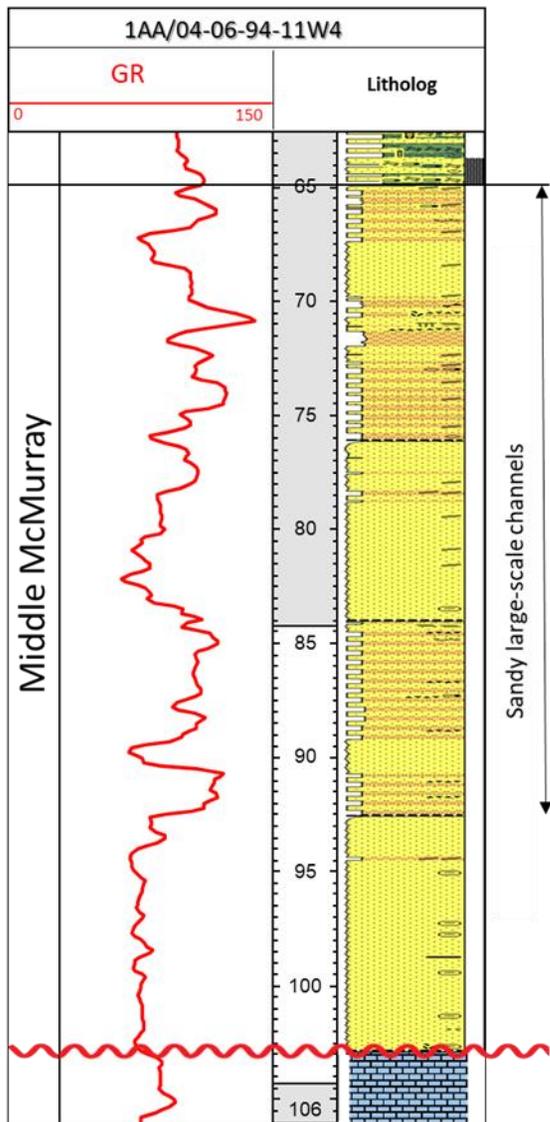


Figure 4.5 Vertical succession of a sand-dominated, large-scale channel in the Middle McMurray Fm.

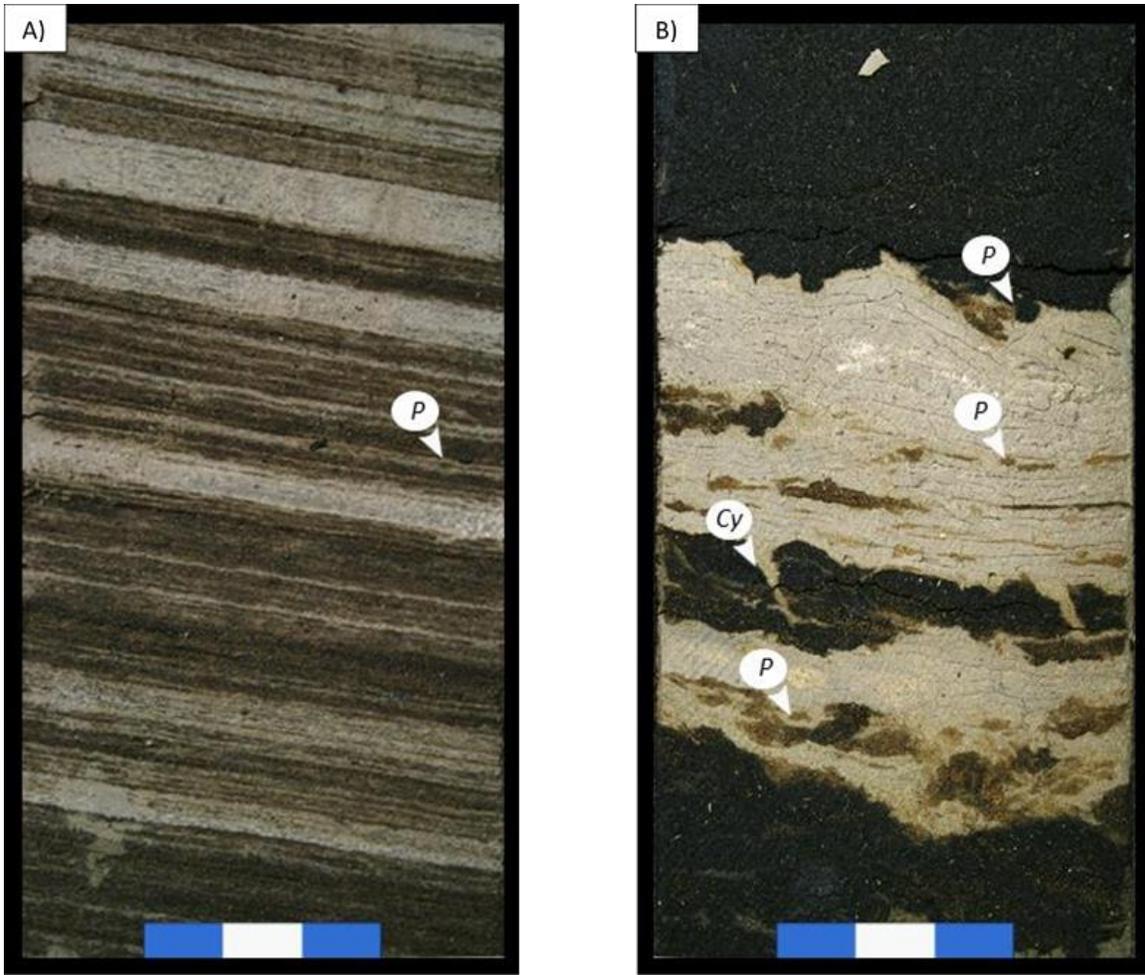


Figure 4.6 Bioturbation in large-scale sandy channels. A) Rhythmic bedding with very low BI in IHS of a sandy large-scale channel B) Bioturbation in large-scale sandy channels. BI 0-1 in the sand beds and BI 0-2 in the muds. *Cylindrichnus* (Cy) and *Planolites* (P)

### ***Large-scale channels – F7-bearing IHS:***

Large-scale, sand-dominated channels with the presence of F7 in the vertical succession (i.e., wells 05-08-094-12W4 and 06-19-094-12W4) are very similar in thickness characteristics to those of the F5 mud-dominated, large-scale channels. F3 deposits are present at the base of the succession with total thicknesses ranging from 3m - 8m. The individual beds of cross-bedded sand are also thin, reaching a maximum of 30cm. Sands, instead, contain occurrences of current ripples with an abundant mud drapes. Mud-clast breccias of F4 are not observed within vertical successions that contain F7. This possibly suggests a greater tidal influence in these systems, which affected deposition during the lateral migration and general aggradation of a relatively low-energy channel. The thin interval of F3 in this type of succession could be due to erosion suffered by the channel at the time of deposition or a result of the positioning of the point bar, which may have been located downstream of the system. The F7+/-F5 IHS intervals range from 15 to 35m thick. By migrating downstream, the preservation of the downstream IHS deposits is enhanced (Smith, 2009; Hubbard, 2011; Labreque, 2011; Ghinassi, 2016) due to weakening of the current at the bend apex, allowing deposition of mud by suspension settling. This is in contrast to what happens upstream, where the point bar IHS is eroded due to persistent channel migration, preserving coarser and sandier sediments (Labreque, 2011; Fustic, 2012; Ghinassi, 2016).

F7-bearing sand-dominated large-scale channel deposits are typically more bioturbated overall (BI 2-4), and both sand and mud beds may show pervasive bioturbation locally. The mud beds show generally higher bioturbation indices (BI 3-5). Trace fossil diversity is also increased, and shows robust *Cylindrichnus*, *Skolithos*, *Thalassinoides*, *Teichichnus*, *Palaeophycus* and *Diplocraterion* in the sand, and *Planolites*, *Cylindrichnus*, *Skolithos*, *Teichichnus* and *Gyrolithes* in the mud. However, BI values can vary locally, owing to thin intervals of F5 interstratified within intervals of F7. Based on the suite of trace fossils combined with the lithological details, the F7-bearing sand-dominated large-scale channels could be interpreted as an abandoned channel that was cut-off from the main trunk channel. After meander cut off, the abandoned channel would have continued to receive basin water during high tides. As such, the abandoned channel would have experienced a reduction in deposition rate coupled with brackish-water conditions not diluted by fluvial discharge. These persistent brackish-water conditions, combined with the lower sedimentation rates allowed the mud and

sand beds to be colonized and pervasively burrowed. Short periods of elevated fluvial input may have caused the sporadic presence of intervals of F5 with weakly bioturbated muds to become interstratified with F7. These low BI mud beds are interpreted to have been deposited rapidly due to flocculation.

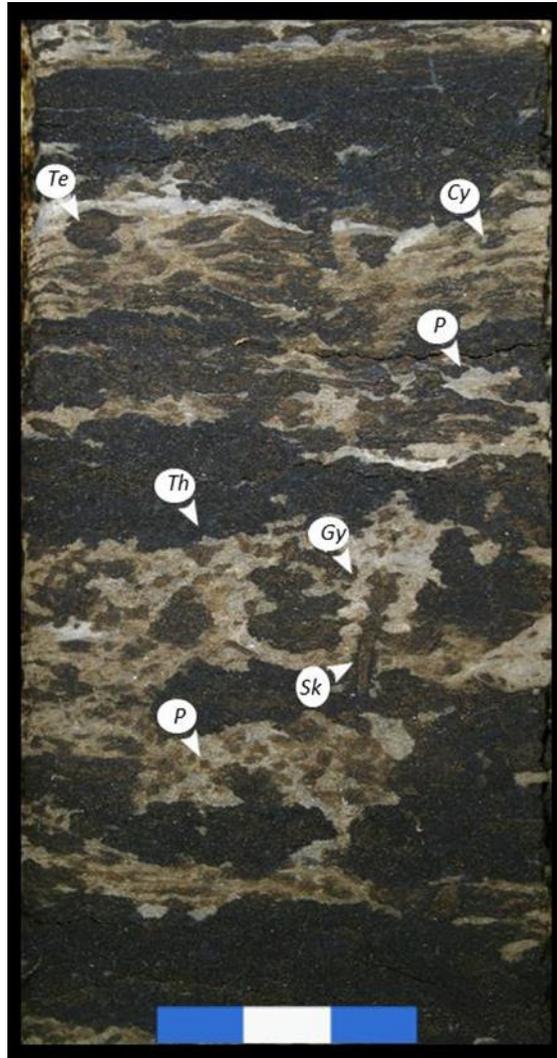


Figure 4.7 High BI in sand and mud beds of a F7-bearing sand-dominated large-scale channel. Unit shows BI 3-4, with *Cylindrichnus* (Cy), *Gyrolithes* (Gy), *Planolites* (P), *Thalassinoides* (Th) and *Skolithos* (Sk)

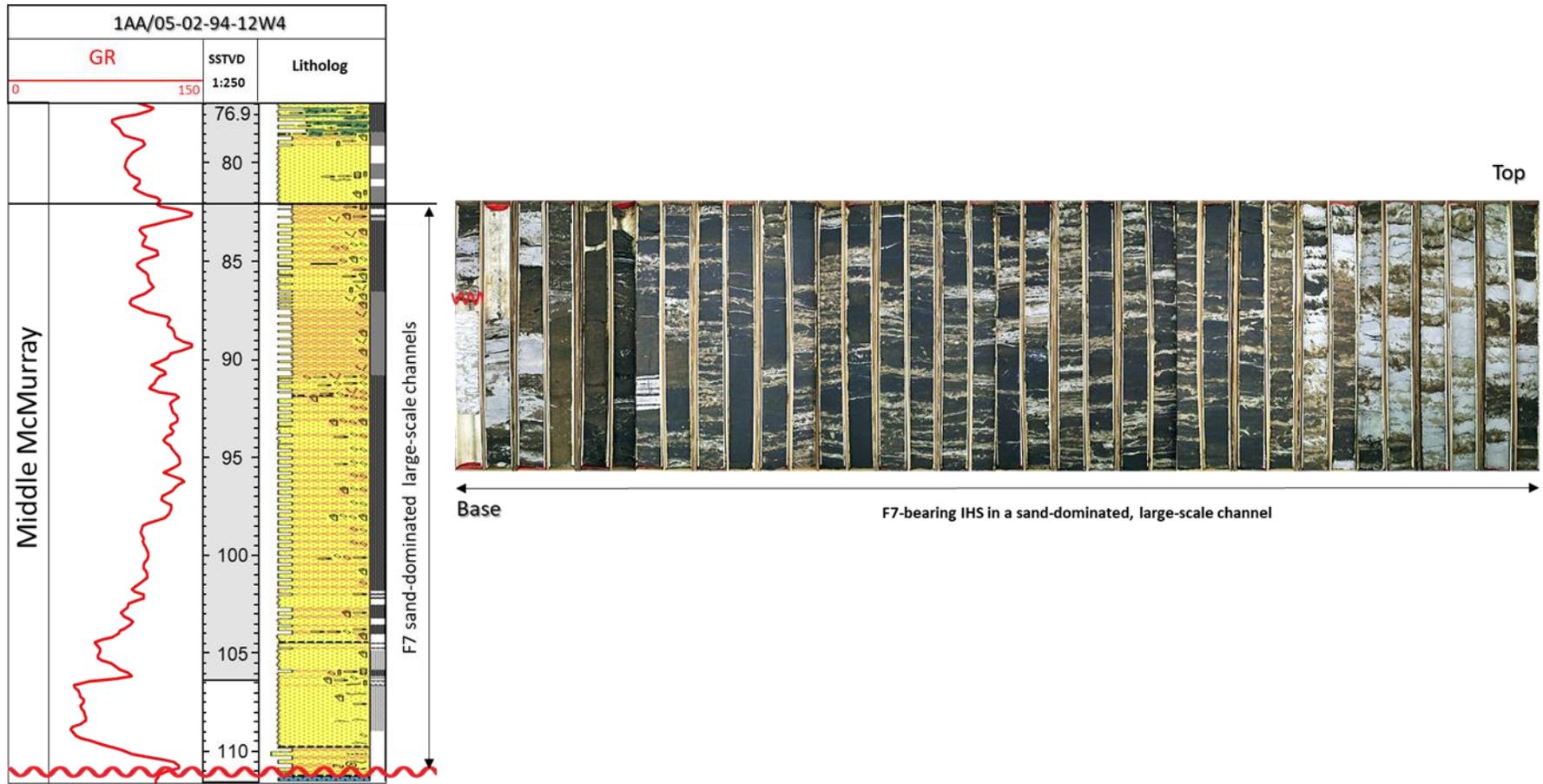


Figure 4.8 Vertical succession of F7-bearing IHS in a sand-dominated, large-scale channel in the Middle McMurray Fm.

### ***Large-scale channels with mud-dominated IHS:***

Mud-dominated large-scale channels are readily discernible in the Central-C area, owing to the abrupt increase in the proportion of mud in the heterolithic intervals visible on well logs. The most common occurrence of muddy large-scale channels is characterized by the presence of FA2, represented by F3/F4 overlain by F5 IHS deposits. Mud-dominated large-scale channels show pronounced differences in terms of BI values and bed thicknesses compared to their sand-dominated large-scale channel counterparts. Further, they also tend to have some similarities with the small-scale channels (Table 4.1 and Fig. 4.9).

### **-Large-scale channels – F5-dominated IHS:**

F5-mud-dominated large-scale channels are represented by relatively thin F3/F4 intervals at the base of the channel, overlain by thick intervals of F5. Complete intervals average 30m thick (Table 4.1). The total combined thickness of F3/F4 basal sediments ranges between 1 to 5 m. F4 isn't consistently present in successions of this type of channel. Where present, it can reach thicknesses of up to 5m, with individual mud clasts up to 20 cm in diameter. The cross-bedded sands are thinner compared to the sandier expression of the large-scale channels, and where present reach thicknesses up to 50cm (Table 4.1). This thinning of the cross-bedded sands at the base of the succession suggests a position closer to the margin of the channel downstream, specifically in the concave scroll pattern where the content of silt of the overlying IHS increases (e.g., Smith, 2009). These 'muddy' IHS could be compared to the fine-grained sediments that are deposited in the more distal part of the point bar, commonly referred to as the 'counter point bar' (Smith, 2009). The thickness of the IHS deposits increases noticeably in comparison to those measured from the sandy large-scale channels. F5-dominated IHS within large-scale mud-dominated channel deposits ranges between 14-34m thick. The mud beds are more variable in their thickness and distribution compared to the sand beds. This might suggest a stronger fluvial influence in the system, with very weak rhythmicity provided by tides. Additionally, the character of the mud (which is weakly bioturbated) may indicate rapid deposition of fine-grained sediment as part of the traction bedload, caused by the flocculation of mud in tandem with input from river currents (e.g., Ranger and Pemberton, 1988, Ranger and Pemberton, 1992).

BI values vary from 1 to 3 within the F5-dominated muddy large-scale channels. Sands typically show a higher bioturbation intensity (BI 1-3; Fig.4.10), with *Cylindrichnus* as the dominant trace fossil, and associated *Planolites*, *Gyrolithes* and *Skolithos*. Most mud beds display low bioturbation intensities (BI 1-2) with suites dominated by *Planolites*, and less common occurrences of *Gyrolithes* and rare *Cylindrichnus* subtending from the sand beds and cross-cutting the mud beds. The trace fossils in the sands are mostly robust, whereas those in the mud beds are predominantly diminutive. Nonetheless, both robust and diminutive forms can be found in both bed types. This implies that the sediment supply of mud must have been high and that the beds were rapidly deposited, leading to elevated physico-chemical stress in the environment and inhibiting colonization of the mud by opportunistic organisms. By contrast, it appears that there was sufficient time between deposition of the sand beds and mud accumulation to allow organisms to colonize the sandy substrate.

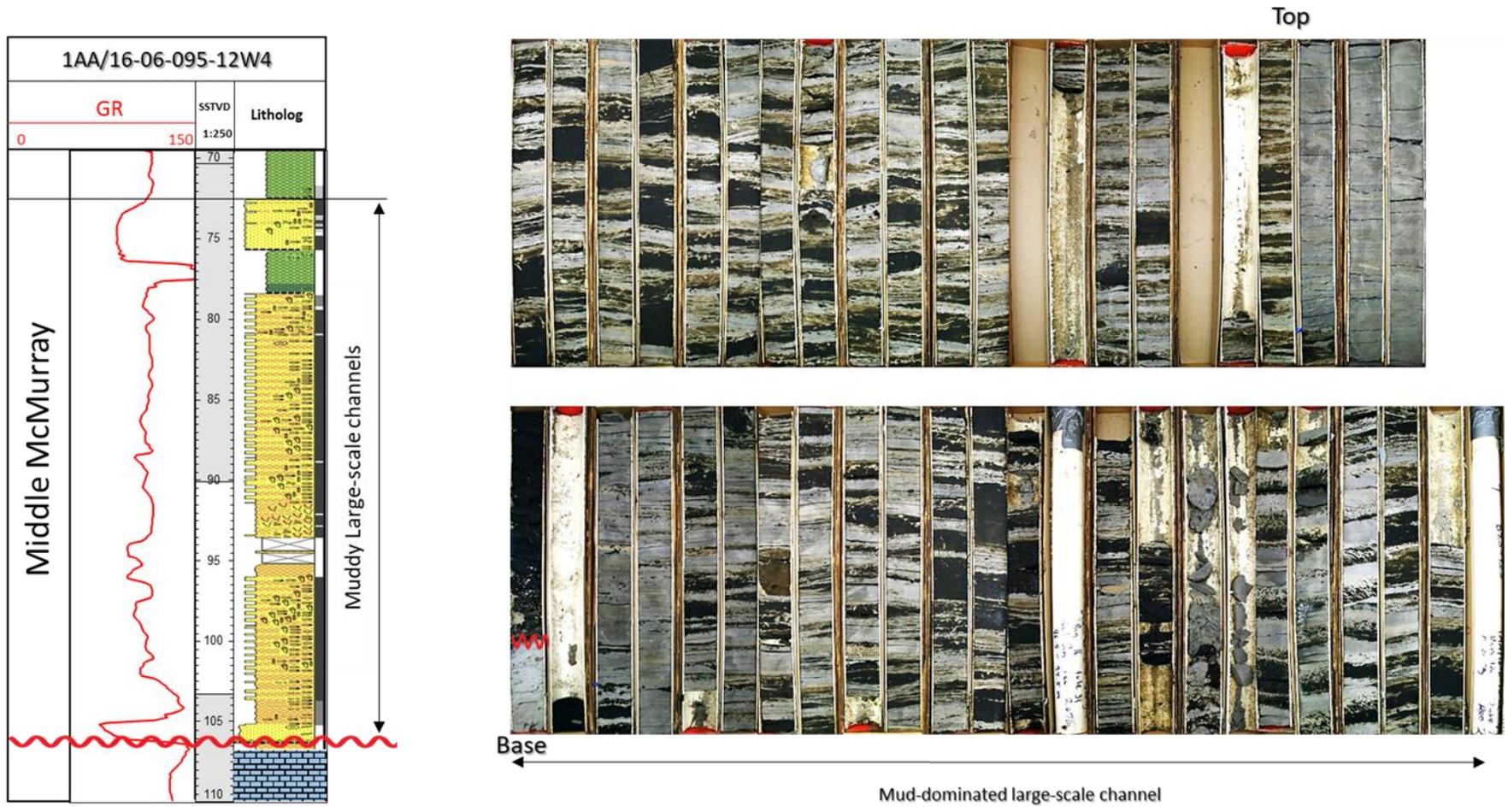


Figure 4.9 Vertical succession of F5-dominated muddy large-scale channel in the Middle McMurray Fm

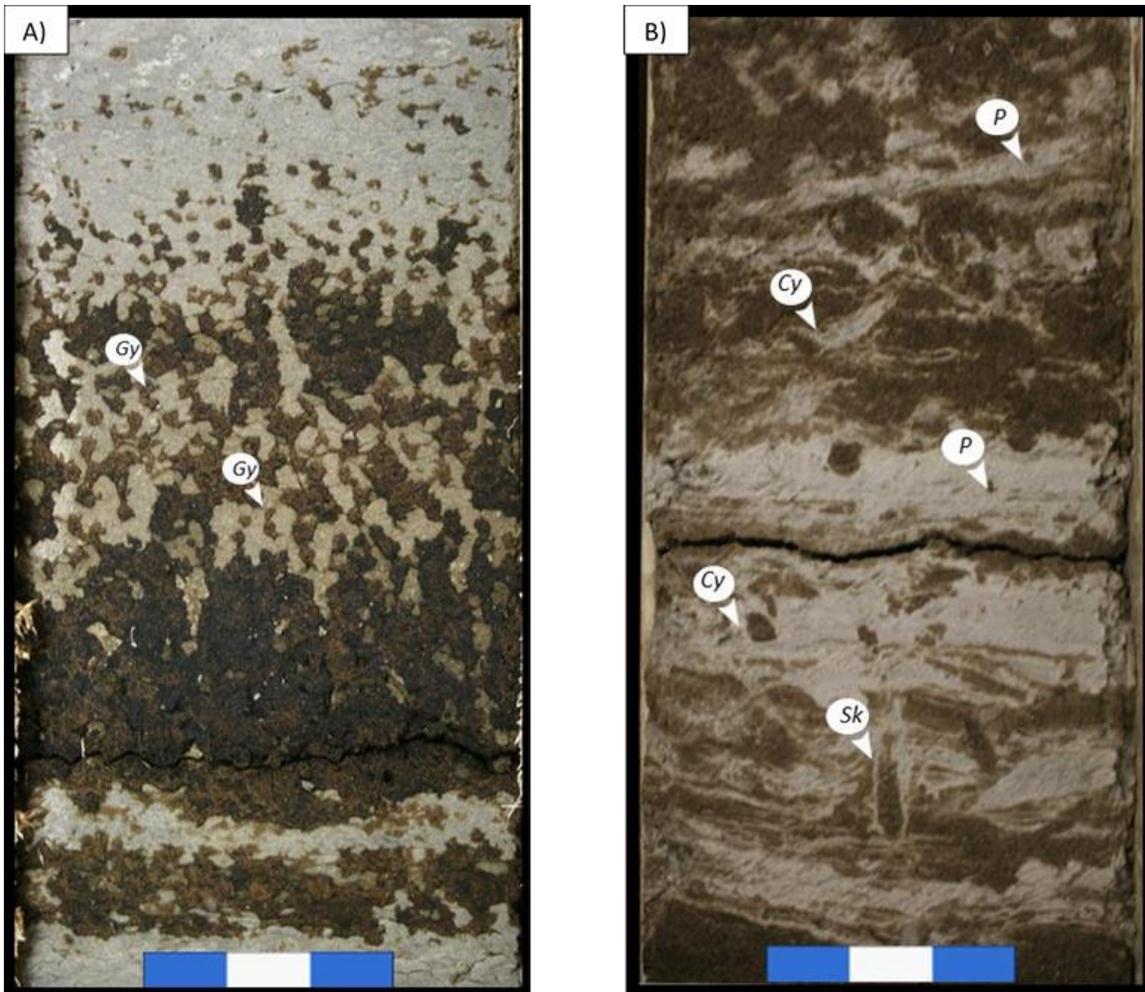


Figure 4.10 Bioturbation in muddy large-scale channels. A) Monogeneric association of diminutive *Gyrolithes* (*Gy*) at the top of a sand bed in F5- dominated muddy large-scale channel. B) High BI in sand (3-4) and lower in mud (1-2) in a F5-dominated muddy large-scale channel. Trace fossils include *Planolites* (*P*), *Cylindrichnus* (*Cy*) and *Skolithos* (*Sk*).

### **4.3. Mapping Trends and Geometries of Large- and Small-Scale Channel Types**

In order to determine the general trend of the channel geobodies in the Middle McMurray of the Central-C area, wire-line logs from 872 wells and cored intervals from 41 wells were used to produce isopach (Fig 4.13 and Fig 4.14) and net sand maps (Fig 4.15). These maps were generated, taking into account the sediments deposited between the base and the top of the middle McMurray Formation. These maps illustrate the main trend of the fluvial-dominated (trunk) paleovalley, which represents the large-scale channel deposits. The main trend suggests that fluvially dominated tidal-fluvial channel discharge was generally from SE to NW and contains the thicker intervals of Middle McMurray in the study area (Fig 4.13 and Fig 4.14).

The maximum thickness of the Middle McMurray within the Central-C area can reach nearly 50m. The minimum thickness is 0m, which occurs towards the west where topographic highs are present. In general, the Middle McMurray in the Central-C area is between 20m and 45m thick.

There seems to be two main sediment distribution patterns observable in the isopach map (Fig. 4.13). One pattern shows greater thicknesses (considered to be the main trunk channel in the area) coming from the SE, and continuing to the NW. The total thickness of the Middle McMurray along this trend varies between 35m and 50m. The second trend, consisting of thinner stacked intervals appear to come from the south (the small-scale tributaries), which merge with the thicker trend in the northern part of the study area. The thickness of the Middle McMurray in this trend is between 20m and 30m. There might be a third trend present, marked by sediment input from the East, and joining the main trend direction towards the NW. However, this is tenuous, based on the general paucity of data in the area. Validation of this trend could be the subject of future research.

In the net-sand map, the meandering character of the channels is better observed than in the thickness map. In the isopach map, the shape is less meandering, showing more a general trend of the Middle McMurray sediments. Thick sand zones with meander shapes in the Central-C area are believed to represent the positions of the large-scale channels. The meander geometry and main trunk tidal-fluvial channels

encompass the sandier zones expressed in the net sand map. The sand contents and thicknesses of the small-scale channels are interpreted to record small tributaries feeding into the large-scale channels. An interesting technique could be applied in order to identify sandy point bars and their corresponding muddy counter point bars in the map. One can track the sandier deposits apparent in the net sand maps to where they start to disappear. A comparison with the isopach map might still show thick intervals in that area. The transition where the isopach values stay high but the net-sand values decline might be interpreted as the inflection point where the point bar gives way to the counter point bar.

The Central-C spatial variability in channel scale can be favorably compared to the types of meanders observed on the coast of Georgia, USA, where the estuaries are characterized by fluvial influx into the coastal plain and characterized by fluctuating discharge and large saline zones in a mesotidal setting (i.e., Ogeechee River, Satilla River, etc.) (Dame, 2000) (Fig. 4.11 and Fig. 4.12). Looking at a general view of the Georgia coast in the U.S., specifically where the Ogeechee River and the Blackbeard rivers are located, it can be observed that the Ogeechee and Blackbeard rivers both carry the bulk of the fluvial flow (Fig. 4.11 and Fig. 4.12). The adjacent areas show small-scale channels that drain the surrounding flats and feed into the main trunk river (Ogeechee River) (Fig. 4.11 and Fig. 4.12).

The large-scale, fluvially dominated tidal-fluvial channels within the Central-C area possess thicknesses that range from 25 to 45m of the total middle McMurray succession. Small-scale channels are significantly thinner, producing successions ranging from 5 to 15m in total thickness. In the Central-C area, specifically towards Townships 91-93 and Ranges 11-12W4, a meander shape appears to be related to the deposits of the trunk channel, and could represent a channel loop that was cut-off, allowing the flow to shift from going to the west to the northwest (Fig. 4.12 and Fig. 4.14). The main channel positions are characterized by total thicknesses ranging from 38 to 45m.

The main paleovalley should have receive flow and sediment from the small-scale tributaries in adjacent areas. In the Central-C area, there seems to be evidence of such input from small-scale tributaries coming from the south, and feeding the main trunk tidal-fluvial system draining from the time-equivalent flats that surround the

paleochannels (i.e., the Ogeechee River). A different set of small-scale channels are observed to be located in positions between the older meander and the main trunk channel. The complexity of the tidal-fluvial estuarine system of the Middle McMurray can be compared to a similar modern system apparent in a satellite image from the Georgia Coast (Fig. 4.11). In the Ogeechee River system, it can be observed that small tributaries that are draining the tidal flats between main tidal-fluvial trunk channels, and feed into the main tidal-fluvial large-scale channels (Fig. 4.11 and Fig. 4.12). Also, the large-scale tidal-fluvial channels can migrate laterally across broadly contemporaneous small tributaries and become erosionally amalgamated. Also, there is a possibility that a large-scale tidal-fluvial river (e.g., Ogeechee River) and another contemporaneous large-scale tidal-fluvial river (e.g., Blackbeard River) can converge (Fig. 4.11 and Fig. 4.12). Another possibility is that a slight fall in base level may occur and erosionally juxtapose deposits that are not, in fact. In order to prove which of these is reasonable, a detailed sequence stratigraphic study is required.

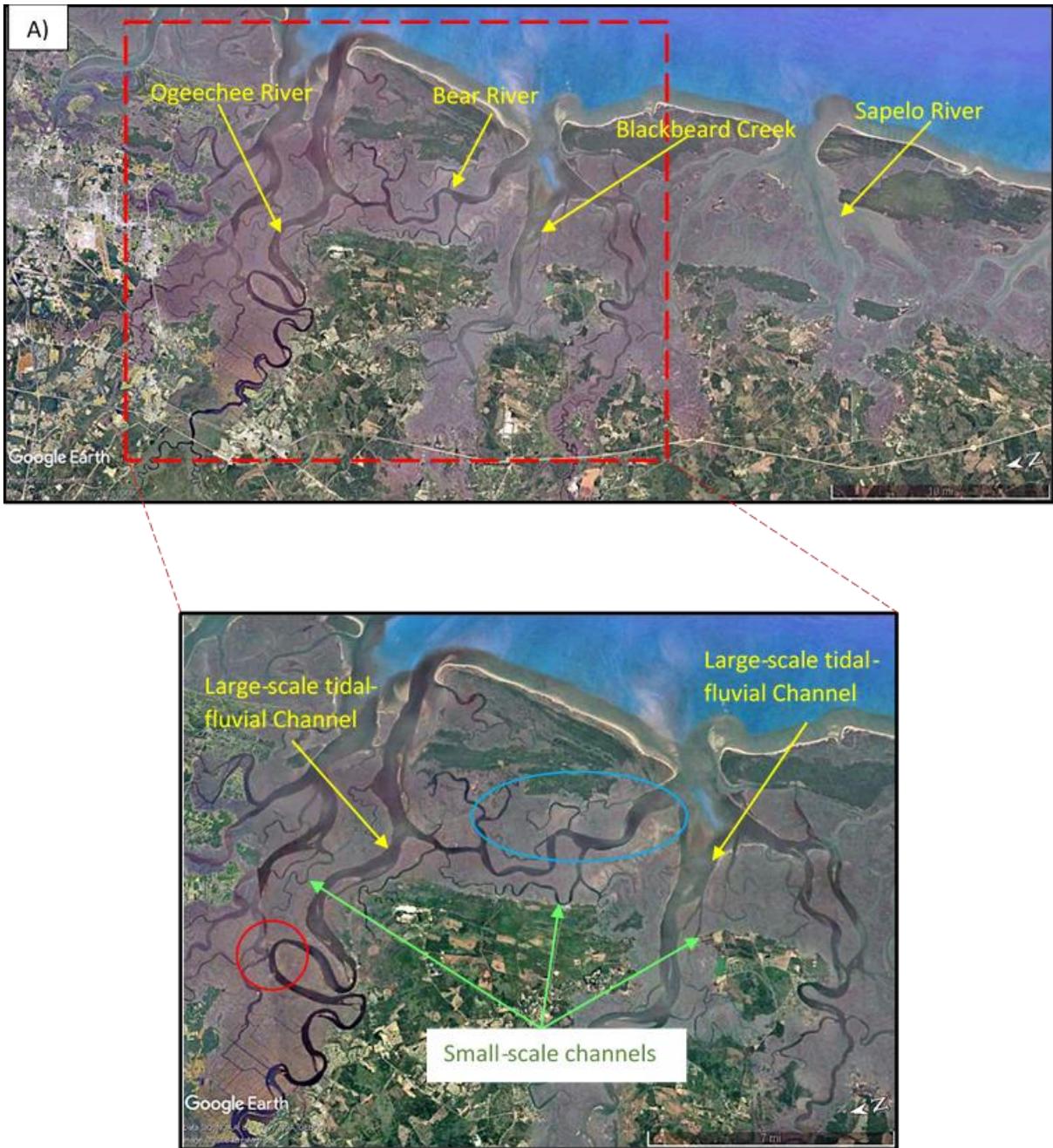


Figure 4.11 Modern example of a coastal plain estuarine system of the Georgia coast, USA. A) Overview showing the complexity of an estuarine, tidal-influenced system, and the distribution of tidal-fluvial large-scale channels and small-scale tributaries draining the flats and feeding the main trunk channels. B) Zoom in of the Ogeechee River and Blackbeard Creek area. Contemporaneous possible convergence of two large-scale tidal-fluvial channels (blue oval). Possible large-scale tidal-fluvial channel (Ogeechee River) about to cross-cut a contemporaneous small-scale channel (Red circle).



Figure 4.12 Modern example of a coastal plain estuarine system on the Georgia coast, USA. A) General overview of a tidal-fluvial channel complex. B) Possible early stage of abandonment of the channel in a modern example, similar to the meander shape observed in the net-sand map in the Central-C area (Fig. 4.13, 4.14 and 4.15)

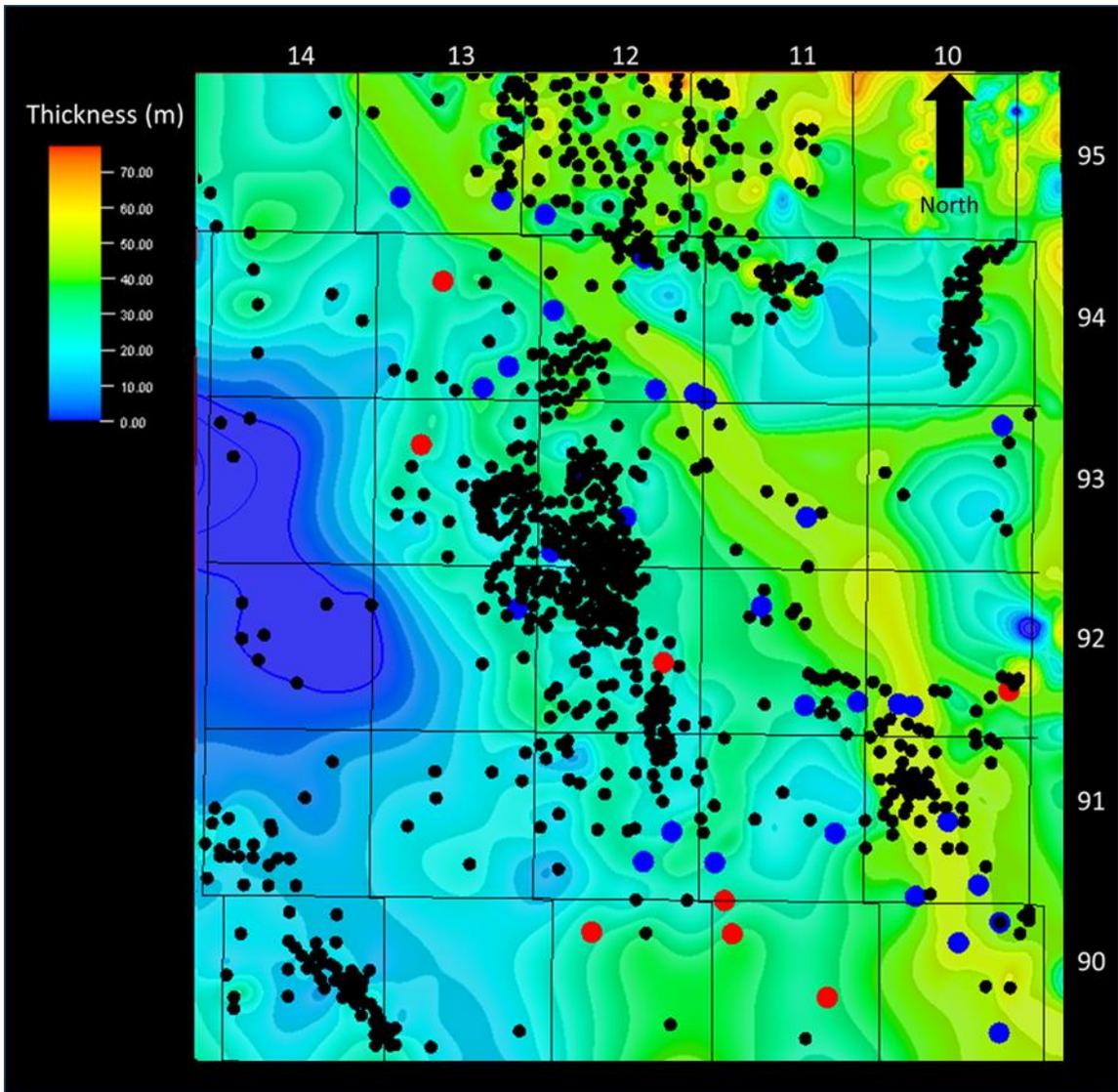


Figure 4.13 Isopach map showing the main depositional trends in the study area. Red dots represent small-scale channels. Blue dots represent large-scale channels. Black dots represent wells with LAS used to create the map.

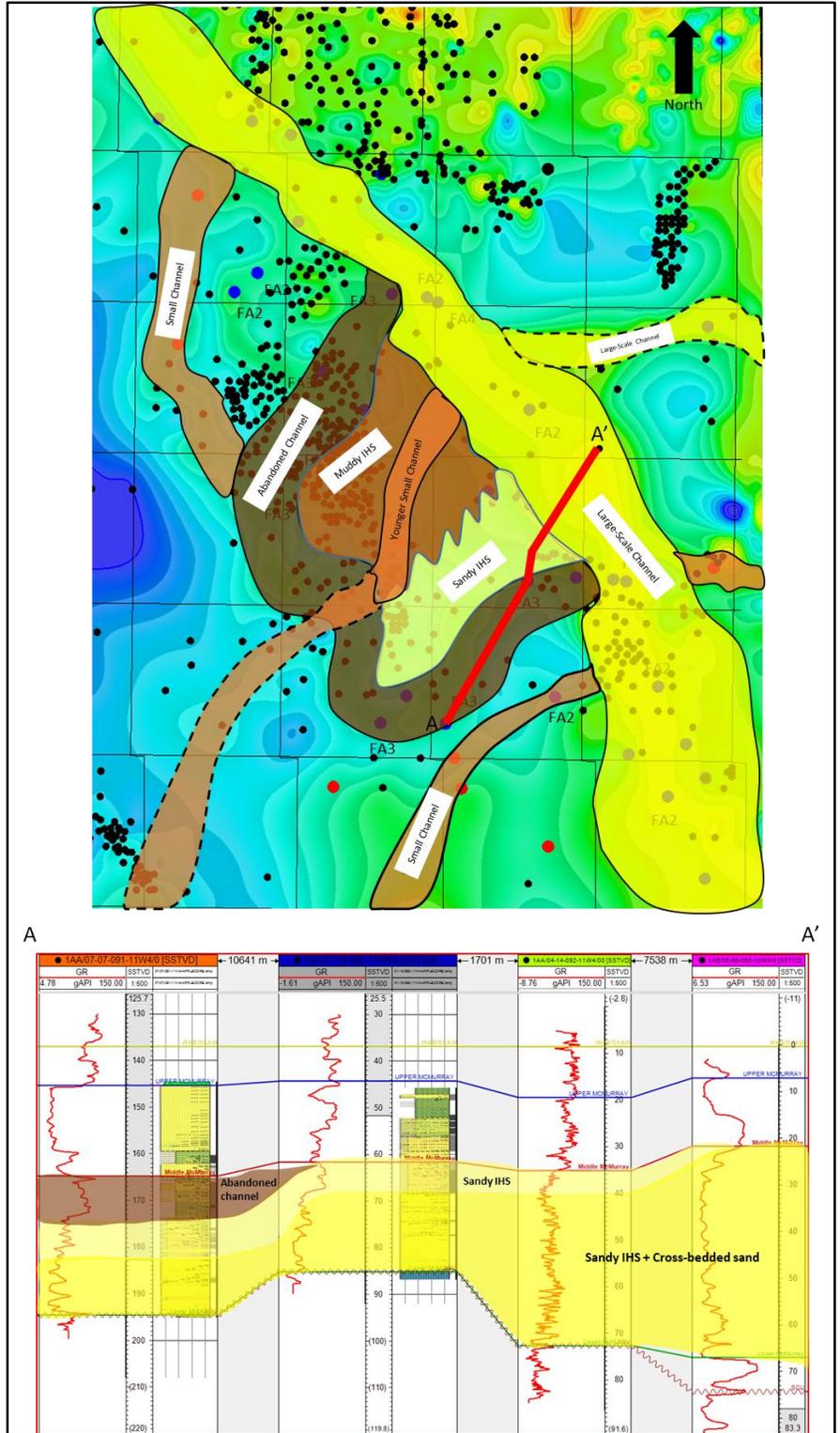


Figure 4.14 Thickness map with Facies Associations distribution and schematic cross-section showing the transition from trunk channel to abandoned channel.. The small-scale channel in between the trunk channel and the abandoned channel is interpreted to represent a small-scale channel cutting out an older large-scale channel.

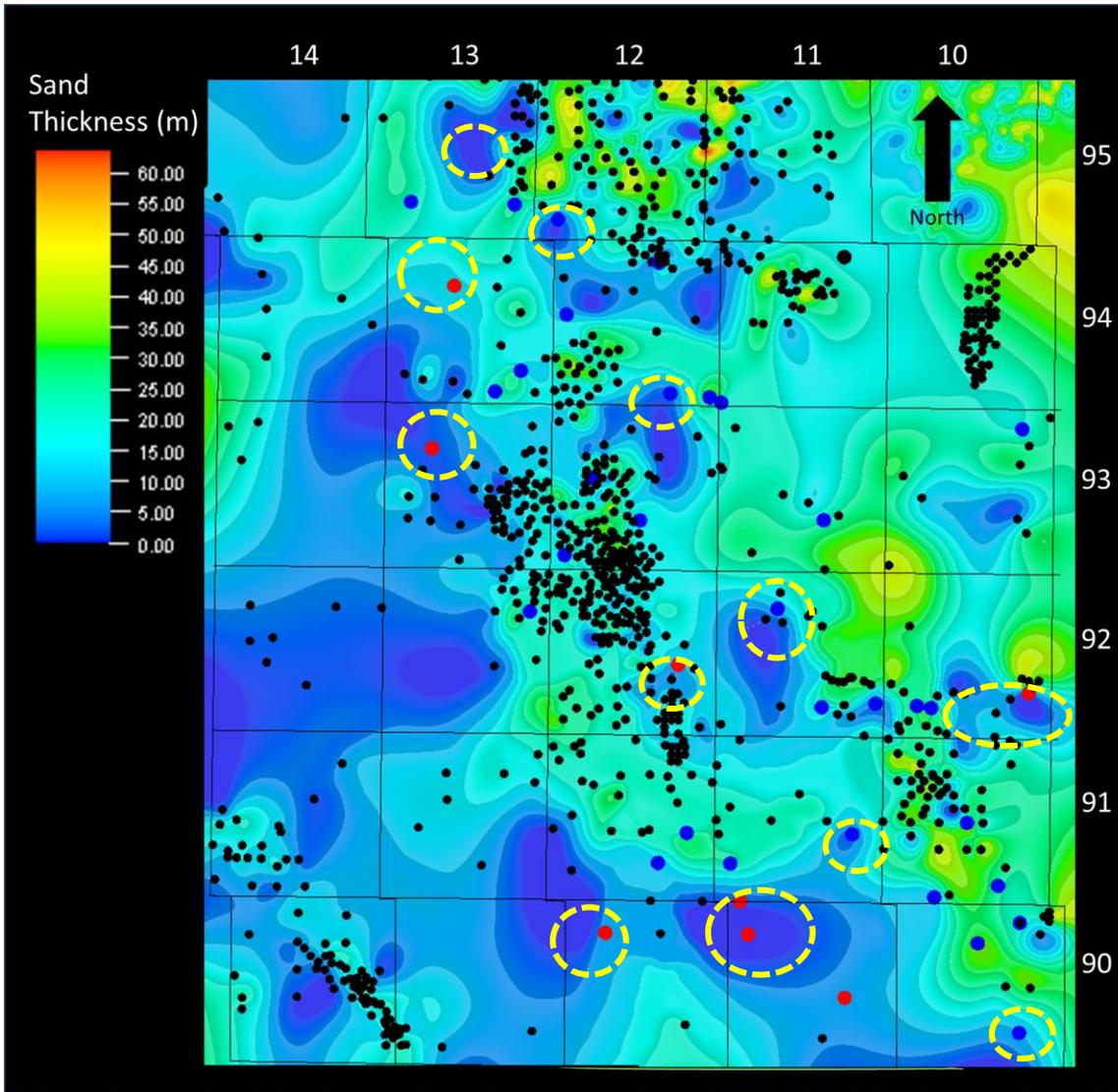


Figure 4.15 Net-sand map showing the thicker expressions of the sandy intervals. More meandering shape of the sandy Large-scale channel in the Central-C area is observed. Dashed yellow circles represent when the sand values drop off but the isopach stay high, consistent with the system passing into the counter point bars/muddy point bars.

#### 4.4. Marine influence in the Study Area

Assessing the degree of marine influence in the area was one of the main objectives of this research. It was postulated that trunk channel systems in the Central-C area, being the principal conduits of river-sediment influx into the system would tend to under-represent the degree of marine influence in the environment. Smaller-scale channels, carrying less of the river flow might record less physico-chemically stressed deposition and so be a better indicator of the actual degree of marine influence in the area.

There are several factors to consider in order to identify the marine influence in the area, but the most relevant would be to identify main indicators of physico-chemical stress (Gingras et al., 2012). Physical stress seems to affect the substrate colonization by processes such as strong physical energy as well as rapid and high deposition rates. Such conditions lead to low diversity trace fossil suites as well as low bioturbation intensities. However, the main indicator of the degree of marine influence surrounds how chemically stressed the system is, by identifying salinity-stressed settings and areas with diminished oxygen levels (Pemberton et al., 1982, Gingras et al., 2012). In order to evaluate these conditions, identifying and observing the size and diversity of the trace were employed to understand the chemical stress in the area.

In the Central-C area, two main types of channel scale were identified: small-scale channels and large-scale channels. The small-scale channels show a typical suite associated with salinity-stressed environments, consisting of facies-crossing elements such as *Cylindrichnus*, *Palaeophycus*, *Planolites*, *Skolithos*, *Teichichnus*, *Thalassinoides*, with low numbers of *Diplocraterion*, *Gyrolithes*, and rare fugichnia. Bioturbation intensities in the sand and mud beds typically reach BI 3-4 and 1-2, respectively. By contrast, the sandy large-scale channels without F7 (F7 representing the abandonment channel facies) shows mostly *Cylindrichnus* in the sand and *Planolites* in the mud, and BI values of 1-2 and 0-2, respectively. The F5-dominated muddy expression of the large-scale channels (counter point bar) possess *Cylindrichnus* as the dominant trace fossil, and associated *Planolites*, *Gyrolithes* and *Skolithos*, with BI values in the sand and mud beds averaging 1-3 and 1-2, respectively. The F7-bearing muddy large-scale channels contain suites more akin to those of the small-scale channels, showing *Cylindrichnus*, *Skolithos*, *Thalassinoides*, *Teichichnus*, *Palaeophycus* and

*Diplocraterion* in the sand with a BI of 2-4, and *Planolites*, *Cylindrichnus*, *Skolithos*, *Teichichnus* and *Gyrolithes* in the mud with a BI of 3-5.

In the large-scale channels overall, the diversity of the trace fossils is considerably lower compared to the suites typifying the small-scale channels. The trace fossil sizes are predominantly diminutive, especially in the sandy expressions of the large-scale channels. This diminutive size is considered an opportunistic organism's reaction to living under chemically stressed conditions (Gingras et al., 2012). This implies that elevated chemical stresses operated in the tidal-fluvial large-scale channel, negatively impacting substrate colonization by opportunistic organisms. The most likely chemical stresses were variable and markedly reduced salinities. Exacerbating this were physical stresses such as high flow velocities and elevated sedimentation rates.

By contrast, the small-scale channels possess trace fossil suites that are more diverse and more robust, and show higher BI values compared to those of the large-scale channels. This could indicate that these channel environments were less physical-chemically stressed. The small-scale channels presumably carry less fluvial flow, with most of the discharge composed of waters draining the adjacent intertidal area. This may have allowed a greater range of organism behaviours and less requirement for marked shifts osmoregulation of the tracemaking organisms, leading to greater ichnological diversity and more robust traces (cf. Gingras et al., 2012). Thus, the higher diversity and bigger size of traces fossils in the small-scale channel may be strong indicators of reduced salinity stress and a provide a superior record of the degree of marine influence in the area.

Interestingly, the large-scale abandoned channels (F7-bearing mud-dominated) intervals show trace fossil diversities and sizes that mimic those of the small-scale channels. This is interpreted to reflect the particulars of the abandonment process of tidal-fluvial channels in the paralic realm. Like fluvial meander cut offs, tidal-fluvial channels no longer receive significant fluvial flow. However, in fluvial meander cut offs, oxbow lakes develop, which are subject to long-term periods of evaporation, minimal influx of oxygenated water and general stagnation with concomitant reduced oxygenation. By contrast, abandoned channels in the intertidal zone would receive oxygenated and food-laden marine waters each tidal cycle, coupled with a reduced deposition rate. As such, abandonment facies (e.g., F7) are characterized by elevated

diversity, less diminution and increased bioturbation intensity. As a result, the general setting of the abandoned channel might be broadly similar to that occurring within the small-scale channels.

For future research projects, if the interest is in trying to analyze the degree of marine influence in an area by using micropaleontological proxies, it is recommended that the muds occurring in small-scale channel IHS and abandonment channels be sampled preferentially over the low BI thicker mudstones in the IHS of the trunk channel systems. The small scale channels and abandoned channels carry less of the fluvial flow and have generally slower depositional rates, favoring greater concentrations of marine microfossils, such as dinocysts and arenaceous foraminifera, and therefore giving a more accurate indication of the degree of marine influence in the setting.

## Chapter 5. Conclusions

1. The McMurray Formation in the Central-C area of the McMurray Sub-basin in Alberta was subdivided into 12 recurring depositional facies, utilizing sedimentological and ichnological elements analyzed from 41 cored wells. As the main objective of this research was to analyze the different types of channel complexes and their apparent degree of marine influence in the Middle McMurray interval, only 5 sedimentary facies (F3, F4, F5, F6 and F7) and 6 sub-facies (F5A, F5B, F6A, F6B, F7A and F7B) were evaluated in detail in the interval of interest.

2. The Middle McMurray is characterized by a fining-upward succession. At the base, cross-bedded sands (F3) are present, locally found to be interstratified with mud-clast breccias (F4). These are overlain by bedsets of inclined heterolithic stratification (IHS), expressed as F5, F6 and/or F7. F5 is characterized by sporadically bioturbated massive to planar laminated mud and burrowed sand in IHS composite bedsets. F6 is typified by weakly bioturbated, current-generated rhythmically distributed IHS bedsets. F7 is characterized by pervasively bioturbated, current-generated IHS composite bedsets.

3. Four recurring facies associations were identified within the Middle McMurray (FA1, FA2, FA3 and FA4), reflecting deposition of the different types of channels and channel-related bar deposits. FA1 consists mostly of aggradational heterolithic bedsets of F5, which locally coarsen upwards and are capped by F7, and is interpreted to represent IHS associated with counter point bars at the margins of channel bodies. FA2 is represented at the base of the succession by cross-stratified sand and chaotically bedded mud-clast breccia deposits of Facies 3 and Facies 4, respectively, overlain by weakly bioturbated mud-dominated heterolithic bedsets of Facies 5. FA2 represents fining-upwards successions associated with channel deposits and muddy point bar/counter point bar deposits. FA3 comprises a fining-upward succession characterized by F4/F3 at the base, overlain gradationally by F7A and F7B. FA3 is interpreted as channel-related IHS point bar deposits and abandoned channel deposits. Lastly, FA4 is characterized by a fining-upward succession consisting of mud-clast breccia (F4) at the base, overlain by cross-bedded sand (F3), and capped by composite bedsets of rhythmically bedded sand and light brown/gray mud (F6). FA4 is interpreted

to represent tidal-fluvial IHS that shows a stronger tidal influence, manifest by pronounced rhythmicity in the deposition of sands and muds. These four facies associations were established by considering the stacking patterns and geometries of the recurring facies in the Central-C area. These variations are employed to characterize the channels and to differentiate them using cores and well logs.

4. Two main categories of channel size were identified in this research, defined as “small-scale” channels and “large-scale” channels. Small-scale channels are defined as those recording successions  $\leq 15\text{m}$ . Large-scale channels are defined as those recording successions  $> 15\text{m}$  and, in the study area, locally reach a maximum thickness of  $45\text{m}$ . Depositional characterization of these channel types was based on the details of the trace fossil suites, distribution and intensity of bioturbation, primary sedimentary structures, bed thicknesses of the cross-bedded sands, mud-clast breccia intervals at the bases of successions, variations in mud clast sizes in the breccia zones, and variations in the characteristics of the IHS intervals (e.g., bed thickness, bioturbation intensity, burrow distributions and trace fossil diversities).

5. Each channel scale could be subdivided into sand-dominated and mud-dominated expressions, based on the relative percentage of mud vs. sand ( $<50\%$  vs  $>50\%$ ) within the successions.

6. The vertical successions of small-scale channels are associated with muddy IHS deposits (FA1) or sandy/muddy IHS deposits (FA2). Commonly, relatively thin expressions of individual beds of cross-stratified sand (5cm to 25cm) within F3/F4 occur at the bases of the successions, forming stacked bedsets ranging from 15cm to 2m thick. F3 and F4 bedsets are also thin, ranging from 75cm to 5m thick, which are indicative of small to modest sized bedforms. The thicknesses of the mud-clast breccia intervals range from 20 cm to 3.5 m. IHS intervals overlying the cross-stratified sands of F3 also vary in thickness, showing an approximate average of 7m. The BI is relatively high, showing values of 3-4 in the sand beds and BI 1-3 in the mud beds. These channels display reduced evidence of physico-chemical stress compared to the large-scale channels. The small-scale channels appear to have carried less of the fluvial discharge and mainly drained the intertidal areas. These brackish-water channels appeared to have been more suitable for colonization of the substrates by facies-crossing organisms. By showing a higher diversity of robust trace fossils, these small-

scale channel types are interpreted to be an ideal record of the degree of marine influence in the study area.

7. Large-scale channels with sand-dominated IHS (FA4 and FA2) are believed to represent the fluvially dominated tidal-fluvial trunk channel system in the Central-C area. The basal F3 interval ranges from 7.5m to 30m thick. F4, where present, reaches 6.5m in thickness. Individual cross-beds within the sand-dominated large-scale channels range from 20cm up to 1.3m thick, indicating that the channels carried enough sediment with sufficient energy to induce the migration of some fairly large dunes. The IHS bedsets in the sand-dominated large-scale channels range from 5m to 9.5m thick. Bioturbation intensities in the upper part of the IHS interval are very low (BI 1-2) in both the sand and the mud beds. The physico-chemical stress indicated by facies within these channels is very high, and inhibited organism colonization of the substrate. Thus, the marine evidence within these channels is less well expressed compared to the deposits of small-scale channels or abandoned channels. The sand-dominated large-scale channels are interpreted to represent the upstream parts of active tidal-fluvial point bars of the trunk channels.

8. Large-scale channels with F7-bearing sand-dominated IHS (FA3) are interpreted as abandoned channels that were cut-off from the main trunk channel. These channels are characterized by F3 deposits at the bases of the successions, with total thicknesses ranging from 3m - 8m. The F7+/-F5 IHS intervals range from 15 to 35m thick. F7-bearing sand-dominated large-scale channel deposits are typically more bioturbated overall (BI 2-4) in the upper part of the IHS. Both sand and mud beds may show pervasive bioturbation, with the muds showing generally higher bioturbation indices (BI 3-5). The elevated BI suggests similar physico-chemical characteristics to the small-scale channels. After meander cut off, the abandoned channel would have continued to receive basin water during high tides. The persistent brackish-water conditions, combined with lower sedimentation rates would have allowed the mud and sand beds to be colonized and become pervasively burrowed.

9. Muddy large-scale channels consist mainly of FA2 and are interpreted as muddy point bar/counter point bar deposits. They show pronounced differences in terms of BI values and bed thicknesses compared to their sand-dominated channel counterparts. The combined F3/F4 basal deposits range from 1 to 5 m. thick The IHS

intervals within mud-dominated large-scale channel deposits range between 14-34m thick. These F5-dominated muddy large-scale channels show bioturbation intensities that typically vary from BI 1-3. Sands typically show a higher bioturbation intensity (BI 1-3), with the mud beds displaying slightly lower BI values (BI 1-2). The trace fossils in the sands are mostly robust, whereas those in the mud beds are predominantly diminutive. This implies that physico-chemical stresses were elevated during mud deposition, suggesting a high supply of mud and its rapid deposition. By contrast, it appears that there was sufficient time between deposition of the sand beds and mud accumulation to allow organisms to colonize the sandy substrate.

10. Isopach and net-sand maps were generated in the study area in order to illustrate the main trend of the channel complex within a tidally influenced, brackish-water channel system. Two main trends are identified. One pattern shows greater thicknesses (considered to be the main trunk channel in the area) coming from the SE and continuing to the NW. The second pattern consists of thinner stacked intervals that appear to come from the south (the small-scale tributaries), and merge with the thicker trend in the northern part of the study area.

11. The complexity in spatial variability in channel scales and distribution of the channels within the Middle McMurray Formation in the Central-C area can be better understood by observing modern fluvial-tidal estuarine system. By observing the coastal plain estuaries along the Atlantic coast of Georgia, USA, it is clearly observed that the main trunk tidal-fluvial channels (e.g., Ogeechee River and Blackbeard Creek) carry the main fluvial discharge, whereas the small-scale tributaries drain the intertidal areas between them. The distribution of these channels show that tidal-fluvial trunk channels can cross-cut the small-scale tributaries that are, nonetheless, broadly contemporaneous with them. Also, it is observed that large-scale tidal-fluvial channels can converge locally. Finally, some spatial relationships likely record younger large-scale tidal-fluvial channels eroding and cross-cutting older large- and small-scale channel systems.

12. The degree of marine influence in the Central-C area was determined by identifying evidence of physico-chemical stress in the different types of channels. The large-scale channels display evidence of higher physico-chemical stress within the estuarine system. Physical stress is indicated by the higher flow velocities (characterized

by larger cross-bed sets) and higher sedimentation rates. Chemical stress is interpreted to record lower salinity and more marked variations in salinity, owing to greater fluvial discharge through the system. As consequence, trace fossil diversities are very low and the traces are diminutive. Further, bioturbation intensities are low and sporadically distributed. By contrast, the small-scale channels appear to have carried less fluvial discharge and may have mainly drained the intertidal areas into the trunk channels. Physical energy and depositional rates appear to have been lower and salinities generally higher and more stable, leading to a less stressed environment for the organisms. Trace fossil diversities are higher, ichnogenera are more robust, and bioturbation intensities are higher and locally pervasive. Interestingly, the large-scale abandoned channels (F7-bearing IHS) show ichnological characteristics comparable to those of the small-scale channels. Abandoned channels in the intertidal zone would receive oxygenated and food-laden marine waters each tidal cycle, coupled with a reduced deposition rate. As such, abandonment facies (e.g., F7) are characterized by elevated diversity, less diminution and increased bioturbation intensity. Correspondingly, small-scale channels and abandoned channels are suggested to be the ideal successions for assessing the degree of marine influence in the area, because they lack significant fluvial flow and are characterized by generally reduced deposition rates.

13. For future research projects, it is recommended that micropaleontological studies aiming to analyze the degree of marine influence in the area should sample the mudstones deposited in small-scale channels and abandoned channels. The reduction of fluvial sediment influx and slower depositional rates would favor greater concentrations of marine microfossils (e.g., dinocysts and foraminifera).

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## **Appendix A.**

### **Well tops**

**Description:**

Table with the well tops of the informal members (Middle and Lower) of the McMurray Formation

**Filename:**

Well\_Tops.PDF

## **Appendix B.**

### **Core Lithologs**

**Description:**

Core lithologs of the cores described in this research.

**Filename:**

Lithologs.PDF