The Nature of Inclined Heterolithic Stratification in a Mixed Tidal-Fluvial Setting: Depositional Processes, Sedimentology and Ichnology, Middle Arm, Fraser River, Canada

by

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B.Sc., University of Calgary, 2008

Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

in the

Department of Earth Sciences

Faculty of Science

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SIMON FRASER UNIVERSITY

Fall 2012

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Abstract

The dynamic interplay of hydrodynamic processes in the subequally mixed tidal-fluvial Middle Arm, lower Fraser River dictates the character of inclined heterolithic stratification (IHS) developed on channel bars. Intertidal zone and upper subtidal zone sediments are deposited in mm- to cm-scale, rhythmically alternating sand and mud beds, and this trend appears to continue into the lower subtidal part of the bar. Rhythmic lamina-sets are interbedded with dm-scale sand beds reflecting seasonal changes in river discharge. Surface samples from the intertidal zone are mud-dominated on the upstream and downstream ends of each bar, whereas the center of each bar is sandy, such that bars exhibit a mud-sand-mud profile. Muddy bedsets in the intertidal zone are laterally extensive for up to 1 km in the along-strike direction. Muddy bedsets in the subtidal zone appear to extend for similar distances. Ichnological trends reflect the relative input and persistence of brackish-water in the channel. Burrow diversity, burrow density, and trace sizes increase in the seaward direction.

Keywords: IHS; inclined heterolithic stratification; mixed tidal-fluvial, lower Fraser River; tidal cyclicity; Middle Arm
I dedicate this thesis to my family. Thank-you for all your love and support through all my life’s endeavours.
Acknowledgements

First, I would like to acknowledge all of my fellow students at Simon Fraser University for their kindness and support. Every student made SFU an enjoyable working environment that I looked forward to coming to. I would like to thank Korhan Aryanci, Bonn Coyuco, Brittan Jones and Adam Montgomery for their assistance in the field and lab. Thank you to Andrew LaCroix and Joanna Czarnecki who helped in the field, but also who were great officemates and helped me build ideas for my research. Thanks to my other officemates, Vincent Twomey and Meghan Hewton, for tolerating the sedimentologists around you and providing a friendly working atmosphere.

Many thanks to the Coast Guard at the Sea Island Coast Guard Station for the use of their boat launch, dock and facilities for the duration of my fieldwork. I would like to thank the organizations that helped fund this project: Nexen, Imperial Oil, Suncor, Statoil, and the National Sciences and Engineering Council of Canada (NSERC).

I would like to thank Dr. James MacEachern for his mentorship and knowledge he shared with me in the classroom and in conversation. All of the department faculty and staff were extremely helpful and supportive during my studies. Thanks to Glenda Pauls, Rodney Arnold, Matt Plotnikoff and Tarja Vaisanen for having all the answers no matter how outlandish the question. Last, but no least, I would like to extend a special thank you to Dr. Shahin Dashtgard for his guidance and supervision. He was always fully invested in making sure that I had a fun and fulfilling research project. I am very grateful for his dedication to providing an outstanding learning experience.
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1. Introduction

1.1. Introduction

Inclined heterolithic stratification (inclined interbeds of sand and mud (IHS)) is a common stratal architecture in bitumen-hosting reservoirs of the middle McMurray Formation, Alberta. In the subsurface, where bitumen-extraction is mainly achieved through steam-assisted gravity drainage (SAGD), mud beds in IHS successions pose significant barriers to steam injection. To aid in predicting the distribution and lateral continuity of mud beds, it is first necessary to determine the depositional environments in which it is produced. In modern settings where IHS is developed, the lateral and vertical extent of mud and sand beds can be mapped, and as such, modern settings host IHS deposits are used as analogs for predicting the continuity of reservoir (sand) and non-reservoir (mud) sedimentary beds and bedsets. Modern IHS analogs also provide detail at the facies scale that aid in identifying depositional environments in the subsurface. Modern examples of IHS are reported from fluvially dominated (Gingras et al., 1999; Smith et al., 2009; Smith et al., 2011), tide-influenced and fluvially dominated (Smith, 1985; Sisulak and Dashtgard, 2012), fluvially influenced and tide-dominated (Smith, 1985, 1987; Gingras et al., 1999), and tide-dominated (Choi et al., 2004; Pearson and Gingras, 2006; Dalrymple and Choi, 2007; Choi, 2010) settings. Surprisingly no examples have been reported from admixed tidal-fluvial settings. This research focuses on bars in the Middle Arm of the lower Fraser River, a mixed tidal-fluvial system,
evaluating them as analogs to IHS formation in the rock record. The architecture, sedimentology and ichnology of the Middle Arm bars are mapped and characterized.

The Middle Arm is a mixed tidal-fluvial influenced channel that discharges approximately 5% of the Fraser River’s total flow (WCHL, 1977). Within the Middle Arm, the vertical and lateral extent of mud and sand beds are assessed on a semi-detached point bar, an in-channel bar, and a channel-margin bar. The sedimentology and ichnology of the sediments on these bars are compared to past and on-going studies of IHS in the Fraser River. In particular, the results are compared to recent work done on the tide-influenced, fluvially dominated South Arm Marshes (SAM; Sisulak and Dashtgard, 2012). The Middle Arm research sites are located in areas that have a greater tidal influence and are exposed to higher salinities than experienced at the SAM. The results of this comparison provide a framework for recognizing varying degrees of tidal and brackish-water influence along the spectrum of IHS produced in river-dominated to tide-dominated channels.

The three main objectives of this thesis are:

1.) Define sedimentological and ichnological characteristics of channel bars in a mixed tidal-fluvial setting.

2.) Integrate the findings with other sedimentological and ichnological work done on the Fraser River. This is done to develop a more regional perspective on how the hydrodynamic processes and water chemistry of the river affect deposition and the resulting character of the channel deposits.
3.) Present data as an analog to equivalent deposits in the rock record. In particular, the main focus is on defining process-response relations distinctive to mixed tidal-fluvial channelized settings.

This thesis is divided into four chapters. Chapter one provides background information on what inclined heterolithic stratification is, and a series of modern environments in which this bedding architecture is developed. A description of the study area and the methods employed in this research project are also described in chapter one. Chapter 2 provides background information on the biology and ichnology of brackish-water environments, with a particular focus on the biology and ichnology of the lower Fraser River. Chapter three presents most of the research data collected for this study. The research and results pertaining to the three objectives defined above, are discussed in chapter three. Finally, chapter four summarizes the findings of this study, and mainly restates the findings of chapter three as they pertain to the objectives of this thesis.

1.2. Inclined Heterolithic Stratification (IHS)

1.2.1. Definition and Evolution of Terminology

A variety of terms have been used to describe inclined strata of interbedded sand and mud, prior to Thomas et al. (1987) proposing the term “IHS”. The most common precursor term for IHS was epsilon cross-stratification (ECS), defined by Allen (1963) based on a model for point-bar stratification reported from tidal creeks by Reineck (1958). In 1965, Allen constrained the use of the term ECS to deposits formed by lateral accretion of point bars in tidally or fluvially dominated rivers (Smith, 1985). Thomas et al. (1987) found that ECS was too restrictive and didn’t encompass the different varieties of
IHS that are encountered. He defined IHS as, “modern and ancient, large-scale, waterlain, heterogeneous siliciclastic sedimentary sequences, whose constituent strata are inclined at an original angle to horizontal or palaeohorizontal” (Thomas et al., 1987). Thicknesses between 1- 30 m, and dips (from 1 - 36° (12° average)) are typical of IHS successions (Mossop and Flach, 1983; Thomas et al., 1987). Inclined strata are rarely deposited passively from suspension settling, and are more commonly deposited via deltaic progradation or lateral accretion on point bars. Formation of IHS by lateral accretion on point bars is regarded as the most common mode of deposition.

Thomas et al. (1987) proposed terminology to describe IHS successions. An IHS set is defined as “a solitary package of uniformly inclined strata composed of two alternating coarser and finer lithologies”. A composite set comprises an IHS set that passes gradationally down-dip into sandstone. Stacked IHS sets bound by discontinuities are termed “cosets”: the constituent sets within a coset can be parallel, with all the beds dipping in the same direction, or each set can dip in different directions (bi- or polydirectional). If the constituent sets in cosets are parallel with unidirectional or codirectional dips, then the sets are described as an imbricate coset. Individual inclined units typically fine upwards and consists either of a normally graded bed or distinct coarse- and fine-grained members that together make up a couplet. Sedimentary structures commonly found in sand beds in such couplets include trough cross-bedding, planar-parallel lamination, graded bedding, and ripple cross-lamination. The basal contacts of sand beds in couplets is typically erosive, while the upper contact is sharp or gradational. The fine-grained beds are typically parallel, wavy, massive or planar parallel cross-laminated. Soft-sediment deformation and slump features, produced by rapid sedimentation and channel bank failure, are also common.
Six different grain-size fining trends within point bar IHS successions are recognized (Figure 1.1). A fining in grain-size is interpreted to correlate to decreases in flow velocity and/or water depth.

![Figure 1.1: IHS point bar model](image)

**Figure 1.1: IHS point bar model**

The six main grain-size fining trends seen in IHS deposits generated from point-bar lateral accretion: 1) down-flow proximal to distal fining; 2) lateral fining into an overbank succession; 3) vertical fining-upward; 4) up-dip fining within individual inclined beds; 5) fining of the coarse-grained members of successive inclined units, perpendicular to inclined bounding surfaces; and, 6) fining perpendicular to bounding surfaces within individual inclined beds. (Modified by S.M. Hubbard after Thomas et al., 1987).

**1.2.2. Cyclicity in IHS – Characteristics and Depositional Processes**

Within IHS successions, tidal bundles are also commonly present, wherein neap/spring and diurnal tidal cycles are reflected by deposition of rhythmic heterolithic units (Visser, 1980; Thomas et al., 1987; De Boer et al., 1989, Choi et al., 2004). Tidal bundles can be found in an array of tide-influenced depositional settings and are not limited to lateral accretion of point bars. In fact, tidal bundles are commonly deposited horizontally. Tidal bundles are composed of mm- to cm-scale rhythmic alternations of sand and mud, where deposition of the coarse-grained member (typically sand or silt) is
linked to deposition by ebb- and flood-tidal currents, and mud (either silt or silt/clay) is deposited from waning tidal currents and during slack water periods. In tidal systems, one current is typically dominant, and sand- and/or silt-dominated bedforms are oriented in the direction of the dominant current. Variations in individual lamina thicknesses are either a reflection of the diurnal inequality of semi-diurnal tides, or a product of sediment availability. In semi-diurnal tidal systems, a complete neap-spring cycle is manifested by 28 sand/mud couplets (Figure 1.2). Thicker and sandier lamina-sets correspond to spring tides, whereas thinner and muddier lamina-sets indicate neap tides. When the moon is closest to the earth during perigee, the thickest neap-spring cycles are deposited. The thinnest neap-spring cycle deposits are associated with lunar apogee.
Figure 1.2 (previous page): Tidal rhythmites

Example of tidal rhythmites from an IHS succession in the Sukmo Channel, Han River, Korea. A) Photograph of alternating thinner apogean spring-tide deposits (AS) with thicker perigean neap-spring deposits (PS). The white arrows point to the muddy deposits associated with neap tides. The white box is around the area zoomed in B and C showing diurnal deposition. The scale bar is 1 cm. B,C) Photograph and line drawing of laminae with varying thicknesses: a reflection of the diurnal inequality of the semidiurnal tide. Thick laminae are associated with the larger tide of the day (L), while thin laminae are deposited during the smaller tide (S). DI (diurnal inequality) is the thickness of deposition from a single day composed of a thick lamina deposited during the larger tide of the day (L) and a thinner lamina deposited during the small tide (S). (Modified from Choi et al., 2004).

While tidal bundles are not synonymous with IHS, they are inherently linked to tides, and the rhythmic nature of IHS beds has been documented and attributed to the tidal cycles (Smith, 1987; De Boer et al., 1989; Choi et al., 2004; Pearson and Gingras 2006; Dalrymple and Choi, 2007). A key observation from modern IHS deposits is the increase in mud-bed abundance and rhythmicity of bedding with increased tidal influence (Smith, 1987). Sand-dominated IHS successions with more irregular interbedding of sand and mud are thought to be characteristic of fluvially dominated environments, where fluctuations in river flow is the primary hydrodynamic process controlling deposition (Calverley, 1984; Smith, 1987; Sisulak and Dashtgard, 2012). Seasonal changes in fluvial influx are manifest as non-rhythmic alternations of sand and mud, with sand deposited during high discharge and mud deposited during waning river-flood conditions (Sisulak, 2011).

Whereas seasonal and tidal controls on deposition are responsible for mm- to dm-scale bedding metre-scale lithologic cycles within IHS of the McMurray Formation are interpreted to be the result of inter-annual climatic processes and decadal solar cycles (Labrecque et al., 2011). Labrecque et al. (2011) hypothesize that if sedimentation rates are rapid (> 60 cm/yr), then shorter wavelength cycles (2 – 4 m thick) are likely related to inter-annual climatic oscillations. Thick, coarse-grained beds
are attributed to La Niña, during which time North America experiences colder temperatures and increased precipitation. Fine-grained units are deposited during mild El Niño conditions, which occur every 2-7 years, and last 6 months to 2 years (Ropelewski and Halpert, 1986). Labrecque et al. (2011) further suggest that interannual, shorter wavelength (2-4 m) cycles related to El Niño-La Niña events, overprint or are interstratified with longer wavelength (10+ m) cycles produced during periods of lower sedimentation rates (< 20 cm/yr) and on time scales between one to five decades. The dominant control on these decadal cycles is hypothesized to be long-term climatic phases driven by solar radiation that occur approximately every 10 years (Friis-Christensen and Lassen, 1991; Mauas et al., 2008; Labrecque et al., 2011), although this correlation is speculative. A correlation between the number of sunspots and precipitation has also been documented. Higher levels of solar radiation result in increased precipitation, which leads to increased sedimentation rates and the deposition of sand in fluvial settings (Mauas et al., 2008). Deposition of finer-grained intervals may be linked to decreased solar irradiance (Labrecque et al., 2011).

1.3. IHS in Modern Channelized Environments

IHS deposits have been reported in several different environments around the world. The nature of the IHS from each setting differs because of the relative energy inputs of rivers and tides, brackish-water influence, and climatic variability. Comparing and studying deposits from various settings aids in understanding how hydrodynamic and climatic conditions affect IHS deposition and character. Below are descriptions of five environments where modern IHS was studied, ranging from the nearly fully marine,
tide-dominated Shepody River, New Brunswick, Canada to the wholly fluvial Athabasca River, Alberta, Canada.

### 1.3.1. Shepody River, New Brunswick, Canada (Pearson and Gingras, 2006)

Point bar and tidal flat deposits from the estuarine mouth of the Shepody River, New Brunswick, Canada comprise mud-dominated IHS produced in a megatidal environment (Figure 1.3; Pearson and Gingras, 2006). The deposits are composed of interlaminated to thinly interbedded mud and sand. The laminae are rhythmically bedded, with a cyclicity in laminae thicknesses that is attributed to the neap-spring tidal-current variation.

In addition to tidally controlled laminae thicknesses, seasonal controls are responsible for alternating burrowed and laminated beds (Figure 1.3). Laminated beds lacking bioturbation are deposited from the early winter to early spring when temperature, oxygen and salinity conditions restrict sediment colonization (Pearson and Gingras, 2006), and ice and storm scouring remove surficial (upper 5 cm) sediments. Bioturbated beds are deposited and colonized from late spring to early fall. Trace diversity and trace suite composition varies with point bar elevation. In the upper subtidal to lower intertidal zones, *Polykladichnus* and *Skolithos* are dominant; *Arenicolites*, *Diplocraterion*, *Polykladichnus*, *Palaeophycus* and *Planolites* are abundant in the middle intertidal zone; and, *Siphonichnus* and *Polykladichnus* characterize the upper intertidal zone.
1.3.2. **Sukmo Channel, Han River Delta, Korea (Choi et al., 2004, Dalrymple and Choi, 2007; Choi, 2011)**

The Sukmo Channel of the Han River Delta, Korea is an example of a megatidal (>8 m) setting where IHS is produced, and tidal cyclicity is manifest in the rhythmicity of
sand/mud interbedding (Figure 1.4; Choi et al., 2004). The distributary channel is 40 m deep. In the section described, the basal 15 m comprises trough cross-bedded sand, and the upper 25 m is dominated by IHS (Figure 1.4; Choi et al., 2004). At the base of the channel, flood-oriented dunes persist on the point bar side, despite ebb-dominated flow in the channel. The explanation provide by Choi et al. (2004) for this is that the point bar is sheltered from the full force of the ebb current as its maximum velocity occurs on the cutbank side of the channel. On the point bar side of the channel, the flood current is strongest, which is reflected by the orientation of the dunes. The IHS on the point bar dips into the channel at a maximum angle of 14° and consists of interstratified fine-grained sand, sandy silt, and silt arranged into an overall fining-upward profile. Within the IHS, well-developed tidal rhythmites occur in the middle and upper intertidal zones. Laminae thicknesses and lithology patterns coincide with three cycles of tidal rhythmicity: semi-diurnal tides, neap-spring cycles, and apogean-perigean cycles. Nevertheless, full preservation of the cycles is rare because erosional events disrupt depositional continuity. The tidal effects in the Han River are so strong that seasonal effects on deposition are masked.

Burrowing is rare to absent in the Sukmo Channel despite the stable salinities and persistent nearly fully marine conditions for most of the year (approximately 28.5 psu). Minimum salinity in the channel is 9.6 psu during flood discharge (Choi et al., 2004). The lack of bioturbation is attributed to the high sedimentation rates on the bar. Burrowing is only present in the upper intertidal zone where deposition is slower. The primary burrowing organisms are small crabs, which produce Psilonichnus.
**Figure 1.4: The Han River Delta, Korea**

A) Location of the Sukmo Channel study area within the Han River Delta, Korea. B) Satellite image of the Sukmo Channel (Image source: Google Earth). C) Bathymetric profile of the Sukmo Channel. A dashed box encloses the area where the sedimentology of point bar deposits was studied. D) Litholog of a typical point bar succession within the macrotidal Sukmo Channel. The succession displays a fining in grain size and an increase in mud beds upward. (Modified from Choi et al., 2004).
1.3.3. **Willapa River, Washington, USA (Smith, 1985, 1987; Gingras et al., 1999)**

The Willapa River is mesotidal with a mean spring tidal range of 3.4 m (Figure 1.5; Smith, 1985; Smith, 1987). IHS comprises the main stratal architecture of point bar deposits. The IHS dips into the channel from 9.5° to 18° with an average dip of 12.7°. The base of each IHS succession comprises gravel and mudballs that rest on an erosional contact with underlying mud beds. Characteristics of Willapa River IHS include: rhythmic alternation of sand and mud beds (Figure 1.5); small-scale, ripple cross-stratified, fine- to medium-grained sand; thin (1 mm) beds of organic matter in both sand and mud beds; mudballs entrained in sand; and, an increase in bioturbation up the point bar. Point bars in the Willapa River display an upward fining in grain size and a downstream increase in mud beds (Smith, 1987; Smith, 1998; Hubbard et al., 2010). The downstream increase in mud beds continues around meander bends, where sand-rich point bars grade into mud-dominated counter point bar deposits (Hubbard et al., 2010). The alternation of sand and mud in the Willapa River is hypothesized to reflect variations in seasonal fluvial discharge, although, rhythmic beds and lamina-sets are attributed to tidal processes (Smith, 1985; Smith, 1987; Smith, 1988).
1.3.4. **South Arm Marshes, Fraser River Delta, British Columbia, Canada (Sisulak, 2011; Sisulak and Dashtgard, 2012)**

The sedimentology of the South Arm Marshes (SAM), lower Fraser River was characterized by Sisulak (2011) and Sisulak and Dashtgard (2012). The in-channel bar is located in the tide-influenced, fluvially dominated Main Channel (Figure 1.6).
Moderately well- to well-sorted, medium- to coarse-grained sand is deposited at the base of the channel (> 6.5 m depth relative to the maximum high tide level (MHT)). Grain size and sorting are consistent in the channel for the length of the bar. Ebb-oriented dunes (1-2 m in height and 20-50 m in length) within the Ladner Reach and the Main Channel have been documented on the subtidal channel floor (Pretious and Blench, 1951; Villard and Church, 2005).

In water depths from 3 – 6.5 m below MHT, grain size fines with decreasing water depth, and from the upstream to downstream side of the bar (Figure 1.7; Sisulak and Dashtgard, 2012). Vibracores from the lower intertidal to upper subtidal portion of the bar comprise IHS. Sand beds are cm- to m-scale in thickness, and are either current rippled, homogeneous, or trough cross-bedded. Mud beds are either horizontal, curvilinear, parallel laminated, or homogeneous. The homogeneous appearance of sand and mud beds is likely a function of preservation. Common lenticular and wavy bedding in mud beds are observed. Mud clasts and organic detritus are sporadically distributed throughout the IHS successions. Every core exhibits an upward fining and upward increase in mud content. Correlations of the vibracores indicate a downstream increase in mud beds and mud-bed continuity.

Seasonal cyclicity in sand and mud deposition was observed in the intertidal zone of the SAM (Sisulak and Dashtgard, 2012). In June 2009, the intertidal surface on the upstream side of the bar was dominated by ebb-oriented current ripples composed of moderately well-sorted, fine- and medium-grained sand. Surface sediments became increasingly muddy downstream. Sedimentary structures developed in the intertidal zone include flaser bedding, current ripples, minor wave ripples, parallel-laminated sand, and mud clasts. Mud clasts are associated with undercutting of the salt marsh, tidal creeks
cutting through the intertidal zone, and erosion of muddy sediments. Slumping of the channel bank occurred during periods of increased fluvial discharge. In late July-August 2009, on the upstream side of the bar, mud was deposited as a thin (1-3 cm) layer and was concentrated in current-ripple troughs. Observations from March 2010 showed that 1 to 5 cm of mud had accumulated and been compacted over the current-rippled sand that was deposited during the freshet. Consequently, the main control on sand and mud deposition is attributed to seasonal changes in flow volume, with sand deposited during the spring freshet and mud mainly deposited from the waning freshet flow.
Figure 1.6: South Arm Marshes location map

A) Location of the Fraser River delta, British Columbia, Canada. B) Location of the South Arm Marshes (SAM) in-channel bar. C) Satellite image of the SAM. (Image source: Google Earth).
Figure 1.7 (previous page): Cross-sections from the South Arm Marshes in-channel bar

A) Satellite image of the SAM with vibacore locations, cross-section lines and grab sample locations. B) Cross-section of the upstream side of the bar with grain-size profiles from grab sample transects extending from the lithologs further down into the subtidal zone. The sediments on the upstream side of the bar are predominantly sandy, and are considerably less muddy than the downstream side. C) Cross-section of the downstream side of the bar. Mud beds are more dominant and laterally continuous than on the upstream side. Most of the cores on both ends of the bar display a fining in grain size and an increase in mud beds upward. The zero mark is maximum high tide (MHT) level and the blue line marks the average low tide (ALT) position and the approximate boundary between the intertidal and subtidal zone. (From Sisulak and Dashtgard, 2012).

The trace suite in the South Arm Marshes is dominated by diminutive vertical structures (Sisulak, 2011; Sisulak and Dashtgard, 2012), which is consistent with other studies done on brackish-water environments (e.g., Beynon et al., 1988; Pemberton and Wightman, 1992; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2007). The salinity of the Fraser River around the South Arm Marshes ranges from 0 – 10 psu depending on the time of year (Kostachuk et al., 1998, Sisulak and Dashtgard, 2012). During the spring freshet, when peak fluvial discharge occurs, the saltwater wedge is pushed out of the river, resulting in prolonged freshwater conditions (0 psu). When fluvial discharge is at its lowest and during spring high tides, the saltwater wedge extends well upstream of the SAM, and peak salinities of 8 to 10 psu are reached. During the spring freshet, the persistent freshwater and the high rate of sand transport and deposition produces inhospitable conditions for organisms, and bioturbation is rare to absent (Sisulak and Dashtgard, 2012). Colonization and burrowing coincides with low flow conditions when salinity is highest: this is also when mud is deposited. The main burrowing organisms present are Corophium sp. and Nereid polychaetes. Together, these animals produce a trace suite in mud beds dominated by Arenicolites, Palaeophycus, Skolithos and Polykladichnus. The seasonal changes in bioturbation intensity results in the interbedding of non-bioturbated sand beds (freshet deposits; Figure 1.8A) and bioturbated mud beds (ambient deposits; Figure 1.8B).
Greater bioturbation intensities are found in the downstream end of the in-channel bar where mud is more prevalent.
Figure 1.8 (previous page): Bioturbation variability across the South Arm Marshes in-channel bar

The map shows the location of two box cores whose x-radiographs are shown in A and B. A) Box core from the upstream end of the bar comprising current ripple cross-laminated sand. No bioturbation is visible. B) Box core from the downstream end of the bar. The white brackets represent one season of deposition. Sand-rich beds (lighter gray) are deposited during the spring freshet, while mud-rich beds (darker gray) are deposited from the waning freshet flow and during base flow. The sand beds contain little bioturbation due to the high sedimentation rate and low salinity associated with freshet flow. The mud beds are pervasively bioturbated and are colonized under base flow conditions. (Modified from Sisulak and Dashtgard, 2012).

1.3.5. Athabasca River, Alberta, Canada (Calverley, 1984; Smith, 1985; Smith et al., 2011)

IHS from the wholly fluvial end of the tidal-fluvial spectrum was reported from the Athabasca River, Alberta, Canada (Calverley, 1984, Smith et al., 2011). The point bar successions from the Athabasca River display fining-upward trends and a proximal-to-distal fining trend (Calverley, 1984). The sand-mud bedsets do not show any rhythmicity with regards to vertical thickness variations, and bioturbation is rare to absent. The processes responsible for mud deposition are unknown, but backwater effects associated with storms, very high water levels in the receiving basin (Lake Athabasca) concomitant with river flooding, and the falling stage of floods are proposed factors (Calverley, 1984; Smith, 1985). Sand deposition is attributed to early- and high-stage river floods. The irregular occurrence of mud beds in the successions is attributed to the random nature of floods.

In addition to point bar deposits, counter point bars and eddy accretion deposits were studied from the Peace-Athabasca delta. Counter point bar deposits are found directly downriver of point bars after the inflection point in the meander bend (Figure 1.9). Eddy accretion deposits are located on the outer bends of meandering channels where the river impinges against resistant sediment at high angles (40 - 140°; Figure 1.10). Counter point bars are also formed where a channel abuts against resistant
sediment, but these impinge at low angles (10 to 40°). These deposits contain more silt than either point bar or eddy accretion deposits. Lithologically, counter point bar deposits contain the most silt (55 – 86%). Point bars in the area contain 95 – 100% sand, while eddy accretion deposits contain up to 80% sand.
Figure 1.9: Counter point bar deposits of the Peace River

A) Satellite image of the Peace River, Alberta, Canada, with the location of the vibracores shown in (C) (image source: Google Earth). B) Counter point bar model. C) Cross-section of vibracores from the Peace River (locations indicated in (A)). There is an increase in mud beds at the transition from the point bar to counter point bar deposits (Modified from Smith, 2011).
Figure 1.10: Athabasca River, Alberta

A) Satellite image of the Athabasca River, Alberta; showing an eddy accretion belt and vibracore locations. B) Lithologs of vibracores taken along the eddy accretion belt, with locations shown in (A). C) Schematic diagram depiction the eddy accretion deposit (EAD) model. (Modified from Smith et al., 2011).
1.4. Study Area

1.4.1. Fraser River Delta and Distributaries

The Fraser River drains a 228 000 km$^2$ area and is the largest river that empties into the Pacific Ocean on the west coast of Canada (Figure 1.11; Milliman, 1980; Monahan et al., 1993; Villard and Kostachuk, 1998). The Fraser delta is bounded by the Coast Mountains to the north and the Cascade Mountains to the south, which progrades westward into the Strait of Georgia. The delta is relatively young, with initiation beginning at the end of the last glaciation (10 ka), when the Fraser River began to deposit sediment directly into the Strait of Georgia (Clague et al., 1983). The delta extends 15 to 23 km west from its defined apex at New Westminster and meets the sea along a 40 km long perimeter. Twenty-seven kilometres of the perimeter forms the western coastline of the delta, while the remaining thirteen kilometres faces south into Boundary Bay (Clague et al., 1983).

In its lower reaches, the Fraser River has four main distributaries: Canoe Pass, the Main Channel (South Arm), the Middle Arm, and the North Arm (Figure 1.11B). The discharge and sediment volumes passing through each distributary varies significantly. The Main Channel carries the majority of the flow (74%), whereas Canoe Pass, North Arm, and Middle Arm contain 18%, 7% and 5% of the flow, respectively (WCHL, 1977; Mikhailov et al., 2007). The Fraser River is sand-rich (35% sand) and transports $17 \times 10^6$ tonnes of sediment to the coast annually (Milliman, 1980; McLaren and Tuominen, 1996; Kostaschuk et al., 1998, Mclean et al., 1999). Most of the Fraser River sediment load (80%), and all of the sand is transported during the snowmelt-induced freshet in late May to July. Only 3 to 9% of the total Fraser River sediment supply enters the North Arm / Middle Arm distributaries (Church et al., 1990).
Three bars in the Middle Arm were studied, including a channel-margin bar (most landward bar; CMB), an in-channel bar (ICB), and a semi-detached point bar (most seaward deposit; PB; Figure 1.11C). The CMB is 1.9 km long and has a maximum intertidal width of 150 m. The ICB has an intertidal zone that extends 170 m into the river and is 1.1 km long. The PB is 1.7 km long and 830 m wide and is attached to the laterally extensive tidal flats of the lower delta plain. The approximate boundary between the intertidal- and subtidal-zones is marked by the average minimum low tide in 2011, which is 3.40 m (from average maximum high tide (AMHT)). The average depths of the channel adjacent to the CMB, ICB, and PB, are 6.2 m, 4.3 m, and 5.4 m (from AMHT), respectively. The maximum depth of the channel is located in the thalweg next to the CMB, and is 8.5 m (from AMHT) deep. Within the study area, however, the Middle Arm has an average depth of 5.3 m (relative to AMHT) and an average width of 300 m.

1.4.2. Fraser River Hydrodynamics and Salinity Conditions

River discharge is highest during the freshet and ranges between 5 130-15 200 m³/s (Water Survey of Canada, http://www.wateroffice.ec.gc.ca). For the rest of the year, average flow is ~ 1 000 m³/s. Tides influence flow within the lower Fraser and are measurable up to 90 km upstream (Hughes and Ages, 1975; Kostachuk and Atwood, 1990; Mikhailov et al., 2007, Dashtgard et al., in press). Saltwater incursion up the Fraser distributaries has been reported up to 30 km upstream. The tides are semi-diurnal and range from 2 – 5 m throughout the neap-spring cycle. The average tidal range is 3.1 m. Subequally mixed tidal-fluvial conditions exist within the Middle Arm of the Fraser River, wherein the channel is subjected to relatively equal influence of river processes and tides.
The study area is subjected to oligohaline (0.5-5 practical salinity units (psu)) to polyhaline (18-30 psu) waters. Vertical and lateral salinity gradients change daily with the tidal cycle, and seasonally with changes in fluvial discharge (Hughes and Ages, 1975). In general, daily salinity fluctuations correlate strongly with the diurnal tidal cycle: the highest salinities are recorded during high tide, while the lowest salinities occur during low tide. Seasonal salinity changes are related to seasonal changes in river discharge. The maximum upstream extent of saltwater incursion occurs when flow is at a minimum. The saltwater wedge is displaced seaward when discharge is high. Consequently, minimum salinity values occur during the freshet, and peak salinities occur when river discharge is low.
Figure 1.11: Study Area

A) (Inset map) Location map of the Fraser River delta, British Columbia, Canada. B) Schematic geographic/bathymetric map of the Fraser delta. The Middle Arm study area is outlined by the dashed red box. The active delta front extends from the Tsawwassen ferry terminal (*) to the North Arm. The maximum landward extent of saltwater incursion is defined by the solid red line. C) Map of the three Middle Arm bars: the channel-margin bar (CMB), the in-channel bar (ICB), and the point bar (PB). (Image source: Google Earth.)
1.5. Methods

The majority of fieldwork was undertaken during the freshet in June and July, 2011. Additional surface observations and some sediment samples were acquired in March, 2012. Surface sediment samples, base-of-channel grab samples, box cores, infaunal population counts, and vibracores comprise the main sampling techniques used in the field (Figures 1.12 and 1.13). On the PB, samples were taken along seven transects, spaced approximately 250 m apart, with three stations per transect, spaced approximately 150 m apart (Figure 1.14). On the CMB and ICB, samples were taken along six transects, each with one to three stations spaced 50-100 m (Figure 1.14). Thirteen stations were sampled on the ICB and ten were taken from the CMB (Figure 1.14). At each intertidal station, sedimentary structures and burrow distributions were recorded and photographed. Twenty-nine, 15 and 11 sediment samples were taken from the PB, ICB, and CMB, respectively in June-July 2011. An additional 6, 3 and 3 sediment samples were taken from the PB, ICB, and CMB, respectively in March 2012. Each surface sample consists of approximately 250 g of sediment from the upper 5 cm.

The intertidal zone transects on the PB and ICB were extended across the width of the channel by acquiring grab samples of channel-bottom sediments at approximately 50 m intervals (Figures 1.13E and 1.14). Thirty-two grab samples were taken from the channel adjacent to the PB and 20 were taken adjacent to the ICB (Figure 1.14). One-metre intervals were marked along the rope attached to the grab sampler in order to measure water depth. Water-depth profiles were constructed by using the water depths measured while grab sampling, the time of sample acquisition, and tide tables. Depth measurements acquired from grab sampling were combined with depth data from the
Canadian Hydrographic Service (CHS) nautical chart of the Middle Arm to construct bathymetric contour maps of the field area.

All sediment samples (surface- and grab-samples) were taken back to the laboratory, and grain size was measured through both sieving and using a Mastersizer® particle-size analyzer. During sieving, samples were agitated through 6 sieves, proceeding from \(-1\) Φ (2 mm) to \(4\) Φ (0.0625 mm; Figure 1.13D). The Mastersizer® can detect particles less than 0.0625 mm in size, using laser diffraction technology (Figure 1.13F). In preparation for analysis in the Mastersizer®, samples were mixed with hydrogen peroxide (to remove organics), and then with sodium hexametaphosphate to inhibit clay flocculation. Grain size results were then entered into GRADISTAT (Blott and Pye, 2001) to determine grain-size distributions and to evaluate statistical parameters.

One to two box cores (0.28 m x 0.17 m x 0.06 m; Figure 1.13B) were taken at each station, totalling 22 from the PB, 13 from the ICB, and 10 from the CMB. An additional 6, 3 and 3 box cores were retrieved from the PB, ICB, and CMB, respectively, in March 2012. Box cores were pressed into the sediment and their orientations were measured. Each core was then taken to the lab and was either x-ray imaged (muddy and sandy sediment; Figure 1.13C) or resin peeled (sandy sediment). Both techniques reveal sedimentological and ichnological structures.

Vibracores (3 m long, 0.076 m diameter; Figure 1.13A) were also collected at sites along the lower intertidal zone: 7 cores were taken from the PB, and 4 cores from the ICB. Cores were taken back to the lab and cut longitudinally in half. One half of the core was photographed and sampled for grain size. The other half was resin peeled and logged in detail, recording all sedimentological and ichnological features observed.
Finally, infauna population counts were completed at each station to measure the distribution, intensity of bioturbation, and kinds of infauna and burrows present. At each site, three, 0.4 m x 0.4 m x 0.3 m deep holes were excavated, and the sediment from these holes was sieved to recover and count bivalves and other large invertebrates. In order to count smaller infauna, three, 0.15 m x 0.15 m x 0.15 m sediment samples were extracted and sieved through a 4 mm mesh. The three counts at each station were converted into numbers per square meter, and then averaged.

Figure 1.12: Sampling methods
Depicts the sampling methods employed at all three bars. Average depth and bar profile is based on the PB. (Modified from Sisulak, 2011).
Figure 1.13: Photos of research equipment

A) VibraCore being set-up on the tidal flat. The other end of the flexible hose of the cement shaker (top left) is attached to a motor that provides the power to vibrate the pipe through the sediment. B) Picture of a box core (0.28 m x 0.17 m x 0.06 m). C) Box core sediment in an x-ray tray. The sediment is then x-rayed to reveal sedimentary and biogenic structures. The tray is 25 cm long and 2 cm thick. D) Sieve shaker used for grain size analysis. E) Petite Ponar grab sampler used for retrieving sediment from the base of the channel. F) Mastersizer®, particle-size analyzer.
Figure 1.14: Distribution of sampling across the Middle Arm bars

Sampling locations at the PB, ICB, and CMB (A, B and C respectively) in June and July 2011. Grab samples from the base of the channel are marked by black dots. Intertidal zone locations where box coring, animal population counts and surface sediment sampling was conducted are indicated by both red and yellow dots. Yellow dots indicate intertidal stations where vibracores were acquired. Locations marked by stars are locations re-visited in March, 2012. A) PB: 35 surface sediment samples, 132 animal population counts, 28 box cores, 32 grab samples and 7 vibracores. B) ICB: 18 surface sediment samples, 43 animal population counts, 16 box cores, 20 grab samples and 4 vibracores. C) CMB: 14 surface sediment samples, 33 animal population counts and 13 box cores. No grab samples were acquired due to a floatplane runway in the channel adjacent to the bar.
1.6. References


2. Neoichnology of the Fraser Delta

2.1. Introduction

The Fraser River delta contains a variety of infauna whose abundance and distribution vary depending on a wide-range of physical and chemical stresses that affect them. Stresses that affect organism abundance and distribution include: salinity; sedimentation rate; turbidity; subaerial exposure; hydraulic energy; substrate type and consistency; grain size; water oxygenation; temperature; and food availability (Swinbanks and Murray, 1981; Ekdale and Mason, 1989; Wheatcroft, 1990; Pemberton and Wightman, 1992; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005a, b; Dashtgard, 2011a, b). In shallow water, salinity exerts the greatest stress on infauna, and is variable along the lower Fraser River, across the lower delta plain, and out into the Strait of Georgia (Fig. 1.11). The salinity gradient also shifts position within the channel, both as a function of tidal stage (Figure 3.4; Hughes and Ages, 1975; Thomson, 1981), and seasonally with changing river discharge (Figure 3.5; Chapman and Brinkhurst, 1981; Kostaschuk and Luternauer, 1989). Most organisms require stable salinity levels, and the number of species able to tolerate marked salinity changes is limited (Howard and Frey, 1973; Pemberton and Wightman, 1992; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005a, b). Moreover, the diversity of infauna is significantly higher in marine environments, such that settings subjected to water with stable salinity levels between 32-35 psu supports more diverse and robust infaunal communities.
In Chapter 2, the brackish-water model is defined and summarizes the results of infaunal population studies done on the Fraser Delta. Infaunal distributions give insight into the main stresses that are controlling the distribution of organisms across the Fraser River and delta. Finally, neoichnological studies of the lower Fraser River and lower deltaplain are described, as these data provide the basis upon which the neoichnological descriptions of the Middle Arm study area (outlined in chapter 3) are based.

2.2. Brackish-Water Model

The animal-sediment relationships of many modern and ancient environments subjected to salinity fluctuations and/or brackish water have been studied (e.g., Howard and Frey, 1973; Beynon et al., 1988; Pemberton and Wightman 1992; MacEachern and Pemberton, 1994; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2007; Dashtgard and Gingras, 2012). From these studies, seven biological / ichnological characteristics of brackish-water environments have been established. (1) A reduction in diversity is observed with respect to both freshwater and fully marine trace assemblages: the preserved assemblage corresponds to an impoverished marine suite (Slobodkin and Sanders, 1969; Barnes, 1989). (2) Brackish-water communities comprise more infauna than epifauna because the sediment dampens the effect of salinity fluctuations (Figure 2.1; Sanders et al., 1965; Knox, 1986). (3) Structures of inferred trophic generalists (i.e., omnivores and scavengers) dominate, which results in a trace assemblage dominated by morphologically simple burrows (Grassle and Grassle, 1974). For example, 35% of organisms in Dutch estuaries were determined to be opportunistic omnivores in a study by Wolff (1973), while 6-16% were omnivores in adjacent freshwater and fully marine environments. (4) The number of
freshwater species declines rapidly with increasing salinity, whereas marine species decline gradually with salinity reduction (Barnes, 1989). (5) While infaunal diversity is low in brackish-water environments, infaunal density can commonly be high due to the abundance of available food, and the generally sheltered nature of brackish-water, marginal-marine environments (Rosenberg et al., 1977). (6) The trace-fossil suite commonly contains elements common to both the Skolithos and Cruziana ichnofacies. The alternation between feeding behaviours that define the two ichnofacies (Skolithos = filter feeding; Cruziana = deposit feeding) reflects the fluctuating energy conditions in brackish-water settings as well as the abundant food supply. (7) Burrows are diminutive in size compared to their marine counterparts. Diminution enables organisms to better osmotically regulate and control the ionic concentrations of body fluids in reduced salinity environments. Remane and Schleiper (1971) showed that five species of bivalves reduced their size by as much as 35% when salinity was reduced from 35 to 5 psu. A bias towards smaller traces in brackish-water environments could also be due to high mortality rates and population composition rather than true diminution (Rees et al., 1977; Chapman and Brinkhurst, 1981; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005a, b; Gingras et al., 2011). High mortality rates due to salinity stress produce a bias towards juvenile forms and ultimately results in a diminutive trace assemblage. Gingras et al. (1999) found that in Willapa Bay, Washington, the diminution is a result of smaller diameter species opportunistically colonizing substrates in salinity stressed conditions. Chapman and Brinkhurst (1981) noted that diminution and preferential colonization by juveniles is the result of an annual die-off of infauna during the freshet (i.e., persistent freshwater for two months).
Figure 2.1: Diurnal salinity changes from the Avon-Heathcote Estuary, New Zealand

Interstitial and bottom-water salinity recorded hourly over a single tidal cycle from the Avon-Heathcote Estuary, New Zealand. The sediment acts as a buffer against salinity fluctuation, such that interstitial salinity varies between 18-24 psu while salinity in the water column ranges from 2-31 psu. Low tide (LT) and high tide (HT) are indicated on the x-axis. (Modified from Knox, 1986).

2.3. Fraser River Deltaplain

2.3.1. Active Lower Fraser River Deltaplain

The Fraser River delta currently progrades into the Strait of Georgia along a 27 km perimeter on the west coast of British Columbia. The distribution of infauna along the active lower deltaplain (between Tsawwassen and the North Arm; Fig. 1.11) was characterized in detail by Dashtgard (2011b). There are a variety of burrowing organisms present on the active lower deltaplain, wherein the majority of infauna are bivalves with lesser numbers of crustaceans and polychaetes (Figure 2.2). Bivalves are particularly common on the downdrift side (north end) of the main arm of the Fraser River. Filter-feeding bivalves are not as abundant on the southern tidal flats. Surface-deposit-feeding and subsurface deposit-feeding animals, including Nereid polychaetes
and the crustaceans *Neotrypaea californiensis* and *Corophium* sp., dominate the updrift side of the main distributary. The bivalves generate structures comparable to *Siphonichnus*, whereas crustaceans produce *Thalassinoides*, *Arenicolites* and *Psilonichnus*-like burrows (Figure 2.2; Gingras et al., 2008; Dashtgard, 2011a,b). Rare vermiform organisms produce *Arenicolites*, *Gyrolithes*, *Skolithos*, *Palaeophycus* and *Polykladichnus*-like structures (Figure 2.2). The traces are mainly constructed by filter-feeding and surface-deposit-feeding infauna, with rare burrow networks constructed by mobile, subsurface deposit feeders.
**Figure 2.2 (previous page): Fraser River delta, active lower delta plain neoichnology**

A) Locations of x-radiographs and photos of sediment from the Fraser River delta, active lower delta plain. B) Mud overlying muddy sand with *Siphonichnus*-like burrows produced by *Macoma balthica* and U-shaped *Arenicolites*-like structures generated by *Corophium* sp. C) Mud with a vertical *Macoma balthica* burrow, a threadworm burrow, and a *Polykladichnus*-like burrow produced by *Nereis* sp. D) Sandy mud to mud with high bioturbation intensity. E) Interbedded parallel laminated muddy sand and wave-rippled sand. Bioturbation intensity is high for the majority of the unit, but low to moderate bioturbation intensity is observed in the bottom 5 cm of the image. F) Bedding plane view of muddy sand. Burrowing is sparse, with the majority of burrows produced by threadworms. *Polykladichnus*-like burrows are rare. The blue and white scale bar at the bottom of the image is 5 cm. G) Sandy mud with a moderate diversity of vertical burrows. The black and white sections on the scale bars are 1 cm each. (From Dashtgard, 2011b).

### 2.3.2. Boundary Bay

On the southern coast of the Fraser River delta, the tidal flats of Boundary Bay extend along a 13 km perimeter from Tsawwassen to White Rock (Fig. 1.11). Approximately 2.2 ka ago, the delta onlapped the Pleistocene highland at Point Roberts, effectively removing direct fluvial input to Boundary Bay (Murty and Roberts, 1989). The lack of fluvial input resulted in stable polyhaline conditions in the bay, with salinities ranging between 27-30 psu (Swinbanks and Murray, 1981; Dashtgard, 2011a). Polyhaline conditions are sufficiently high that marine infauna can thrive in Boundary Bay. Vermiform animals, crustaceans and bivalves are the primary tracemakers in Boundary Bay (Figures 2.3 and 2.4). The distribution and intensity of burrowing varies across the tidal flat due to stresses other than salinity, including hydraulic energy, grain size, duration of subaerial exposure, and the sedimentation rate. Sedimentation rates and subaerial exposure are the overriding stresses on infaunal distributions in Boundary Bay (Dashtgard, 2011a). Where the sedimentation rate is highest, bioturbation intensities and burrow diversities are lowest. This is due to a limited colonization window available to organisms, because substrates are rapidly buried and re-exposed (Wheatcroft, 1990; Dashtgard, 2011a). In addition, a high sedimentation rate makes it
difficult for an organism to sustain its ideal depth from the surface, and continually shifting position within a substrate is not optimal for most infauna (Bromley, 1990).

Increased subaerial exposure imparts desiccation and oxygen stresses (Swinbanks and Murray, 1981; Dashtgard, 2011a). One organism that can tolerate a considerable amount of subaerial exposure is the crustacean *Neotrypaea californiensis* (Figure 2.3H; Swinbanks and Murray, 1981). *Neotrypaea* produces unlined *Thalassinoi*des-like structures (Figure 2.3H). The unlined nature of its burrow means it is exposed to oxygen stressed interstitial waters every time it is exposed at low tide. As a result, *Neotrypaea californiensis* has adapted to tolerate significant amounts of anoxia and is found in areas with significant degrees of subaerial exposure (4 to 9 days of continuous exposure; Swinbanks and Murray, 1981). However, *Neotrypaea californiensis* is the exception, and at Boundary Bay, the majority of the infauna colonize topographic lows and areas where subaerial exposure is minimized (Swinbanks and Murray, 1981; Dashtgard, 2011a).
Figure 2.3 (previous page): Boundary Bay infauna

A) The polychaete *Abarenicola pacifica* in its U-shaped burrow attributed to *Arenicolites*. B) The hemichordate *Saccoglossus* sp. in its spiral-shaped, *Gyrolithes*-like burrow. C) Small part of a sand-lined burrow (white arrow) with the polychaete *Axiotella* sp. *Axiotella* generates lined- *Skolithos*-like burrows and is a head-down deposit feeder. D) The white arrows point to the polychaete *Heteromastus*. These polychaetes are very thin and are considered to develop cryptobioturbation. E) The filter-feeding bivalve *Nuttallia obscurata* extends two siphons to the surface and produces *Siphonichnus*-like traces. The scale is 5 cm. F) The bivalve *Mya arenaria*, with its one siphon extended to filter-feed, producing *Siphonichnus*-like traces. G) Complex, three-dimensional, branching burrow network produced by *Nereis* sp. (inset photo). *Nereis* burrows can be similar to *Polykladichnus, Arenicolites, Palaeophycus, Thalassinoides* or *Skolithos*. H) The crustacean *Neotrypaea californiensis* (inset photo) produces *Thalassinoides*-like burrows, comparable to the one in the image. I) The photo is of a *Hemigrapsus* sp. (inset photo) generated structure. The burrow is an irregular U-shaped *Psilonichnus*-like structure. Each black and white section on the field scale bars is 1 cm. (From Dashtgard, 2011a).
**Figure 2.4 (previous page): Boundary Bay x-radiographs**

X-radiograph images from the southwest end of Boundary Bay. **A)** X-radiograph taken from between two large asymmetrical dunes. The sediment comprises current-ripple ‘cr’ and combined-flow-ripple ‘cf’ laminated sand. Several burrows generated by *Nereis* sp. The diameter of the burrows are equal, suggesting that they all belong to the same *Nereis* sp. generated burrow network. A small escape structure is indicated (fugichnia ‘fu’). **B)** Sand with north-west migrating current ripples taken midway between the crest and a trough of a large asymmetrical dune. **C)** Highly bioturbated with sand dominated by *Gyrolithes*-like ‘Gy’ burrows constructed by *Saccoglossus* sp. The bivalve *Macoma nasuta* ‘ma’ and a disarticulated shell ‘s’ are indicated in the photo. **D)** Sand with a high bioturbation intensity. Discernible burrows include: *Arenicolites*-like, *Siphonichnus*- and *Palaeophycus*-like structures. Also in the image are disarticulated shells ‘s’, a gastropod shell ‘ga’, the bivalve *Nuttallia obscurata* ‘nu’ and threadworm burrows ‘t’. **E)** Dual-siphon *Siphonichnus*-like ‘Si’ burrows constructed by *Nuttallia obscurata* ‘nu’. Threadworm burrows ‘t’ that contribute to cryptobioturbation are also indicated. The image is from a tidal-channel point bar. The sediment has been completely reworked by *Nuttallia obscurata* and the polychaetes *Nephtys* sp. **F)** *Nereis* sp.- and *Saccoglossus* sp.- generated *Polykladichnus*-like ‘Po’ and *Gyrolithes*-like ‘Gy’ structures, respectively. Near the base of the core is organic-rich lamination ‘lm’. Roots ‘rt’ are present at the top of the core. (From Dashtgard, 2011a).

Turbidity and salinity are the two main stresses responsible for the differences in infaunal communities between the abandoned lower delta plain in Boundary Bay and the active lower delta plain on the west side of the delta (Dashtgard, 2011a,b). Filter-feeding bivalves are abundant on the active lower delta plain, while in Boundary Bay there are fewer filter-feeding organisms and more subsurface-deposit-feeding vermiform animals (Figure 2.5). Not only is there a greater abundance of vermiform animals at Boundary Bay, but there is greater diversity as well. *Saccoglossus* sp. and *Axiotella* sp. are two worms that are present at Boundary Bay but do not colonize the active delta plain (Figure 2.5). *Saccoglossus* sp. constructs *Gyrolithes*-like burrows, while *Axiotella* sp. produces burrows that resemble lined *Skolithos* (Figures 2.3, 2.4 and 2.5). The abundance of crustaceans is comparable for both areas.

The presence of abundant filter-feeding infauna suggests that turbidity is higher across the active lower delta plain than in Boundary Bay (Dashtgard, 2011a,b). The higher diversity and density seen at Boundary Bay compared to the active lower
deltaplain is attributed to higher and more stable salinities along the abandoned side of the delta. The salinity range in the lower delta plain is 0-15 psu, whereas at Boundary Bay it is 26-31 psu. Lower salinities in the active lower deltaplain lead to reduced trace diversities (Dashtgard, 2011a,b).

Figure 2.5: Fraser River delta, active vs. abandoned (Boundary Bay) lower delta infaunal diversity

A graph comparing infaunal diversity in the active lower plain to the abandoned lower deltaplain of the Fraser River delta. The most notable difference is the decrease in veriform animals and increase in bivalves in the active lower deltaplain. The abundance of crustaceans is comparable between the two sites. (From Dashtgard, 2011b).
2.3.3. **North Arm**

From June 1977 to August 1978, Chapman and Brinkhurst (1981) investigated the effects of seasonal changes in interstitial salinity on benthic invertebrate populations in the North Arm of the lower Fraser River. Six stations along the Fraser River were established: station one was at the maximum upstream location and station six was located the furthest downstream (Figure 2.6).

At stations 1 and 2, mainly freshwater oligochaetes were found and the diversity of organisms was lowest at these sites (Figure, 2.6). As well, a decline and disappearance of some species occurred during low river flow and salinity intrusion in the early spring. At Station 3, interstitial salinities reached a peak of 20 psu during low flow, at which time freshwater species were rare and juvenile marine oligochaetes and polychaetes were present. Stations 4, 5, and 6 were dominated by marine organisms (Figure 2.6), including marine polychaetes, oligochaetes, and bivalves. The last occurrence of freshwater oligochaetes was found at Station 4 when salinity was lowest (less than 7 psu). Unlike Station 3, mature forms of the infaunal population were prevalent at Stations 4-6.

Evaluation of benthic infaunal distributions indicates a gradation from abundant freshwater oligochaetes to a prolific marine population (bivalves and polychaetes) in the downstream direction (Figure 2.6). Nonetheless, populations are dynamic at any given location in the estuary. Chapman and Brinkhurst (1981) show a correlation between seasonal variations in interstitial salinity levels and seasonal shifts in benthic distributions. Although there are extreme diurnal salinity changes within the water column, the interstitial salinities are less variable (Chapman, 1981). The time needed for the water column salinities to equilibrate with interstitial salinities depends on the
substrate porosity and permeability. Substrates in the North Arm are composed of a high proportion of silt, which slows salinity re-equilibration times, and requires prolonged exposure for equilibration to occur (Chapman, 1981). Diurnal shifts in the subtidal benthic communities were not observed to occur, suggesting that interstitial salinity is the prevailing factor that controls infaunal populations. During the spring freshet (2-3 months), freshwater organisms are displaced downstream, and during low fluvial discharge (9-10 months), marine species move upstream. These shifts are due to the salinity tolerances of the various species present in the Fraser River.
<table>
<thead>
<tr>
<th>Species</th>
<th>Stations</th>
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<tr>
<td><em>Limnodrilus profundicolai</em></td>
<td>6</td>
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<tr>
<td><em>Ophionais serpentinain</em></td>
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<tr>
<td><em>Limnodrilus udekemianus</em></td>
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<td><em>Vejdovskyella comata</em></td>
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<tr>
<td><em>Specaria fraseri</em></td>
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<td><strong>Chironomids</strong></td>
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<td><em>Tubifex tubifex</em></td>
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<tr>
<td><em>Limnodrilus hoffmeisteri</em></td>
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<td><em>Nais communis</em></td>
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<td><em>Nais elinguis</em></td>
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<td><em>Paranais frici</em></td>
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<td><em>Paranais litoralis</em></td>
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<td><em>Anisogammarus confervicolus</em></td>
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<td><strong>Polychaeta</strong></td>
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<td><em>Nereis limnicola</em></td>
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<td><em>Tubificoides gabiellae</em></td>
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<td><em>Capitella capitata</em></td>
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<td><em>Corophium sp.</em></td>
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<td><em>Eteone longa</em></td>
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<td><em>Amphictonis sp.</em></td>
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<td><em>Macoma balthica</em></td>
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<td><em>Polydora kempi japonica</em></td>
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<td><em>Armandia brevis</em></td>
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<td><em>Mytilus edulis</em></td>
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<td><strong>Nemertea</strong></td>
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<tr>
<td><em>Cumella sp.</em></td>
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<tr>
<td><em>Macoma nasuta</em></td>
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t=oligochaete (tubificid); n=oligochaete (naidid); a=crustacean (amphipod); c=crustacean (cumacean); p=polychaete; b=bivalve; ★=present on only one occasion
The trace suite in the South Arm Marshes in the Main Channel of the lower Fraser River is dominated by diminutive vertical structures (Sisulak, 2011; Sisulak and Dashtgard, 2012). The salinity of the Fraser River at the South Arm Marshes ranges from 0 – 10 psu depending on the time of year (Kostaschuk et al., 1998; Sisulak and Dashtgard, 2012). During the spring freshet, when peak fluvial discharge occurs, the salt wedge is pushed out of the river resulting in prolonged freshwater conditions (0 psu). When fluvial discharge is at its lowest and during spring high tides, the salt wedge extends well upstream of the SAM, and peak salinities of 8 to 10 psu are reached. During the spring freshet, the persistent freshwater coupled with the high rate of sand transport and deposition produces inhospitable conditions for organisms, and bioturbation is rare to absent (BI 0 – 2; Figure 1.8; Sisulak and Dashtgard, 2012). Colonization and burrowing coincides with low-flow conditions when salinity is highest with BI 0 – 4; this corresponds to periods of increases mud deposition. The main burrowing organisms are *Corophium* sp. and Nereid polychaetes. Together, these animals produce a trace suite in mud beds dominated by *Arenicolites*-, *Palaeophycus*-, *Skolithos*- and *Polykladichnus*-like structures. The seasonal changes in bioturbation intensity results in the interbedding of non-bioturbated sand beds (freshet deposits) and bioturbated mud beds (ambient deposits; Figure 1.8). Greater bioturbation intensities are found in the downstream end of the SAM, where mud is more prevalent (Figure 1.8).
2.4. Conclusion

Differences in infaunal populations within the Fraser River delta are largely controlled by salinity variations. An increase in the density and diversity of infauna corresponds to an increase in salinity toward normal marine values ($32 - 35$ psu; Chapman and Brinkhurst, 1981; Dashtgard 2011a,b; Sisulak and Dashtgard, 2011). Chapman and Brinkhurst (1981) show that the diversity of infauna increases in the downstream direction, and that populations are dynamic along the river due to seasonal variations in river flow that cause seasonal changes in interstitial salinity. With the exception of the polyhaline Boundary Bay, the trace assemblage in the Fraser River delta comprises a low diversity of simple structures generated by trophic generalists (Dashtgard 2011b; Sisulak and Dashtgard, 2012). This is consistent with typical brackish-water assemblages (e.g., Beynon et al., 1988; Pemberton and Wightman 1992; Gingras et al., 1999; Buatois et al., 2005; MacEachern et al., 2005; MacEachern and Gingras, 2007). Another commonality with other brackish-water assemblages is that freshwater organisms decline rapidly with slight increases in salinity, whereas marine organism populations decline more gradually, resulting in an impoverished marine suite of burrows (Chapman and Brinkhurst, 1981). Diminution with increasing salinity stress was only reported by Chapman and Brinkhurst (1981). This diminution was due to a bias towards juvenile forms owing to high mortality rates, and not diminution of organisms for the purpose of osmotic regulation.

Neoichnological studies of the Fraser River delta indicate that salinity variation has a strong control on infaunal distribution and burrowing intensity and variability. Other stresses like sedimentation rate, hydraulic energy, subaerial exposure, grain size and
turbidity impart a secondary control on infaunal distribution. The results from these studies will be compared to the ichnology of the Middle Arm of the Fraser River.
2.5. References

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3. The Nature of IHS in a Mixed Tidal-Fluvial Setting: Depositional Processes, Sedimentology and Ichnology

3.1. Introduction

Inclined heterolithic stratification (inclined interbeds of sand and mud; IHS) is a common stratal architecture in estuarine point bars, in the subsurface, outcrops and in modern environments (Figure 1.1). IHS successions range in thicknesses from 1 - 30 m, and have depositional dips ranging from 1 - 36° (Thomas et al., 1987). In modern settings containing IHS, the lateral and vertical extent of mud and sand beds can be mapped, and the sedimentology and ichnology of these deposits can be characterized in detail. Modern examples of IHS are described from river-dominated (Smith et al., 2009; Smith et al., 2011), estuarine (Smith, 1985; Smith, 1987; Smith, 1988; Gingras et al., 1999; Sisulak and Dashtgard, 2012), and tide-dominated (Choi et al., 2004; Dalrymple and Choi, 2007; Choi, 2010) channels, where sediment deposition is dominated by fluvial, mixed fluvial and tidal, and tidal processes, respectively. Hydraulic conditions not only differ between environments in which IHS is developed, but they also vary significantly within a single channel and between branches and distributaries within the same depositional system. This can result in substantial within system variability in IHS character. This variability has a direct impact on reservoir properties of IHS-dominated units, such as the McMurray Formation of the Athabasca Oil Sands in western Canada (Mossop and Flach, 1983; Muwais and Smith, 1990; Ranger and Pemberton; 1992;
Although published studies of IHS in modern environments are increasingly available, only a few of these studies (e.g., Sisulak and Dashtgard, 2012) link quantified measurements of hydrodynamic processes and water chemistry to the sedimentological and ichnological character of the resulting deposit. Yet, to properly understand deposition in channels across the tidal-fluvial transition, it is necessary to define changes in the character of the sediments relative to their position in the channel, and with changing hydrodynamic conditions and water chemistry (mainly salinity). In the lower reaches of the Fraser River, IHS is formed or is present where saltwater and freshwater mix. The sedimentology, ichnology, and architecture of IHS in the lower Fraser River varies as a function of tidal and fluvial influence, coupled with the degree and the persistence of brackish water in the channels.

Three bars in the subequally mixed tidal-fluvial (i.e., tidal and fluvial processes equally impact sediment deposition) Middle Arm, lower Fraser River comprise the basis of this study. The sedimentology, ichnology, and architecture of the bars are compared to hydraulic and water chemistry data. The results are then compared to a similar study conducted in the tide-influenced, fluvially dominated Main Channel (Sisulak and Dashtgard, 2012), in order to assess changes in the character of the IHS based on the relative influence of tidal versus fluvial processes. From these data, sedimentological, ichnological, and morphological criteria are defined for recognizing mixed tidal-fluvial IHS in the rock record.
3.1.1. **Study Area**

The Fraser River drains a 228 000 km\(^2\) area and is the largest river that debouches into the Pacific Ocean (Strait of Georgia) on the west coast of Canada (Milliman, 1980; Monahan et al., 1993; Villard and Kostaschuk, 1998). In its lower reaches, the Fraser River has four main distributaries: Canoe Pass, the Main Channel, the Middle Arm, and the North Arm. The discharge and sediment volumes passing through each distributary varies significantly. In 1970, measurements of fluvial discharge through various distributaries during the spring freshet (elevated river discharge), indicated that the Main Channel carries the majority of the flow (74%), whereas Canoe Pass, North Arm, and Middle Arm contain 18%, 7% and 5% of the flow, respectively (WCHL, 1977). The Fraser River is sand-rich (36% sand) and transports 17 x 10\(^6\) tonnes of sediment to the coast annually (Milliman, 1980; McLaren and Tuominen, 1996; Kostaschuk et al., 1998, McLean et al., 1999). Most of the Fraser River sediment load (80%), and all of the sand is transported during the snowmelt-induced freshet in late May to July. Only 3 - 9% of the total Fraser River sediment supply enters the North Arm / Middle Arm distributaries (Church et al., 1990).

The Fraser River has undergone significant anthropogenic alteration for the past 150 years. The banks of the river were diked between 1913 and 1919, which fixed the Fraser River distributaries in their current position and no significant lateral shifts have occurred since (Johnson, 1921). A large increase in sediment load in the Fraser has occurred over the past 150 years due to placer mining along the river (Nelson and Church, 2012). Rapid expansion and aggradation on the delta occurred between 1910 and 1954 which corresponds to a period of extensive diking (Hales, 2000). All of these anthropogenic factors have influenced the Fraser delta topography and the
geomorphology of the river and associated channel bar complexes. Although human modification is significant, the Fraser River is undammed which allows for natural hydrodynamic processes to occur from the mountainous catchment basin down to the delta front. This makes the Fraser River an excellent study area where sedimentology and ichnology of channel bars can be compared to natural hydraulic processes and water chemistry.

River flow is highest during the freshet and ranges between 5 130 –15 200 m$^3$/s (Water Survey of Canada, http://wateroffice.ec.gc.ca). For the rest of the year, average flow is ~ 1000 m$^3$/s. Tides are semi-diurnal and range from 2 - 5 m throughout the neap-spring cycle, with an average tidal range of 3.1 m. Tides influence flow within the lower reaches of the Fraser and are observed up to 90 km upstream (Hughes and Ages, 1975; Kostaschuk and Atwood, 1990; Mikhailov et al., 2007; Dashtgard et al., in press). Saltwater incursion in the Fraser distributaries extends up to 30 km upstream.

Three bars in the Middle Arm were studied, including a channel-margin bar (CMB), an in-channel bar (ICB), and a semi-detached point bar (PB; Figure 3.1). The CMB is 1.9 km long and has a maximum intertidal extent of 150 m. The ICB has an intertidal zone that extends 170 m into the river and is 1.1 km long. The PB is 1.7 km long and 830 m wide. The approximate boundary between the intertidal and subtidal zone is marked by the average minimum low tide in 2011, which is 3.40 m below average maximum high tide (AMHT). Within the study area, the Middle Arm has an average depth of 5.3 m (relative to AMHT; Figure 3.2) and an average width of 300 m. The average depths of the channel adjacent to the CMB, ICB, and PB, are approximately 6.2 m, 4.3 m, and 5.4 m (relative to AMHT), respectively. The maximum
The depth of the channel is 8.5 m adjacent to the CMB, 6.1 m adjacent to the ICB, and 8.3 m off the PB (Figure 3.2).

**Figure 3.1: Study area: Middle Arm, lower Fraser River**

A) Location map of the Fraser delta in British Columbia, and of British Columbia in Canada (inset map). B) Schematic geographic/bathymetric map of the Fraser delta. The Middle Arm study area is enclosed within the dashed red box. The maximum landward extent of saltwater incursion is indicated by the solid red line. C) Map of the three Middle Arm bars: the channel-margin deposit (CMB); the in-channel bar (ICB); and the semi-detached point bar (PB). Note that the tidal creek south the PB is only 0.5 m deep at this position during low tide. (Image source: Google Earth).
Figure 3.2: Bathymetry

Bathymetric profiles of the channel. Depths are recorded relative to the average maximum high tide in 2011 (4.30 m above the historical maximum low-tide water level). The yellow 3.40 m contour represents the approximate boundary between the subtidal and intertidal zone, as it is the average minimum low tide level for 2011 (AMLT). A) The depth map for the CMB indicates the channel is deepest at this site. The average depth is 6.2 m and the maximum depth is 8.5 m. B) The depth of the channel adjacent to the ICB averages 4.3 m and attains a maximum depth of 6.1 m. C) The bathymetry map for the PB indicates that the Middle Arm has an average depth of 5.4 m and maximum depth of 8.3 m adjacent to this bar.

3.1.2. Methods

Sample collection was done during the freshet in June and July, 2011 and during base flow in March, 2012. Surface sediment samples, base-of-channel grab samples, box cores, infaunal population counts and vibracores were the main sampling techniques used in the field (Figures 1.11 and 1.12). On the PB, seven transects were
set across the intertidal zone. Transects were spaced approximately 250 m apart, and three stations, spaced approximately 150 m apart, were placed along each transect (red and yellow circles, Figure 3.3). On the CMB and ICB, intertidal stations were set along six transects per bar, each with one to three stations spaced 50 - 100 m apart (Figure 3.3). At each intertidal station, sedimentary structures and burrow distributions were recorded and photographed. Approximately 250 g of sediment were collected from the upper 5 cm at each station.

Grain-size profiles for the point bar and in-channel bar were extended across the width of the channel by acquiring grab samples from the channel bottom every 50 m adjacent to the in-channel bar and every 100 m adjacent to the point bar (Figure 3.3). One-metre intervals were marked along the rope attached to the grab sampler to measure depth. Water depth profiles (Figure 3.2) were then constructed by using the water depth measured while grab sampling, the time of sample acquisition, and tide tables. Depth measurements acquired from grab sampling were combined with depth data from the Canadian Hydrographic Service (CHS) nautical chart of the Middle Arm to construct bathymetric contour maps of the field area.

Sediment samples (both surface- and grab-samples) were oven dried, and then grain size was measured by sieving and using a Mastersizer® particle-size analyzer. During sieving, samples were agitated through six sieves, proceeding from phi size -1 $\phi$ (2 mm) to 4 $\phi$ (0.0625 mm; Figure 1.13D). For Mastersizer® analysis (Figure 1.13F), samples were pre-treated with hydrogen peroxide to remove organics, and then with sodium hexametaphosphate to inhibit clay flocculation. Grain size results were then entered into GRADISTAT (Blott and Pye, 2001) to determine grain-size distributions and statistics. The majority of grain size values presented herein are those measured by the
Mastersizer; however, samples of medium- and coarse-grained sand were determined through sieving.

Sedimentary structures, burrow morphologies and bedding architectures were determined through box coring and vibracoring. One to two box cores (0.28 m x 0.17 m x 0.06 m; Figure 1.12B) were taken at each station. Box cores were pushed into the sediment and their orientations were measured. Each core was then taken to the lab, and was either x-ray imaged (muddy and sandy sediment; Figure 1.12C) or resin peeled (sandy sediment). Both techniques reveal sedimentological and ichnological structures.

Vibracores (3 m long, 0.076 m diameter; Figure 1.12A) were also collected at sites along the lower intertidal zone: 7 cores were taken from the PB and 4 cores from the ICB. Core recovery was affected by dewatering, compaction, loss of sediment from the pipe, and/or the occurrence of compacted or resistant layer that could not be penetrated. To determine the amount of compaction and dewatering that occurred during the coring process, the distance from the top of the core barrel to the top of the sediment was measured. On average, recovered cores were 67% the length of the core barrels, indicating that most cores compacted by 33%. An exception to this, is the most landward core from the ICB, in which sediment compaction and dewatering resulted in a 67% decrease in the length of the core. Only one two-barrel core (6 m length) was acquired, from the downstream end of the PB. The two-barrel core penetrated 4.5 m into the sediment before hitting a resistant layer. The core compacted by 23% resulting in 3.5 m of sediment recovered. Cores were taken back to the lab and cut longitudinally in half. One half of the core was photographed and sampled for grain size, and the other half was resin peeled and logged in detail.
Finally, infauna population counts were taken at each intertidal station to measure the distribution, intensity of bioturbation, and kinds of infauna present. At each site, three, 0.4 m x 0.4 m x 0.3 m deep holes were excavated, and the sediment from these holes was sieved to recover and count bivalves and other large invertebrates (typically, diameter (D) ≥ 0.4 cm, length (L) > 3 cm). Smaller infauna (D = 0.1 - 0.4 cm, L = 1 - 3 cm) were counted by extracting three 0.15 m x 0.15 m x 0.15 m sediment samples and sieving them through a 4 mm mesh. The three counts at each station were then averaged and converted into an area of disrupted (occupied) sediment per square meter (cm²/m²) by using the width of the burrows produced by the various infauna and their population density. The total disrupted sediment area was calculated by adding up the disrupted area for all animals found at each station. Threadworm burrows (D ≤ 0.1 cm) were not included in sediment disruption counts because of the very low preservation potential of these burrows (Dashtgard, 2011a).
Figure 3.3: Distribution of sampling across the Middle Arm bars

Sampling locations at the PB, ICB, and CMB (A, B and C, respectively). A) On the PB, 35 surface sediment samples, 132 animal population counts, 28 box cores, and 7 vibracores were acquired from 21 stations placed along seven transects. Thirty two grab samples from the subtidal portion of the bar were also acquired. The line A-A’ shows the location of the cross section in Figure 8. B) On the ICB, 18 surface sediment samples, 43 animal population counts, 16 box cores, and 4 vibracores were acquired from 13 stations placed along six transects. Twenty grab samples from the subtidal portion of the bar were also acquired. The line B-B’ shows the location of the cross section in Figure 9. C) On the CMB, 14 surface sediment samples, 33 animal population counts and 13 box cores were acquired from 10 stations placed along six transects. No grab samples were acquired, due to the presence of a floatplane runway adjacent to the bar.
3.2. Results

3.2.1. Salinity in the Middle Arm

Hydraulic conditions and water chemistry data is sourced from previously published works from the Middle Arm, and only a limited amount of salinity data was collected during this study. Data from previous studies are still considered to be relevant today because the distributaries of the lower Fraser River are dyked and flow through the channels is monitored and partly controlled. Consequently, annual variations in the volume of flow and sediment passing through each distributary are unlikely to have a significant impact on the hydrodynamic conditions (tidal versus river flow) of the channel (Dashtgard et al. in press). This is made apparent by the similarities in the salinity measurements (Fig. 4) taken during this study, and the more detailed data provided by Hughes and Ages (1975).

Water salinity in the Middle Arm varies from oligohaline (0.5 - 5 psu) to polyhaline (18 - 30 psu; Hughes and Ages, 1975). Vertical and lateral salinity gradients change daily with the tidal cycle and seasonally with changes in fluvial discharge (Figure 3.3; Hughes and Ages, 1975). In general, daily salinity fluctuations correlate strongly with the diurnal tidal cycle. The highest salinities are recorded during high tide, whereas the lowest salinities occur during low tide (Figure 3.4). Seasonal salinity changes are related to seasonal changes in river discharge. The maximum upstream migration of the saltwater wedge (highest persistent salinity) occurs during low fluvial discharge and spring high tides. Minimum salinity values occur during the freshet and spring low tide. The data from Hughes and Ages (1975) also shows a correlation between channel depth and salinity, wherein salinities increase with depth (Figure 3.4).
Figure 3.4: *Salinity and tide data across the Middle Arm*

Salinity and tide data for four different stations along the Middle Arm, taken on August 26 (summer) and November 1 (Winter), 1971, and March 7 (spring), 1972. All data is from Hughes and Ages (1975). Salinity was measured at the surface, and at 3.0 m, 4.6 m, and/or 6.0 metres depth (from chart datum). Average daily fluvial discharge measured at Hope is indicated by ‘Q’ at the top of each column, and average daily surface water temperature is marked by ‘T’ at the bottom of each column.

While water column salinity is important, interstitial-water salinity also directly affects infauna and their burrowing activity. Interstitial salinity data were reported from the North Arm (contains 7% of Fraser River flow) by Chapman and Brinkhurst (1981). Since the 7% of fluvial flow through the North Arm is higher than the 5% estimated to
flow through the Middle Arm, salinity measurements from the North Arm are assumed to be the minimum low-salinity values that could be expected in the Middle Arm. Chapman and Brinkhurst (1981) measured salinity 1, 2, 3 and 6 cm below the sediment surface in cores spaced approximately 350 m apart along the North Arm. A single value for interstitial salinity was determined by averaging the salinities from the four sediment depths (Figure 3.5). Data from stations 3 and 4 in the North Arm are longitudinally adjacent to the sites studied in the Middle Arm; therefore, the salinity measurements from Station 3 are used as a close approximation for the ICB and CMB, and data from Station 4 is considered typical of the PB. At Station 3, interstitial salinities range from < 5 - 20 psu, and at Station 4 from 5 - 24 psu (Figure 3.5). There is no apparent correlation between salinity and precipitation, but fluvial discharge and salinity are clearly related. Minimum salinity values occur during the freshet, and peak salinities occur in January and February when river discharge is lowest. These data indicate that polyhaline conditions exist in the sediment when discharge is at a minimum, but for the majority of the year, interstitial salinity is mesohaline (5 - 18 psu).
Figure 3.5 (previous page): Monthly interstitial salinity, flow and precipitation data

A) Location of Chapman and Brinkhurst’s (1981) stations 2 – 5 from the North Arm of the Fraser River. Stations 3 and 4 (outlined in the yellow boxes) occupy positions in the North Arm that are equivalent to the Middle Arm study areas. Data from Station 3 is considered to be relevant to the ICB and CMB, and data from Station 4 is treated as the equivalent of the PB (Image source: Google Earth). B) Interstitial salinity and river discharge (flow) measurements taken monthly from June 1977 to August 1978 from stations 3 and 4. Daily measurements were taken at Station 3 in the months of February, May and June 1978. At Station 4, daily measurements were taken in November 1977. For those months, the mean of the salinities are plotted. The solid black and red lines are the range of salinities that occurred during the month in which they are positioned (modified from Chapman and Brinkhurst, 1981). Superimposed on the graph is monthly precipitation, taken from the National Climate Data and Information Archive of Environment Canada.

3.2.2. Sedimentology

Sedimentological and ichnological descriptions of the Middle Arm bars are divided, based on data type and water depth. Grab samples of the channel floor are used to characterize the grain size of the subtidal channel margins and the channel base (3.4 - 8.3 m below AMHT). In the lower intertidal zone, and for most of the upper and middle subtidal zone (the bar; 2.7 - 6.7 m below AMHT), vibracores are used to characterize these deposits. Finally, in the intertidal zone (1.5 - 3.4 m below AMHT), box cores, infaunal population counts, and surface sediment samples are the main data sources. These three zones overlap, but this is necessary to compare the datasets.

On the subtidal channel margins and the channel base (3.4 - 8.3 m below AMHT) adjacent to the PB (the most seaward deposit) and the ICB (middle deposit), surface sediments range from poorly sorted silt and very fine-grained sand to moderately well-sorted coarse-grained sand (Figure 3.6). Average grain size of sediment in the thalweg during the spring freshet adjacent to the ICB is 2.8 phi (fine-grained sand), while average grain size is 1.5 phi (medium-grained sand) adjacent to the PB. Grain sizes fine from the base of the channel up onto the channel banks.
**Figure 3.6 : Grain-size distributions for the Middle Arm bars**

A to C) Grain-size contour maps of the CMB, ICB and PB. Values are mean grain size values calculated using the Folk and Ward (1975) method. Red values are from grab samples and black values are from surface sediment samples. Each bar displays a mud-sand-mud profile in the along-strike direction.

Sedimentological and ichnological data from the lower intertidal zone, and upper and middle subtidal zone (2.7 - 6.7 m below AMHT) is mainly derived from vibracores: seven from the PB and 5 from the ICB (Figure 3.3). The sedimentary succession in most cores consists of rhythmically alternating mm- to cm-scale sand and mud intervals that resemble inclined heterolithic stratification (Figure 3.7). Mud beds are more common and more laterally continuous on the PB than the ICB (Figures 3.8 and 3.9). On the PB, mud is deposited and preserved up to 6.7 m below AMHT, and five of the seven PB
vibracores exhibit a decrease in the number of mud beds upward (Figure 3.8). The greatest proportion of sand exists in the middle of the PB, whereas the upstream and downstream ends contain more mud beds; however, the greatest number of mud beds occurs at the downstream end of the PB. The percent sand in each core from the PB, stated downstream to upstream, is: 31%, 37%, 56%, 60%, 65%, 62%, and 55%. The ICB displays an increase in mud beds in the downstream direction, as well as a fining-upwards profile and increase in mud beds from the bottom to the top of the bar (Figure 3.9). The percentage of sand in each core from the ICB, listed from downstream to upstream, is: 59%, 55%, 67%, and 84%.
Figure 3.7 (previous page): IHS from the upstream end of the PB

Litholog of a vibracore taken from the lower intertidal zone of the most landward station on the PB. The core displays an overall fining-upward succession of interbedded sand and mud (IHS). In resin peels, the sands are mainly homogeneous, with rare current-ripple laminations preserved. Organic detritus and iron staining is common throughout. A) Photo of IHS preserved in the resin peel (position of photo shown on the litholog), with alternating mm- to cm-scale thick, silt and upper very fine-grained sand laminae. Note the bivalve-shell fragment (bv), the large sand-filled Siphonichnus (Si), the three Skolithos (Sk), and the Palaeophycus (Pa) in this core peel. Rhythmic alternations of sand and mud are indicated by yellow arrows, which point to the mud beds. Rhythmicity is a reflection of the essentially diurnal (semi-diurnal tide where the second low tide is supressed) tidal cycle in the Fraser River. The white scale bar is 2 cm. B) X-radiograph of a box core highlighting rhythmic interbedding of sand-rich (light gray) and sand-poor (dark gray) lamina-sets. The sand-poor (muddier) lamina-sets are neap-tide deposits, while the sand-rich lamina-sets are spring-tide deposits. The thin pinstripe laminations within the neap-spring deposits reflect the diurnal tidal cycle.

The sediments preserved in vibracores from the lower intertidal zone, and upper- and middle-subtidal zone comprise an average of 41% mud (Figures 3.7, 3.8 and 3.9). The composition of the mud silt with a minor amount of clay (< 9%). Mud beds and mud-dominated lamina-sets are mm- to dm-scale in thickness, and are either: 1) massive appearing; 2) horizontal to low-angle, planar-parallel laminated; or 3) are deposited as mm- to cm-scale, rhythmically alternating sand and mud beds that are rarely preserved as sets of 12-14 couplets (Figure 3.7). Sand beds are mm- to dm-scale in thickness and range from very fine- to medium-grained sand. Sand beds generally appear massive in x-radiographs and in resin peels, but rare trough cross-bedding and local current ripples, starved ripples, planar to gently inclined parallel laminations, combined flow ripples and oscillatory ripples are observed locally (Figures 3.7 and Figure 3.10C). Wavy bedding is common and lenticular and flaser bedding is rare. Rare cm-scale mud clasts are entrained within some sand beds, and abundant organic detritus and wood fragments are found throughout. Iron staining is common around carbonaceous debris.
Figure 3.8 (previous page): Cross-section of the PB

Cross-section of seven vibracores from the lower intertidal zone, and the middle- and upper-subtidal zones of the PB (the most seaward bar). The cross-section line is displayed in Figure 3.3A, and is oriented downstream (west (W)) to upstream (east (E)). Depth is measured from the average maximum high tide and the scale is in metres. The red line marks the average maximum low tide limit (AMLT), which corresponds to the intertidal-subtidal break. The cores are dominantly composed of muddy IHS and contain noticeably more mud beds than at the ICB (Fig. 3.9). There is also a distinct increase in the rhythmicity of bedding with increasing tidal influence in the seaward direction. The continuity of mud beds (brown) is variable, but can extend for over a kilometre. Although sand (yellow) makes up the minority of the bar deposit, the greatest concentration of sand is towards the centre of the bar.

Figure 3.9: Cross-section across the ICB

Cross-section of four vibracores from the lower intertidal zone of the ICB. The cross-section is oriented from downstream (W) to upstream (E), and the cross-section line is indicated on Figure 3B. The depth scale is in metres and the zero mark is the average maximum high tide (AMHT). The red line marks the average maximum low tide limit (AMLT), which corresponds to the intertidal-subtidal break. The bar is composed predominantly of IHS, with subequal amounts of sand (yellow) and mud (brown). However, the downstream end of the bar displays a fining in grain size and an upward increase in number and thickness of mud beds relative to the upstream end.

Sediments deposited in the lower to upper intertidal zone (1.5 - 3.4 m below AMHT) range from poorly sorted coarse-grained silt and very fine-grained sand to well-sorted coarse-grained sand. Of the three bars, the CMB has the greatest proportion of
mud in the intertidal zone (Figure 3.6A). The sedimentary structures observed in sand include ebb-oriented dunes and current ripples, oscillatory ripples, and interference ripples (Figure 3.10). Mud beds are either planar, or wavy where draped over current-rippled sand (Figure 3.10C). Biogenic-sourced mud, mud rip-up clasts, organic debris and shell fragments are locally present within current-ripple troughs.
A mud-sand-mud profile is developed in the alongstrike direction in the intertidal zone of all three bars (Figure 3.6). For the CMB, mud is deposited at the upstream (landward) end, sand dominates the central part of the bar, and mud is deposited at the downstream end (Figure 3.6A). The ICB exhibits a similar trend, with a small accumulation of mud at the upstream end of the bar, which grades seaward into a zone of ebb-oriented sand dunes (Figure 3.9A). The sand dunes abruptly terminate and are replaced by planar mud deposits on the downstream end of the bar (Figure 3.6B). On the ICB, a fining-upward trend is also developed from the lower- to the upper-intertidal zone. On the PB, ebb-oriented, current rippled sand dominates across the middle and upper intertidal zone through the central part of the bar, with mud dominating the upstream and downstream ends (Figure 3.6C). However, at the low-tide limit of the intertidal zone, the bar grades from mud on the upstream side to current rippled sand in the downstream direction.

3.2.3. *Ichnology*

No organisms were recovered from grab samples from the subtidal channel margins and channel base (3.4 - 8.3 m below AMHT). The neoichnological character of the lower intertidal, and upper and middle subtidal zones (2.7 - 6.7 m below AMHT) is
mainly derived from traces preserved in resin peels of vibracores. During the vibracoring process, many of the small burrows and open burrows are destroyed (Sisulak and Dashtgard, 2012). Consequently, the preserved trace assemblage represents the minimum intensity of bioturbation, is biased towards large burrows, and particularly towards sand- and mud-filled burrows. The trace suite in the lower intertidal, and upper- and middle-subtidal zones is dominated by diminutive (approximately D ≤ 0.1 cm) and rare large (D ≥ 0.4 cm) Siphonichnus- and Skolithos-like structures in both sand and mud beds, as well as uncommon Palaeophycus-, Polykladichnus-, Diplocraterion- and Arenicolites-like burrows confined to mud beds (Figure 3.7). The majority of sand beds are devoid of any distinctive traces, but some sand beds with low bioturbation intensities (BI 1-2) are found intermittently. The majority of mud beds display low to moderate bioturbation (BI 1-3), with rare beds displaying no bioturbation.

Infauna identification from intertidal zone stations (1.5 - 3.4 m below AMHT) reveals a variety of infauna. Three bivalves are identified: Macoma balthica (Figure 3.11B), Nuttallia obscurata (Figure 3.11B), and Mya arenaria. Macoma balthica produces small Siphonichnus-like structures (D = 0.1 cm), while Nuttallia obscurata (D = 0.3-0.5 cm) and Mya arenaria (D > 0.4 cm) construct larger Siphonichnus-like burrows. Macoma balthica is present in all of the bars, but preferentially colonizes substrates where mud is deposited on the surface (Figure 3.12). Nuttallia obscurata is only present in sandy substrates at the furthest downstream location (PB; Figures 3.12 and 3.13F). Mya arenaria is only present in muddy substrates in the PB (Figures 3.12 and 3.13E). Thin, Skolithos-like traces (D < 0.1 cm) are abundant in mud and are produced by threadworms (Figure 3.13A, B). The polychaete, Nereis sp. (Figure 3.11C) is rare, but present in every bar (Figure 3.12). Nereis sp. recovered at the CMB were diminutive
compared to those in the PB. *Nereis* sp. can construct a variety of burrow types, including *Polykladichnus*-(Figure 3.11E), *Palaeophycus*, *Arenicolites*, and *Skolithos*-like traces (Gingras et al., 2008; Hauck et al., 2009). The diameter of Nereid burrows range from 0.2 - 0.3 cm at the CMB and ICB, and 0.3 - 0.4 cm on the PB. The small crustacean *Corophium* sp. is the primary tracemaker for small, mud-filled, U-shaped burrows (D = 0.05 - 0.1 cm) that are best described as *Arenicolites*-like (Figure 3.11D), but can be *Diplocraterion*-like if spreiten are present between the shafts (Ingle, 1966). *Corophium* sp. is only found in the PB, but *Arenicolites*-like burrows were found in all bars, indicating that *Corophium* sp. were likely present at each bar at some point in time (Figure 3.12).
Figure 3.11: Photos of burrows and infauna in their burrows

A) Nereid polychaete inside a mud-filled Arenicolites-like burrow taken at the ICB. B) Nuttallia obscurata on the left side of the photo with Macoma balthica on the right, burrowing in sediment from the intertidal zone of the PB. Both bivalves have dual-siphons and produce Siphonichnus-like structures. C) Nereid polychaete inside a Skolithos-like burrow. D) Corophium-generated Arenicolites burrow from the PB. E) Complex, mud-lined Polykladichnus-like burrow, likely produced by a Nereid polychaete. Photo is taken from the CMB.
Figure 3.12: Distribution of infauna across the Middle Arm bars

Infauna distributions during June and July 2011 taken from lower intertidal stations from the Middle Arm. The graph is displayed from downstream on the left to upstream on the right. The different animals along with corresponding burrow morphologies are labelled in the legend on the right. A different vertical scale is used for the density of Macoma balthica because it occurs in much greater abundance relative to other infauna. Each bar displays organism population density graphs with an overall saddle shape corresponding to increased population densities on the upstream and downstream ends reflecting the greater abundance of infauna in mud versus sand. Sand-dominated sediments are highlighted in yellow. Note the introduction of Nuttallia obscurata, Mya arenaria and Corophium sp. at the PB. The graphs show that bivalve distributions and grain size are related. Nuttallia obscurata is found preferentially in sand, while Mya arenaria and Macoma balthica prefer muddy substrates.
Figure 3.13 (previous page): X-ray radiographs of box cores of in situ sediment

Lighter grays are indicative of sand and sand-rich beds and lamina-sets, whereas darker grays indicate mud and mud-rich beds. **A** Planar to wavy parallel laminated mud and fine-grained sand from the upstream end of the CMB. Rhythmicity in bedding is likely related to tidal cyclicity. Darker laminations are organic rich. Bioturbation is sparse and is limited to threadworm burrows (t). **B** Parallel laminated mud from the downstream end of the CMB. The black fragment is wood (wd). Bioturbation is uncommon (BI 2), and limited to Polykladichnus-like (Pk), Skolithos-like (Sk), and threadworm burrows. **C** Upper medium-grained sand from the upstream end of the ICB. Wave ripples (wr), current ripples (cr), organic fragments (or) and wood fragments (wd) are observed throughout. No bioturbation is visible. **D** Muddy IHS from the downstream end of the ICB. Mud beds are defined by the brown bars on the right-hand side of the photo, and sand beds are indicated by yellow bars. Burrowing is moderate (BI 3), and the trace suite includes Palaeophycus-like (Pa), Arenicolites-like (Ar), and Polykladichnus-like. The bivalve Macoma balthica (ma) is found at the base. **E** Siphonichnus-like burrows produced by the bivalve Mya arenaria (mya). The re-adjustment of the bivalve and its siphon produces downward-deflected laminae around the edges of the burrow. Mya is only found in the PB due to higher salinity values at the most seaward site. Wave ripples, Palaeophycus-like burrows and threadworm burrows are also identified. **F** Five Nuttallia obscurata (nu) bivalves in sandy IHS from the middle of the PB. The activity of these bivalves has resulted in significant biogenic reworking (BI 5) and the destruction of primary sedimentary structures.

Bioturbation intensity is expressed by bioturbation indices (BI) determined from box core x-rays, as well as sediment disruption. Sediment disruption is the area occupied by burrows on a square-metre bedding plane (cm²/m²; Figures 3.14).

Bioturbation intensity increases seaward from the CMB to the PB. Sediment disruption reaches a maximum of 14 cm²/m² (0.14% by area) on the CMB, 32 cm²/m² (0.32%) on the ICB, and 117 cm²/m² (1.2 %; Figure 3.14) on the PB. The average amount of sediment disruption on the CMB is 5 cm²/m², 14 cm²/m² on the ICB, and 68 cm²/m² on the PB. Increasing bioturbation intensity is also evident in box cores. Maximum BI at the CMB is 3, while a BI 5 is common at the PB. At the CMB and the ICB, there is a correlation between elevation and degree of sediment disruption, wherein biogenic mixing of sediment decreases from the lower to upper intertidal zone. At the CMB, the amount of sediment disruption decreases from an average of 7 cm²/m² to 3 cm²/m² from the lower to upper intertidal zone. At the ICB, average degree of sediment disruption decreases from 17 cm²/m² to 12 cm²/m², from the lower to upper intertidal zone. There is also a correlation between sediment disruption and grain size, with sediment disruption
higher in mud beds than in sand beds. The average sediment disruption value in mud is
6 cm²/m², 18 cm²/m², and 71 cm²/m² for the CMB, ICB and PB respectively. The average
amount of sediment disruption is lower in sand at the CMB, ICB and PB with an average
of 2 cm²/m², 1 cm²/m², and 58 cm²/m² respectively. This trend is also revealed in box
core x-radiographs. Bioturbation intensity in mud ranges from BI (1-3), BI (2-5), and BI
(2-5) for the CMB, ICB and PB respectively. In sand, the bioturbation intensities
decrease with respect to mud, at the CMB, ICB and PB, with bioturbation intensities
ranging from BI (0-1), BI (0-1), and BI (0-3) respectively. At the PB, BI 5 can be reached
in sand, but is rare, if large bivalves have significantly reworked the sediment.
3.3. Discussion

3.3.1. Character of IHS in the mixed tidal-fluvial Middle Arm

3.3.1.1. Sedimentological Character

Process-response relationships and sedimentological trends that largely determine the character of IHS on bars in the Middle Arm include: 1) vertical grain size
fining trends, 2) laterally extensive mud beds, 3) rhythmic and non-rhythmic bedding, 4) a surface mud-sand-mud profile, 5) an intra-bar stratal down-river fining trend, and 6) an inter-bar increase in mud beds from the ICB to PB. These trends can be used in concert to identify IHS generated in mixed tidal-fluvial settings, and can perhaps be used to differentiate tidal-fluvial IHS from IHS developed in more tidally or fluvially dominated settings.

Surficial grain sizes fine from coarse- and medium-grained sand in the middle of the channel, to mainly mud on the flanks, and reflects a decrease in flow velocities from the thalweg to the channel margins. In the intertidal zone, muddy bedsets are laterally extensive for up to 1 km in the along-strike direction (Figure 3.6).

The mm- to cm-scale, rhythmically alternating sand and mud beds (Figure 3.7) in the intertidal zone, and upper- and middle-subtidal zone reflect tidal controls on sediment deposition, where similar mm- to cm-scale alternations of sand/silt and mud are attributed to diurnal and semi-diurnal tidal changes (De Boer et al., 1989; Ainsworth and Walker, 1994; Choi et. al., 2004; Dalrymple and Choi, 2007). In the Middle Arm, these sand-mud lamina-sets are rarely preserved in sets of 12-14 couplets. Variations in lamina-set thicknesses and composition likely reflect neap-spring tidal cyclicity: sandier lamina-sets corresponding to spring tides and muddier lamina-sets deposited during neap tides.

Rhythmic sand-mud interbeds are commonly interbedded with dm-scale sand beds (Figures 3.7 – 3.9). Decimetre-scale sand interbeds are generally non-rhythmic in their vertical distributions and are interpreted as freshet deposits (e.g., Sisulak and Dashtgard, 2012). All current ripples and dunes in sand beds in the Middle Arm are ebb-
oriented, suggesting that ebb-oriented flows dominate sand transport and deposition, and flood currents are insufficient to remobilize sand. This is consistent with observations of sand transport in the Fraser River, where nearly all of the sand is transported during the freshet (Milliman, 1980; Kostaschuk et al., 1998).

In the upper intertidal zone, mud dominates deposition on the upstream and downstream ends of each bar and the center is sandy, such that bars exhibit a mud-sand-mud longitudinal profile (Figure 3.6). The exact link between the mud-sand-mud profile and hydrodynamic conditions remains unclear. However, it seems plausible that the area of bar accumulation is dependent upon the position of the dominant fluvial / ebb and flood currents, and that the upstream and downstream positions of each bar are located where hydraulic energy is lowest in the diverging or converging flow.

Vibracores are used to assess the sedimentological trends of the bars from the lower intertidal zone, and upper and middle subtidal zone (2.68 - 6.70 m below AMHT). The PB and ICB display an overall decrease in mud beds in the upstream direction. In the PB, mud content decreases from 84% to 59% and in the ICB it decreases from 55% to 31% in the upstream direction. The furthest upstream core from the ICB is difficult to assess as the sediment was subjected to significant compaction and/or dewatering resulting in poor recovery. Nonetheless, there is sufficient data to support an overall downstream-fining.

From assessing the percentage of sand from each core, it is also clear that there is an inter-bar decrease in mud beds from the PB to the ICB. This could be a reflection of bar morphology. The ICB is located along a less sinuous portion of the distributary than the PB. The lowered sinuosity facilitates a straighter flow path, with less flow being
deflected toward the cutbank and higher flow velocity where the bar is being deposited. It has also been shown that there is a relationship between radius of curvature, flow width and the initiation of bend flow separation (Bagnold, 1960; Bridge and Leeder, 1976). Flow separation is favoured in tight bends and leads to a zone of low velocity, where mud deposition is promoted.

3.3.1.2. Ichnological Character

In addition to the sedimentological trends defined above, the ichnology can be used as a proxy for determining physico-chemical stresses experienced by infauna (Gingras et al., 1999; Gingras et al., 2008; Dashtgard, 2011a,b; Dashtgard and Gingras, 2012), which for the Middle Arm bars is mainly attributed to reduced and variable salinity at each site. Salinity conditions in the Middle Arm are relatively high (mesohaline to polyhaline; Figures 3.4 and 3.5) and stable for a brackish-water environment, enabling year-round colonization of the bars by an impoverished marine infauna. This results in limited vertical segregation of burrows in sediments of similar grain size. On the landward bars, CMB and ICB, the trace assemblage is dominated by burrows of filter-feeding, surface deposit-feeding and horizontal mobile deposit-feeding infauna, producing *Polykladichnus*, *Skolithos*, *Arenicolites*, *Palaeophycus* and small *Siphonichnus*-like burrows (Figures 3.11 and 3.13). On the most seaward bar, large *Siphonichnus*-like burrows generated by large resident bivalves occur alongside the same traces found in more landward positions (Figure 3.12).

The most obvious ichnological trend across the three Middle Arm bars is the increase in burrow density and trace size in the seaward direction. Biogenic induced sediment disruption increases from an average of 5 cm$^2$/m$^2$ on the CMB to 68 cm$^2$/m$^2$ on the PB (Figure 3.14).
At the CMB and ICB, there is a decrease in burrow density from the lower to upper intertidal zone (Figure 3.14). This is likely due to an increase in subaerial exposure up the bar (Dashtgard, 2011a, b). Increased subaerial exposure time leads to desiccation and oxygen stresses on infauna. The decrease in sediment disruption from the lower to upper intertidal zone is seen in the CMB and ICB. Average sediment disruption, in the CMB and ICB, in the lower intertidal zone is 7 cm²/m² and 17 cm²/m² respectively. In the upper intertidal zone, average sediment disruption is 3 cm²/m² and 12 cm²/m², in the CMB and ICB respectively. As well, the degree of sediment disruption correlates with grain size: muddier sediments display a higher degree of sediment disruption. Average sediment disruption values in mud increase from 6 cm²/m² to 71 cm²/m² from the CMB to the PB, whereas in sand, sediment disruption increases from 2 cm²/m² to 58 cm²/m² from the CMB to the PB. A reason for the relatively low amount of burrowing in sand beds could be high sedimentation rates, high-energy conditions, substrate consistency, and/or salinity stress (Chapman, 1981; Chapman and Brinkhurst, 1981; Wheatcroft, 1990; Gingras et al., 1999; Buatois et al., 2005; Dashtgard, 2011a; Sisulak and Dashtgard, 2012). Salinity stress is higher in sand because water can flow through porous media easily; therefore, the interstitial salinity fluctuates more rapidly than in mud (Chapman, 1981).

Along with burrow density, the size of burrows increases in the downstream direction. At the CMB and ICB, the trace suite is composed of Skolithos-, Arenicolites-, and Siphonichnus-like burrows, with diameters ranging from 0.05 to 0.4 cm. At the PB, Arenicolites-like structures, generated by Corophium sp. are of a similar size (D = 0.05 to 0.1 cm diameter) to burrows found in more landward positions, but bivalve-generated Siphonichnus-like burrows are mostly > 0.4 cm in diameter. The increase in the burrow
size of bivalves is due to the presence of larger species, namely *Mya arenaria* and *Nuttallia obscurata* at the most seaward site, and not to diminution of a single species (Figure 3.12). An example of diminution is provided by Nereid polychaetes, which are slightly smaller (D = 0.2 to 0.3 cm) at the CMB compared to the PB (D = 0.3 to 0.4 cm); however, this could be true diminution or it’s a bias towards juvenile forms owing to higher mortality rates in stressed environments (Chapman and Brinkhurst, 1981).

### 3.3.2. *Sedimentological expressions of tidally and fluvially controlled deposition*

The sedimentology, ichnology and architecture of IHS deposits in the Fraser River differ as a function of changes in tidal versus fluvial influence. The tide-influenced, fluvially dominated Main Channel (Figure 3.1) displays lithologic variability largely controlled by seasonal changes in river discharge as opposed to tidal cycles. Sand is deposited during the freshet, when river discharge is highest, and mud is deposited during waning freshet flow and base flow (Sisulak and Dashtgard, 2012). The interbedding of muddy bedsets and sand beds in the Main Channel is not rhythmic, reflecting the fluvial controls on sediment deposition. Conversely, IHS from the Middle Arm exhibits significantly more rhythmicity, which is interpreted to result from tidally driven sediment deposition (Figure 3.7).

Rhythmic sand-mud interbeds are commonly interbedded with dm-scale sand beds deposited during high freshet flow (Figure 3.7; Sisulak and Dashtgard, 2012). Based on the observations of sand-mud interbedding from the Middle Arm and from the South Arm Marshes (SAM; Sisulak and Dashtgard, 2012), it appears that the rhythmicity of sand-mud interbeds increases with increased tidal influence, and beds are typically mm- to cm-scale. Fluvially controlled deposition is recorded by more irregular and thicker
sand interbeds that are attributed to seasonal variations in sediment deposition, mainly between base flow and freshet. The thickest sand bed from the SAM is 1.6 m, while at the Middle Arm, the thickest sand bed is only 60 cm.

All bars in the Middle Arm study area display a surficial mud-sand-mud profile and an overall intra-bar increase in mud beds in the downstream direction. The SAM likewise displays an increase in mud beds in the downstream direction and each side of the bar displays a mud-sand-mud configuration. This trend is not observed outside of the brackish-water, tidally influenced reach of the river.

3.3.3. Ichnological expressions of tidally and fluvially controlled deposition

Overall, the trace suite from both the admixed tidal-fluvial Middle Arm and tide-influenced, fluvially dominated Main Channel (Sisulak and Dashtgard, 2012), lower Fraser River are of low diversity and consist of simple, mainly diminutive, dwelling structures of deposit- and suspension-feeding infauna (siphonated bivalves, sessile polychaetes and crustaceans). The trace suite is typical of other brackish-water assemblages (e.g., Pemberton and Wightman, 1992; Gingras et al., 1999; Buatois at al., 2005; MacEachern and Gingras, 2007), as would be expected in an admixed tidal-fluvial setting. At the Middle Arm bars, maximum salinities are above 20 psu and the water column is only fresh at low tide during the spring freshet (Hughes and Ages, 1975; Chapman and Brinkhurst, 1981). However, the freshwater influx during the spring freshet only forces interstitial salinities to drop to 5 psu, which is still tolerable for sediment colonization and survival of some marine organisms.

A significant ichnological difference between the character of the mixed tidal-fluvial Middle Arm bars and the tide-influenced, fluvially dominated Main Channel bar
(SAM; Sisulak and Dashtgard, 2012) is the prevalence of larger burrows and a slightly more diverse trace assemblage in the Middle Arm. The SAM have a trace assemblage comprising *Skolithos- Palaeophycus*, *Polykladichnus*, *Diplocraterion* and *Arenicolites*-like burrows. The Middle Arm has the same assemblage as the SAM, but includes both small and large, bivalve-generated *Siphonichnus*-like structures that are not present at the SAM. The SAM has an infaunal diversity that is 14% of the fully marine tidal flats of Boundary Bay, whereas the Middle Arm has an infaunal diversity of 28% of Boundary Bay (Dashtgard et al., in press). This corresponds to 3 and 6 common animals at the SAM and Middle Arm bars respectively. The presence of the bivalves, which are larger than any species found at the SAM, results in larger burrows at the Middle Arm bars. Diminution is reflected in the maximum diameters of *Nereis* sp. generated burrows. The increase in organism size and diversity seaward within the Middle Arm is attributed to increasing salinity (e.g., Pemberton and Wightman, 1992; Buatois et al., 2005; Dalrymple and Choi, 2007).

The short periods of low salinity in the Middle Arm differs significantly from the Main Channel. In the Main Channel, freshwater conditions are sustained for 2-3 months during the freshet, and infauna either die off or abandon their burrows (Sisulak and Dashtgard, 2012). The seasonal colonization of sediments in the Main Channel is manifest as unburrowed sand and mud beds deposited during the freshet, interlaminated with bioturbated muddy bedsets that accumulate during the remainder of the year. By comparison, continuous burrowing occurs throughout the year in the Middle Arm bars, resulting in a more homogeneous, vertical distribution of burrowing, particularly in beds of similar grain size (Figure 3.12). Nevertheless, sediment disruption values indicate that
bioturbation is more common in mud beds than sand beds in Middle Arm sediments (Figure 3.13).

3.3.4. **Applications to the rock record:**

Sedimentological and ichnological trends defined from IHS developed in the admixed tidal-fluvial Middle Arm provide insight into the character of similar IHS deposits preserved in the rock record. In particular, IHS developed in admixed tidal-fluvial settings should exhibit the following characteristics:

1) The bars in the Middle Arm have the greatest proportion of sand in the middle, and a large decrease in sand content at the downstream ends of bars. The downstream ends of channel bars, regardless of bar type, should be avoided as mud beds are prevalent.

3) Mud beds in the Middle Arm bars are predominantly mm- to dm-scale in thickness, and muddy bedsets will be laterally continuous for up to a kilometre (Figures 3.6 and 3.7). The lateral continuity of muddy bedsets increases towards the top of the Middle Arm bars. Mud makes up approximately 41% of the IHS deposits and mud extends down to the base of the channel. The thickness, number, and lateral continuity of mud beds and muddy bedsets in admixed tidal-fluvial systems suggests that these deposits are unlikely to be the best reservoirs.

4) The trace suite comprises simple, vertical burrows produced by filter-feeding, and surface deposit-feeding infauna, as well as rare horizontal structures produced by subsurface-deposit-feeding infauna. Additionally, burrow distributions tend to be vertically homogeneous through sediments of similar grain size, reflecting the year-round colonization of the substrate by infauna. Vertical segregation of burrows is noted between beds of dissimilar grain size (i.e., sand beds versus mud beds). The size,
density and diversity of burrows increase in the downstream direction, and reflect the downstream increase in salinity.

3.4. Conclusions

Five main sedimentological characteristics define IHS in the admixed tidal-fluvial Middle Arm of the Fraser River: 1) rhythmic bedding; 2) non-rhythmic bedding; 3) a surface longitudinal mud-sand-mud profile; 4) an overall downstream increase in mud beds; and 5) laterally extensive mud beds. 1) Rhythmic alternations of mm- to cm-scale sand and mud laminae and beds reflect tidal cyclicity, indicating that tidal processes, in part, control sediment deposition. 2) Anomalous, non-rhythmic sand beds are intercalated within the rhythmic successions. The thicker sand beds are deposited via fluvial processes during the spring freshet (high discharge). 3) Bars display a surficial mud-sand-mud profile, wherein mud is deposited where flow diverts or converge around the bars. 4) Mud beds increase in the downstream direction reflecting a decrease in flow velocity around meander bends and the deflection of current toward the cutbank. 5) Muddy bedsets are prevalent in IHS successions, and can extend for up to 1 km along-strike in the intertidal zone. The along-strike extent of muddy bedsets appears to continue into the upper- and middle-subtidal zones. The abundance and continuity of muddy bedsets decrease towards the base of the channel.

The reduced salinity and persistence of brackish-water in the Middle Arm is reflected ichnologically. Four main ichnological characteristics define IHS in the admixed tidal-fluvial Middle Arm. 1) The trace fossil suite consists of a low diversity of simple, mainly vertical dwellings constructed by deposit-feeding and suspension-feeding infauna, as well as horizontal tunnels made by mobile deposit-feeding infauna. 2)
Salinity is sufficiently high enough throughout the year (mesohaline to polyhaline) to permit substrates to be continuously colonized by infauna. This leads to vertical homogeneity in burrow distribution in sediment of similar grain size. 3) Bioturbation intensity and burrow sizes increase seaward with increasing salinity. 4) There is a correlation between grain size and infaunal distributions. Typically, burrowing is higher in muddy substrates relative to sandy substrates.
3.5. References


Dashtgard, S.E. (2011a) Linking invertebrate burrow distributions (neoichnology) to physicochemical stresses on a sandy tidal flat: Implications for the rock record *Sedimentology*, 58, 1303-1325.


4. Conclusions

A detailed sedimentological and ichnological study was conducted on channel-bar deposits in the Middle Arm of the lower Fraser River, British Columbia, Canada (Figure 1.11). The main objective of the study was to develop a depositional model for bars with well-developed inclined heterolithic stratification (IHS) in a subequally mixed tidal-fluvial system that could be used as an analog for similar deposits in the rock record. In particular, a model for IHS developed in the Middle Arm can aid in the identification of admixed tidal-fluvial IHS in the subsurface rock record and in predicting reservoir heterogeneity and quality. The information derived from this study provides another example of IHS produced in a channelized setting that occurs along the spectrum of fluvial-dominated to tide-dominated channels (e.g., Smith, 1985, 1987, 1988; Smith et al., 1999; Gingras et al., 1999; Choi et al., 2004; Dalrymple and Choi, 2007; Choi, 2010; Smith et al., 2011; Sisulak and Dashtgard, 2012). This study is also one of only a few IHS studies (e.g., Sisulak and Dashtgard, 2012) linking hydrodynamic processes and water chemistry to the character of IHS.

4.1. Sedimentological and Ichnological Character of Middle Arm IHS

Tidal and fluvial processes control the sedimentological character of bars in the Middle Arm of the lower Fraser River. In the intertidal zone and upper- and middle-subtidal zone, the IHS is mud-dominated. Mud beds extend up to 1 km in length in the
intertidal zone as well as in the upper- and middle-subtidal zone (Figures 3.6 – 3.9). Rhythmic interbedding of mm- to cm-scale sand and mud lamina-sets with non-rhythmic cm- to dm-scale sand beds constitute the dominant bedding architectures in these zones (Figures 3.7 – 3.9). The rhythmicity of bedding and number of mud beds is greatest on the downstream end of each bar (Figures 3.8 and 3.9). Rhythmic bedding is attributed to deposition via tides (e.g., De Boer et al., 1989; Ainsworth and Walker, 1994; Choi et. al., 2004; Dalrymple and Choi, 2007), whereas non-rhythmic sand beds are indicative of deposition during the spring freshet, when discharge is highest (e.g., Sisulak and Dashtgard, 2012). Another sedimentological characteristic considered indicative of deposition in the mixed tidal-fluvial Middle Arm is a surface mud-sand-mud surface profile, wherein the upstream and downstream ends of the bars are characterized by mud, and the middle of each bar is dominated by sand (Figure 3.6). The exact mechanism for producing this mud-sand-mud profile is unknown. Observations from vibracores (2.7-6.7 m, below AMHT) indicate that the number of mud beds increase in the downstream direction. On average, from the CMB and PB, the amount of intra-bar mud increases by 25% from the upstream end of the bar to the downstream end. There is also an inter-bar increase in mud in the downstream direction from the CMB to the PB. The percentage of mud is 34% and 48% in the CMB and PB respectively.

The ichnology of the Middle Arm reflects salinity conditions in the channel, as well as tidally and fluvially controlled deposition. Overall, the trace suite comprises a low diversity assemblage of mainly vertical dwellings of filter-feeding and surface deposit-feeding organisms, with rare horizontal burrows made by mobile deposit feeders. This is consistent with observations from other brackish-water environments (Figures 3.11 and 3.13; Gingras et al., 1999; Buatois et al., 2005; Gingras et al., 2008; MacEachern and
Gingras, 2007; Dashtgard 2011b). Salinity, and likely interstitial salinity as well, in the Middle Arm is mesohaline (5-18 psu) for the majority of the year, which produces a moderate salinity stress on marine organisms, resulting in a lower infauna and trace diversity, and a shift towards morphologically simple burrows (e.g., Remane and Schlieper, 1971; Grassle and Grassle, 1977; Chapman and Brinkhurst, 1981). Since salinity is never persistently below 2 psu, organisms colonize the substrates continuously throughout the whole year. This is manifest as a vertically homogeneous distribution of burrows in sediments of similar grain size (Figure 3.13). Between beds of variable grain size (i.e., sand versus mud beds), more bioturbation is found in mud beds compared to sand beds. Salinity variations along depositional strike are expressed ichnologically by increases in bioturbation intensities and burrow sizes with increasing salinities.

4.2. Comparison of Middle Arm IHS with IHS from the South Arm Marshes

The IHS developed on bars in the Fraser River differs with changing tidal and fluvial influence on deposition and with changing saltwater influence. For example, the IHS developed in the South Arm Marshes (SAM; Sisulak, 2011; Sisulak and Dashtgard, 2012) of the Main Channel in the lower Fraser River varies from IHS that generated in the Middle Arm, mainly in that sand-mud interbeds in the Middle Arm are more rhythmic than in the SAM (Figures 1.7, 3.8 and 3.9). The increase in rhythmicity in the Middle Arm reflects the reduced fluvial domination and concomitant sediment volume, the persistence of brackish water, and the increased tidal influence on deposition. Deposition at the SAM is mainly attributed to seasonal changes in fluvial discharge,
wherein sand is deposited during the spring freshet and mud is deposited from the waning freshet flow (Sisulak and Dashtgard, 2012).

Ichnologically, the trace assemblages found in both the SAM and the Middle Arm are typical of brackish-water environments. The morphologies of burrows are generally similar in both settings; however, the Middle Arm contains larger burrows, and has abundant *Siphonichnus*-like structures produced by bivalves that not present at the SAM. The increase in diversity and size of burrows in the Middle Arm compared to the SAM is attributable to the increased salinity in the Middle Arm. Bivalves are relatively immobile organisms compared to other infauna, like polychaetes and crustaceans. Therefore, when salinity conditions reach suboptimal levels, they die off because they lack the mobility to re-colonize in a different location. This makes bivalves a good indicator of stable salinity conditions. The prevalence of saline conditions in the Middle Arm results in year-round colonization of the substrate by organisms, whereas at the SAM, burrows are abandoned or infauna die during the spring freshet when the sedimentation rate is high and the water is persistently fresh. In the Middle Arm, the vertical burrow distributions are more homogeneous than in the SAM. Vertical segregation of burrowing only occurs between beds of dissimilar grain size, with mud beds more thoroughly bioturbated than sand beds. Marked vertical segregation of burrowing is observed in the SAM, regardless of grain size, wherein unburrowed freshet deposits are interbedded with bioturbated deposits associated with ambient conditions (Figure 1.9; Sisulak and Dashtgard, 2012).
4.3. Applications to the Rock Record

IHS developed in the admixed tidal-fluvial Middle Arm of the lower Fraser River constitutes a possible analog for selected subsurface reservoirs. In particular, the results from the Middle Arm study define criteria to assess the degree of brackish water and tidal influence in paleo-bar deposits based in the intensity of bioturbation and diversity of the suite, as well as from the rhythmicity of bedding. For IHS developed in an admixed tidal-fluvial setting, the trace suite comprises simple, vertical burrows with rare to low numbers of horizontal structures (Figures 3.11 and 3.13). Burrows are distributed somewhat equally between beds of similar grain size, although vertical segregation of burrows occur between beds of dissimilar grain size (i.e., sand beds versus mud beds). The size, density, and diversity of burrows increase in the downstream direction, reflecting the downstream increase in salinity (Figures 3.12 and 3.13).

Sedimentologically, mm- to cm-scale rhythmic sand/mud lamina-sets are indicative of tidal processes, are commonly interbedded with cm- to dm-scale sand beds deposited via fluvial processes.

For reservoirs where the ichnology and sedimentology indicate an admixed tidal-fluvial environment, it is likely that the most sand-rich reservoirs will be encountered in the middle and of bars (Figure 3.6). However, mud beds will likely be mm- to dm-scale in thickness, muddy bedsets will be laterally continuous for up to a kilometre along depositional strike of the bar, and the greatest number of mud beds will be encountered at the downstream end of bars (Figures 3.6 – 3.9). The lateral continuity and thickness of mud beds and muddy bedsets in admixed tidal-fluvial systems suggests that these deposits are unlikely to be the best reservoirs.
4.4. References


Dashtgard, S.E. (2011a) Linking invertebrate burrow distributions (neoichnology) to physicochemical stresses on a sandy tidal flat: Implications for the rock record *Sedimentology*, 58, 1303-1325.


Sisulak, C.F. and Dashtgard, S.E. (2012) Seasonal controls on the development and character of inclined heterolithic stratification in a tide-influenced, fluviually dominated channel: Fraser River, Canada. Journal of Sedimentary Research, 82, 244-257.


### Appendix A. Grain Size and Ichnological Data

#### Grain Size Data from Surface Sediment Samples

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<tr>
<th>Sample Number</th>
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<th>Grain Size Data March 2012</th>
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**Legend:**
- **Red cells indicate no grain size analysis was conducted.**
- **Auger holes were not conducted at these locations.**
Grain Size Data from Grab Samples

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<th>% Mud</th>
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RED CELLS INDICATE NO GRAIN SIZE ANALYSIS WAS CONDUCTED
## Infauna Population Count Data

| Station Number | Latitude | Longitude | Corophium | Nuntalia | Macoma | Miyao | Neris | Total | Corophium | Nuntalia | Macoma | Miyao | Neris | Total |
|----------------|----------|-----------|-----------|----------|--------|-------|-------|-------|-----------|----------|--------|-------|-------|-------|-------|
| CM81           | 45.17438 | -123.16321| 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 3.96      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| CM82           | 45.17412 | -123.16319| 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 3.96      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| CM83           | 45.17465 | -123.16644| 0.00      | 0.00     | 2.54   | 0.00  | 0.00  | 0.00  | 6.17      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| CM84           | 45.17488 | -123.16982| 0.00      | 0.00     | 1.74   | 0.15  | 0.00  | 0.00  | 4.35      | 0.00     | 1.78   | 0.00  | 0.00  | 0.00  | 1.78  |
| CM85           | 45.17540 | -123.17001| 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| CM86           | 45.17498 | -123.17389| 0.00      | 0.00     | 1.74   | 0.00  | 0.00  | 0.00  | 8.70      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 8.70  |
| CM87           | 45.17555 | -123.17866| 0.00      | 0.00     | 2.03   | 0.00  | 0.00  | 0.00  | 4.35      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 4.35  |
| CM88           | 45.17492 | -123.17690| 0.00      | 0.00     | 2.61   | 0.00  | 0.00  | 0.00  | 4.35      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 4.35  |
| CM89           | 45.17686 | -123.18041| 0.00      | 0.00     | 3.48   | 0.00  | 0.00  | 0.00  | 10.14     | 0.00     | 2.66   | 0.00  | 0.00  | 0.00  | 2.66  |
| CM90           | 45.17426 | -123.18039| 0.00      | 0.00     | 4.06   | 0.00  | 0.00  | 0.00  | 4.06      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 4.06  |
| ICB1           | 45.17662 | -123.18797| 0.00      | 0.00     | 2.61   | 0.00  | 0.00  | 0.00  | 10.14     | 0.00     | 2.66   | 0.00  | 0.00  | 0.00  | 2.66  |
| ICB2           | 45.17671 | -123.18986| 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| ICB3           | 45.17660 | -123.18206| 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 0.00  |
| ICB4           | 45.17710 | -123.19163| 0.43      | 0.00     | 1.16   | 0.00  | 0.00  | 0.00  | 1.49      | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 1.49  |
| ICB5           | 45.17732 | -123.19471| 0.00      | 0.00     | 16.23  | 0.00  | 0.00  | 0.00  | 15.94     | 0.00     | 12.17  | 0.00  | 0.00  | 0.00  | 12.17 |
| ICB6           | 45.17776 | -123.19424| 0.00      | 0.00     | 9.28   | 0.00  | 0.00  | 0.00  | 11.59     | 0.00     | 20.87  | 0.00  | 0.00  | 0.00  | 20.87 |
| ICB7           | 45.17917 | -123.19279| 0.00      | 0.00     | 14.78  | 0.00  | 0.00  | 0.00  | 14.78     | 0.00     | 16.23  | 0.00  | 0.00  | 0.00  | 16.23 |
| ICB8           | 45.17781 | -123.19687| 0.00      | 0.00     | 9.86   | 0.00  | 0.00  | 0.00  | 7.25      | 0.00     | 17.10  | 0.00  | 0.00  | 0.00  | 17.10 |
| ICB9           | 45.17958 | -123.19642| 0.00      | 0.00     | 7.25   | 0.00  | 0.00  | 0.00  | 5.80      | 0.00     | 13.04  | 0.00  | 0.00  | 0.00  | 13.04 |
| ICB10          | 45.17899 | -123.19603| 0.00      | 0.00     | 10.43  | 0.00  | 0.00  | 0.00  | 10.43     | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 10.43 |
| ICB11          | 45.17862 | -123.19555| 0.00      | 0.00     | 9.86   | 0.00  | 0.00  | 0.00  | 11.59     | 0.00     | 21.65  | 0.00  | 0.00  | 0.00  | 21.65 |
| ICB12          | 45.17926 | -123.18999| 0.00      | 0.00     | 15.94  | 0.00  | 0.00  | 0.00  | 2.90      | 0.00     | 18.84  | 0.00  | 0.00  | 0.00  | 18.84 |
| ICB13          | 45.17962 | -123.18863| 0.00      | 0.00     | 18.84  | 0.00  | 0.00  | 0.00  | 18.84     | 0.00     | 0.00   | 0.00  | 0.00  | 0.00  | 18.84 |

### Average Infaunal Activity of Each Location

- **Corophium**: 81.28
- **Nuntalia**: 10.24
- **Macoma**: 50.75
- **Miyao**: 12.30
- **Neris**: 25.04
Appendix B. Vibracore Data

Legend

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<td>Low Angle Planar Laminations</td>
<td>Trough Cross-Stratification</td>
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ICB1
LAT: 49.17662 LONG: 123.18797

Date Logged: September 12, 2011
Logged by: Stacy Johnson
Ground: 0.00 m  KB: 0.00 m
Remarks: 182 degrees right

METERS  GRAIN SIZE  Bioturbation Index  Physical Structures  Ichnofoils  Fossils  Remarks

0.1  Fe  2.51 Phi (Fine-Grounded Sand)

0.2  Fe  2.24 Phi (Fine-Grounded Sand)

0.3  Fe  2.56 Phi (Fine-Grounded Sand)

0.4  Thinly laminated mud and sand with an increase in lamination thickness up-section, followed again by thinly laminated mud and sand.
ICB3
LAT:49.17654 LONG: 123.19132

Date Logged: September 12, 2011
Logged by: Stacy Johnson
Ground: 0.00 m KB: 0.00 m
Remarks: 34 degrees left

1.04 Phi (Medium-Grained Sand)

Large Siphonichnus burrow indicated by downward deflecting laminae.

1.56 Phi (Medium-Grained Sand)

3.40 Phi (Very Fine-Grained Sand)

Questionable whether these are true biogenic structures or if it is distortion caused by the core catcher.

Overall, sands are massive. This could either be due to core quality or biturbation.

2.57 Phi (Fine-Grained Sand)
ICB11
LAT: 49.17847 LONG: 123.19934

Date Logged: October 17, 2011
Logged by: Stacy Johnson
Ground: 0.00 m KB: 0.00 m
Remarks: 190 degrees right

GRAIN SIZE
boulder
cobble
pebble
granule
sand
silt
clay

METERS

PHYSICAL STRUCTURES

ACCESSORIES

FOSSILS

REMARKS

4.22 Phi (Very Coarse Silt)

Rare wave ripples and current ripple laminations are present. Most sand appears homogeneous.

4.12 Phi (Very Coarse Silt)

1.48 Phi (Medium-Grained Sand)
Date Logged: September 9, 2011
Logged by: Stacy Johnson
Ground: 0.00 m      KB: 0.00 m
Remarks: 240 degrees left

PB1
LAT: 49.18461 LONG: 123.21767

METERS

0.1

0.2

0.3

0.4

0.5

0.6

0.7

0.8

0.9

1.0

1.1

1.2

1.3

1.4

1.5

1.6

1.7

GRAIN SIZE
boulder
cobble
pebble
granule
sand
silt
clay

PHYSICAL STRUCTURES

ACCESSORIES

ICHNOFOSSILS

FOSSILS

REMARKS

3.11 Phi (Very Fine-Grained Sand)

Rhythmic bedding

Current ripples are ebb-oriented

4.23 Phi (Very Coarse Silt)

2.04 Phi (Fine-Grained Sand)
PB7
LAT: 49.18560 LONG: 123.22414

Date Logged: October 14, 2011
Logged by: Stacy Johnson
Ground: 0.00 m     KB: 0.00 m
Remarks: 88 degrees left

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3.18 Phi (Very Fine-Grained Sand)

1.05 Phi (Medium-Grained Sand)

Two Macoma Shells

Three large sand-filled Siphonichnus burrows

Two small mud-filled Siphonichnus burrows. They are likely Macoma generated.

One large mud-filled Siphonichnus burrow and the rest are large sand-filled Siphonichnus traces in the interval 123 - 150 cm.

4.22 Phi (Very Coarse Silt)

Mud-filled Skolithos
Date Logged: October 14, 2011
Logged by: Stacy Johnson
Ground: 0.00 m    KB: 0.00 m
Remarks: 120 degrees right

PB10
LAT:49.18635 LONG: 123.22809

1.43 Phi (Medium-Grained Sand)

Two large Siphonichrus burrows and one small Siphonichrus (Macoma generated) present, extending into the mud bed and filled with sand from the overlying unit.

4.26 Phi (Very Coarse Silt)
PB13
LAT: 49.18658 LONG: 123.23020

Date Logged: September 12, 2011
Logged by: Stacy Johnson
Ground: 0.00 m    KB: 0.00 m
Remarks: 174 degrees left

1.86 Phi (Medium-Grained Sand)

Overall, core is very poor quality with lots of distortion.
Determining the degree of bioturbation and recognizing sedimentary and ichnological structures is difficult.

4.37 Phi (Very Coarse Silt)
Date Logged: October 14, 2011
Logged by: Stacy Johnson
Ground: 0.00 m  
KB: 0.00 m
Remarks: 60 degrees left

3.32 Phi (Very Fine-Grained Sand)

4.44 Phi (Very Coarse Silt)

Sand-filled Siphonichmus and Skolithos burrows. A large portion of the muds and sands appear homogeneous and could be intensely bioturbated, although, individual burrows cannot be distinguished.

All current ripples observed are ebb-oriented and some are starved ripples. II

2.86 Phi (Fine-Grained Sand)
**PB19**

**LAT:** 49.18503 **LONG:** 123.23590

- **Date Logged:** September 8, 2011
- **Logged by:** Stacy Johnson
- **Sounding:** 0.00 m **KB:** 0.00 m
- **Remarks:** 240 degrees right

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## Appendix C. Box Core Data

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CMB1A

The scale bar on the right is 3 cm long and is the same for the other x-ray images herein. Note that in all images, lighter grey laminations correspond to sandier sediment while darker grey corresponds to muddier substrates.

272° in the downstream direction. Planar parallel laminated mud with rare current ripple laminations. *Skolithos* and rare *Palaeophycus* are visible (BI 1-2).
276° in the downstream direction. Pinstripe laminated mud and horizontal planar to wavy parallel laminated mud and sand. Rare *Skolithos*, *Palaeophycus* and *Arenicolites* (BI 2). The majority of burrowing is by threadworms.
CMB2

4° perpendicular to the downstream direction. Wavy parallel laminated mud. Bedding is distorted in places. Rare Skolithos and abundant Palaeophycus in the bottom half (Bl 1 for the top half and Bl 2 in the bottom half).
4° perpendicular to the downstream direction. Pinstripe laminated and planar parallel laminated mud and sand. Skolithos is common with rare *Palaeophycus* and *Siphonicnhus* (Bl 2).
260° in the downstream direction. Horizontal wavy parallel laminated mud and sand. Rare Skolithos and Palaeophycus (BI 1).
190° perpendicular to the downstream direction.

Low-angle wavy parallel laminated mud and sand. Rare wave ripple laminations in sand beds. *Skolithos* and threadworm burrows are visible (Bl 1).
20° perpendicular to the downstream direction. Horizontal wavy laminated mud and sand. Wood fragments distort laminae. Threadworm burrows are common at the top (BI 1).
$10^\circ$ perpendicular to the downstream direction. Horizontal planar to wavy parallel laminated mud and sand. *Skolithos* and rare *Palaeophycus* are visible (BI 1 at the base increasing to BI 3 at the top).
4° perpendicular to the downstream direction. Horizontal wavy parallel laminated very fine-grained sand and mud with rare current ripple laminations. Rare *Skolithos* (BI 1).
180° perpendicular to the downstream direction.
Horizontal planar to wavy parallel laminated mud. 
*Polykladichnus, Skolithos* and threadworm burrows are present (BI 2 with BI 3 in the upper sixth of the image).
68° perpendicular to the downstream direction. Horizontal wavy parallel laminated mud. Rare *Skolithos* and *Arenicolites*. *Palaeophycus* burrows are abundant in the bottom half of the core (BI 3 at the base decreasing to BI 1 at the top).
264° in the downstream direction. Horizontal planar to wavy parallel laminated mud. Rare *Skolithos*, *Palaeophycus* and *Siphonichnus* with abundant threadworm burrows (B1 3).
260° in the downstream direction. Low-angle to horizontal wavy parallel laminated mud. *Skolithos* and *Palaeophycus* burrows are sporadically distributed (BI 3 - 4).
181° perpendicular to the downstream direction. Fine-grained sand. Resin peel is poor quality overall. Some current ripple lamination is visible. Iron oxide staining is present near the top of the core.
170° perpendicular to the downstream direction. Current ripple laminated medium-grained sand. Rare *Skolithos* and *Palaeophycus* (BI 1). *Macoma balthica* shell in the upper right hand side of the image.
86° in the upstream direction. Medium-grained sand with a 6 cm thick planar parallel laminated mud bed in the middle. Faint trough cross-bedding is visible in the sand beds. Shell fragments are present in the upper sand bed. One iron oxide stained *Skolithos* is identifiable in the lower sand bed (BI 0 -1).
110° in the upstream direction. Ebb-oriented current rippled medium-grained sand and rare planar parallel laminated mud. Black ellipse in the middle left hand side of the image is a wood fragment. Rare threadworm burrows (BI 0 - 1).
256° in the downstream direction. Upper medium-grained sand. Wave ripples, current ripples, organic fragments and wood fragments are observed. No bioturbation is visible (BI 0).
158° in the upstream direction. Medium-grained sand. Image is distorted by cracks in the core. Faint current ripple laminations are visible. (BI 0)
210° perpendicular to the downstream direction. Horizontal planar to wavy parallel laminated mud. *Skolithos, Siphonichnus, Polykladichnus*, and *Palaeophycus* and threadworm burrows are visible (Bl 2 - 3). Two *Macoma* shells are 3 and 4 cm from the top.
118° in the upstream direction. Mud dominant core with pinstripe laminations and horizontal planar to wavy parallel laminations. *Skolithos, Palaeophycus, Arenicolites, Diplocraterion* and *Siphonichnus* are visible in the image (BI 1 - 2 in the bottom 10 cm and BI 3 - 4 for the upper 14 cm).
218° perpendicular to the downstream direction. Mud with some thin black streaks, which are cracks in the core. *Palaeophycus*, *Arenicolites*, and *Skolithos* are present (Bl 1 - 2).
120° in the upstream direction. Horizontal wavy parallel laminated mud. *Skolthos*, *Polykladichnus*, *Arenicolites* and rare *Palaeophycus* are visible (BI 3 - 4). The black ovals in the middle and 3 cm from the top of the core are *Macoma* shells.
198° perpendicular to the downstream direction. Horizontal wavy parallel laminated mud. Abundant *Skolithos* and *Arenicolites* with rare *Palaeophycus* and threadworm burrows (BI 4).
198° perpendicular to the downstream direction. Core comprises mud with rare planar parallel laminations. *Skolithos* and threadworm burrows are abundant and *Palaeophycus* and *Arenicolites* are rare (BI 4 - 5). Two *Macoma* shells are in the upper right and left hand corners of the image.
212° perpendicular to the downstream direction. Wavy to planar parallel laminated mud with rare sand laminations. Sand laminations contain wave ripples and current ripple laminations. *Skolithos*, *Arenicolites* and *Palaeophycus* are abundant in the upper third of the core (BI 0 - 1 in the lower 2/3 of the core and BI 3 - 4 in the upper third).
210° perpendicular to the downstream direction.
Mud with rare sand laminations. Rare planar parallel laminations are visible. Bottom third of the core has no visible bioturbation. A third of the way up is a 3 cm thick mud lamination with abundant threadworm burrows. The upper 2/3 of the core has visible Skolithos, Polykladichnus, Arenicolites and Palaeophycus (BI 4 - 5).
126° in the upstream direction. Horizontal planar to wavy laminated mud. *Skolithos* and *Palaeophycus* are common (Bl 3).
100° in the upstream direction. Planar parallel laminated mud. The trace suite includes *Palaeophy cus*, *Arenicolites*, *Polykladichnus*, and *Siphonichnus* (BI 3). A *Macoma balthica* shell is present 3 cm from the bottom and is in the center of the x-ray image.
283° in the downstream direction. Core contains laminated mud and fine-grained sand. Current ripple laminations are visible in the bottom half of the core. *Siphonichnus* and *Palaeophycus* are discernible in the image (Bl 1 or the bottom half and Bl 3 - 4 in the upper half).
290° in the downstream direction. Bottom half of the image comprises ebb-oriented current rippled fine-grained sand. Upper half is composed of admixed mud and very fine-grained sand. Bottom half has a BI of 1 with mud-filled Siphonichnus burrows extending down into the sand from above. The upper half contains abundant Siphonichnus, Skolithos, Arenicolites and rare Paleophycus (BI 4 - 5).
40° perpendicular to the downstream direction. Core comprises mud with faint planar parallel laminations visible at the base. Large black ellipse in the centre left of the image is an impression left by the bivalve *Mya arenaria*. *Siphonichnus* and rare *Palaeophycus*, *Skolithos* and threadworm burrows are visible (Bl 5).
286° in the downstream direction. Core is composed of mud with rare cm-scale thick sand laminations. Faint planar parallel laminations are visible. Trace suite includes *Siphonichnus*, *Skolithos*, and rare *Palaeophycus* (Bl increases gradually from 2 - 4 up the core).
PB3

276° in the downstream direction. Fine-grained sand and mud. Extending from the top of the core is a Siphonichnus trace left by one of the Siphons of Nuttallia obscurata (BI 4).
298° in the downstream direction. Silt with planar parallel laminations and wave ripples. Large black oval is the shell of *Mya arenaria*. *Mya* generates *Siphonicnhus* burrows and causes laminae to deflect downward around the edges of the burrow. *Palaeophycus* and threadworm burrows are also present (Bl 2).
190° perpendicular to the downstream direction. Core comprises mud with rare cm-scale fine-grained sand laminations. Rare horizontal wavy parallel laminations are visible. *Siphonichnus* and *Skolithos* are abundant, while *Arenicolites* and *Palaeophycus* are rare (BI 3).
174° perpendicular to the downstream direction. Medium-grained sand with a couple of mud laminations at the top of the core. Current ripple laminations are visible near the top, while the rest of the sand is homogeneous. Large black circle in the middle-left is a Nuttallia obscurata shell. Siphonichnus, Palaeophycus and Skolithos are visible (BI 3).
290° in the downstream direction. Mostly medium-grained sand with 7 cm of mud at the top of the core. Current ripple laminations are visible in the sand and planar parallel laminations are visible in the mud. *Siphonichnus* is the dominant trace in this core (BI 4).
10° perpendicular to the downstream direction. Bioturbated mud with rare planar parallel laminations. Large, black vertical ellipse is a *Mya arenaria* shell. Visible structures include abundant *Siphonichnus* and rare *Arenicolites* and *Palaeophycus* (Bl 4 - 5).
282° in the downstream direction. Fine-grained sand with rare mm-scale mud laminations. Rare current ripple laminations are observed. The two black ovals 6 cm from the base on the right side of the image are Nuttallia obscurata shells. The trace suite includes Siphonichnus, Skolithos and rare Palaeophycus (Bl 4 - 5).
290° in the downstream direction. Medium-grained sand with rare mud lenses. Sand has been biogenically re-worked, but some planar parallel laminations are visible. Five *Nuttallia obscurata* bivalves are in the core. The activity of these bivalves generate *Siphonichnus* burrows (BI 5).
8° in the upstream direction. Sandy mud. Rare planar parallel laminations and current ripple laminations. Abundant threadworm burrows and eel grass in the upper 8 cm of the core. Rare *Palaeophycus* (Bl 2 - 3).
290° in the downstream direction. Medium-grained sand. Poor-quality peel, sand appears mainly homogeneous. Ebb-oriented current ripples are visible in the upper 5 cm of the peel. Some shell fragments are sporadically distributed. Unable to determine BI due to data quality.
290° in the downstream direction. Muddy sand. No visible primary sedimentary structures. Five Nutallia obscurata shells are present in the core. No discernible biogenic structures, but lack of primary sedimentary structures and abundance of bivalves suggests significant re-working (Bl 6).
290° in the downstream direction. Fine-grained sand. Wave ripple laminations at the top of the core. Abundant shell fragments and one whole *Nuttallia obscurata* bivalve in the middle left of the core. Visible structures include *Siphonichnus* and *Arenicolites* (Bl 5).
268° in the downstream direction.

Fine-grained sand. Sand is homogeneous with ebb-oriented current ripples in the upper 3 cm of the core. One *Nuttallia obscurata* shell is 6 cm from the top and on the right side of the core. On the left of the *Nuttallia* shell is a mold left by *Macoma balthica*. *Palaeophyccus* and *Skolithos* are visible (BI 5).
330° perpendicular to the downstream direction. Bottom third comprises planar parallel laminated mud. Middle third is bioturbated fine-grained sand. Upper third is current ripple laminated medium-grained sand with mud drapes over some of the ripples. *Siphonichnus* and *Skolithos* are visible in the resin peel (Bl 2 for the bottom third, Bl 4 for the middle, and Bl 0 for the top).
251° perpendicular to the downstream direction. Medium-grained sand. Three *Nuttallia obscurata* shells and three *Macoma balthica* shells are in the core. *Nuttallia obscurata* shells are more circular and greater than 2 cm wide and long, while *Macoma balthica* shells are elliptical and are < 2 cm long and < 0.3 cm wide. *Siphonichnus* is the only discernible trace (Bl 5).
352° perpendicular to the downstream direction. Medium-grained sand with cm-scale mud lamina at the top. Core is homogeneous with two *Macoma* shell fragments and rare *Siphonichnus* and *Palaeophycus* (BI 4).
258° in the downstream direction. The bottom 14 cm is sandy mud and the upper 10 cm comprises upper fine-grained sand. Two *Nuttallia obscurata* shells are visible. *Siphonicnhus* and *Palaeophycus* are present (BI 4).
320° perpendicular to the downstream direction. Medium-grained sand with a 6 cm mud bed. Sand beds display low-angle parallel laminations and possibly trough cross-bedding. Mud is wavy parallel laminated. Shell fragments, *Skolithos* and *Siphonichnus* are discernible (BI 3).
278° in the downstream direction. Upper fine-grained sand with a cm thick mud lamina at the very top that drapes over a wave ripple. One *Nuttallia obscurata* shell is at the base in the middle of the core. To the upper left of the *Nuttallia* shell is a *Macoma balthica* shell. *Siphonichnus, Palaeophycus* and threadworm burrows are the discernible traces in the core (Bl 4).
238° in the downstream direction. Medium-grained sand with a couple of cm-scale thick mud beds. Sand is homogeneous with some visible *Siphonichnus* and *Palaeophycus* traces (Bl 2).
270° in the downstream direction. Core comprises upper fine-grained sand with a 3 cm thick mud bed at the top of the core. The mud bed displays current and wave ripples. Rare *Arenicolites* and *Palaeophycus* are present (BI 1).
32° perpendicular to the downstream direction. Upper fine-grained sand. Traces include *Palaeophycus* and *Siphonichnus* (BI 3).
270° in the downstream direction. Fine-grained sand with rare dark, organic-rich laminations. Current ripple laminations are visible at the top of the core. One large, 10 cm long, *Mya arenaria* shell is in the bottom left corner. Other shell fragments are present along with wood fragments. *Siphonichnus* and threadworm burrows are the dominant biogenic structures (BI 2).
20° perpendicular to the downstream direction. Admixed sand and mud. Rare shell fragments are sporadically distributed. *Siphonichnus*, *Arenicolites* and threadworm burrows are discernible (BI 3).