University of Alberta

Neoichnology and Sedimentology of the Fluvial-Tidal Transition Zone of the Columbia River Delta, Northwest U.S.A.

by

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Abstract

The Columbia River Delta, northwest U.S.A., is a complex depositional environment at the mouth of the second largest United States' river. Through the study of tidal sand bars within the fluvial-tidal transition, neoichnological and sedimentological characteristics of the mixed-energy brackish-water setting were established. Neoichnological analysis determined trace assemblages of the area are consistent with the *Teichichnus* ichnofacies, with the most intense burrowing found along the bar tops and intertidal zone. Additionally, the ichnogenera burrowing depth, density and burrow diameter decrease moving up-river, and there is larval tidal recruitment of marine trace-makers into the oligohaline zone. Sedimentological analysis of the dataset led to the identification of six facies for the tidal bars of the Columbia River Delta, which were synthesized into one facies association. The more obvious sedimentological tidal indicators are not present in the representative facies and are much more subtle, encompassing changes in flow regime within a single facies.

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Chapter 1 – Introduction

Introduction

In the last few decades, there has been a significant increase in the understanding of facies architecture and the stratigraphy of deltas. However, the understanding of tide-influenced and tide-dominated deltas, as well as of mixed-energy deltas, is not as advanced as river- and wave-dominated deltas. In subsurface examples of tide-dominated deltas, it is apparent the stratigraphy is complex. There is a considerable need for the development of predictive models based on modern analogues to aid in the understanding and interpretation of subsurface, ancient deposits. The simple definition of a delta – “a progradational sediment body at the mouth of a river, formed of sediment supplied by the river, and containing fluvially-influenced deposits” (cf. Dalrymple *et al*., 1992; Dalrymple, 1999, 2000; Dalrymple *et al*., 2003) – has allowed for the identification of numerous modern tide-dominated and mixed-energy deltas. An estuary is defined as a transgressive system that receives sediment from both fluvial and marine sources, commonly occupies the seaward end of a drowned valley, contains facies influenced by wave, tide and fluvial processes, and extend from the landward limit of tidal facies at the their heads to the seaward limit of coastal facies at their mouths (Boyd *et al*., 2006). The primary differences between deltas and estuaries are that deltas are progradational and the sediment is derived from fluvial sources, whereas estuaries are transgressional and the sediment is derived from both fluvial and marine sources. The Columbia River is classified as a delta herein since its sediment is fluvially-derived and it is progradational in nature, with the sediment by-passing the inner reaches of the system and is deposited subaqueously at the river mouth.

The coupling of (neo)ichnological data with sedimentological observations has increased the understanding of tide-dominated deltaic deposits, particularly within the fluvial-tidal transition zone. This zone is brackish in nature, covering a specific group of environmental conditions. The variable nature of brackish-water environments imposes stresses on the organisms that populate them. The salinity of brackish-water systems varies over both individual tidal cycles and seasonal tidal cycles. The zone of brackish-water influence fluctuates and changes its position depending on seasonal fluvial discharge and tidal cyclicity (Dalrymple *et al*., 2003; MacEachern *et al*., 2005b). Additionally, deltaic sediment is rhythmically disrupted by ebb and flood currents within the tidal cycle. The interaction of the flood current with the river current causes sediment disruption, while the convergence of the ebb current with the river current allows for the generation of the current-speed maximum (Dalrymple & Choi, 2007). The bedload material of a delta is transported via the dominant current direction, whereas the suspended material generally follows the residual circulation that is created by the interaction between fresh and saline water (Dalrymple & Choi, 2007).

Brackish-water conditions found within tide-dominated deltas impose biological stresses on the organisms inhabiting these environments (MacEachern *et al*, 2005a). The fluctuating salinity, sediment disruption and high suspended sediment concentrations in the channels creates extremely variable environmental conditions that are not always conducive to animal habitation (Howard *et al*., 1975; MacEachern *et al*, 2005a). Consequently, there are relatively few organisms that are able to survive under these conditions when compared to normal marine conditions (MacEachern *et al*, 2005a). The number of species found within this environment is generally low, with the minimum diversity at a salinity of approximately five parts per thousand (ppt) (Buatois *et al*., 1997). Diversity increases seaward and represents an impoverished marine assemblage (Remane, 1934; Remane, 1958; Howard *et al*., 1975; Barnes, 1989; Gingras *et al*., 1999; Pearson & Gingras, 2006; Hauck *et al*., 2009). Organisms that are adapted to live in this hostile environment have often developed specific strategies for dealing with these conditions.

Research from the Columbia River Delta from the northwest United States documents the neoichnology and sedimentology of the very-low-salinity region of the fluvial-tidal transition zone within a mixed-energy (tide- and wave-influenced) delta. This study provides criteria for identifying neoichnological trends along tide-dominated bars along a longitudinal transect of the Columbia River Delta, as well as delineates facies for the tidal sand bars, along the fluvial-tidal transition. Although there have been many neoichnological studies that have considered bioturbation in brackish-water environments (Howard & Dorjes, 1972; Frey, 1975; Basan & Frey, 1977; Frey & Pemberton, 1987; Frey *et al*., 1987; Gingras *et al*., 1999; De, 2000; Dashtgard & Gingras, 2005; Hertweck *et al*., 2005; Pearson & Gingras, 2006; Gingras *et al*., 2008; Gunn *et al*., 2008; Hauck *et al*., 2009; Dashtgard, 2011a,b; Gingras *et al*., in press), the neoichnological characterization of very-low-salinity fluvial-tidal settings has not been presented in the literature. Additionally, the sedimentological facies trends of this zone have not been well documented in either modern (Aitken *et al*., 1988; Dalrymple *et al*., 2003; Choi *et al*., 2004; Pearson & Gingras, 2006; Dalrymple & Choi, 2007; Dashtgard *et al*., 2008; Hauck *et al*., 2009) or ancient (Hori *et al*., 2002; McIlroy, 2004; Rebata *et al*., 2006; Kitazawa, 2007) studies. There have been numerous studies to describe and interpret sedimentological trends of deltas, but few have considered environments that are mixed-energy with both a strong tidal and wave influence and low salinity.

Study Area

The Columbia River is the second largest river in the United States, and is the largest to drain into the northeastern Pacific Ocean. Its drainage basin covers an area that is approximately 660,480 km^2, encompassing seven states and two Canadian provinces (Simenstad *et al*., 1990). The river supplies about 9.7 million metric tons of sediment to the delta annually, and contributes 60 (winter) to 90 (summer) percent of the freshwater input to the Pacific Ocean between San Francisco Bay and the Straits of Juan de Fuca (Simenstad *et al*., 1990).

The Columbia River Delta is located along the border of Oregon and Washington in the northwest United States (Fig. 1-1). It is characterized as mesotidal (tidal range between two and four metres), with mixed, semi-diurnal tides. The delta is tide-dominated, with a tidal prism of 50,926 m^{3}s^{-1} (Buonaiuto & Kraus, 2003). The Columbia River Delta is contained within a basin of Tertiary-aged sedimentary and volcanic bedrock, and has been in-filled with Pleistocene and Holocene sediments (Simenstad *et al*., 1990).

The Columbia River's main channel is relatively straight and contains several tidally-influenced sand bodies. Sand bars in the area typically migrate up and down the delta portion of the system, and sand accumulations are locally up to 30 m thick Sherwood & Creager, 1990. Overall, the system is primarily composed of fine sand with muddy pockets near the margins (Sherwood & Creager, 1990). The accommodation space in the lower Columbia River delta is destroyed by the presence of shallow tidal flats, shoals, central islands, and lateral accretion floodplains. The dominant sedimentary process appears to be channelized sediment throughput and transient bar-storage (Sherwood & Creager, 1990).

Fig. 1-1: Columbia River Delta study area location. The Columbia River Delta borders the states of Washington and Oregon in the Pacific north-west of the United States. Note the total size of the study area is quite large, covering a river length of approximately 75 km.

Previous Work

The Columbia River Delta has been studied extensively as it is the gateway to the major port of Portland, Oregon, and provides extensive fishing grounds for salmon, sturgeon, steelhead and other fish. The study of the Columbia River Delta began in the 1850's by the U.S. Coast and Geodetic Survey (USCGS), now known as the National Ocean Survey (NOS), who conducted surveys of the tides and bathymetry (Simenstad *et al*., 1990). The first major dam was constructed in 1933 (Sherwood *et al*., 1990). However, large-scale regulation of the flow cycle of the Columbia River did not begin until about 1969 (Sherwood *et al*., 1990). It was at this point when the variability of the monthly mean river flow was dramatically reduced and flow was severely affected through the management of dam storage (Sherwood *et al*., 1990).

The U.S. Army Corps of Engineers conducted circulation studies on the Columbia River Delta with the deepening of the channel in 1932 and 1959. Following the 1959 studies, another series of studies were carried out on the delta, including flushing time calculations, salt transport, circulation theory, and engineering and modelling studies (Simenstad *et al*., 1990).

The Columbia River Estuary Data Development Program (CREDDP) was set up in 1974 to increase the understanding of the sedimentology, hydrology, and ecology of the area. Between 1974 and 1984, CREDDP carried out physical and biological studies on the Columbia River Delta, which aided in the development of the delta, and in making informed land and water use decisions (Simenstad *et al*., 1990). Other studies conducted between 1974 and 1984 included the distribution of sedimentary organic matter, suspended particle load leaving the delta to the ocean, studies of fish, benthic infauna and epifauna, birds, and the distributions of total particulate organic carbon and total dissolved carbon (Simenstad *et al*., 1990). For a complete historical overview of the Columbia River Delta, the reader is directed to Sherwood *et al*. (1990).

Main Objectives

Chapter 2 identifies and interprets the neoichnological trends of tide-dominated sand bars along the Columbia River Delta (i.e., from the fluvial-dominated through to the tide-dominated regions of the distributary). Using neoichnological data in combination with salinity, total organic carbon and grain-size, trends are established in this low-salinity zone of the delta.

Chapter 3 describes and interprets the distribution and texture of sediments, allowing for the creation of facies in the tidal sand bars of the Columbia River Delta. These facies were grouped into a facies association. These facies and facies association were used to aid in the comparison with ancient environments in the rock record.

Chapter 4 summarises the objectives and outcomes of the thesis. The applicability of the neoichnological analysis and facies observations within the fluvial-tidal transition of modern tide-dominated deltas to the rock record is discussed.

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Chapter 2 – Neoichnological trends at the fluvial-tidal transition of the Columbia River Delta, northwest U.S.A.

Introduction

A delta is defined as "a progradational sediment body at the mouth of a river, formed of sediment supplied by the river, and containing fluvially-influenced deposits" (cf. Dalrymple *et al*., 1992; Dalrymple, 1999, 2000; Dalrymple *et al*., 2003). There are three significant forms of energy that affect deltaic processes, including river currents, tidal currents, and waves (Fig. 2-1). River currents decrease in strength seaward due to a decrease in hydraulic gradient (Dalrymple & Choi, 2007). Tidal currents are divided into ebb (seaward-directed) currents and flood (landward-directed) currents. The tidal maximum generally occurs in deltas near where the distributary channels bifurcate (Fig. 2-1). Past the tidal maximum, tidal currents increase in strength moving landward until they are compressed into a smaller cross-sectional area. Tidal currents then decrease in strength owing to an increase in friction due to a smaller channel cross-section up to the tidal limit (Dalrymple & Choi, 2007).The wave energy of deltas is at a maximum at the mouth before the wave energy dissipates due to friction (Fig. 2-1; Dalrymple & Choi, 2007).

Sediment within the tidally-influenced fluvial channels is derived from both fluvial discharge and from the sea. Typically, the sand-size fraction is derived from landward sources and enters the system via rivers. However, the suspended sediment may be derived from both the river and from the ocean (i.e., brought in by tidal currents). Generally, the suspended sediment concentration (SSC) is relatively low, as the fluvial-tidal transition zone lies landward of the turbidity maximum (Fig. 2-1). The turbidity maximum is the area where the SSC is at its greatest, and occurs where the fluvial suspended sediment interacts with the marine suspended sediment. The turbidity maximum is not in a fixed position, and primarily changes position based on fluvial discharge (Gelfenbaum *et al*., 1983; Allen *et al*., 1990; Dalrymple & Choi, 2007). The salinity of brackish-water systems varies over both individual tidal cycles and seasonal tidal cycles. The zone of brackish-water influence fluctuates and changes its position depending on seasonal fluvial discharge and tidal cyclicity (Dalrymple *et al*., 2003; MacEachern *et al*., 2005a).

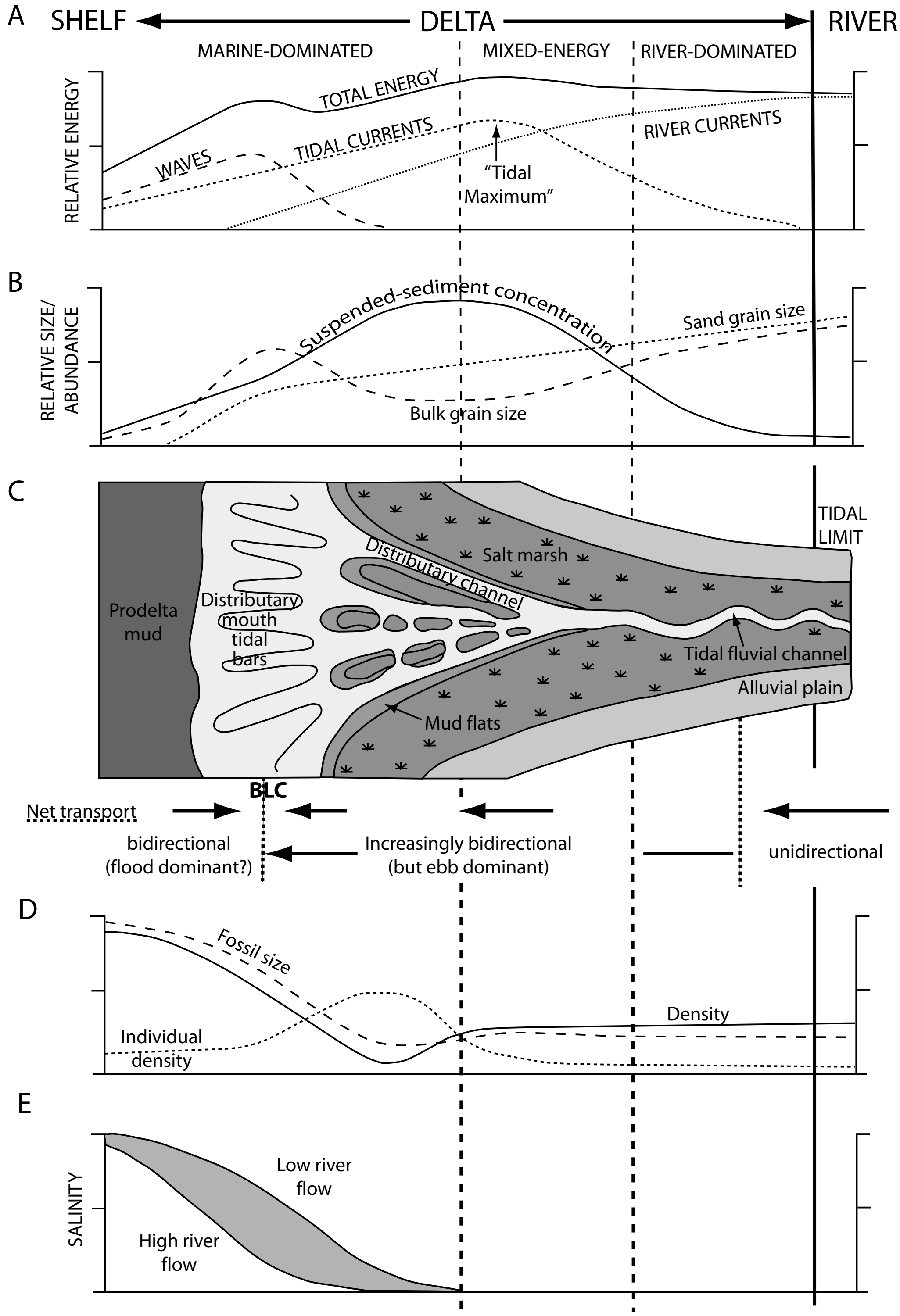
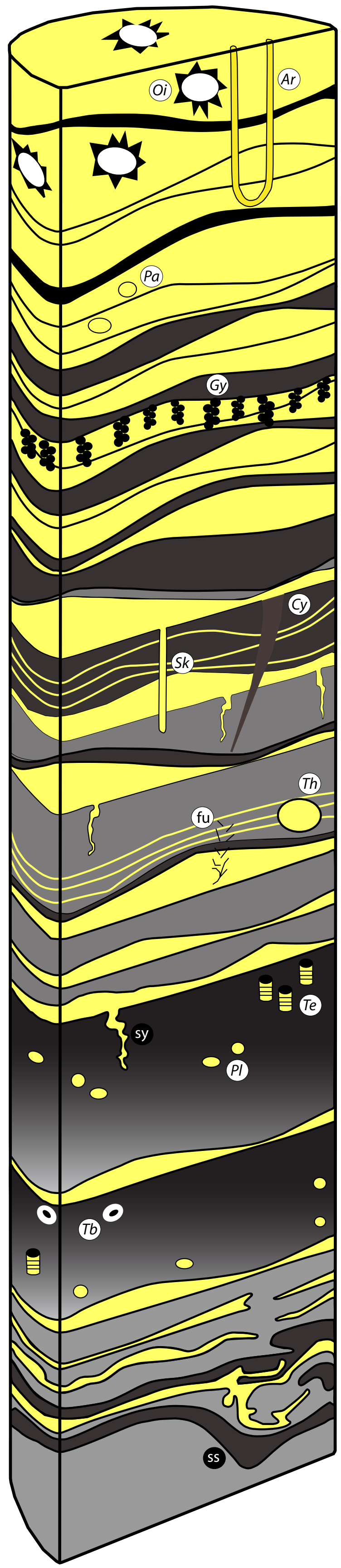


Fig. 2-1: General illustration of a tide-dominated delta, exhibiting latitudinal variations in grain size, energy, salinity gradient and benthic infauna (Modified after Dalrymple & Choi, 2007). A demonstrates the grain-size distribution of the delta. In the tidal-fluvial channel and the upper reaches of the distributary channel, the grains are dominantly sand-sized, with minimal presence of suspended sediment. B displays the energy regime of the delta. In the areas of interest (tidal-fluvial channel, mud flats, salt marsh, and distributary channels), the dominant form of energy is river

Deltaic ichnology is poorly understood, especially in tide-dominated settings where ancient examples are often not preserved, and very few neoichnological studies have been conducted (Dashtgard, 2011). The ichnological signal of deltaic successions includes lowered bioturbation intensities, strongly sporadic distributions of trace fossils, numerous unburrowed events (turbidites and tempestites), general size reductions of some ichnogenera, common reestablishment of structures, impoverished marine trace-fossil suites, juxtaposition of salinity stressed suites and fully marine suites, suppression of the *Skolithos* ichnofacies and its elements, and the predominance of the *Cruziana* ichnofacies assemblages, even in clean sandy intervals (Fig. 2-1; Fig. 2-2; MacEachern *et al*., 2005a,b; Pemberton & MacEachern, 2006).

Brackish-water conditions found within tidally-dominated deltas impose biological stresses on the organisms inhabiting these environments. The fluctuating salinity, sediment disruption and high suspended sediment concentrations in the channels creates extremely variable environmental conditions that are not always conducive to animal habitation. Consequently, there are relatively few organisms that are able to survive under these conditions when compared to normal marine conditions. The number of species found within this environment is generally low, with the minimum diversity at a salinity of approximately 5 ppt. Diversity increases seaward and represents an impoverished marine assemblage (Fig. 2-1; Remane, 1934; Remane, 1958; Barnes, 1989; Gingras *et al*., 1999; Pearson & Gingras, 2006; Hauck *et al*., 2009). Organisms that are adapted to live in this hostile environment have often developed specific strategies for dealing with these conditions. Specifically, the organisms tend to be r-selected strategists (opportunists) that colonize the sediment rapidly. They reproduce often and in large numbers, are infaunal, and display a few feeding strategies, such as both deposit and suspension feeding (Sanders *et al*., 1965;

currents. However, the tidal currents still have a presence well into the tidal-fluvial channel. In C, we are largely concerned with the tidal-fluvial channel, mud flats, salt marsh, and the distributary channels with regard to the Columbia River Delta. Observe the overall funnel morphology and the distributary channel separation by islands. D illustrates the salinity variation of the delta at both high and low river flow. In the areas of concern, the salinity gradient appears to not enter into the upper distributary channel and the tidal-fluvial channel. However, this is not the case in the Columbia River Delta, where the salinity gradient extends well into the tidal-fluvial channel, and even into the strictly fluvial channel. E shows organism distribution throughout a tide-dominated delta. In this figure, individual density, burrow size, and overall density/diversity are relatively low in the upper distributary channel and the fluvial channel. Conversely, in the Columbia River Delta, the individual density can be quite high far into the tidal fluvial channel, even though the size and overall density may be low.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Levinton, 1970; Pianka, 1970; Howard *et al*., 1975; Knox, 1986; Jumars, 1993; MacEachern *et al.*, 2005a,b; Hauck *et al*., 2009). The animals tend to occur in monospecific assemblages with high mortality rates, leaving a predominantly juvenile population with a smaller-than-average body size (Rees *et al*., 1977; Gingras *et al*., 1999; Lettley *et al*., 2005).

The typical brackish-water ichnofossil assemblage has been summarized by several authors, and has been found to be consistent in many modern and ancient brackish water deposits. The trace fossil assemblage of a brackish-water environment is characterized by: 1) relatively small body size compared to the marine counterparts due to the hostile conditions; 2) morphologically simple trace fossils, such as *Planolites*; 3) low diversity of trace fossils, often producing monospecific assemblages; 4) high trace fossil densities due to high rates of reproduction; 5) dominance of infaunal traces compared to epifaunal traces (Fig. 2-2; Pemberton *et al*., 1982; Ranger & Pemberton, 1992; Lettley *et al*, 2005; MacEachern *et al*., 2005a; MacEachern & Gingras, 2007); and 6) traces comprising the *Teichichnus* ichnofacies (Pemberton *et al*., 2010).

The aim of this chapter is to identify and interpret the neoichnological trends seen in tide-dominated bars along a longitudinal transect of the Columbia River Delta (i.e., from the fluvial-dominated through to the tide-dominated regions of the distributary). Using neoichnological data in combination with salinity, total organic carbon and grain-size, trends can be established in this low-salinity zone of the delta.

Study Area

The mesotidal Columbia River Delta, located in the northwestern United States along the border of Washington and Oregon (Fig. 2-3), is contained within a valley of volcanic and sedimentary bedrock. This valley has been partly infilled with Pleistocene and Holocene sediments from the Columbia River basin (Simenstad *et al*., 1990). The main channel of the Columbia River is relatively straight and contains several tidally-influenced sand bodies. Sand bars in the

Fig. 2-2 (previous page): Split-core model of a typical brackish-water assemblage. Traces and sedimentary structures include *Arenicolites* (*Ar*), *Cylindrichnus* (*Cy*), *Gyrolithes* (*Gy*), *Ophiomorpha* (*Oi*), *Palaeophycus* (*Pa*), *Planolites* (*Pl*), *Skolithos* (*Sk*), *Teichichnus* (*Te*), *Terebellina* (*Tb*), *Thalassinoides* (*Th*), fugichnia (fu), synaeresis cracks (sy), and soft-sediment deformation (ss). Yellow colour indicates sandy sediments, whereas increasing shades of grey indicates increased mud content. Note that the Columbia River Delta exhibits an even more pronounced impoverished marine assemblage than is depicted in this model. Modified after MacEachern *et al*., 2005b.

area typically migrate up and down the delta portion of the system, where sand accumulations are locally up to 30 m thick. Overall, the system is primarily composed of fine sand with muddy pockets near the valley margins (Sherwood & Creager, 1990). The lack of accommodation space in the lower Columbia River Delta is due to the presence of shallow tidal flats, shoals, central islands, and lateral accretion floodplains. The dominant sedimentary process appears to be channelized sediment throughput and transient bar-storage (Sherwood & Creager, 1990).

The Columbia River Delta experiences a wet coastal climate influenced by the warm, moist air masses that move over the Cascade and Coast mountain ranges (Simenstad *et al*., 1990). The hydrograph for the delta undergoes three river seasons, which are divided into fall, winter, and spring flows. The fall season is between August and November, and is marked by the lowest flows. The winter season also generally has a low river flow, but is frequently interrupted by periods of higher flow due to winter storms that bring precipitation, high winds and waves. The spring season has the highest river flow due to melt water and spring rains (Sherwood & Creager, 1990).

The Columbia River Delta is mesotidal and experiences mixed, semi-diurnal tides, with a mean tidal range of 2.0 m at the mouth. Tidal height fluctuations can be observed as far upstream as the Bonneville Dam (225 km from the river mouth), whereas tidal current reversals occur as far as 85 km upstream (Gelfenbaum, 1983). However, according to Jay *et al*. (1990), tidal influence is scarcely detectable beyond approximately 160 km upriver from the mouth. The limit of seawater intrusion has been published as being located at Harrington Point, approximately 37 km upriver from the mouth (Gelfenbaum, 1983). In spite of this, through the course of this study, this has been shown to be incorrect, with the limit of intrusion being located significantly farther upriver (detailed below).

The Columbia River Delta is a mixed-energy delta, with strong tidal and wave influences. The tidal prism is significantly larger than the fluvial discharge, promoting the strongly tidally-influenced nature of the system. With each tide, the area exchanges approximately 50,926 m^3s^{-1} of water (Buonaiuto & Kraus, 2003). The fluvial output of the Columbia River, however, has a mean seasonal high water discharge of approximately 8778 m^3s^{-1} (Jay, 1984). Additionally, the prevalence of coast-normal bars and systems of tidal channels in the Columbia

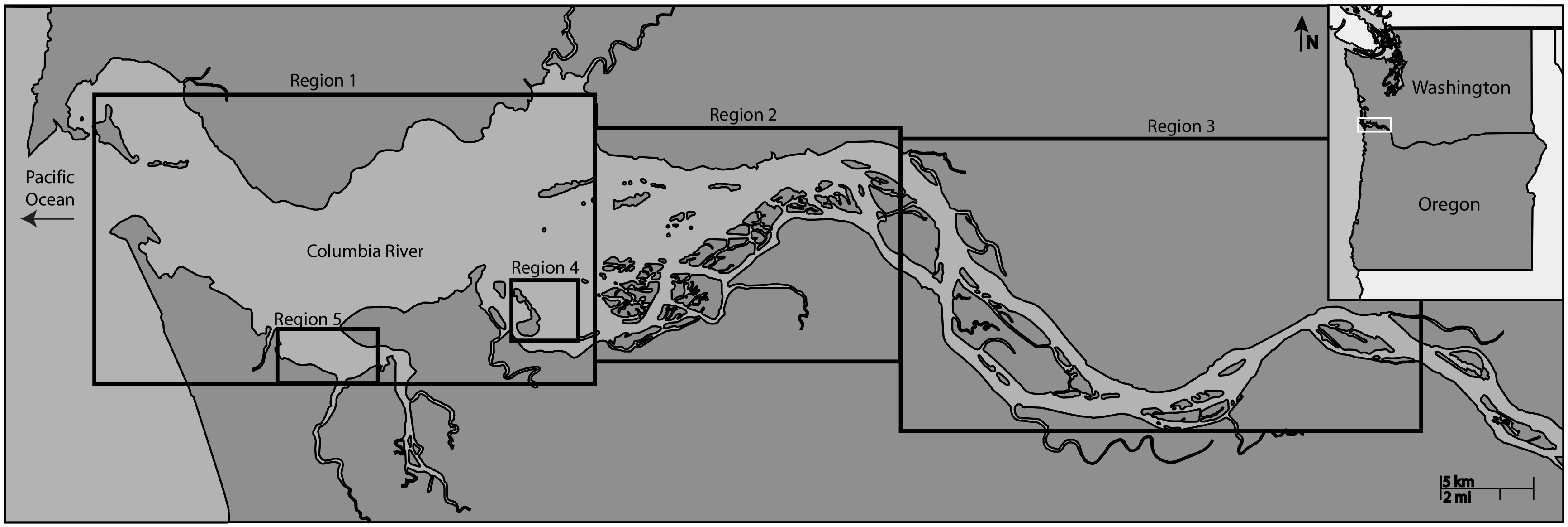


Fig. 2-3 (following page): Columbia River Delta study area location. The Columbia River Delta borders the states of Washington and Oregon in the Pacific north-west of the United States. Note the total size of the study area is quite large, covering a river length of approximately 75 km. The outlined regions subdivide the area based on observed ichnofauna, organism size and diversity, overall grain size, and sedimentary structures. Region 1 ranges from the mouth of the Columbia River Delta to approximately 25 km up-river; Region 2 extends from approximately 25 km to 45 km up-river; Region 3 spans from 45 km to about 75 km up-river; Regions 4 and 5 are localized, sheltered bays within the study area and were thus considered separately. Obvious sedimentary features on the map include the elongate fluvial-tidal sand bars throughout all of Regions 2 and 3, as well as multiple tidal channels cross-cutting the bars. Modified after Gelfenbaum, 1983.

River Delta are indicative of tidal dominance, as it demonstrates the tidal currents are responsible for more sediment movement than the fluvial currents, determining the overall geomorphology (Dalrymple & Choi, 2007). With respect to the strong wave-influence, waves at the mouth of the Columbia River Delta cause rapid diffusion and deceleration of the fluvial output. Sediment discharge from the Columbia River is high, so sediment is transported at high rates across the mouth leading to the development of sandy beach ridges via longshore drift (Smith *et al*., 1999). The sediment is primarily transported north along the coast, but is also transported south. The Willapa barrier, which protects Willapa Bay north of the study area, is a 38 km-long peninsula that is predominantly composed of sediment derived from the Columbia River (Smith *et al*., 1999).

There is substantial anthropogenic influence surrounding the Columbia River Delta. Approximately 25,000 people live around the delta, who are supported by an economy of fishing, logging, tourism and agriculture (Simenstad *et al*., 1990). Additionally, as the delta provides access to the major port of Portland, Oregon, the U.S. Army Corps of Engineers carry out intensive dredging, filling, and channelization projects to assist in navigation, which have created sizeable modifications in the geomorphology of the delta (Simenstad *et al*., 1990).

Previous Work

The Columbia River Delta has been studied extensively as it is the gateway to the major port in Portland, Oregon, and provides extensive fishing grounds for salmon, sturgeon, steelhead and other fish. The study of the Columbia River Delta began in the 1850's by the U.S. Coast and Geodetic Survey (USCGS), now known as the National Ocean Survey (NOS), who conducted surveys of the tides and bathymetry (Simenstad *et al*., 1990).

The U.S. Army Corps of Engineers carried out circulation studies on the Columbia River Delta with the deepening of the channel in 1932 and 1959. Following the 1959 studies, another series of studies were carried out on the delta, including flushing time calculations, salt transport, circulation theory, and engineering and modelling studies (Simenstad *et al*., 1990).

The Columbia River Estuary Data Development Program (CREDDP) was set up in 1974 in order to increase the understanding of the sedimentology, hydrology and ecology of the area. Between 1974 and 1984, CREDDP carried out physical and biological studies on the Columbia River Delta, which aided in the development of the delta and in making informed land and water use decisions (Simenstad *et al*., 1990). Other studies conducted between 1974 and 1984 included the distribution of sedimentary organic matter, suspended particle load leaving the delta to the ocean, studies of fish, benthic infauna and epifauna, birds, and the distributions of total particulate organic carbon and total dissolved carbon (Simenstad *et al*., 1990). For a complete historical overview of the Columbia River Delta, the reader is directed to Sherwood *et al*. (1990).

Methods

Permanent sand bars along the delta were selected based on location and tidal flat size/exposure. Sixty six stations were placed based on tidal flat size, presence/absence of benthic infauna and location within the study area. The stations were plotted using a handheld Global Positioning System (GPS). Each station was sampled by collecting hand samples, box cores, benthic animals and measuring surface salinity. The hand samples had a wet weight of approximately 300 g, and were analyzed for sediment grain size and total organic carbon (TOC) content.

The box cores collected a sample measuring 30 cm x 18 cm x 6 cm. Each of the cores was peeled using an epoxy resin to emphasize the sedimentary and ichnological structures, as well as to create a sample set. Each of the cores was also x-rayed using a Soyee portable x-ray system and a Scan-x digital imaging system, looking at evidence of bioturbation and internal structure.

Salinity was measured in the field using a handheld salinity refractometer in units of parts per thousand (ppt). The measured salinities were taken at low tide. Collected benthic animals were preserved in dilute isopropyl alcohol.

Grain size analysis was done by drying the samples in a convection oven at 105°C for 24 hours to remove interstitial water (McKeague, 1978). Once dry, the samples were manually disaggregated with a mortar and pestle, and sifted through screens -2 ϕ (4 mm) to 4 ϕ (0.0625 mm) in size. Any sediment smaller than 4 ϕ was analysed using x-ray absorption with a Micrometrics Sedigraph 5100. The sedigraph samples were placed in an oven at 550°C for four hours to remove any organic carbon. Three grams of each sample was then combined with 40 mL of 0.05 % sodium metaphosphate to prevent flocculation, and placed on a magnetic mixer for three minutes. The samples were then each placed in a sonic bath for one minute before loading into the sedigraph.

Total organic carbon (TOC) analysis was carried out on each of the samples. The samples were initially dried at 105°C for 24 hours in a convection oven to remove interstitial water (McKeague, 1978). The samples were then manually disaggregated using a mortar and pestle, and were analyzed using the loss on ignition (LOI) method (Heiri *et al*., 2001). The samples were weighed prior to analysis, and then once again after four hours in a high-temperature oven at 550°C. The percentage-difference between the initial weight and final weight was calculated as TOC.

Results

Physical Factors Affecting Infauna

Grain-size distribution (sediment texture)

Overall, the Columbia River Delta is dominantly fine- to medium-grained sand with varying amounts of silt and clay (Table 2-1; Fig. 2-4). Near the mouth of the river, the grain size ranges from medium-grained sand to greater than coarse-grained sand. Between approximately the middle of the study area (approximately 25 km from the mouth) to the most inland sample locales, the prevailing grain size is fine- to medium-grained sand with fluctuating proportions of coarser grained sediments, very fine-grained sand and silt. In sheltered locales and local bays, the grain size is dominantly comprised of fines (silt and clay), with varying proportions of very fine- to coarse-grained sand size particles.

TOC

The average TOC of the study locales is 2.79 % (Table 2-1; Fig. 2-4). Sheltered locales that contain higher proportions of silt and clay display the highest TOC values. The sandy sample areas have TOC values that range between 0.73 % and 1.63 %, whereas the muddy sample areas have a TOC range of 2.33 % to 7.96 %.

Salinity

Overall, the salinity decreases up-river (Table 2-1). There is a maximum sampled salinity of 19 ppt near the mouth (approximately 5 km inland). At

Delta Location		Benthic Environment				Ichnology
Region	Subenvironment	Sediment Texture	TOC (%)	Salinity (ppt)	Sedimentary Structures	Potential Trace Fossils
1	Sand Island	Moderately well sorted; fine to medium sand	0.9611	12	Mostly homogenized; areas with planar tabular bedding near bar edge; intense to complete bioturbation	*Arenicolites*, *Planolites*, *Polykladichnus*, *Siphonichnus*, *Skolithos*, cryptobioturbation
	Chinook, WA (i)	Moderately well sorted; fine sand	1.1903	19	Mostly homogenized; rare to trough cross-stratification; bioturbation moderate to absent	*Arenicolites*, *Planolites*, *Polykladichnus*, cryptobioturbation
	Chinook, WA (ii)	Moderately well sorted; coarse silt to very fine sand	0.8415	18	Completely bioturbated; no discernable sedimentary structures	*Arenicolites*, *Planolites*, *Polykladichnus*, *Skolithos*
	Desdomona Sands	Moderately sorted; fine sand	1.1580	11	Common trough cross-stratification, moderate flaser bedding and planar parallel lamination, rare asymmetrical ripples; bioturbation low to absent	*Planolites*, *Polykladichnus*, *Siphonichnus*, *Skolithos*
	Taylor Sands	Poorly sorted; medium sand	1.3936	2	Mostly homogenized with indistinct bedding structures; bioturbation intense to complete	*Arenicolites*, *Planolites*, *Polykladichnus*, *Skolithos*, cryptobioturbation
	Rice Island	Moderately sorted; medium sand	1.2092	0	Mostly homogenized; indistinct ripples; bioturbation moderate	*Arenicolites*, *Planolites*, *Polykladichnus*, *Skolithos*, *Thalassinoides*
2	Miller Sands	Very poorly sorted; fine sand	1.6257	0	Partially homogenized; planar parallel lamination, organic debris; moderate to absent bioturbation	*Arenicolites*, *Camborygma*, *Planolites*, *Polykladichnus*, *Skolithos*, cryptobioturbation
	Seal Island	Very poorly sorted; coarse silt	3.1214	1	Deformed planar parallel and planar trough lamination, rare trough cross-stratification; bioturbation moderate to intense	*Arenicolites*, *Camborygma*, *Palaeophycus*, ?*Piscichnus*, *Polykladichnus*, *Skolithos*
	Karlson Island	Very poorly sorted; coarse silt to very fine sand	2.6537	1	Mostly homogenized; indistinct sedimentary structures, minor organic debris; bioturbation intense	*Camborygma*, *Planolites*, *Polykladichnus*, *Skolithos*, *Thalassinoides*
	Grassy Island	Poorly sorted; fine sand	1.3414	0.5	Partially homogenized; rare asymmetrical ripples, moderate planar tabular cross-stratification; bioturbation moderate	*Arenicolites*, *Camborygma*, *Palaeophycus*, ?*Piscichnus* *Planolites*, *Polykladichnus*, *Skolithos*
3	Fitzpatrick Island	Moderately sorted; fine sand	1.2357	0.5	Mostly trough cross-stratification; common wavy bedding; bioturbation rare to moderate	*Arenicolites*, *Camborygma*, *Palaeophycus*, *Planolites*, *Polykladichnus*, *Skolithos*
	Coffee Pot Island (i)	Moderately well sorted; fine sand	0.9602	1	Completely homogenized; no discernable sedimentary structures; bioturbation intense to complete	*Planolites*, *Skolithos*, *Thalassinoides*
	Coffee Pot Island (ii)	Moderately sorted; medium sand	0.8089	1	Partially homogenized; planar tabular bedding; bioturbation moderate	*Arenicolites*, *Palaeophycus*, *Planolites*, *Thalassinoides*
	Cooper Island	Poorly sorted; fine sand	2.5105	1	Partially homogenized; common flaser bedding; asymmetrical ripples, trough cross-stratification, organic debris; bioturbation moderate	*Palaeophycus*, ?*Piscichnus*, *Planolites*, *Polykladichnus*, *Skolithos*
	Gull Island	Poorly sorted; fine to medium sand	1.2643	0.5	Mostly homogenized; indiscernible sedimentary structures, moderate organic debris; bioturbation moderate to intense	*Arenicolites*, *Palaeophycus*, *Planolites*, *Skolithos*, *Thalassinoides*
	Crims Island	Very poorly sorted; fine sand	2.3730	0.5	Partially homogenized; common asymmetrical ripples & indistinct sedimentary structures; bioturbation moderate to intense	*Planolites*, *Skolithos*, bivalve cast, ?fugichnia
4	Cathlamet Bay	Very poorly sorted; medium to coarse silt	7.9593	3	Common planar parallel lamination, indistinct sedimentary structures, moderate rooting; bioturbation absent to common	*Arenicolites*, *Palaeophycus*, *Planolites*, *Polykladichnus*, *Skolithos*, *Thalassinoides*
5	Youngs Bay	Moderately well sorted; very fine to medium silt	7.9322	6	Mostly homogenized; disrupted parallel laminations, indistinct sedimentary structures; bioturbation intense to complete	*Palaeophycus*, *Planolites*, *Polykladichnus*, *Skolithos*

Table 2-1: Summary of the sedimentological and ichnological characteristics of the regions within the Columbia River Delta. Sediment texture refers to the grain sorting and the average grain size at the given location. Sedimentary structures illustrate the most common structures present at the locale, but may not be an all-inclusive list. Of note are the comparatively high TOC values for Regions 4 and 5, the higher salinities located in Region 1, and the relatively poorer degree of sorting and finer grain size in Region 2 compared to Region 1 and Region 3.

approximately 20 km inland, the salinity levels off to a range between 0 and 2 ppt up to and including the furthest-inland sample location.

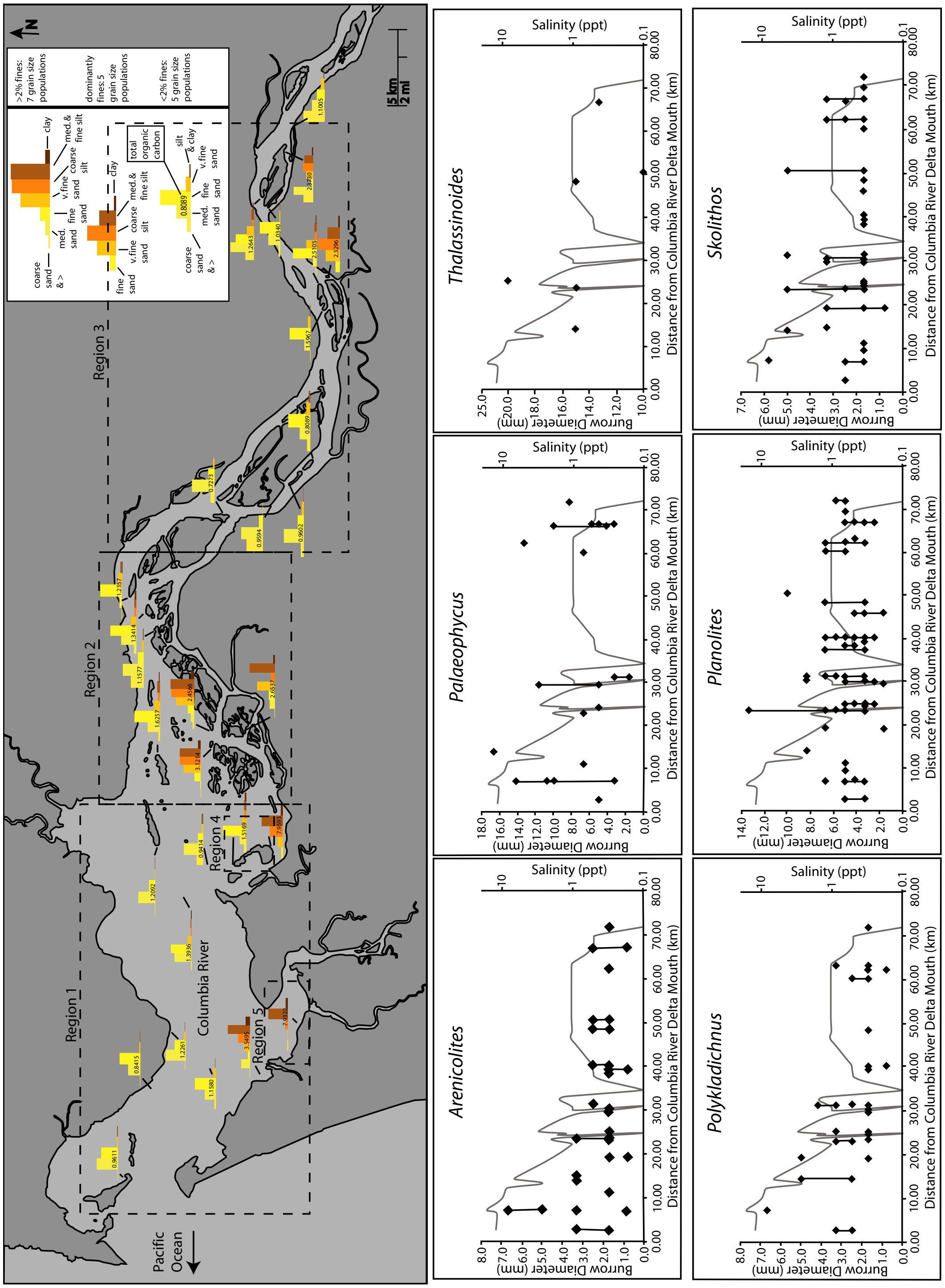
Depositional Environments – Ichnology

The organisms described below comprise the common trace makers of the Columbia River Delta. A total of 16 benthic taxa were observed frequently in the study area. The principal burrows represent three phyla and two subphyla: 1) Mollusca, including classes Bivalvia and Gastropoda; 2) Annelida, including classes Polychaeta (subclasses Palpata and Scolecida) and Clitellata (subclasses Oligochaeta and Hirudinea); and 3) Arthropoda, including the subphyla Crustacea (orders Amphipoda, Decapoda and Isopoda) and Hexapoda (class Insecta).

The traces produced by the benthic infauna, as well as the physical description of the depositional environments are summarized in Table 2-1. Additionally, the *Camborygma*-like and *Arenicolites*-like burrows created by crayfish and mayfly nymphs, respectively, are compared to the documented trace fossils *Camborygma* and *Arenicolites* from the rock record on the basis of diagnosis, occurrence and potential trace-makers in Table 2-2. The most commonly observed traces of the study area are presented in x-rays in figs 2-5 and 2-6. A complete collection of box core x-rays are found in Appendix A.

Burrows/traces that are generally produced by several different organisms, such as *Skolithos*, *Thalassinoides* and *Planolites*, maintain approximately the same size distributions throughout the study area (Fig. 2-4). Traces that are typically formed by a specific form of organism, however, show an overall decrease in burrow diameter up-river. Such traces include *Arenicolites*, *Palaeophycus* and *Polykladichnus* (Fig. 2-4).

The bar tops were generally well-burrowed compared to the subtidal portions of the bars. A higher diversity of traces, as well as a higher burrow density, was observed on the bar tops compared to the subtidal areas of the bars. Additionally, continental traces, such as *Camborygma* created by the crayfish and *Arenicolites* formed by the mayfly nymphs, appear on the bar tops and in the high intertidal zone, but not in the subtidal parts of the bars (Table 2-2). Continental traces observed in the study area can be quite large in both burrow diameter and burrow depth. The *Camborygma*-like crayfish burrows can be up to a decimetre in diameter and extend to a depth of approximately 30 cm. The *Arenicolites*-like



Pacific Ocean
Columbia River
Region 1
Region 2
Region 3
Region 4
Region 5
N
5 km
2 mi
Arenicolites
Palaeophycus
Thalassinoides
Polykladichnus
Planolites
Skolithos
Salinity (ppt)
Burrow Diameter (mm)
Distance from Columbia River Delta Mouth (km)

mayfly nymph burrows may be up to approximately one centimetre in diameter, and can extend to a depth of about 15 cm to 20 cm.

Neoichnology of Regions within the Columbia River Delta

Region 1

Region 1, which ranges from the mouth of the Columbia River Delta to approximately 25 km up-river, is the highest energy region of the study area. Many of the distributary islands in the region are located in high-energy areas, and are not conducive to burrowing – the highest bioturbation intensities are witnessed in sheltered locations of the islands. The traces seen in this region include an abundance of deposit-feeding strategies, resulting in a dominance of vertical and horizontal burrows (Table 2-1; figs 2-4 & 2-5). The burrows in this region are predominantly comprised of *Skolithos*-like, *Arenicolites*-like, *Polykladichnus*-like and *Planolites*-like trace fossils, as well as cryptobioturbated beds. Other traces in the region include surface feeding traces created by sturgeon (*Piscichnus*-like traces), almond-shaped *Lockeia* (a resting trace created by bivalves in a firmground on Sand Island), surface trace created by *Chirodotea sp*., *Siphonichnus*-like traces formed by *Mya arenaria* and *Macoma balthica,* and star-shaped surface feeding traces of nereid polychaetes. The sedimentary structures observed throughout this sand-rich region include homogenized sediment, flaser bedding, ripple laminae and planar to low-angle cross-laminae. Region 1 comprises dominantly medium-grained sand to greater than coarse-grained sand,

Fig. 2-4 (following page): (upper) Grain-size and TOC distributions in the Columbia River Delta study area. Region 1 is predominantly comprised of fine- to medium-grained sand, and has an average TOC of 1.4101%. Region 2 is mostly fine-grained sand and silt, and has an average TOC of 1.8989%. Region 3 consists mainly of fine- to medium-grained sand, and has a mean TOC of 1.4240%. Region 4 largely consists of fine-grained sand, silt and clay, and exhibits a wide range of TOC values, from 1.5169% on the river-facing, sandy side of the area to 7.9593% in the sheltered, finer-grained area of the region. Region 5 is principally comprised of fine- to medium-grained silt, and has an average TOC of 7.9322%. A broad tripartite division of grain-size and TOC can be observed moving from Region 1 to Region 3, with Regions 1 and 3 being slightly coarser grained and lower in organic carbon than Region 2. (lower) Graphs display the most commonly observed ichnofauna, burrow diameter at each sampling locale, and salinity at each sampling locale with distance from the mouth. Salinity sharply decreases to between 0 ppt and 2 ppt at approximately 20 km from the mouth of the Columbia River Delta. Note the broadly decreasing trend in burrow diameter moving from the mouth to the up-river study locales in the *Arenicolites*-like, *Polykladichnus*-like and *Palaeophycus*-like traces. These burrows are generally formed by a specific trace-maker. However, burrows that are commonly created by several different organisms maintain nearly the same size distributions throughout the study area, including *Skolithos*-like, *Thalassinoides*-like and *Planolites*-like traces.

	Arenicolites (Salter, 1857)	*Camborygma* (Hasiotis & Mitchell, 1993)	*Arenicolites* (this study)	*Camborygma* (this study)
Diagnosis	Simple U-tubes without spreite, perpendicular to the bedding plane Size, tube diameter, distance of limbs and burrow depth varies Limbs rarely somewhat branched Walls commonly smooth, occasionally lined Openings of limbs may flare Feeding and dwelling structures	Quasi-vertical ro quasi-horizontal shafts with a range of complexity of branching patterns and chamber formation Lateral to downward branches and chambers of various size, shape and location within the burrow system 1 to 14 cm in diameter 10 to 400+ cm in depth - length is variable Burrow walls have a combination of surficial features, including scratch marks, scrape marks, striations, knobby-hummocky texture, and mud- and pebble-linings Dwelling and reproduction structures	Simple U-tubes without spreite, perpendicular to bedding plane Smooth-walled limbs, unlined Typically between 0.5 and 1 cm in diameter and up to 15 to 20 cm deep Limbs approximetely 2 to 4 cm apart Limbs almost exclusively vertical; some openings are flared Feeding and dwelling structures	Cylindrical burrows forming 3D branching systems consisting of horizontal networks connected to surface by more or less vertical shafts Smooth-walled limbs, unlined Up to a decimetre in diameter and up to 30 cm deep Feeding and dwelling structures
Possible Tracemakers	Polychaetes, amphipod crustaceans, insects	Crayfish	Mayfly nymphs	Crayfish
Occurrence	Arenaceous substrates in low energy shoreface or tidal flats May be indicative of mixed tidal flats	Weakly- to well-developed paleosols Proximal to distal alluvial and marginal-lacustrine environments	Very fine-grained sediment (clay and silt) to slightly sandy muddy sediment of tidal flats Intertidal bar tops	Intertidal sand and mud flats Salt marsh

Table 2-2: Table comparing *Arenicolites* and *Camborygma* to the continental traces created by mayfly nymphs and freshwater crayfish. The traces are compared to the modern burrows created on the basis of diagnosis, potential trace-makers, and occurrence. The table indicates mayfly nymphs create burrows analogous to *Arenicolites*, whereas crayfish make burrows equivalent to *Camborygma*.

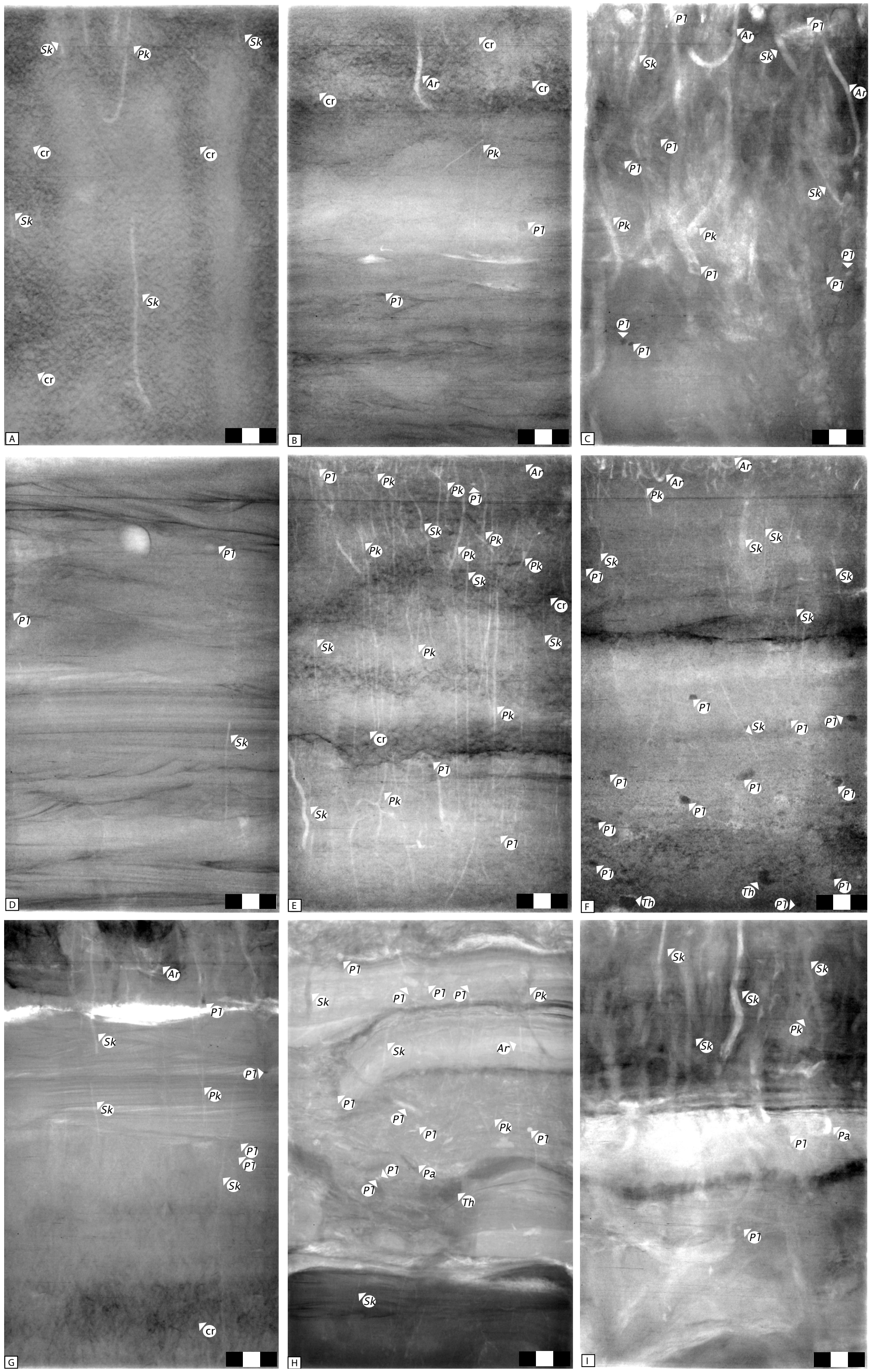
with minimal deposits of silt and clay.

Region 2

Region 2, ranging from approximately 25 km to 45 km from the mouth of the Columbia River Delta, includes environments such as tidal channels, tidal sand bars and sheltered locales. The trace diversity is higher than in Region 1, although the average burrow size is generally smaller (Table 1; figs 2-4, 2-5 & 2-6). The most common burrows observed included *Skolithos*-like, *Arenicolites*-like and *Planolites*-like traces. Other traces include *Polykladichnus*-like, *Palaeophycus*-like, *Camborygma*-like and *Thalassinoides*-like traces, as well as potential drag casts of ?*Piscichnus*, crawling traces of Unionid clams, and star-shaped surface feeding traces of nereid polychaetes. The sedimentary structures of Region 2 include homogenized sediment, current ripples, planar laminae, graded bedding, trough cross-stratification, flaser and wavy bedding, and indistinct sedimentary structures. Region 2 consists mainly of fine-grained to coarse-grained sand along the principal distributary channel and silt- and clay-rich sediments in sheltered locales around the distributary islands.

Region 3

Region 3, located between approximately 45 km and 75 km from the mouth of the delta, includes environments such as tidal channels, tidal sand bars and sheltered locales, much like Region 2. However, Region 3 includes an abundance of vertical and horizontal burrows, including *Skolithos*-like, *Arenicolites*-like and *Planolites*-like traces (Table 2-1; figs 2-4 & 2-6). There are also *Polykladichnus*-like, *Palaeophycus*-like, *Camborygma*-like and *Thalassinoides*-like traces, crawling traces of Unionid clams, as well as ?fugichnia and bivalve casts. The burrows in Region 3 are the smallest in the study area, and contain the lowest concentrations of the secondary traces (i.e., *Polykladichnus*-like, *Palaeophycus*-like and *Thalassinoides*-like burrows). The sedimentary structures have been almost completely obliterated in the zone of bioturbation, but are preserved below this zone. The structures include homogenized sediment (dominant), straight swept laminae, flaser bedding, planar laminae, asymmetrical ripples, and indistinct sedimentary structures. Region 3 is dominantly made up of fine- to medium-grained sand with varying proportions of silt and clay sediments in the more sheltered sampling locations.



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Regions 4 and 5

There are also two subenvironments sampled in the study area – Cathlamet Bay (Region 4) and Youngs Bay (Region 5). These bays are dominantly composed of fine-grained sediment and are largely sheltered from the dominant fluvial current, but are still subjected to the tidal flow.

At Cathlamet Bay, the traces are primarily horizontal with fewer vertical traces observed (Table 2-1; figs 2-4 & 2-5). Additionally, the traces are significantly smaller in average diameter than those in Youngs Bay. The horizontal traces all resemble *Planolites* with rare *Thalassinoides*-like traces, and the vertical traces include *Skolithos*-like, *Polykladichnus*-like and *Arenicolites*-like burrows. Sedimentary structures observed at Cathlamet Bay include planar laminae, soft sediment deformation and possible ripples.

At Youngs Bay, the traces are principally comprised of vertical burrows that resembled *Skolithos*, *Polykladichnus*, and *Palaeophycus*, with a lesser abundance of horizontal burrows, which are similar to *Planolites* and *Palaeophycus* (Table 2-1; figs 2-4 & 2-5). The burrows are up to 1 cm in diameter, and are all created by nereid polychaetes. The sedimentary structures found within this bay include dominant homogenization of the sediment with partial/faint planar laminae and partial wavy laminae.

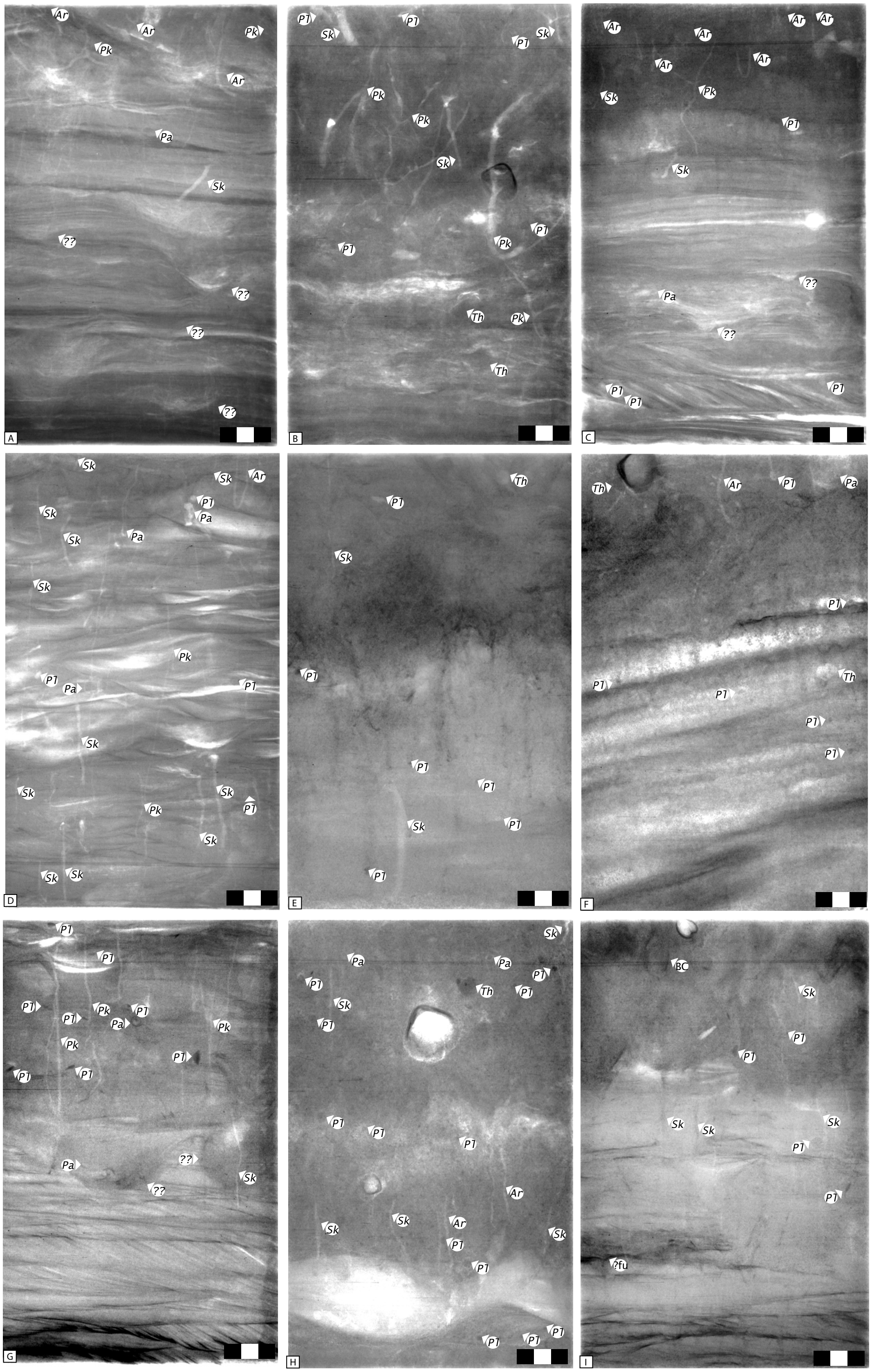
Interpretation and Discussion

Physical Parameters and the Distribution of Infauna

Salinity and Diminution

Of the physical parameters studied, salinity has had the strongest effect on the size and distribution of infauna. The effects of salinity and its relation to diminution have been well established in both modern and ancient environments (Remane & Schlieper, 1971; Gingras *et al.*, 1999; Buatois *et al*., 2005; Gingras *et*

Fig. 2-5 (previous page): X-rays of Region 1 (A to F), part of Region 2 (G), Region 4 (H), and Region 5 (I). For region locations, see Figure 2-3. Locations of the x-rays are as follows: (A) Sand Island; (B) Chinook, WA; (C) Chinook, WA; (D) Desdemona Sands; (E) Taylor Sands; (F) Rice Island; (G) Miller Sands; (H) Lois Island (Cathlamet Bay); and (I) Youngs Bay. Abbreviations for ichnogenera are: *Arenicolites* (*Ar*), *Palaeophycus* (*Pa*), *Planolites* (*Pl*), *Polykladichnus* (*Pk*), *Skolithos* (*Sk*), *Thalassinoides* (*Th*), cryptobioturbation (cy), and potential drag casts of *?Piscichnus* (*??*). Note the variations in burrow diameter, burrow depth, trace diversity, and different sedimentary structures present between the x-rays within each region, as well as the variations from region to region.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C
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D
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E
Th P1 Sk P1 P1 P1 Sk P1 P1
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Th Ar P1 Pa P1 P1 Th P1 P1 P1
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al., 2005; MacEachern *et al*., 2005a,b). This study on the Columbia River Delta suggests the size of infauna does decrease with decreasing salinity, as observed in Fig. 2-4. The most obvious diminution trends are seen in the *Arenicolites*-like and *Polykladichnus*-like traces, although subtle changes are observable in the other traces identified. The salinity in Region 1 is the highest in the study region, with salinities as high as 19 ppt at the most oceanward locales. The trace makers in Region 1 tend to create burrows with higher than average diameters compared to the rest of the study area. Additionally, the organism diversity and trace diversity are higher in this region compared to the others. In Region 1, large *Siphonichnus*-like traces, as well as larger-than-average *Palaeophycus*-like, *Polykladichnus*-like, *Arenicolites*-like, *Skolithos*-like, and *Thalassinoides*-like traces were also identified.

Near the transition from Region 1 to Region 2, the salinity decreases to between 0 ppt to 2 ppt and stays fairly constant throughout the remainder of the study area (Fig. 2-4). For the rest of the study area, the average size of the most common traces is relatively consistent in this oligohaline to freshwater zone. Specifically, the *Planolites*-like and *Skolithos*-like traces show very little size variation compared to the others.

At the landward-end of the study area, up to 75 km inland, nereid polychaetes and *Corophium sp*. are the dominant trace makers, even though they are marine organisms. However, nereid polychaetes (Lyster, 1965; Ushakova & Sarantchova, 2004) and *Corophium sp*. (McLusky, 1968; Cunha *et al*., 2000) are unable to reproduce at such diminished salinities. The presence of these organisms at these oligohaline, tidally-influenced locations indicates the likelihood of tidal larval recruitment of these organisms. The tidal-dominance in the Columbia River Delta extends into the fluvial-tidal transition zone far up-river, recharging the populations of marine organisms in near-fresh water. The size of the fluvial-tidal transition zone in the Columbia River Delta compared to other modern locales is significant. For example, Willapa Bay, Washington is contained by a

Fig. 2-6 (previous page): X-rays of Region 2 (A to D) and Region 3 (E to I). For region locations, see Figure 2-3. X-ray locations are: (A) Seal Island; (B) Karlson Island; (C) Grassy Island; (D) Fitzpatrick Island; (E) Coffee Pot Island; (F) Coffee Pot Island; (G) Cooper Island; (H) Gull Island; and (I) Crims Island. Abbreviations for ichnogenera are: *Arenicolites* (*Ar*), *Palaeophycus* (*Pa*), *Planolites* (*Pl*), *Polykladichnus* (*Pk*), *Skolithos* (*Sk*), *Thalassinoides* (*Th*), cryptobioturbation (cy), potential drag casts of *?Piscichnus* (*??*), bivalve cast (BC) and ?fugichnia (?fu). Note the variations in burrow diameter, burrow depth, trace diversity, and different sedimentary structures present between the x-rays within each region, as well as the variations from region to region.

27 km-long spit, separating it from the Pacific Ocean (Gingras *et al*., 1999), and a series of lagoons and estuaries are contained within Kouchibouguac Bay in New Brunswick, which extends for approximately 29 km, and is contained by arcuate barriers (Hauck *et al*., 2009). The spits, lagoons, etc. of these other environments inhibit the tidal influence, whereas the Columbia River Delta is not as extensively contained and thus does not have the same barriers to tidal extent. The comparably large size of the Columbia River's fluvial-tidal transition suggests tidal larval recruitment is the most logical process to account for the dominance of marine trace-makers well into the oligohaline zone.

Sediment Texture and Total Organic Carbon (TOC)

The sediment texture in the Columbia River Delta exerted moderate control on the distribution of infauna compared to salinity. Sediment texture provides constraints on burrow morphology, feeding patterns and behaviours of infaunal organisms (Dashtgard *et al*., 2008). While most of the burrows observed in the study area comprise facies-crossing opportunistic behaviours, some of the infaunal organisms only constructed burrows in specific sediment types, while others constructed burrows within a variety of sediment textures.

The crayfish found within the Columbia River Delta, for example, were always found in sandy to muddy sand substrates where they created shallow *Camborygma*-like burrows. Mayfly nymphs, on the other hand, produced *Arenicolites*-like burrows in very fine-grained sediment (clay and silt) to slightly sandy muddy sediment. Asian clams [*Corbicula* spp. (including *C. manilensis*), which are present throughout the study area, were generally shallowly burrowed in sandy substrates with very little to no fine grained material. These clams were only observed in Regions 2, 3 and 4, where the sediment was sandy and the salinity was oligohaline to fresh. There were two species of *Corophium* observed, *C. spinicorne* and *C. salmonis*, which both formed *Arenicolites*-like and, less commonly, *Skolithos*-like burrows regardless of the sediment texture. The nereid polychaetes of the Columbia River Delta were generally found in muddy sediments to sandy mud, and rarely in dominantly sandy substrates. These polychaetes created a variety of burrows, including *Arenicolites*-like, *Polykladichnus*-like and *Skolithos*-like burrows.

The TOC content was directly related to grain size, with higher values corresponding to finer grained sediments (Fig. 2-4). The highest TOC percentages

(2.33 % to 7.96 %) occurred in the two smaller, restricted environments – Regions 4 and 5. Higher TOCs were also calculated for the more sheltered, finer grained locales of Region 2, whereas the lowest TOCs (0.73 % and 1.63 %) were calculated for the sandier, coarser grained Regions 1 and 3. In these areas of high TOC percentages, the overall bioturbation intensity was comparably high as the infaunal organisms exploited the organic matter for food.

The sand flats, which had very little fine grained sediment, had TOC values ranging from approximately 0.7 to 1.5 percent. Even in these substrates, the organisms dominantly exhibited deposit-feeding behaviours, although more suspension-feeding behaviours were present compared to the finer grained, higher TOC sample locations. The bioturbation intensity here was lower than in the aforementioned high TOC locations. However, this may also be contributed to the higher energy regime of the sand flats as much as the lower TOC concentrations.

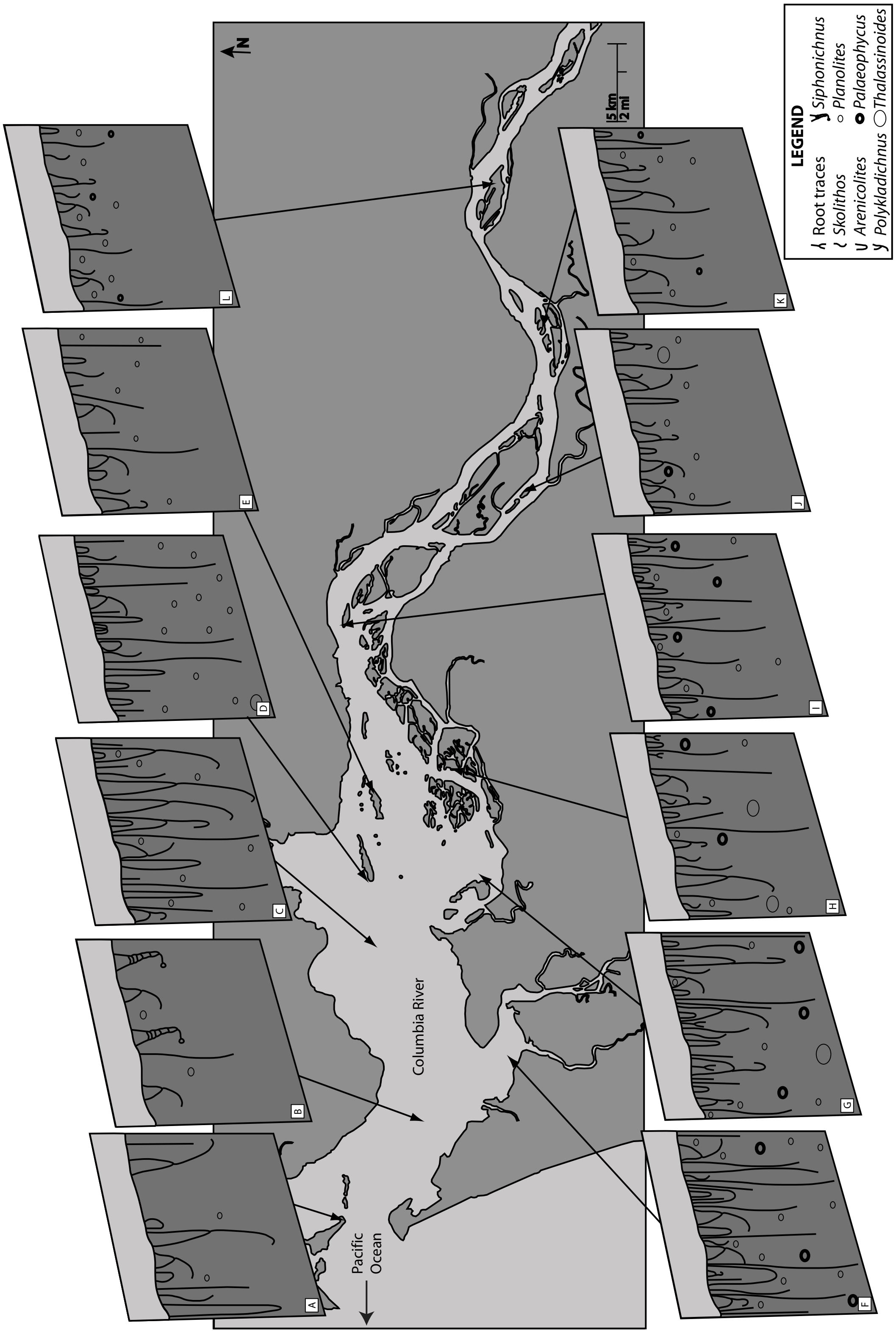
Ichnological Distribution in Mixed-Energy Deltas

Using neoichnological characteristics from the Columbia River Delta, combined with the sedimentary parameters, an ichnological model for mesotidal deltas can be constructed (Fig. 2-7). Using modern environments to describe and interpret ichnological features allows for a strong correlation between distribution of infauna, salinity and sediment texture, which can ultimately be applied to the rock record.

Region 1 is characterized by: 1) common cryptobioturbation; 2) common deposit-feeding and suspension-feeding burrows; 3) dominance of vertical burrows; 4) trace construction akin to *Skolithos*, *Arenicolites*, *Planolites* and *Polykladichnus*; and 5) less frequently *Thalassinoides* and *Siphonichnus* (Table 2-1; Fig. 2-5).

Region 2 is characterized by: 1) common deposit-feeding and suspension-feeding burrows; 2) rare cryptobioturbation; 3) vertical burrow dominance; 4) trace construction analogous to *Skolithos*, *Arenicolites*, *Planolites*, *Thalassinoides* and *Polykladichnus*; and 5) less commonly *Camborygma*, *Palaeophycus* and *?Piscichnus* (Table 2-1; figs 2-5 & 2-6).

Region 3 is characterized by: 1) common deposit-feeding and suspension-feeding burrows; 2) rare cryptobioturbation; 3) dominance of vertical burrows; 4) common burrows akin to *Skolithos*, *Arenicolites*, *Polykladichnus*, *Palaeophycus*,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Camborygma and *Thalassinoides*; and 5) less commonly *?Piscichnus*, ?fugichnia, and bivalve casts (Table 2-1; Fig. 2-6).

Region 4 is characterized by: 1) higher concentrations of deposit-feeding burrows compared to suspension-feeding burrows; 2) common to intense cryptobioturbation; 3) common burrows resembling *Planolites*, *Polykladichnus*, *Skolithos* and *Arenicolites*; and 5) less commonly *Palaeophycus* and *Thalassinoides* (Table 2-1; Fig. 2-5).

Region 5 is characterized by: 1) almost exclusively deposit-feeding burrows; 2) rare suspension-feeding burrows; 3) intense biogenic reworking of the muddy sediments; 4) burrows analogous to *Polykladichnus*, *Planolites*, *Skolithos* and *Arenicolites*; and 5) less commonly *Palaeophycus* (Table 2-1; Fig. 2-5).

The trends observed in Fig. 2-7 illustrate general trace distribution, diversity, and size at the given locales throughout the study area. The model indicates that moving up-river leads to shallower burrows limited in their vertical distribution, as well as a more sporadic burrow distribution. Furthermore, while species diversity tends to diminish up-river, individual burrow densities can still be intense. Detailed neoichnological trends were also observed and documented along a typical intertidal flat of a tidal sand bar (Figs. 2-8 to 2-10). Box cores were collected both parallel and perpendicular to a transect across the intertidal flat to best illustrate the neoichnological trends. The sediment is generally muddy to silty sand, and traces observed tend to be the most common forms seen within the fluvial-tidal transition zone (i.e. *Arenicolites*-like, *Palaeophycus*-like, *Planolites*-like, *Polykladichnus*-like and *Skolithos*-like traces) . Along the upper intertidal flat near the supratidal transition (Fig. 2-8), the majority of bioturbation is contained within the upper 10 centimetres of the sediment. Additionally, the sediment is not as intensely bioturbated and display a lower trace diversity when compared to the mid- and lower intertidal flat area. Along the mid-intertidal flat on a typical tidal

Fig. 2-7 (previous page): Ichnological trends throughout the Columbia River Delta study area. Each block represents the general trace distribution, diversity, and size at the particular locale. A: Sand Island; B: Desdemona Sands; C: Taylor Sands; D: Rice Island; E: Miller Sands; F: Youngs Bay; G: Cathlamet Bay; H: Karlson Island; I: Fitzpatrick Island; J: Coffee Pot Island; K: Cooper Island; and L: Crims Island. Moving up-river, the burrows become shallower and more sporadically distributed. However, continental traces may be quite large, such as those created by mayfly nymphs and crayfish (large *Arenicolites*-like and *Camborygm*a-like traces, respectively). Additionally, individual burrow densities can be intense at the up-river end of the study area, even though species diversity is generally diminished.

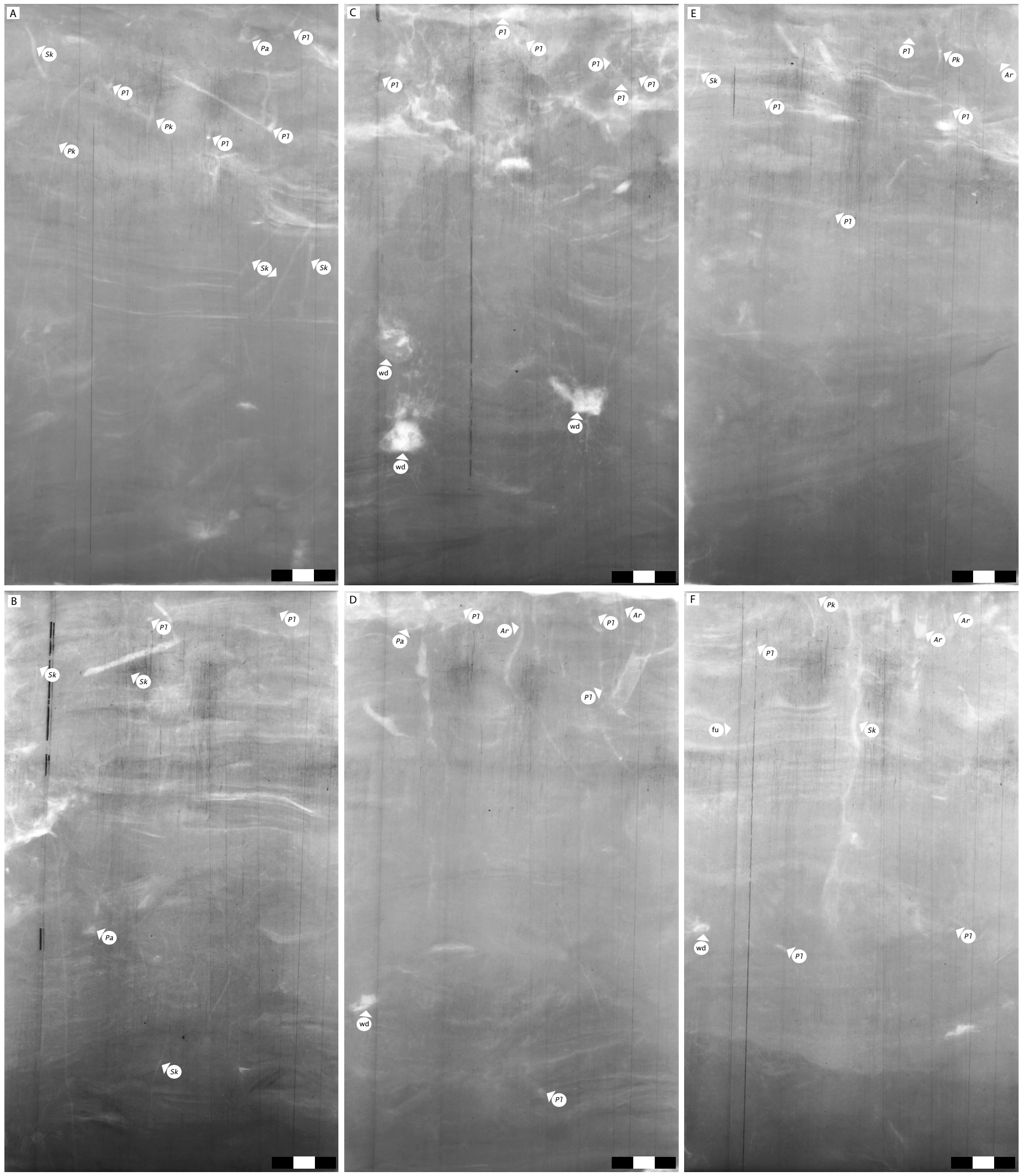


Fig. 2-8: X-ray transect of the upper intertidal flat of a tidal bar near the supratidal transition to illustrate neoichnological trends. A. X-ray collected at 0 m (starting position) parallel to transect line at the intertidal flat – supratidal flat/salt marsh transition (*Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). B. X-ray collected at 0 m (starting position) perpendicular to transect line at the intertidal flat – supratidal flat/salt marsh transition (*Pa*: *Palaeophycus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). C. X-ray collected at 1.5 m from 0 m parallel to transect line on the upper intertidal flat (*Pl*: *Planolites*-like traces, wd: wood debris). D. X-ray collected at 1.5 m from 0 m perpendicular to transect line on the upper intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pl*: *Planolites*-like traces; wd: wood debris). E. X-ray collected at 2.5 m from 0 m parallel to transect line on the upper intertidal flat (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). F. X-ray collected at 2.5 m from 0 m perpendicular to transect line on the upper intertidal flat (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; fu: fugichnia).

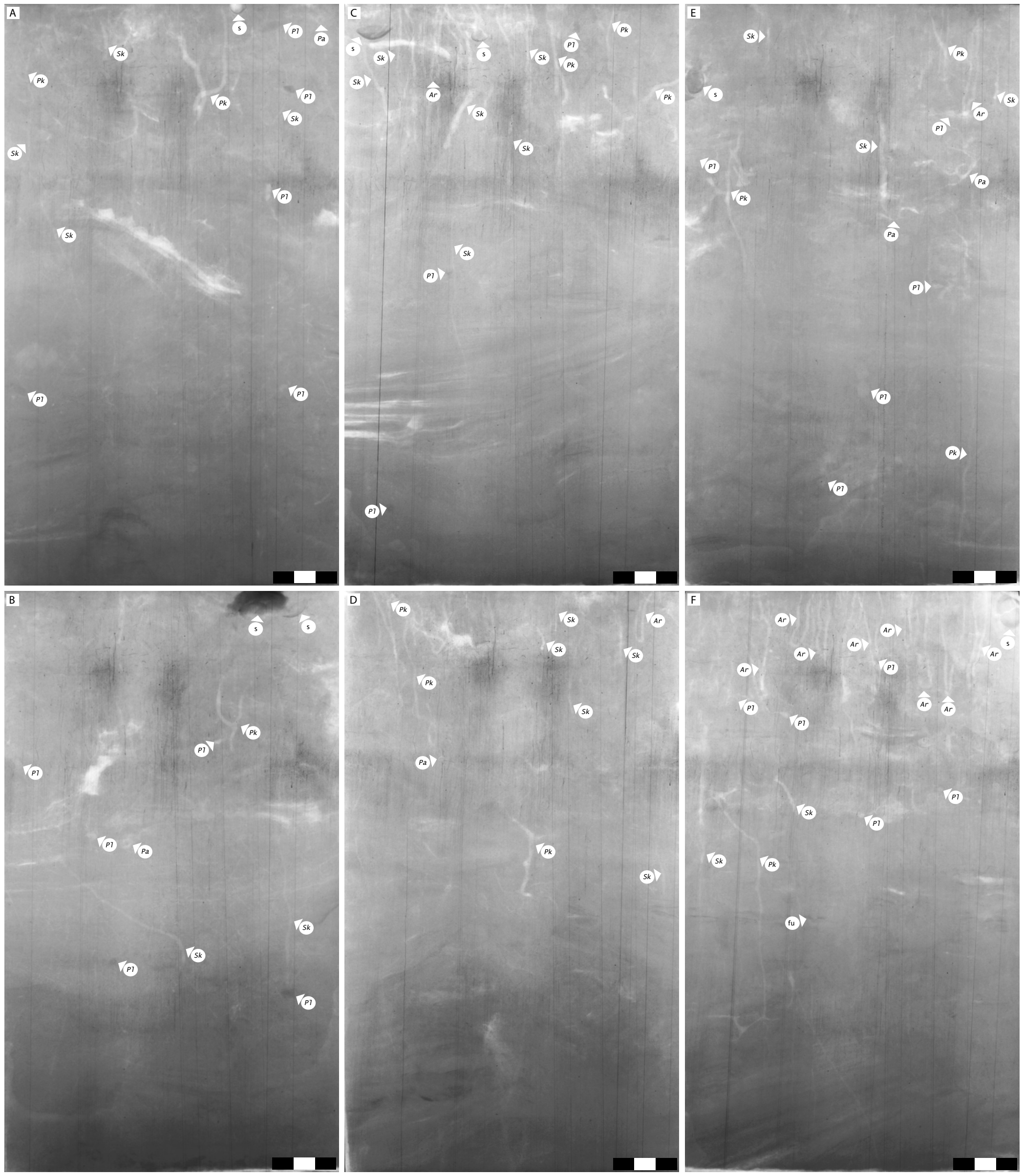


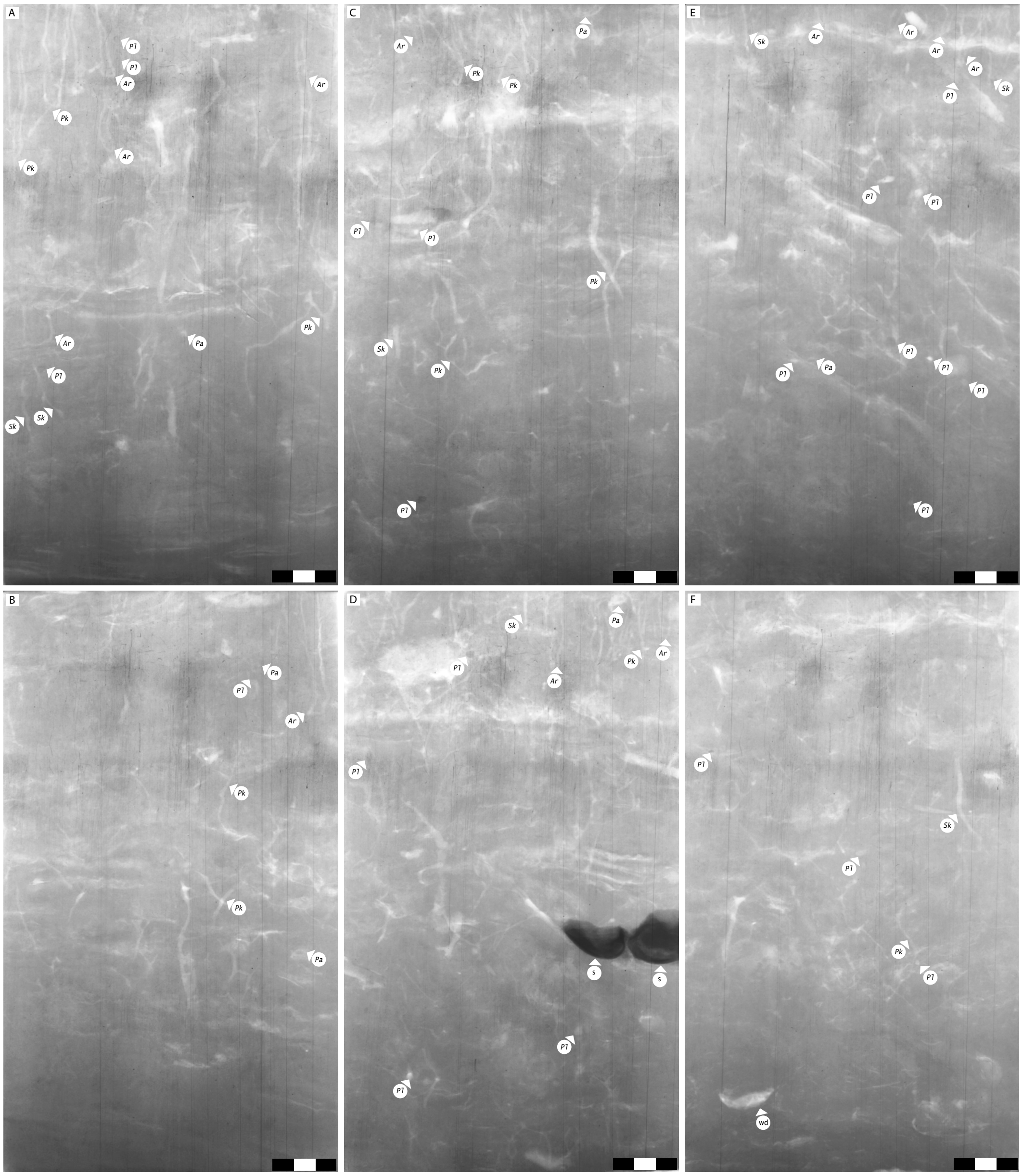
Fig. 2-9: X-ray transect of the mid-intertidal flat of a tidal bar to illustrate neoichnological trends. A. X-ray collected at 4.0 m from 0 m parallel to transect line on the mid-intertidal flat (*Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; s: bivalve shell). B. X-ray collected at 4.0 m from 0 m perpendicular to transect line on the mid-intertidal flat (*Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; s: bivalve shell). C. X-ray collected at 6.0 m from 0 m parallel to transect line on the mid-intertidal flat (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; s: bivalve shell). D. X-ray collected at 6.0 m from 0 m perpendicular to transect line on the mid-intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Sk*: *Skolithos*-like traces). E. X-ray collected at 8.0 m from 0 m parallel to transect line on the mid-intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; s: bivalve shell). F. X-ray collected at 8.0 m from 0 m perpendicular to transect line on the mid-intertidal flat (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; fu: fugichnia; s: bivalve shell).

sand bar (Fig. 2-9), the bioturbation has extended deeper into the sediment, but is mostly confined to the upper 15 centimetres. Bivalve shells are more common in this section of the intertidal flat as compared to the upper and lower sections, and the diversity of bioturbation has increased in comparison with the upper intertidal flat samples. Along the mid- to lower intertidal flat of the tidal bar (Fig. 2-10), bioturbation has increased in intensity and relative diversity compared to the upper portions of the intertidal flat. Bioturbation mostly reaches the bottom of each x-ray, but the burrows formed are often unidentifiable. In the upper and mid-intertidal flat locales, there was minimal sedimentary structure preservation in the bottom portions of the x-rays. However, in the mid- to lower intertidal flat samples, all sedimentary structures were obliterated by bioturbation. Overall, there is an increase in bioturbation diversity and intensity along the intertidal flat between the upper section near the supratidal flat/salt marsh transition and the lower section nearer to the subtidal bar.

Conclusions

Taking into account the observed neoichnology of the Columbia River Delta, several conclusions can be made. First, the Columbia River Delta study area contains organisms that make burrows consistent with the *Teichichnus* ichnofacies. Second, there must be larval tidal recruitment of marine trace-makers into the oligohaline, tidally-dominated zone as *Corophium sp*. and nereid polychaetes are unable to reproduce at such low salinities. Third, the tops of the tidal-fluvial bars and intertidal zone are more pervasively burrowed compared to

Fig. 2-10 (following page): X-ray transect of the mid- to lower intertidal flat of a tidal bar to illustrate neoichnological trends. A. X-ray collected at 9.5 m from 0 m parallel to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). B. X-ray collected at 9.5 m from 0 m perpendicular to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces). X-ray collected at 9.5 m from 0 m parallel to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). C. X-ray collected at 11.0 m from 0 m parallel to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). D. X-ray collected at 11.0 m from 0 m perpendicular to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; s: bivalve shell). E. X-ray collected at 12.5 m from 0 m parallel to transect line on the mid- to lower intertidal flat (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). F. X-ray collected at 12.5 m from 0 m perpendicular to transect line on the mid- to lower intertidal flat (*Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; wd: wood debris).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the subtidal zone due to the more stressful conditions found lower on the tidal-fluvial bars. Fourth, continental traces may be quite large (greater than 1 cm in diameter), and create *Arenicolites*-like and *Camborygma*-like traces. Next, ichnogenera burrowing depth, density and burrow diameter decrease moving up-river. Last, sheltered locales, such as Cathlamet Bay (Region 4) and Youngs Bay (Region 5), act as traps for fine grained sediment.

This neoichnological framework should be applied with care as mixed-energy deltaic settings with both strong wave and tidal influence commonly undergo exceptionally variable conditions. Variables such as rate of sedimentation, climate and salinity change over tidal cycles and/or seasonally in response to fluvial flux. These characteristics are distinctive to each locale, and may deviate from other observations from the Columbia River Delta.

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Chapter 3 – Sedimentological and ichnological facies trends of tidal sand bars in the fluvial–tidal transition of the Columbia River Delta, northwestern U.S.A.

Introduction

Facies analysis is used in environmental description and interpretation, both in ancient and modern studies. Facies are laterally equivalent bodies of sediment with distinctive characteristics (Walker, 1992). The Swiss geologist Amanz Gressly is recognized for first using the term facies in 1838 for modern scientific use during his work in the Jura Mountains (Gressly, 1838; Cross & Homewood, 1997). Johannes Walther proposed the law of the correlation (or succession) of facies, or more simply, Walther's Law (Walther, 1894; Middleton, 1973). This law embodies a significant stratigraphic concept – that a direct environmental relationship exists between lateral facies and vertically stacked or superimposed successions of strata (Middleton, 1973). Walther also understood the importance of studying modern environments and processes in order to fully understand their ancient counterparts (Middleton, 1973). This paper focuses on sedimentary facies within distributary channels of the mixed-energy (strongly wave- and tide-influenced) delta of the Columbia River.

Facies Distribution in Deltas

The study and distribution of deltaic facies, specifically within the fluvial-tidal transition zone, is related to the relative strength of tidal and fluvial currents, as well as sediment concentrations and transport. Deltas are one of the many marginal marine environments that have been studied extensively both in the ancient and modern realms. A delta is defined as "a progradational sediment body at the mouth of a river, formed of sediment supplied by the river, and containing fluvially-influenced deposits" (cf. Dalrymple *et al*., 1992; Dalrymple, 1999, 2000; Dalrymple *et al*., 2003).Tide-dominated and mixed-energy deltas are poorly understood, and not as well documented as compared to their river- and wave-dominated counterparts (Hori *et al*., 2002; McCrimmon & Arnott, 2002; Dalrymple *et al*., 2003; McIlroy, 2004; Dalrymple & Choi, 2007).

The fluvial-tidal transition zone of deltas may range in length from a few kilometres to hundreds of kilometres. The inner end of this zone represents the tidal limit, and is the point at which tidal action is sufficient to leave a recognizable record in the sedimentary deposits. However, the outer end of the zone is placed at the point where seaward widening becomes sufficient enough to allow the formation of multiple elongate bars (Dalrymple & Choi, 2007). Tidal modulation of river flow causes significant alterations in current speed. However, the dominance of river flow ensures the seaward-directed currents are stronger and the net sediment transport is seaward (Dalrymple & Choi, 2007).Therefore, tidal dominance in a delta is primarily determined by the dominance of tidal sediment transport over sediment transported by river currents and waves, which in turn determines the overall geomorphology of the delta (Dalrymple & Choi, 2007). This is evidenced by the presence and prevalence of coast-normal elongate tidal bars and tidal channel networks (Dalrymple & Choi, 2007). These bars migrate and accrete laterally, behaving similarly to point bars. The occurrence of tidal bars on the inside of the channel meander bends allows for deposition to mimic point bars, with sediment deposited on the side of the bar adjacent to the channel. Additionally, the slightly oblique orientation of the bars to the dominant current allows for sedimentation in a down-flow direction. Nonetheless, this produces lateral accretion deposits as the bars are essentially parallel to the current (Dalrymple & Choi, 2007). Tidal bars that are formed in locations with minimal suspended sediment concentrations (SSCs) are unlikely to form Inclined Heterolithic Stratification (IHS) deposits compared to areas with proportionally high SSCs. In its place, the tidal bars will fabricate stacked dune cross-beds with gently inclined set boundaries (Dalrymple & Choi, 2007).

The objectives of this paper are to: 1) construct a facies classification for tidal sand bars in the Columbia River Delta; 2) propose facies association(s) for these tidal sand bars; and 3) identify key features observed in the facies association(s) to aid in the applicability to ancient environments. The vast majority of the facies initially appear fluvial, even though they are tidal in nature. Therefore, it is important to distinguish features that would allow for the recognition of this type of tidal deposit in ancient deltaic systems.

Study Area

The Columbia River Delta is situated along the border between Oregon and Washington in the northwest United States (Fig. 3-1). The delta is contained within a basin of volcanic and sedimentary bedrock that has been partly in-filled with Pleistocene and Holocene sediments from the Columbia River basin

(Simenstad *et al*., 1990). It is characterized as mixed-energy, with strong tidal and wave influence. The Columbia River Delta has a tidal prism of 50,926 m^3s^{-1} (Buonaiuto & Kraus, 2003), and is mesotidal, with a tidal range of approximately two metres at the mouth. The tides are classified as mixed and semi-diurnal in nature. The main channel of the river is relatively straight and contains several tidally-influenced sand bodies. Sand bars in the area typically migrate up and down the delta portion of the system with sand accumulations ranging up to 30 m thick. The system is dominantly composed of fine sand with muddy pockets near the margins and in localized bays (Sherwood & Creager, 1990). Accommodation space in the lower Columbia River Delta has been destroyed by the presence of shallow tidal flats, shoals, central islands, and lateral accretion floodplains (Sherwood & Creager, 1990).

Tidal height fluctuations can be observed as far upstream as Bonneville Dam (225 km from the river mouth), and tidal current reversals occur as far as 85 km upstream (Gelfenbaum, 1983). However, according to Jay *et al*. (1990), tidal influence is scarcely detectable beyond approximately 160 km upriver from the mouth. The principle study locales within the Columbia River Delta are at the very low end of the brackish-water spectrum, ranging from 0.5 parts per thousand (ppt) to approximately 2 ppt.

The focus of this study is to determine the sedimentological and ichnological trends seen in the tidal sand bars within the Columbia River Delta. Three bars were chosen based on location within the delta and on overall surface sedimentology to determine broad trends. The bars chosen for study, from up-river to seaward locales, include Coffee Pot Island, Karlson Island and Lois Island, respectively. Coffee Pot Island, the most up-river locale, is the sandiest location and is parallel with the main channel of the river. It is approximately 2.5 km long and 350 m wide. Karlson Island is centrally located and is dominantly comprised of slightly muddy to silty sand. This island is relatively sheltered but is not far from the main channel, and it is approximately 3.1 km long and 1.5 to 2.0 km wide. Lois Island is the muddiest of the vibracore locales, and is approximately 3.4 km long and 1.5 km wide at its broadest part. It is primarily composed of silt with some sandy areas, and is the most sheltered location (with the exception of the tip of the island, which is near the main channel, and is subsequently the sandiest part of the island).

Methods

This study employed several methods in order to conduct a facies analysis of three tidal sand bars in the Columbia River Delta. Three locations were vibracored on three separate tidal sand bars within the Columbia River Delta, totalling nine cores (Fig. 3-1). Three metre steel pipes with a nominal diameter of 7.62 cm were vibrated into the intertidal flats using the techniques outlined by Glew *et al*. (2001; and the references within). The pipes were inserted into the flats using a modified cement shaker, capped with a flex cap, and removed using a block-and-tackle (Fig. 3-2). Typical recovery ranged from 2.1 m to 2.5 m. The steel pipes were cut lengthwise in half, with one half photographed, peeled using epoxy resin and x-rayed, and the other half sampled for grain size and total organic carbon (TOC) analysis. Sedimentological and ichnological analysis of the cores was done using both the epoxy resin peels and the x-rays.

X-rays were taken of the cores using a Soyee portable x-ray system (SY-31-100P) in steel trays with dimensions of 30 cm x 7 cm x 1.5 cm. The x-rays were collected 2 m from the source with a setting of 80k Vp / 20 mA under exposure times between 1.5 seconds and 1.7 seconds, depending on the mud content of the core sample. The x-rays were processed using a Scan-x digital imaging system.

Grain size analysis was conducted by drying the samples in a convection oven at 105°C for 24 hours to remove any interstitial water (McKeague, 1978). Once dry, the samples were manually disaggregated with a mortar and pestle, and sifted through screens -2 ϕ (4 mm) to 4 ϕ (0.0625 mm) in size using a Tyler RO-Tap Test Sieve Shaker. Sediment smaller than 4 ϕ was analysed using x-ray absorption with a Micrometrics Sedigraph 5100. The sedigraph samples were then placed in an oven at 550°C for four hours to remove any organic carbon. Three grams of each sample was then combined with 40 mL of 0.05% sodium metaphosphate to prevent flocculation, and placed on a magnetic mixer for three minutes. The samples were then each placed in a sonic bath for one minute before loading into the sedigraph.

Total organic carbon analysis was also carried out on each of the samples. The samples were initially dried and disaggregated using the methods outlined above (McKeague, 1978). The samples were then analyzed using the loss on ignition (LOI) method (Heiri *et al*., 2001). The samples were weighed prior to

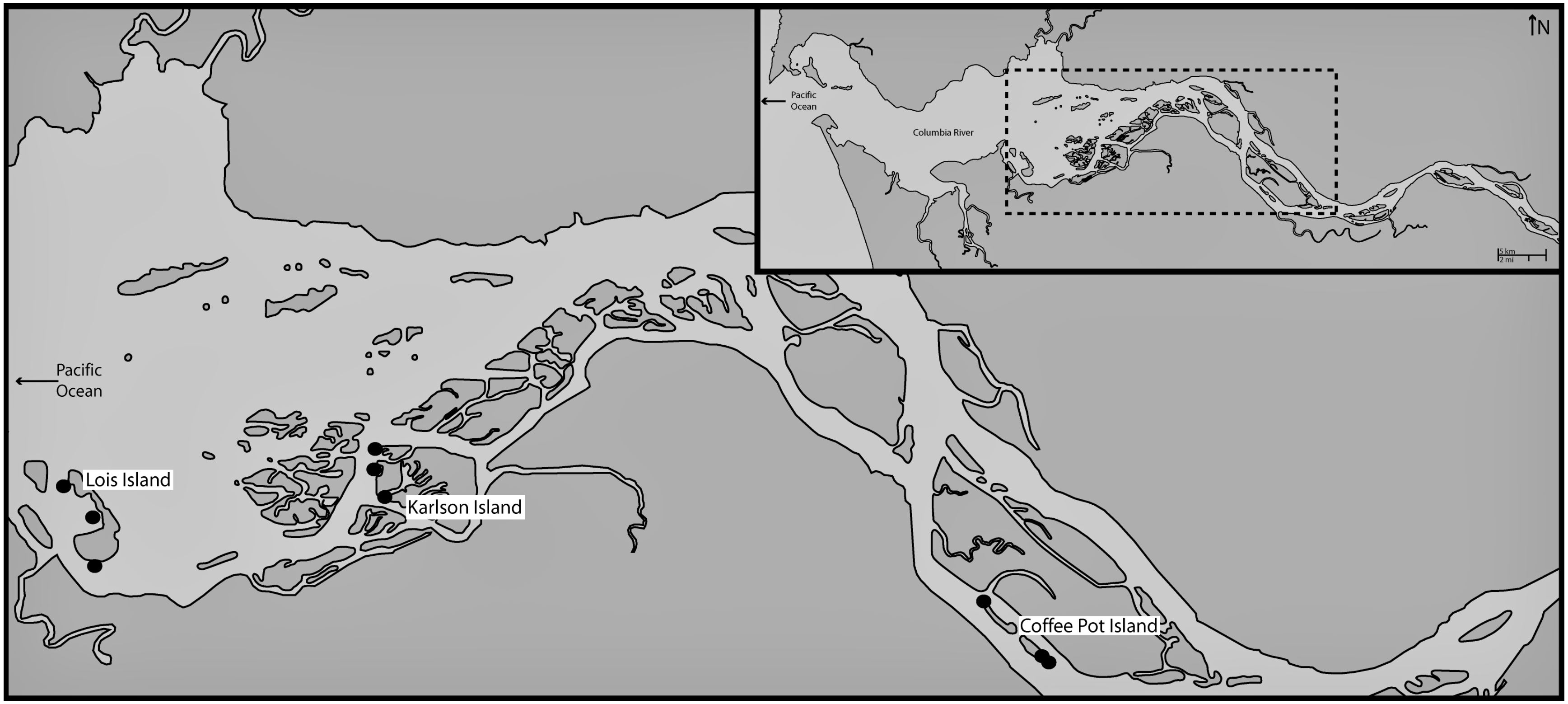


Fig. 3-1: Columbia River Delta tidal bar study location. The Columbia River Delta borders the states of Washington and Oregon in the Pacific north-west of the United States. Note the total size of the study area is quite large, covering a river length of approximately 75 km. The outlined region is where the vibracores were located, with the specific coring locations noted (black dots). Three vibracores were collected per tidal bar to illustrate trends within individual tidal bars as well as to identify proximal to distal trends in the study region.

analysis, and then once again after four hours at 550°C. The percentage difference between the initial weight and final weight was calculated as TOC.

Box cores and surface samples (i.e., clam-gun cores, grab samples, trenches) were used to supplement vibracore data when required, specifically for ichnological interpretation at the top of the vibracores. Ichnological data from surface samples collected at the same sampling locales as the vibracores was used for top-vibracore ichnology as the top-vibracore was typically lost during collection. The box cores collected a sample that measures 30 cm x 18 cm x 6 cm. Each of the box cores was treated in the same manner as the vibracores, each of them peeled with epoxy resin, x-rayed, sampled for grain size and TOC, and the peels were photographed.

Facies Descriptions and Interpretations

In the selected tidal sand bars of the Columbia River Delta, six facies were identified in the collected vibracores based on discrete groupings of sedimentary structures, grain size and ichnological characteristics. The following is a comprehensive discussion of the observed facies. The facies have been summarised in Table 3-1. Vibracore logs, as well as the legend for figures and the vibracores, are located in Appendix B.

Facies 1 – Massive to laminated silty mud

Description:

Facies 1 was found both at the most oceanward vibracore locales near Cathlamet Bay on Lois Island and at the most up-river locales on Coffee Pot Island (Fig. 3-3). It is characterized by thinly laminated to apparently massive light brown silty mud. The thickness of Facies 1 is variable, ranging from 30 cm to 75 cm. Facies 1 has few visible sedimentary structures. Visible sedimentary structures include one to five cm thick ripples and planar cross-stratified laminae, as well as rare fine to very fine lenticular sand beds. Commonly, this facies appears massive. Rare organic debris is visible, as is very rare carbonaceous debris. Bioturbation is rare to absent, and is only observed at the top of one core in this facies. The two traces observed were *Skolithos*-like burrows, up to 8 cm long, 3 mm wide, and are in-filled with fine sand.

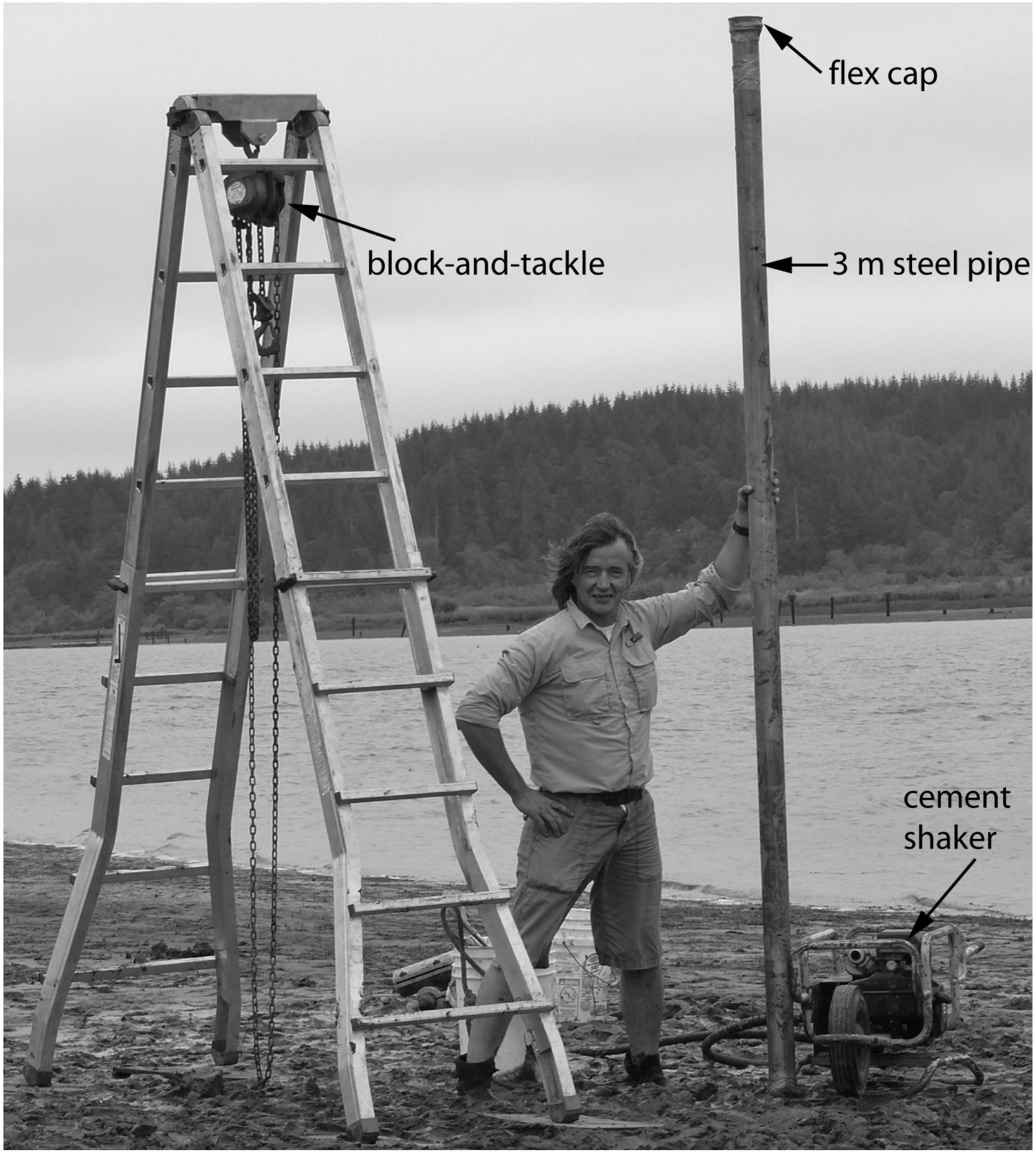


Fig. 3-2: Example of the vibracoring set-up used in this study.

The lower contact of Facies 1 with the underlying unit is sharp where present, with either Facies 2 (rippled to small-scale cross-bedded sand), Facies 3 (high-angle cross-bedded sand) or Facies 6 (organically laminated rippled sand).

Interpretation:

Based on their position at the top of the core and their sedimentary characteristics, the deposits of Facies 1 correspond to intertidal mud flats. Small-scale current ripples were formed by unidirectional flow in the lower end of the lower flow regime (Harms & Fahnestock, 1965; Klein, 1970; Reineck & Singh, 1980). Low-angle cross-stratified to planar cross-stratified laminae were likely formed by the migration of these ripples, and the subsequent erosion of the ripple crests (Harms & Fahnestock, 1965), however, upper flow regime events cannot be discounted. The lenticular sand beds are generally indicative of variable current velocities (Reineck & Wunderlich, 1968; Reineck & Singh, 1980; Carmona *et al*., 2009), which are common in tidal environments. The dominance of silty mud suggests deposition under quiescent conditions (Klein, 1977; Carmona *et al*., 2009), potentially during slack water between flood and ebb tides or potentially the result of mud flocculation during times of higher fluvial discharge (Klein, 1977). The deposition of organic and carbonaceous debris likely occurs during slack water (Dalrymple & Choi, 2007).

The paucity of bioturbation suggests deposition in a stressed environment. The rate of sedimentation may have been too high for infauna to inhabit the sediment or the salinity may have been too low or variable, or potentially a combination of the two. There is also the consideration of anthropogenic influences contributing to the stressed conditions of the environment. The *Skolithos*-like burrows observed represent opportunistic behaviours of suspension feeders or opportunistic carnivores.

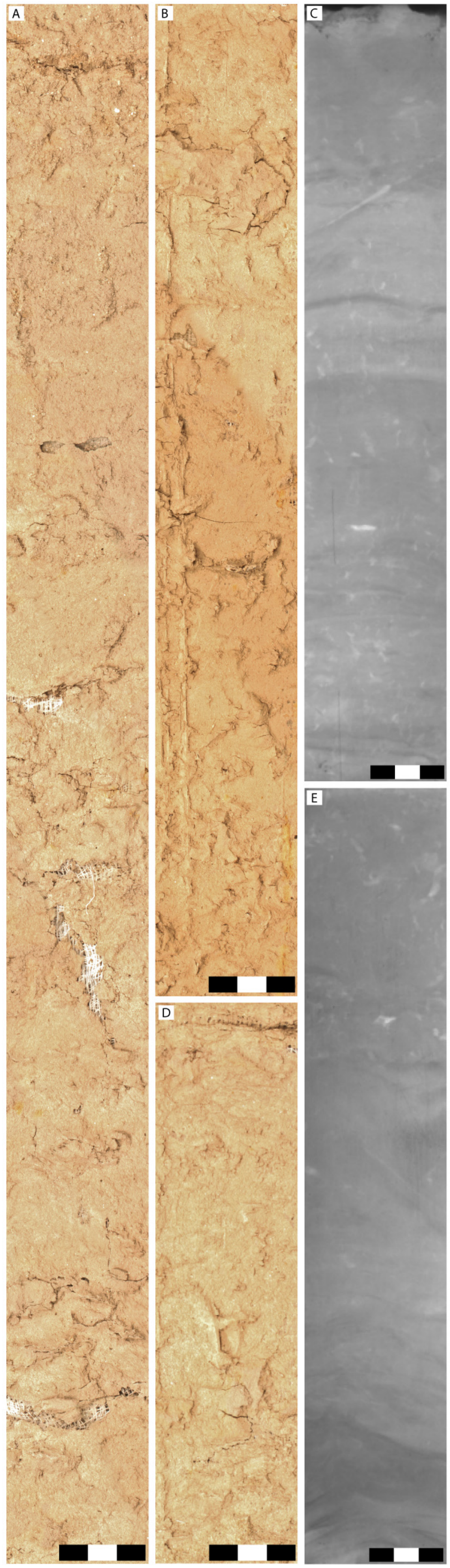
Facies 2 – Rippled to small-scale cross-bedded fine-grained sand

Description:

Facies 2 is the most common facies observed in the Columbia River Delta. It is dominantly characterized by fine-grained sand with minor very fine- and medium-grained sand (Fig. 3-4). The thickness of Facies 2 is quite variable, ranging from 30 cm to 240 cm, but is generally between 50 cm and 100 cm thick. Sedimentary structures in Facies 2 are commonly small-scale ripples that are one to five cm thick and small-scale cross-bedding. Other structures present include rare planar laminae, rare mud flasers, and rare wavy bedding up to five cm thick. There are also occasional silty mud beds up to three cm thick with very fine- to fine-grained sand laminae contained within either ripples or lenticular bedding. Laminae of organic debris, occasionally associated with very coarse-grained shelly carbonate grains, are common throughout Facies 2. Above these organic laminae/carbonate lags, there are generally rippled or cross-stratified sands. Additionally, there is occasional disseminated organic debris and very rare wood

Facies	Occurrence/Contacts	Lithology	Physical Sedimentary Structures	Texture and Lithological Accessories	Ichnological Characteristics	Interpretation	Facies Association
F1 Massive to laminated silty mud	- lower contact is sharp with either F2, F3 or F6	- primarily light brown silty mud - rare fine to very fine-grained sand - 30 cm to 75 cm thick - average thickness of 31 cm in most up-river locales - average thickness of 70 cm in most oceanward locales	- commonly appears massive - 1 to 5 cm thick ripples and planar cross-stratified laminae - rare fine to very fine sand lenticular beds	- rare organic debris - very rare carbonaceous debris	- bioturbation is rare to absent - 2 *Skolithos*-like traces observed up to 8 cm long, 3 mm wide, in-filled with fine sand	- intertidal mud flats - lower end of the lower flow regime to slack water	*FA1* *Tidal sand bars*
F2 Rippled to small-scale cross-bedded fine-grained sand	- lower contact is sharp where present with either F1 or F6 - commonly is the lowermost unit collected	- dominantly fine-grained sand - minor very fine- and medium-grained sand - 30 cm to 240 cm thick - generally between 50 cm and 100 cm thick	- most commonly small-scale ripples that are 1 cm to 5 cm thick - common small-scale cross-bedding - rare planar lamination - rare mud flasers - rare wavy bedding up to 5 cm thick - occasional silty mud beds up to 3 cm thick with very fine- to fine-grained sand laminae contained within ripples or lenticular bedding	- common organic debris laminae, occasionally associated with very coarse-grained carbonate grains - occasional disseminated organic debris - very rare wood fragments - very rare bioclastic debris at the top of the facies	- no evidence of bioturbation	- intertidal sand flat - lower end of the lower flow regime - periodic slack water deposition	
F3 High-angle cross-bedded medium sand	- lower contact is sharp with either F1 or F2	- principally medium- to coarse-grained sand - heavy mineral-rich - variable thickness, from 30 cm to 97 cm to 160 cm	- very common high-angle cross-bedding - common ripples - rare deformed laminae	- very coarse-grained carbonate laminae, defining high-angle cross-beds and deformed laminae, and disseminated throughout - clam shells of *Corbicula sp.* are present at the top - common lithic pebbles at the top	- no evidence of bioturbation	- high-energy, fluvially-dominated intertidal sand flats - upper end of the lower flow regime - periodic lower end lower flow regime conditions	
F4 Interbedded very fine- to fine-grained sand with very fine sandy silt	- lower contact is sharp with either F2 or F6	- very fine- to fine-grained sand - interbeds of very fine-grained sandy silt - 55 cm to 70 cm thick	- commonly finely rippled - SSD 8 cm to 10 cm thick of intermixed fine-grained sand and very fine-grained sandy silt - rare laminated very fine-grained sandy silt beds, up to 10 cm thick, with fine-grained sand defining ripple laminae	- small round mud pebbles at top of SSD - rare wood fragments within the very fine-grained sand - occasional disseminated organic debris	- no evidence of bioturbation	- mixed intertidal flat - lower end of the lower flow regime - periodic slack water deposition	
F5 Rooted fine- grained sand	- lower contact sharp with F6	- dominantly fine-grained sand - rare silt - 20 cm thick	- commonly rippled - silt, where present, is laminated	- predominant rooting, 1 mm in diameter, iron oxidized - occasional organic debris defining ripple laminae	- bioturbation is minimal to absent - 1 potential *Skolithos*-like burrow present at the top, 4 mm in diameter, in-filled with fine-grained sand	- sand-dominated intertidal flat near the supratidal flat transition - lower end of the lower flow regime - periodic slack water deposition	
F6 Organically laminated rippled fine-grained sand	- lower contact sharp with F2	- dominantly fine-grained sand - lenses of very fine-grained sand and silt - thickness between 43 cm and 190 cm - average thickness of 115 cm	- dominantly small-scale ripples, 1 cm to 3 cm thick - occasional planar laminated beds between the ripple sets - silt lenses are generally associated with the ripples, up to 5 mm thick in sets up to 5 cm thick	- very common organic laminae, frequently defining the ripples, rarely bounded by silt on one or both sides	- no evidence of bioturbation	- subtidal bar deposition - primarily lower end of the lower flow regime - occasional upper flow regime deposition - occasional slack water deposition	

Table 3-1 (following page): Summary of facies characteristics.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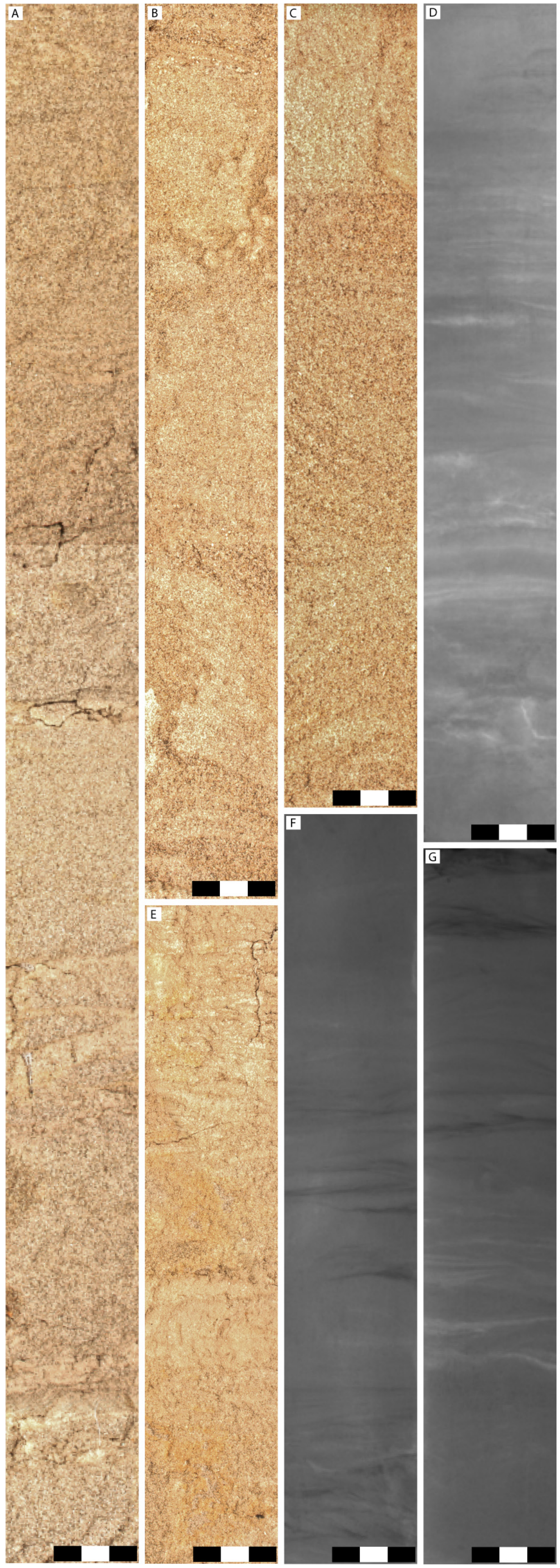
fragments within the facies, as well as very rare bioclastic debris at the top of the facies when present. There is no evidence of bioturbation present in the vibracore peels or x-rays for Facies 2.

The lower contact of Facies 2 is sharp where present, and is associated with either Facies 1 (massive to laminated silty mud) or Facies 6 (organically laminated rippled sand). However, Facies 2 is the lowermost unit observed in six of nine vibracores, therefore the lower contact was not observed. Facies 2 is commonly the uppermost unit observed in the vibracores (first in four of nine cores).

Interpretation:

Due to its occurrence at the top of the core and its sedimentary character, the rippled to small-scale cross-bedded fine-grained sand of Facies 2 is representative of the intertidal sand flat. The presence of small-scale current ripples indicates unidirectional flow in the lower end of the lower flow regime (Harms & Fahnestock, 1965; Klein, 1970; Reineck & Singh, 1980). Rare planar laminae are symptomatic of unidirectional flow in the upper flow regime (Harms & Fahnestock, 1965; Reineck & Singh, 1980). The presence of mud flasers and wavy bedding suggests flocculation of fine sediment and deposition during quiescent slack water between higher current velocities of the lower flow regime (Reineck & Wunderlich, 1968; Reineck & Singh, 1980). The silty mud beds with rippled and/or lenticular sand suggest deposition under fluctuating current flow conditions – the silty mud being deposited during slack water and the sand deposition taking place in the lower flow regime. Organic debris-rich laminae also occurred under quiescent conditions, such as during slack water (Dalrymple & Choi, 2007). The presence of the very coarse-grained carbonate laminae were likely deposited under relatively higher current velocities because of the coarse grain size. The occasional association of these carbonate grains with the organic debris laminae is indicative of variations in current flow velocities. The occurrence of both lower and upper flow regime structures in Facies 2, small-scale

Fig. 3-3 (previous page): Facies 1 – Massive to laminated silty mud, interpreted to represent intertidal mud flats. A. Resin peel with the potential Skolithos-like borrows can be seen, as well as minor current ripple laminae. B. Resin peel showing the common massive appearance of facies, with occasional organic debris observed. C. X-ray illustrating occasional bedding and mottling of the sedimentary fabric. It is not known if this mottling is due to bioturbation or root-turbation. D. Resin peel showing organic-rich laminae. E. X-ray illustrating current ripple laminations and planar cross-stratified laminae.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ripples and planar laminae respectively, indicates changes in current velocities, typical of tidal environments. This is further supported by the presence of mud flasers and wavy bedding, which are generally associated with tidal environments, as well as by the presence of associated organic laminae and very coarse-grained carbonate laminae.

The lack of observed bioturbation structures suggests deposition in a stressed environment. This may have been due to highly variable salinities, high sedimentation rates, and/or shifting substrates. The low salinities observed along the intertidal sand flats of the Columbia River delta are not generally conducive to bioturbation. Additionally, the rates of sedimentation in the area are quite high, with large volumes of sediment being transported and deposited.

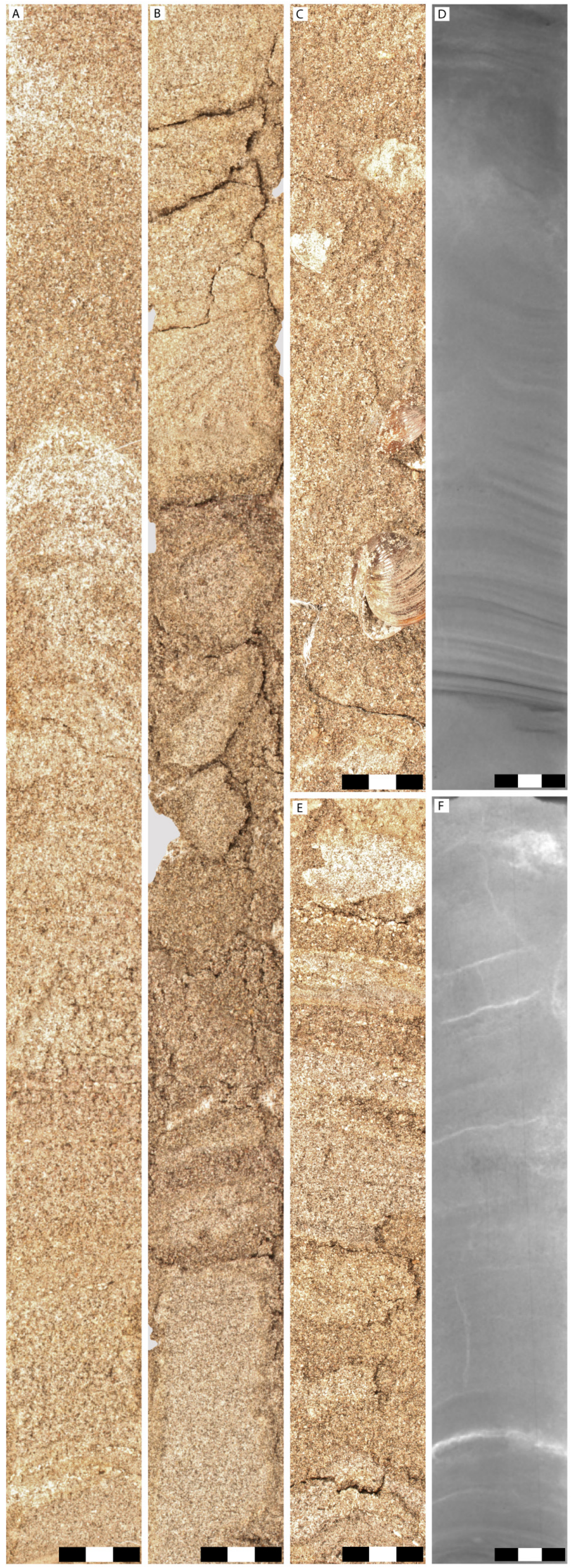
Facies 3 – High-angle cross-bedded medium sand

Description:

Facies 3 is only found at the most up-river locale of Coffee Pot Island in two of the three vibracores. It is characterized by heavy mineral-rich medium- to coarse-grained sand, which is typically not observed elsewhere (Fig. 3-5). The thickness of Facies 3 is variable, ranging from 30 to 160 cm in the three areas where it is observed. The principle sedimentary structure observed in Facies 3 is high-angle cross-bedding. Other sedimentary structures observed include common ripples and rare deformed laminae, defined by very coarse-grained carbonate laminae. Very coarse carbonate grains are common throughout the facies, both disseminated throughout and defining many of the high-angle cross-beds. Clam shells of *Corbicula* sp. are present at the top of the Facies 3, as are common lithic pebbles at the base of the core. There is no evidence of bioturbation present in the vibracore peels or x-rays for Facies 3. The lower contact is sharp with either Facies 1 (silty mud) or Facies 2 (rippled to cross-bedded sand).

Interpretation:

Fig. 3-4 (previous page): Facies 2 – Rippled to small-scale cross-bedded fine-grained sand, interpreted as intertidal sand flats. A. Resin peel with rare wavy bedding and silty mud beds. B. Resin peel showing ripples and cross-bedding, as well as laminae of organic debris associated with very coarse-grained carbonate grains. C. Resin peel with small-scale cross-bedding. D. X-ray illustrating rare planar laminations, as well as small-scale ripples and cross-laminations. E. Resin peel showing organic debris laminae and disseminated organic debris. F, G. X-rays illustrating small-scale ripples and cross-laminations, as well as organic debris and/or mud-rich laminae.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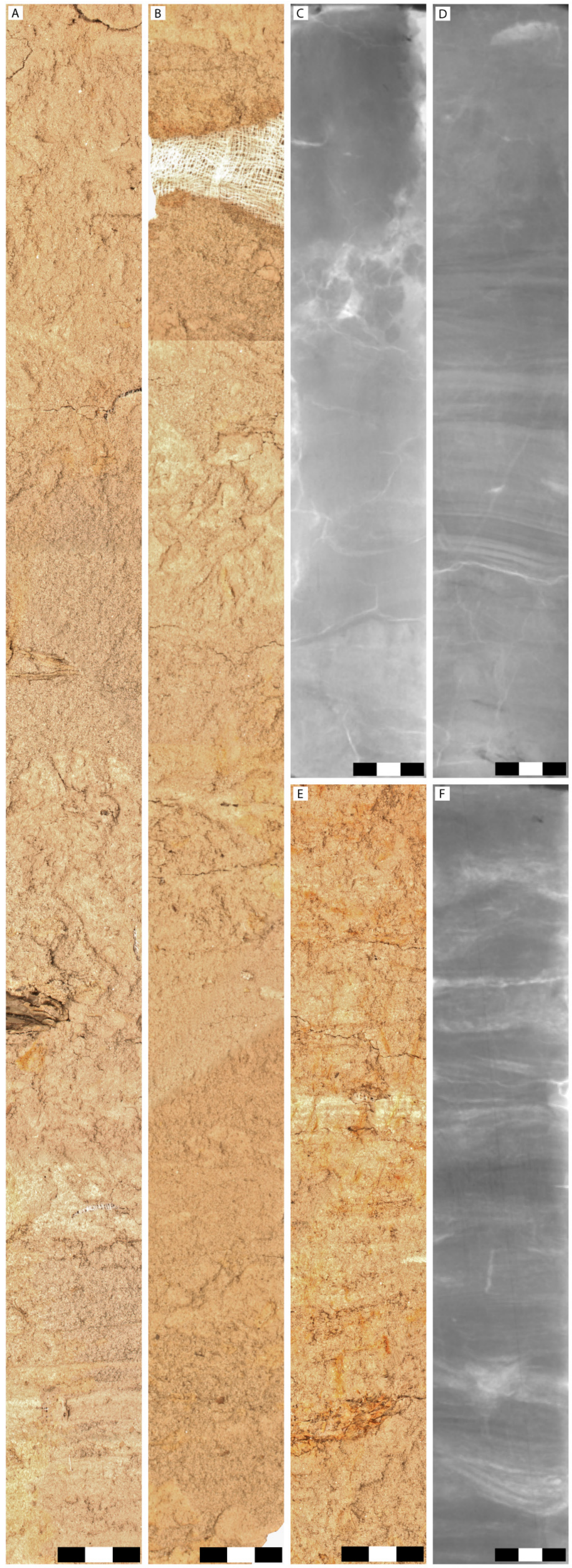
Based on their position at the top of the core, and their sedimentary characteristics, the deposits of Facies 3 correspond to comparably high-energy, fluvially-dominated intertidal sand flats. The high-angle cross-stratification was formed under conditions of unidirectional flow near the upper end of the lower flow regime. High-angle cross-stratification consists of cross-stratification with angles of inclination between approximately 20 degrees and the angle of repose, which is commonly 30 degrees in saturated, fine- to medium-grained sand (Hoyt, 1967). It generally forms on the leeward side of ripples through the avalanching of grains into quieter water. The presence of small-scale current ripples is also indicative of unidirectional flow (Harms & Fahnestock, 1965; Reineck & Singh, 1980); however, these ripples are generally formed at the lower end of the lower flow regime. The deformed laminae defined by the very coarse carbonate grains may indicate deposition during relatively higher current velocities because of the grain size. The laminae may have been deformed through sediment loading with high rates of deposition (Klein, 1977; Reineck & Singh, 1980; Carmona *et al*., 2009), or through dewatering processes. The clam shells at the top of the Facies 3 indicate the sediment was suitable for habitation by infaunal organisms. Lithic pebbles are suggestive of high current velocities, as high velocities would have been required to transport these pebbles from their source. The complete lack of mud in the system is peculiar as other identified facies display thin muddy laminae at the very least. In Facies 3, any mud that may have been deposited was likely winnowed out with the changing tidal currents and the comparatively high flow velocities. Heavy minerals were left in the sand because of their moderately high density and grain size. The occurrence of both upper end lower flow regime and lower end lower flow regime structures in Facies 3, high-angle cross-stratification and small-scale current ripples respectively, indicates changes in current velocities, which is typical of tidal environments. The high-angle cross-stratification supports the interpretation of this facies as being fluvially-dominated, whereas the occurrence of the clam shells in the upper portions of the facies aids in the identification of this facies as intertidal sand flats.

Fig. 3-5 (previous page): Facies 3 – High-angle cross-bedded medium sand, interpreted as high-energy, fluvially-dominated intertidal sand flats. A. Resin peel showing deformed laminae that are defined by very coarse-grained carbonate grains, as well as occasional ripples and high-angle cross-stratification. B. Resin peel of high-angle cross-stratification. C. Resin peel of *Corbicula sp.* clam shells and lithic pebbles are the top of the facies. D. X-ray demonstrating high-angle cross-laminations, as well as a potential water escape feature. E. Resin peel showing very-coarse carbonate grain laminae and small-scale current ripples. F. X-ray illustrating high-angle cross-stratification and deformed laminae.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The lack of observed trace fossils suggests deposition in a stressed environment. This may have been due to low salinities due to the fluvial-dominance of the environment, or the high current velocities present. However, the presence of the intact clam shells suggests these sediments were inhabited by infaunal organisms, but the bioturbation structures were not preserved.

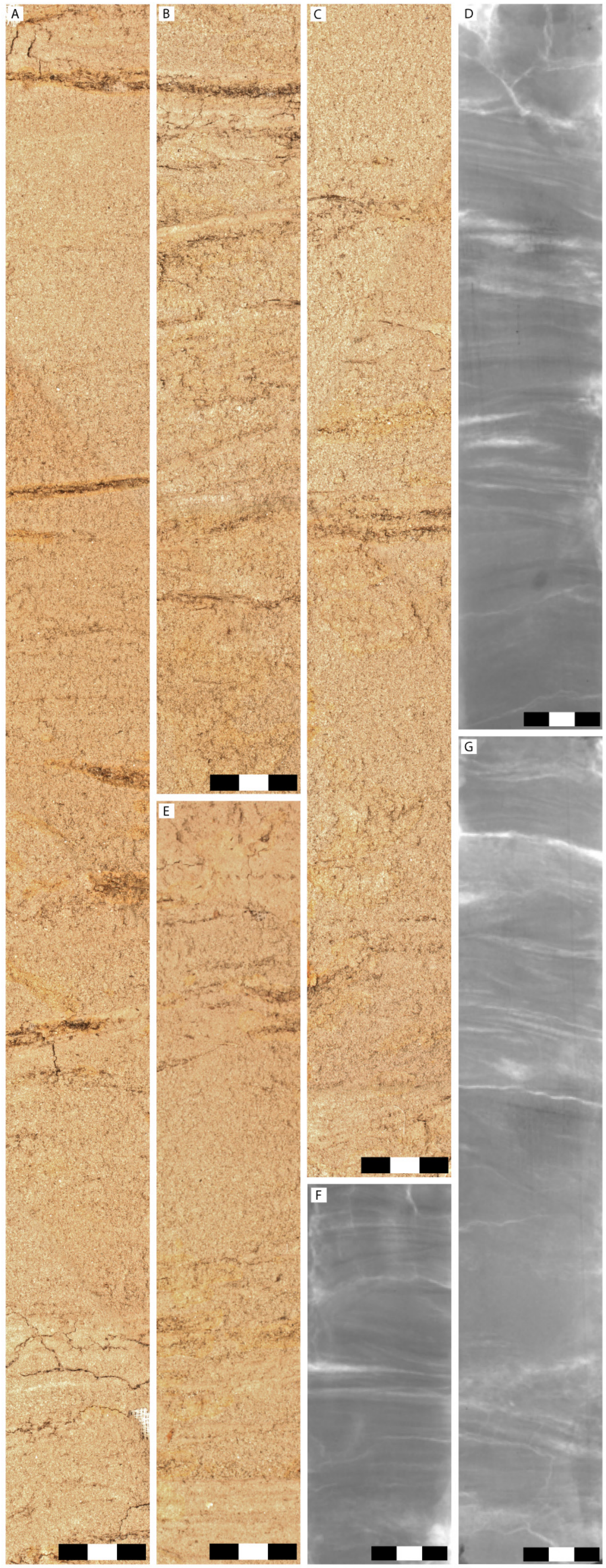
Facies 4 – Interbedded very fine- to fine-grained sand with very-fine sandy silt

Description:

Facies 4 is found only in the central locale, Karlson Island, in two of the three vibracores. It is characterized by very fine- to fine-grained sand interbedded with very fine-grained sandy silt (Fig. 3-6). Facies 4 is variable in thickness, ranging from 55 to 70 cm. This facies is commonly finely rippled. Also observed is soft sediment deformation (SSD) consisting of intermixed fine-grained sand and very fine-grained sandy silt. The SSD is approximately eight to 10 cm thick, and has small round mud pebbles associated with it at the top contained within the fine-grained sand. The typical nature of Facies 4 moves from fine-grained sand with disseminated organic debris into SSD and then into fine-grained sand, which gradationally moves into very fine-grained sand. This is generally repeated twice per appearance of the facies. At the gradation between the very fine- and fine-grained sand there is also potential SSD. Rare wood fragments are contained within the very fine-grained sand. Also seen are rare laminated very fine-grained sandy silt beds, up to 10 cm thick, with fine-grained sand defining ripple laminae. There is no evidence of bioturbation present in the vibracore peels or x-rays for Facies 4.

The lower contact of Facies 4 is sharp with either Facies 2 (rippled to small-scale cross-bedded sand) or Facies 6 (organically laminated rippled sand). This facies forms the uppermost unit of two vibracores.

Fig. 3-6 (previous page): Facies 4 – Interbedded very fine- to fine-grained sand with very fine sandy silt and Facies 5 – Rooted fine-grained sand. Facies 4 (A to D) has been interpreted to represent mixed intertidal flats, whereas Facies 5 (E to F) has been interpreted as sand-dominated intertidal flats near the supratidal transition. A. Resin peel showing small-scale current ripples, rare wood fragments, and interbedding with sandy silt, especially near the bottom of the peel. B. Resin peel illustrating soft sediment deformation (SSD) of sand and silt, as well as disseminated organic detritus. C. X-ray demonstrating small-scale current ripples. D. X-ray showing interbedded sand and silt, as well as small-scale current ripples. E. Resin peel illustrating intense rooting of the facies, which have been iron oxidised. As well, there are thin silt laminae and organic debris laminae. F. X-ray showing current ripple laminae and rare silt laminae.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Interpretation:

Once more, due to its occurrence at the top of the core and its sedimentary character, the interbedded very fine- to fine-grained sand with very-fine sandy silt of Facies 4 is representative of a mixed intertidal flat. The small-scale fine current ripples signify deposition under conditions of unidirectional flow in the lower end of the lower flow regime (Harms & Fahnestock, 1965; Klein, 1970; Reineck & Singh, 1980). Soft sediment deformation (SSD) is indicative of rapid sediment deposition and subsequent deformation due to differential overloading (Klein, 1977; Reineck & Singh, 1980; Carmona *et al*., 2009). The intermixing of fine-grained sand and very fine-grained sandy silt, with fine-grained sand overlying the SSD, suggests the fine sand was rapidly deposited over the sandy silt before it dewatered, causing deformation. The presence of small rounded silty mud pebbles at the top of the SSD signifies reworking of silty mud, potentially in a nearby tidal channel, and subsequent deposition on the mixed flat and incorporation into the facies. The gradation from fine-grained sand to very fine-grained sand over the SSD suggests waning flow conditions. Laminated very fine-grained sandy silt beds designates deposition under lower flow velocities compared to that of the rippled sand, potentially being deposited during slack water, a feature of tidal environments. The fine-grained sand that defines ripple laminae within these silt beds implies deposition under varying current velocities, further reinforcing the interpretation of a tidal environment. The disseminated organic debris contained within the fine-grained sand underlying the SSD may indicate proximity to a salt marsh, and suggest the fine-grained sand was deposited at sufficiently low flow velocities to allow for this debris to remain in the system and not be winnowed out by currents. Also, wood fragments within the very fine-grained sand further supports proximity to the salt marsh. The presence of sedimentary structures formed in both the lower end of the lower flow regime and in slack water, the fine-grained sand and the laminated silt beds, respectively, indicates variations in current velocities, which is characteristic of tidal environments.

Fig. 3-7 (previous page): Facies 6 – Organically-laminated rippled fine-grained sand, interpreted to represent subtidal bar deposits. A, B, C. Resin peels showing small-scale current ripples that are commonly mantled by organic detritus. Organic laminae are common throughout, and are occasionally bordered on either side by silt. D. X-ray illustrating current ripples, cross-laminations, and laminae comprised of organic detritus. E. Resin peel demonstrating small-scale current ripples, commonly mantled by organic detritus. F, G. X-rays showing small-scale current ripples, commonly mantled by organic detritus.

The paucity of bioturbation suggests deposition in a stressed environment. The high sedimentation rate may have made the sediment inhabitable or the salinity may have been too variable.

Facies 5 – Rooted fine-grained sand

Description:

Facies 5 is present as the uppermost facies in one core in the central locale of Karlson Island. It dominantly comprises fine-grained sand with rare silt laminae, and is approximately 20 cm thick (Fig. 3-6). Facies 5 is commonly rippled, which is largely masked by heavy rooting. There are pervasive plant roots approximately one mm in diameter that have been iron oxidized. Additionally, there is occasional organic debris defining ripple laminae. Bioturbation in Facies 5 is minimal to absent, with one potential *Skolithos*-like burrow present at the top of the facies. The burrow is four mm in diameter and in-filled with fine-grained sand.

The lower contact of Facies 5 is sharp with Facies 6 (organically laminated rippled fine-grained sand). Facies 5 forms the uppermost unit where present.

Interpretation:

Based on its position at the top of the core, and the sedimentary characteristics, the deposits of Facies 5 are consistent with the sand-dominated intertidal flat near the supratidal flat transition. The small-scale current ripples were deposited at the lower end of the lower flow regime under unidirectional flow conditions (Harms & Fahnestock, 1965; Klein, 1970; Reineck & Singh, 1980). Occasional organic debris mantling the ripple laminae suggests deposition under waning flow conditions, potentially during slack water (Dalrymple & Choi, 2007). The dominance of plant roots within the facies suggests deposition near the supratidal transition (Dalrymple *et al*., 2003). The oxidation of these plant roots indicates periodic exposure to the air (Dalrymple *et al*., 2003), a common feature in tidal environments. The presence of silt laminae interbedded with fine-grained sand implies changes in current velocities, a feature characteristic of tidal environments, with the silt potentially being deposited during slack water. The combination of organic debris and silt laminae with the small-scale rippled fine-grained sand suggests alternating current flow velocities (Dalrymple & Choi, 2007), suggestive of a tidal environment. The dominance of plant roots signifies deposition on the intertidal flat rather than subtidally.

The scarcity of bioturbation suggests deposition under stressful conditions. This may have been due to salinities that were too low or variable, high rates of sedimentation, and/or exposure. The observation of one potential *Skolithos*-like burrow represents the opportunistic behaviours of suspension feeders. Additional potential burrows may have been masked by the extensive rooting.

Facies 6 – Organically laminated rippled fine-grained sand

Description:

Facies 6 is very common among the Columbia River Delta observed facies, but is not observed at the most up-river cored locations on Coffee Pot Island. It is characterized by laminated fine-grained sand with lenses of very fine-grained sand and silt (Fig. 3-7). The thickness of Facies 6 is variable, ranging from 43 to 190 cm. The average thickness of the facies is approximately 115 cm. Sedimentary structures observed are dominantly small-scale ripples, one to three cm thick. Occasionally, there are planar laminated beds between the ripple sets. The silt lenses are generally associated with the ripples, and are up to five mm thick in sets up to five cm thick. It is common for the rippled silty laminae to grade into ripples of very fine- to fine-grained sand. Organic laminae are very common, and frequently define the ripples. Rarely, the organic laminae may be bounded on either side by silt. There is no evidence of bioturbation present in the vibracore peels or x-rays for Facies 6.

The lower contact of Facies 6 is sharp with Facies 2 (rippled to small-scale cross-bedded fine-grained sand), where present.

Interpretation:

Based on its position stratigraphically lower in the cores, and the associated sedimentary structures, the organically laminated rippled fine-grained sand deposits of Facies 6 is consistent with deposition on subtidal bars. The small-scale current ripples are representative of unidirectional flow, formed at the lower end of the lower flow regime (Harms & Fahnestock, 1965; Klein, 1970; Reineck & Singh, 1980). The planar laminated beds suggest deposition in the upper flow regime under unidirectional flow conditions (Harms & Fahnestock, 1965; Reineck & Singh, 1980). Silt lenses and laminae of organic debris indicate deposition in quiet water conditions, such as during slack water (Klein, 1977; Dalyrmple and Choi, 2007). The gradation from silt laminae to very fine- to fine-grained sand ripples implies an increase in current flow velocities. The interbedding of small-scale current ripples with planar laminated beds suggests changes between the lower flow regime and the upper flow regime, a feature typical of tidal environments. Additionally, the presence of silt laminae and organic debris laminae within the rippled sand suggests alternations between quiet water conditions, likely slack water, and the lower flow regime, which is also a characteristic of tidal environments. The common occurrence of organic laminae in Facies 6 compared to other facies suggests increased preservation of active and slack water periods.

The lack of observed bioturbation structures suggests deposition in a stressful setting. The salinity may have been too low or variable, the sedimentation rate may have been too high, and/or shifting substrates may have contributed to an inhospitable environment. Additionally, the periods of low current velocities may have been too short to allow for sediment colonization between the periods of higher current velocities.

Facies Associations

Facies associations are defined as “groups of facies genetically related to one another and which have some environmental significance” (Collinson, 1969). Facies associations are important in environmental reconstruction, especially in studies of ancient environments. Grouping of facies by architectural elements provides the potential to expose unique physical and biological features of a specific environment. The subsequent discussion examines the relationship of the previously described six facies in terms of a single facies association.

Facies Association 1 – Tidal Sand Bar

The facies described from the Columbia River Delta tidal sand bars form one facies association, with minor proximal to distal differences. The most common facies seen throughout each of the studied bars is Facies 2 (interpreted as intertidal sand flats), which links the most proximal locale to the most distal locale in that it appears in seven of the nine vibracores. In up-river locations, Facies 3 (interpreted as high-energy, fluvially-dominated intertidal sand flats) dominates and distinguishes the proximal tidal sand bars from the distal tidal sand bars. This is likely due to the increased fluvial energy up-river compared to near the mouth, where tidal influences are more prominent. Additionally, the sampled proximal locales border the deep, dredged channel of the Columbia River, further increasing the influence of fluvial currents in the area. In central through to distal locales, Facies 6 (interpreted as subtidal bars) begins to appear. However, the lack of this facies in more proximal locations is likely due to it simply not being collected with the relatively short core lengths. Near central sampling environments, Facies 4 (interpreted as mixed intertidal flat) and Facies 5 (interpreted as sand-dominated intertidal flat near the supratidal flat transition) prevail, potentially forming transitional facies in the proximal to distal trend among the tidal sand bars. In the most distal sample locations, only Facies 1 (interpreted as intertidal mud flats), Facies 2 (interpreted as intertidal sand flats) and Facies 6 (interpreted as subtidal bars) were observed. Since these three facies were found throughout the study area, the distal locations potentially represent the standard for the facies association of the tidal bars of the Columbia River Delta.

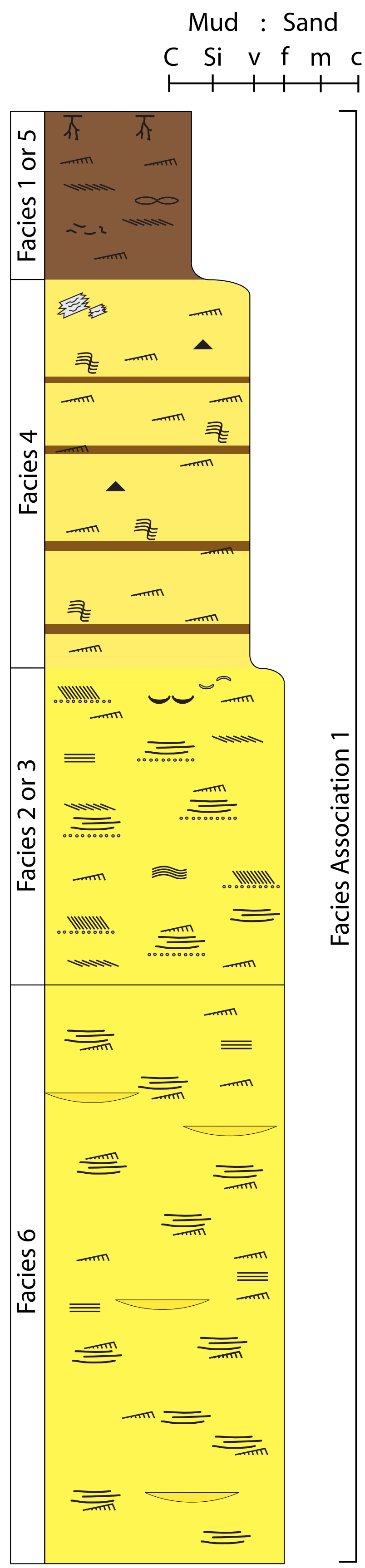
An idealized vertical facies succession would be Facies 1 or Facies 5 overlying Facies 4, overlying Facies 2 or Facies 3 which in turn overlie Facies 6 (Fig. 3-8). This idealized vertical succession essentially follows the archetypal facies succession for tidal flats-tidal sand bars, which is represented by the supratidal salt marsh, intertidal mud flats, intertidal mixed sand and mud flats, intertidal sand flats, and intertidal point bar and subtidal point bar deposits (Klein, 1977; Dalrymple *et al*., 2003). Where there is active deposition, such as the tidal bars of the Columbia River, tidal bars aggrade into the intertidal flats and ultimately are colonized by salt marsh vegetation (Dalrymple *et al*., 2003). Generally, tidal bars are largely comprised of channel deposits, generating lateral accretion deposits (Dalrymple & Choi, 2007). The set thicknesses commonly thin upward and the sediments normally fine-upward (Dalrymple & Choi, 2007).

Discussion

The facies seen in the Columbia River Delta tidal bars provide insight to the depositional parameters of an environment that is commonly under-represented in the literature, especially with respect to modern studies. There are several features that have emerged through the analysis of the tidal bars in the Columbia River, which include: 1) the lack of obvious tidal structures in the observed sedimentary record, even though it is known the sediments were collected in a strongly tidally-influenced environment; 2) differences in the proximal to distal facies trends that link to a single facies association; 3) the effect of the flood and ebb tidal currents on the bedforms observed; 4) the bar tops (interpretations of mud, mixed and sand intertidal flats) were noticeably bioturbated, but bar tops and thus the bioturbation is often not preserved in the rock record; and 5) tidal evidence and the importance of these observations to the rock record.

There is a noticeable lack of common tidal sedimentary structures in the observed facies seen in the Columbia River Delta tidal bars, even though the sediment was collected from a strongly tidally-influenced environment. The most obvious features associated with tidal regimes include herringbone cross-stratification and bi-directional cross-laminae(Klein, 1977; Reineck & Singh, 1980; Willis *et al*., 1999; Dalrymple *et al*., 2003; Boggs, 2006; Plink-Bjorklund, 2008), lenticular to wavy to flaser bedding (Reineck & Wunderlich, 1968; Klein, 1977; Reineck & Singh, 1980; Willis *et al*., 1999; McCrimmon & Arnott, 2002; Dalrymple *et al*., 2003; Boggs, 2006), Inclined Heterolithic Stratification (IHS; McCrimmon & Arnott, 2002), fluid mud deposits (Dalrymple *et al*., 2003), double mud drapes (Martinius *et al*., 2001; Dalrymple *et al*., 2003; Plink-Bjorklund, 2008; Carmona *et al*., 2009), reactivation surfaces (Klein, 1977) and sand-mud couplets (Klein, 1977; Martinius *et al*., 2001; Hori *et al*., 2002). In the tidal bars of the Columbia River, however, none of these structures were observed, with the exception of minor lenticular, wavy and flaser bedding. The tidal sedimentology of these deposits was discerned by the analysis of more subtle features. For example, seen in all the facies identified were deposits of mud mantling many of the current ripples, as well as forming distinct individual laminae, which is a common feature of tidal deposition (Klein, 1977; Dalrymple & Choi, 2007). Additionally, organic debris commonly formed laminae and often mantled the ripples. Deposition of mud and organic debris generally occurs during quiescent water conditions, such as time of slack water between high and low tides. The occurrence of lower-end lower flow regime structures (i.e., current ripples), with slack water depositional structures (i.e., mud laminae and lenticular bedding), implies changes in flow regime, which is indicative of tidal

Fig. 3-8 (following page): Idealized vertical succession of the facies for Facies Association 1, tidal bars in the fluvial-tidal transition of the Columbia River Delta. See Appendix B for legend of symbols.

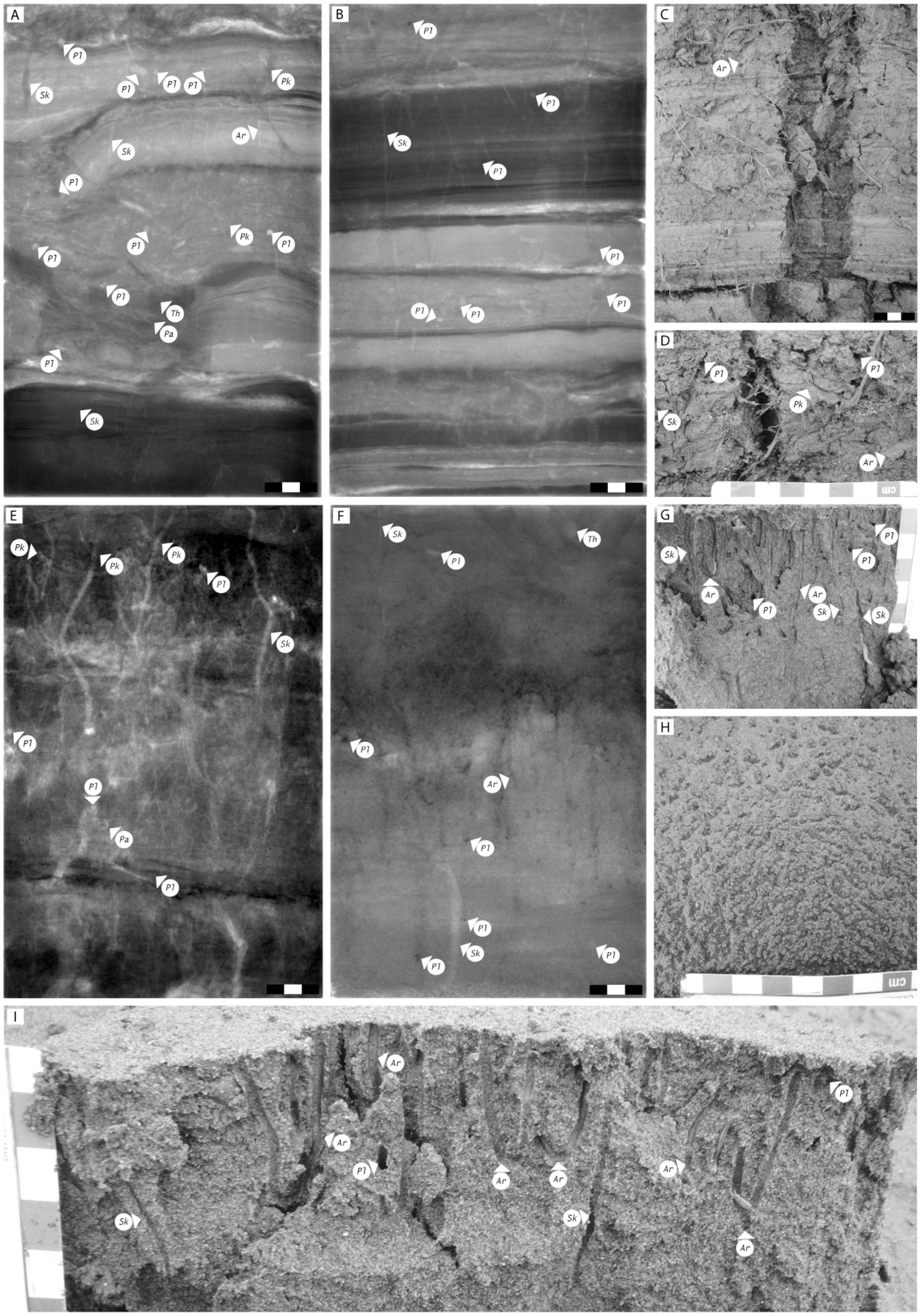

Mud : Sand
C Si v f m c
Facies 1 or 5
Facies 4
Facies 2 or 3
Facies 6
Facies Association 1

deposition. Furthermore, there are occasional upper flow regime structures within the same facies as lower flow regime and slack water structures, which further reinforce the interpretation of tidal deposition. An auxiliary piece of information to support tidal deposition is the benefit of having collected the sediment from intertidal flats under mesotidal conditions – while the sedimentary structures are not transparently tidal in origin, knowledge of the depositional setting cannot be discounted.

As discussed in Facies Association 1, trends seen from proximal to distal are subtle and are minor enough to allow for the interpretation of a single facies association rather than several. Minor local variability has been set aside in an attempt to discern the overall facies trends within the tidal sand bars of the Columbia River Delta. These tidal bars are found within the fluvial-tidal transition of a mixed-energy delta, which is an incredibly complex depositional environment – it is improbable to believe the same facies could be deposited in the same stratigraphical order in each of the tidal sand bars in a study locale as large as the Columbia River Delta. This paper has attempted to produce a framework to better the understanding of general trends observed in tidal sand bars within a modern mixed-energy deltaic setting, specifically when the overall character of the sediments is not blatantly tidal in nature.

There have been numerous studies published wherein the author(s) have interpreted a tidal depositional environment, but lacked the more obvious tidal indicators (herringbone cross-stratification, sand-mud couplets, double mud drapes, etc; Klein, 1970; Boersma & Terwindt, 1981; Dalrymple *et al*., 2003; Dalrymple & Choi, 2007). This has largely been attributed to the dominance of either the flood or ebb tidal current and thus the preservation of one or the other (De Boer *et al*., 1989; Dalrymple & Choi, 2007). Sediment is generally deposited

Fig. 3-9 (following page): X-rays, clam-gun cores, and surface grab samples of Facies 1 (A to D) and 2 (E to I) to illustrate the neoichnology of each facies. A, B. X-rays at surface (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; *Th*: *Thalassinoides*-like traces). C, D. Clam-gun cores at surface (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). E, F. X-rays at surface (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; *Th*: *Thalassinoides*-like traces). G. Grab sample at surface (*Ar*: *Arenicolites*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). H. Plan view of surface illustrating the high burrow densities possible. I. Grab sample at surface (*Ar*: *Arenicolites*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces).


A
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on the side of the elongated tidal bar with the subordinate current, which results in the preferential preservation of sedimentary structures formed by the weaker current (Dalrymple & Choi, 2007). The tidal bars of the Columbia River Delta are likely undergoing a similar process, with either the flood or ebb currents dominating sediment deposition.

Sand bar tops, in this study were interpreted as mud, mixed and sand intertidal flats, and were noticeably bioturbated, often quite pervasively (figs 3-9 and 3-10). While these features were not observed in the vibracore facies, burrows were observed in equivalent surface samples and box cores Observations and interpretations in Chapter 2 looked at the surface of the various tidal bars and the surface ichnology observed for the interpreted intertidal flats (Facies 1 through 5) is consistent with the *Teichichnus* ichnofacies (c.f. Pemberton *et al*., 2010). This ichnofacies is based on specific animal-sediment relationships, including: 1) head-up deposit-feeding behaviours; 2) trace-maker leaves burrow to hunt for food; 3) passive predation; 4) minor filter feeding behaviours; and 5) swift reaction of opportunistic trophic generalists to deposits of plentiful food, promoting the formation of intermittent biogenically mottled sedimentary structures (Pemberton *et al*., 2010). Biogenic structures found on tidal bar tops in the Columbia River Delta include *Arenicolites*-like, *Palaeophycus*-like, *Polykladichnus*-like, *Planolites*-like, *Skolithos*-like and *Thalassinoides*-like traces (figs 3-9 and 3-10), which are commonly associated with strongly facies-crossing components of more marine groups (Pemberton *et al*., 2010).

Where potential burrows were identified in the vibracores, the burrows were not obvious and were rare. It has been assumed the bioturbation was obliterated during the vibracoring and transportation process due to the lack of consolidation and high water saturation of the sediment. Additionally, there is evidence within some of the bar top facies of sediment distortion, which may have occurred during vibracore collection and/or transportation. There have been significant rates of compaction and distortion of sediment collected using the vibracore methods, ranging between 10 and 60 percent, with 40 percent compaction common (Glew *et al*., 2001). Since the cores were collected in a modern setting, the majority of the burrows were not in-filled with sediment, and possibly collapsed during the collection and transportation process.

Tops of tidal bars are generally not preserved in the rock record (Willis *et*

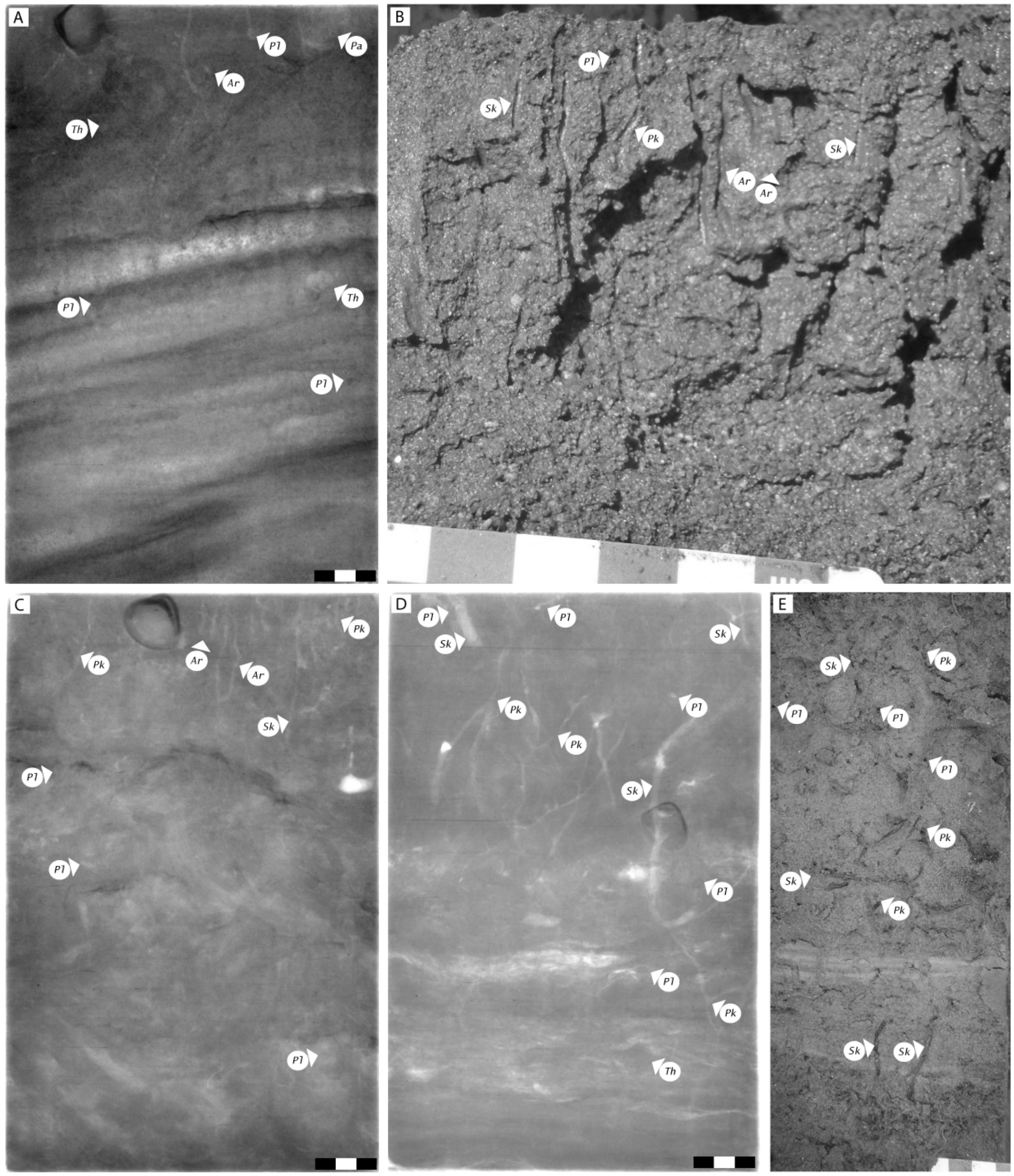

Fig. 3-10: X-rays, clam-gun cores, and surface grab samples of Facies 3 (A to B), 4 (C) and 5 (D to E) to illustrate the neoichnological character of each facies. A. X-ray at surface (*Ar*: *Arenicolites*-like traces; *Pa*: *Palaeophycus*-like traces; *Pl*: *Planolites*-like traces; *Th*: *Thalassinoides*-like traces). B. Grab sample at surface (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). C. X-ray at surface (*Ar*: *Arenicolites*-like traces; *Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces). D. X-ray at surface (*Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces; *Th*: *Thalassinoides*-like traces). E. Clam-gun core at surface (*Pk*: *Polykladichnus*-like traces; *Pl*: *Planolites*-like traces; *Sk*: *Skolithos*-like traces).

al., 1999; Willis & Gabel, 2001), and preservation is generally favoured in areas of moderate to high sedimentation rates (Klein, 1977). This may have a significant impact on the identification of tidal bars in the rock record, particularly when the tidal depositional structures are not immediately obvious and the bioturbation was in the unpreserved surface sediments.

The unapparent tidal nature of the identified facies of the Columbia River Delta presents challenges if attempting to identify similar deposits in the rock record. The careful identification of sedimentary structures, especially sand and mud relationships, combined with available ichnological data may be the key for ancient recognition. Alternation between upper flow regime, lower flow regime and slack water structures gives insight to depositional regime, and includes such physical sedimentary structures as small-scale current ripples mantled with either mud or organic detritus, occasional lenticular, wavy and flaser bedding, and coarser materials (e.g., lithic pebbles, very coarse carbonate grains, bivalve shells) in facies that also contain other tidal indicators. When available, ichnological evidence should be incorporated to further the understanding of the depositional regime. Brackish-water ichnological features are commonly used to substantiate environmental interpretations.

The identification of tidal structures and facies, as well as trends between proximal to distal facies, may have been improved in several ways. Deeper vibracoring, combined with vibracoring along a grid or transect network would improve the understanding of the facies both laterally and with depth. As well, vibracoring the subtidal portions of the tidal bars would enhance the comprehension of these deposits. The use of geophysical techniques, such as high-resolution seismic and ground penetrating radar (GPR) would enable the identification and interpretation of larger sedimentological trends along the tidal bars and would provide an exceptional supplement to the dataset.

Conclusions

Several conclusions can be drawn from the results of this study. First, there are six facies identified for the tidal bars within the fluvial-tidal transition of the Columbia River Delta. Second, five of the six identified facies are variations of the intertidal flat environment, and were differentiated from one another based largely on sedimentary characteristics and overall grain size. Third, the six facies form a single facies association – tidal sand bars – displaying minor proximal to distal differences. Fourth, typical sedimentological tidal indicators are not present in the facies of the tidal bars. Tidal indicators in this environment are much more subtle and include changes in flow regime (upper, lower and slack water) within a single facies. This was represented by such sedimentary structures as the association of sandy current ripples mantled with mud and/or organic detritus, laminae of mud and organic detritus throughout sand-dominated facies, planar laminae interbedded with current ripples and low angle cross-laminae, etc. Fifth, the lack of bi-directional tidal features is likely due to the dominance of either the flood or ebb tidal current, with the preservation of sedimentary structures formed by the subordinate current. Sixth, the neoichnological features of the facies were not preserved in the vibracores. However, the vibracore dataset was supplemented by surface box cores, which allowed for the identification of the neoichnology. Lastly, neoichnological trends in the Columbia River Delta tidal bars are consistent with the *Teichichnus* ichnofacies. Taken as a whole, the tidal bar facies association in this very-low-salinity, tide-dominated yet strongly fluvial setting provides an additional modern analogue when attempting to identify this environment in the rock record.

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Chapter 4 – Summary and Conclusions

This thesis explored the neoichnological and sedimentological trends along the fluvial-tidal transition zone of the Columbia River Delta, northwest U.S.A. The principal objectives were to conduct a detailed analysis on the neoichnology in this zone, as well as describe and interpret the sedimentological facies in the study area. These observations led to the creation of a neoichnological model for very-low-salinity zones along the fluvial-tidal transition zone in mixed-energy deltas with strong wave- and tide-influence, along with the recognition of specific sedimentary characteristics to potentially allow for the identification of these facies in the rock record.

Study Area and Depositional Setting

The Columbia River Delta is located along the border of Oregon and Washington in the northwest United States. It has been characterized as mesotidal with mixed, semi-diurnal tides. The delta is considered to be mixed-energy in nature, with a tidal prism of 50,926 m^3s^{-1} (Buonaiuto & Kraus, 2003) and strong wave-influence at its mouth. The Columbia River Delta is contained within a basin of Tertiary-aged sedimentary and volcanic bedrock that has been in-filled with Pleistocene and Holocene sediments (Simenstad *et al*., 1990).

The main channel of the Columbia River is relatively straight and contains several tidally-influenced sand bodies. Sand bars in the area generally shift up and down the delta, with sand accumulations up to 30 m thick in places. Overall, the system is primarily composed of fine-grained sand with muddy pockets in local bays (Sherwood & Creager, 1990). The accommodation space in the lower Columbia River Delta has largely been obliterated by the presence of shallow tidal flats, shoals, central islands and lateral accretion floodplains (Sherwood & Creager, 1990). The dominant sedimentary process is channelized sediment throughput and transient bar-storage (Sherwood & Creager, 1990).

Ichnological Framework and Sedimentary Facies Trends

Ichnology of tide-dominated and mixed-energy deltas is poorly understood, even though the sedimentological characteristics have been well documented (McIlroy, 2004; Dalrymple & Choi, 2007; Carmona *et al*., 2009). There are many studies in which authors have recognized a variety of ichnofossils in core and outcrop, but do not deduce the implications these assemblages have on the classification of the depositional environment.

Chapter 2 addressed the neoichnology observed within the fluvial-tidal transition zone in the Columbia River Delta and its implications on the potential identification of these assemblages in the rock record. Tidal sand bars were selected along the fluvial-tidal zone along a longitudinal transect enabling the recognition of ichnological trends throughout the mixed-energy, very low salinity study area. Following the analysis of the tidal bar neoichnology, several trends were identified: 1) the Columbia River Delta study area contains organisms that make burrows consistent with the *Teichichnus* ichnofacies; 2) there must be larval tidal recruitment of marine trace-makers into the oligohaline, strongly tidally-influenced zone as *Corophium sp*. and nereid polychaetes observed are unable to reproduce at such low salinities; 3) the tops of the tidal-fluvial bars and the intertidal zone are more pervasively burrowed compared to the subtidal zone due to the more stressful conditions found lower on the tidal-fluvial bars; 4) continental traces may be quite large (greater than 1 cm in diameter), and create *Arenicolites*-like and *Camborygma*-like traces; 5) ichnogenera burrowing-depth, density, and burrow diameter decrease moving up-river; and 6) sheltered locales, such as Cathlamet Bay and Youngs Bay, act as traps for fine grained sediment. In summary, the neoichnological assemblages of the Columbia River Delta within the fluvial-tidal transition are characteristic of very-low-salinity environments and are consistent with the *Teichichnus* ichnofacies, and are primarily observed on the intertidal flats of the bar tops rather than at very low intertidal flat or subtidal zones.

Deltas are progradational bodies of sediment that are formed by river-supplied sediment at the mouth of a river and include deposits of fluvially-influenced sediments (cf. Dalrymple *et al*., 1992; Dalrymple, 1999, 2000; Dalrymple *et al*., 2003). The sediment in the Columbia River Delta is brought into the system via the Columbia River. Chapter 3 focused on the development of a facies classification scheme for the sediments within the fluvial-tidal transition zone of the Columbia River Delta, largely based on sedimentary characteristics derived through the analysis of nine vibracores extracted from three tidal sand bars. The identification of six facies, which form one facies association, allowed for the recognition of specific sedimentary features that, when grouped together, distinguish tidal sand bars in the fluvial-tidal transition zone of a tide-dominated delta. Recognition of tidal indicators in the observed facies is relatively subtle, and included changes in flow regime (upper, lower and slack water) within a single facies. This was represented by such sedimentary structures as the association of sandy current ripples mantled with mud and/or organic detritus, laminae of mud and organic detritus throughout sand-dominated facies, and planar laminae interbedded with current ripples and low angle cross-laminae. The lack of obvious tidal indicators, such as bi-directional current features and herringbone cross-stratification, has been attributed to the dominance of either the flood or ebb tidal current, with the preservation of sedimentary structures formed by the subordinate current.

Applications to the Rock Record

There has been little work conducted on the high-resolution ichnological character of deltas (e.g. Bann & Fielding, 2004; McIlroy, 2004; Rebata *et al*., 2006), and none on very low salinity zones of modern deltas. However, it is increasingly recognized that sedimentary strata associated with the fluvial-tidal transition can account for the presence of excellent reservoir rocks. Therefore, the ability to identify and characterize the fluvial-tidal transition is, in this context, important. The use of ichnology in combination with sedimentary facies is a tool that should aid in the identification of these fluvial-tidal transition rocks.

In this study, it has been shown that brackish-water fauna are present at salinities as low as 0.5 ppt. The distribution of these organisms, while relatively sporadic, can extend approximately 75 km up-river, where organism densities may still be quite high even though the vertical distribution becomes limited. With this in mind, it may be possible to interpret ancient depositional environments with characteristics of low-salinity brackish-water, which may have been previously interpreted as otherwise, based on the ichnological distribution.

The tops of tidal bars are commonly not preserved in the rock record (Willis *et al*., 1999; Willis & Gabel, 2001), and preservation is generally favoured in areas of moderate to high sedimentation rates (Klein, 1977). This may have a significant impact on the identification of tidal bars in the rock record. The identification of six facies within this low-salinity brackish-water zone in the Columbia River Delta are typically absent of archtypal tidal sedimentary features, and most often appear fluvial in nature, even though they are known to be tidal. Therefore, it is important to distinguish specific, more subtle features that may help in the identification and interpretation of this type of deposit in the rock record, especially in combination with the ichnology.

Ancient strata that have been inferred to represent fluvio-tidal transitions are currently being exploited, such as the Clearwater Formation (McCrimmon & Arnott, 2002; Feldman *et al*., 2008) and the McMurray Formation (Pemberton *et al*., 1982; Crerar & Arnott, 2007; MacEachern & Gingras, 2007) in Alberta, as well as the Ile Formation of the Kristin Field, Haltenbanken, Offshore Mid-Norway (McIlroy, 2004).

Conclusion

The fluvial-tidal transition zone of the Columbia River Delta has been observed to be an atypical brackish-water environment, in that it is dominantly characterized by very low salinities. The Columbia River Delta is a mixed-energy delta, with strong wave and tidal influence. The characterization of neoichnological and sedimentological characteristics of this environment has brought to light several features that may prove useful in the identification of these deposits in the rock record. There is a significant need for the development of predictive models for mixed-energy deltas with strong tidal influence based on modern analogues to aid in the understanding and interpretation of subsurface, ancient deposits. It is the hope that the observations from this study may provide an additional modern analogue for these deltas, especially within the fluvial-tidal transition zone. A thorough comprehension of this dynamic environment and the complex distribution of the ichnology and sedimentary facies contained within the fluvial-tidal transition zone in mixed-energy deltaic systems will facilitate more accurate models.

Through the course of this study, it came to light that there are gaps in current modern field studies. In future efforts, there are specific types of work required where research is currently lacking. Such research areas include: 1) the low salinity spectrum of the fluvial-tidal transition zone when identifying the neoichnology of brackish-water zones, especially within strongly tidally-influenced mixed-energy deltas; 2) the incorporation of these zones into the study of modern deltas and estuaries; 3) the changes in species diversity and thus trace fossil type with very small changes in salinity; and 4) the changes in trace assemblages in these very low salinity zones moving from the salt marsh through to the subtidal channel deposits. Further research into these areas would be valuable in garnering a more thorough understanding of the fluvial-tidal transition zone of strongly tidally-influenced mixed-energy deltas.

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Appendix A
X-rays

Location	Sample Number	Coordinates
Sand Island	34i	N46°16'07.6'', W124°00'20.1'' ±3m
Sand Island	36i	N46°16'09.0'', W124°00'36.4'' ±2m
Washington (Chinook) Coast	50i	N46°15'22.4'', W123°56'11.0'' ±3m
Washington (Chinook) Coast	51i	N46°15'31.1'', W123°56'03.3'' ±3m
Washington (Chinook) Coast	52i	N46°15'37.2'', W123°55'57.7'' ±2m
Desdemona Sands	33i	N46°12'41.3'', W123°54'49.5'' ±3m
Young's Bay	14i	N46°09'52.9'', W123°52'32.9'' ±6m
Young's Bay	15i	N46°09'53.4'', W123°53'13.4'' ±6m
Washington Coast	45i	N46°14'28.8'', W123°52'49.8'' ±3m
Taylor Sands	27i	N46°13'37.8'', W123°46'42.4'' ±7m
Taylor Sands	28i	N46°13'43.9'', W123°46'31.7'' ±6m
Lois Island	9ii	N46°12'08.4'', W123°44'11.9'' ±6m
Lois Island	10i	N46°11'14.0'', W123°43'26.1'' ±5m
Lois Island	11i	N46°10'36.5'', W123°43'36.4'' ±4m
Lois Island	11ii	N46°10'36.5'', W123°43'36.4'' ±4m
Lois Island	12i	N46°10'46.1'', W123°42'58.5'' ±6m
Lois Island	13i	N46°11'57.5'', W123°43'48.4'' ±5m
Lois Island	64i	N46°10'42.8'', W123°43'03.5'' ±2m
Rice Island	29i	N46°14'52.0'', W123°43'51.1'' ±4m
Miller Sands	30i	N46°14'58.0'', W123°37'58.2'' ±2m
Seal Island	21i	N46°12'32.5'', W123°37'59.8'' ±5m
Seal Island	22i	N46°12'45.3'', W123°38'35.8'' ±4m
Karlson Island	20i	N46°11'47.4'', W123°37'33.7'' ±5m
Karlson Island	26i	N46°12'24.7'', W123°37'25.8'' ±5m
Marsh Island	54i	N46°12'52.9'', W123°37'10.4'' ±2m
Woody Island	63i	N46°15'02.3'', W123°32'22.1'' ±4m
Grassy Island	59i	N46°15'03.2'', W123°31'34.2'' ±2m
Grassy Island	60i	N46°15'17.3'', W123°30'49.6'' ±2m
Fitzpatrick Island	61i	N46°15'43.5'', W123°30'06.9'' ±3m
Fitzpatrick Island	62i	N46°15'44.4'', W123°30'04.5'' ±7m
Tenasillahe Island	19i	N46°12'29.2'', W123°25'50.5'' ±5m
Coffee Pot Island	17ii	N46°10'07.9'', W123°24'22.5'' ±6m
Coffee Pot Island	16i	N46°09'13.6'', W123°23'00.1'' ±6m
Cooper Island	48i	N46°08'50.7'', W123°15'23.3'' ±2m
Cooper Island	47i	N46°09'03.0'', W123°13'48.1'' ±3m
Wallace Island	46i	N46°08'36.2'', W123°13'46.5'' ±3m
Oregon Coast	49i	N46°09'32.1'', W123°12'51.8'' ±5m
Gull Island	55i	N46°11'05.8'', W123°09'39.1'' ±4m
Gull Island	55ii	N46°11'05.8'', W123°09'39.1'' ±4m
Crims Island	56i	N46°10'47.1'', W123°10'04.0'' ±3m
Crims Island	57i	N46°10'11.4'', W123°07'40.7'' ±2m
Oregon Coast	58i	N46°10'00.7'', W123°05'52.0'' ±4m

Table A: Location and sample numbers of collects x-rays

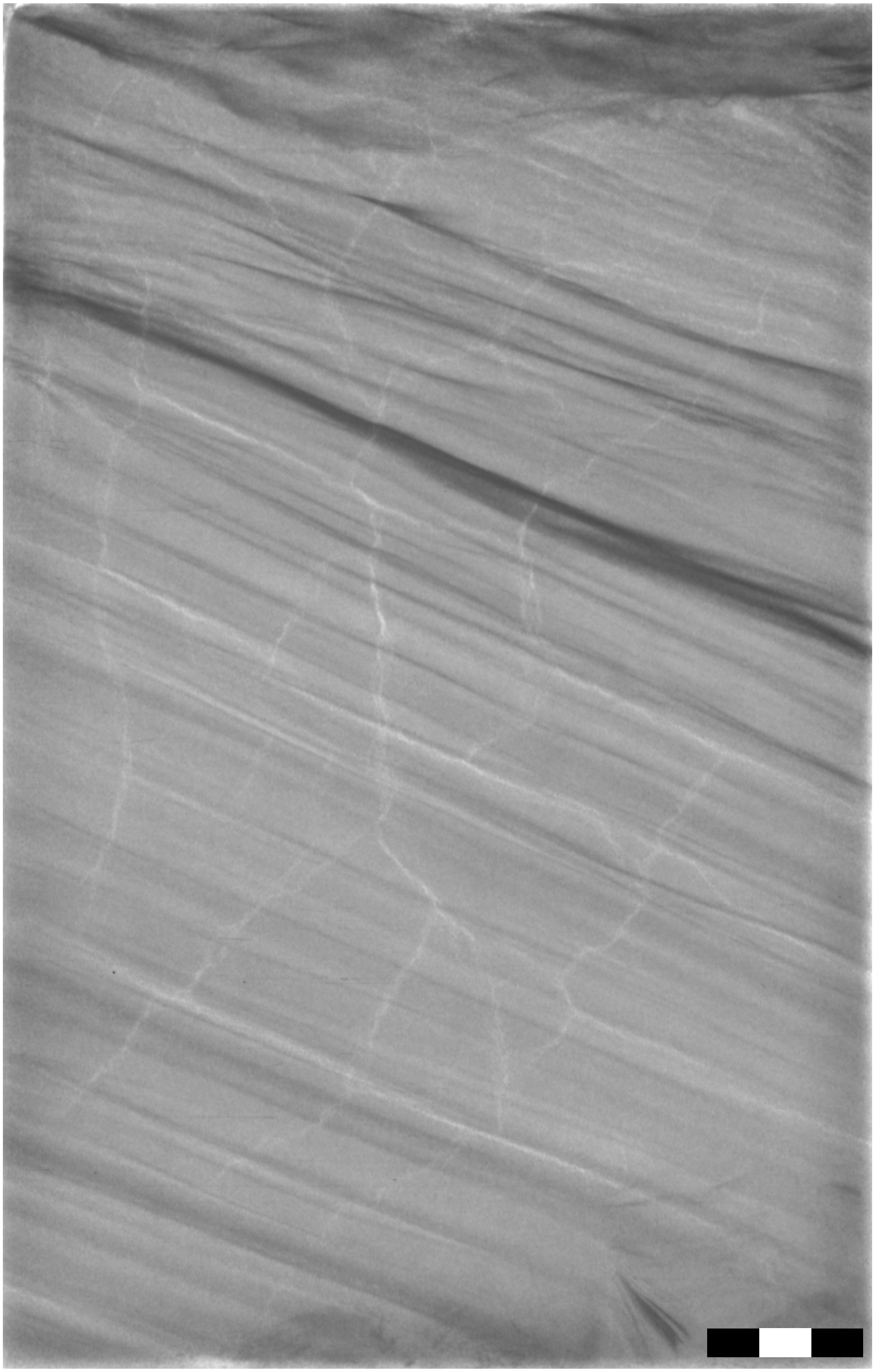

Fig A-1: Heavy mineral-rich sand flat on Sand Island. Salinity of 12 ppt.

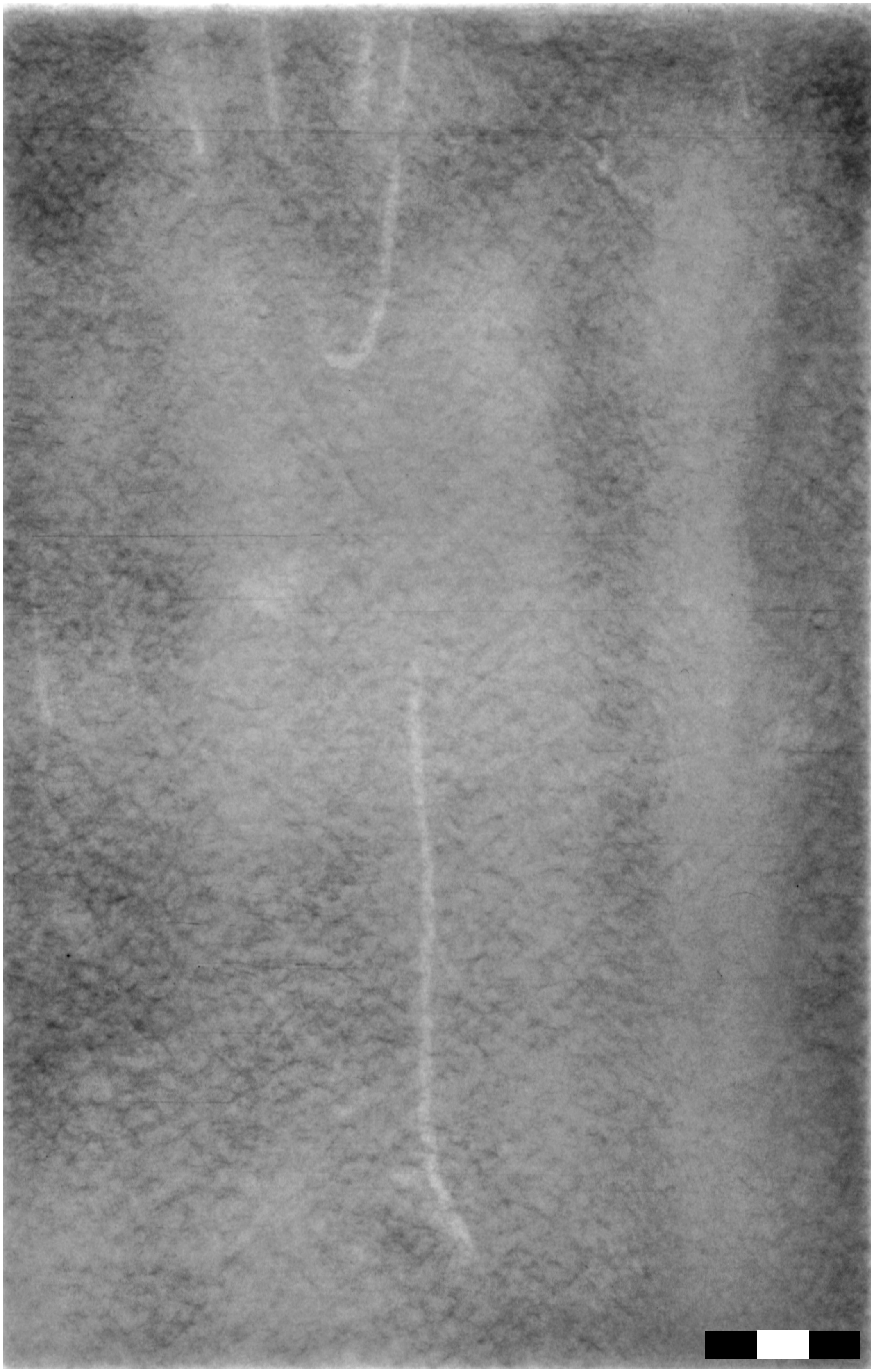

Fig. A-2: Sand flat on Sand Island. Salinity of 12 ppt.

Fig. A-3: Sand flat along Washington coast near Chinook. Salinity of 12 ppt.

Fig. A-4: Sand flat along Washington coast near Chinook. Salinity of 19 ppt.

Fig. A-5: Mud flat along Washington coast near Chinook. Salinity of 18 ppt.

Fig. A-6: Sand flat on Desdemona Sands. Salinity of 11 ppt.

Fig. A-7: Mud flat in Young's Bay. Salinity of 7 ppt.

Fig. A-8: Mud flat in Young's Bay. Salinity of 6 ppt.

Fig. A-9: Heavy mineral-rich sand flat along Washington Coast. Salinity of 9 ppt.

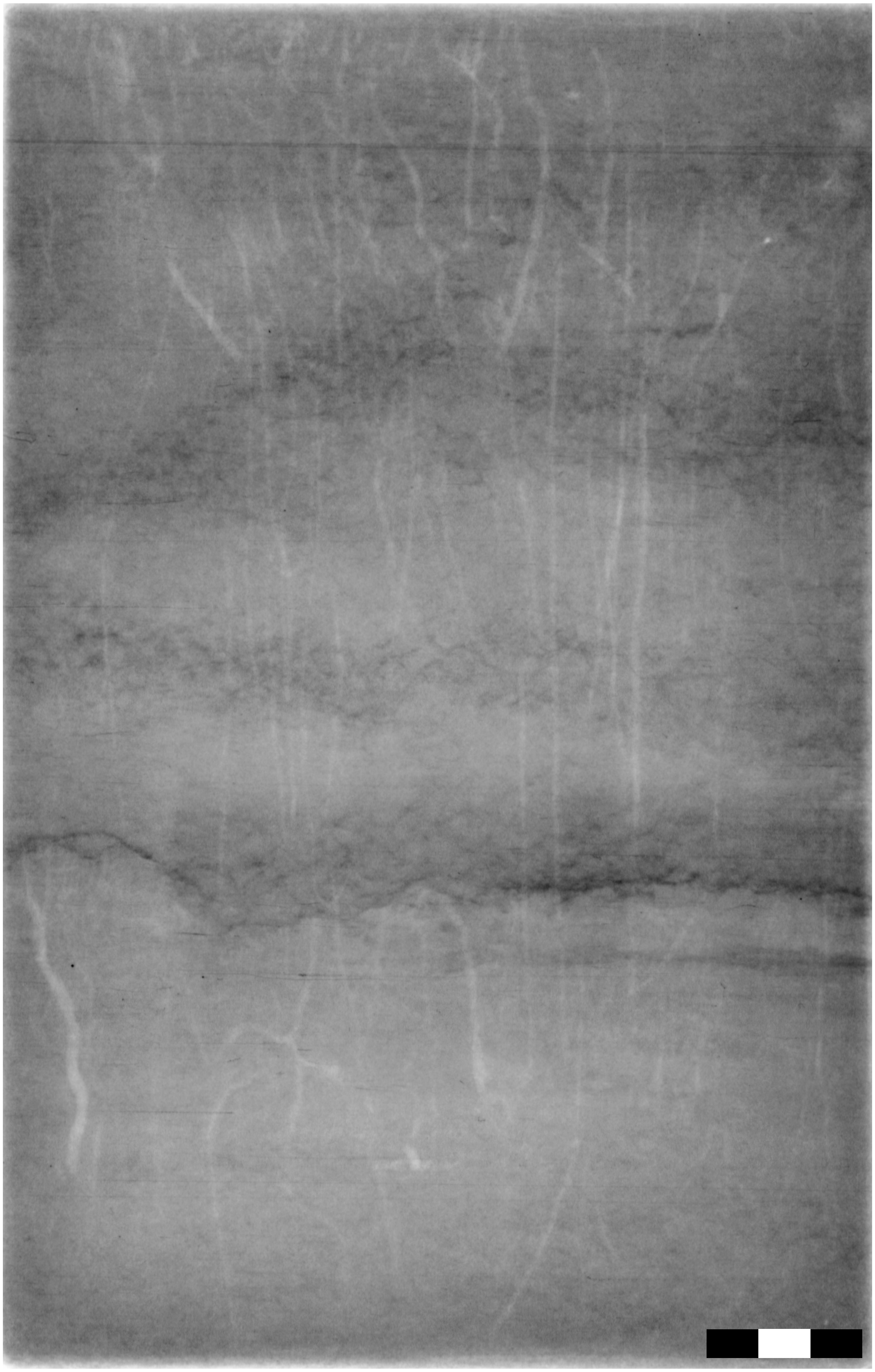

Fig. A-10: Sand flat on Taylor Sands. Salinity of 2 ppt.

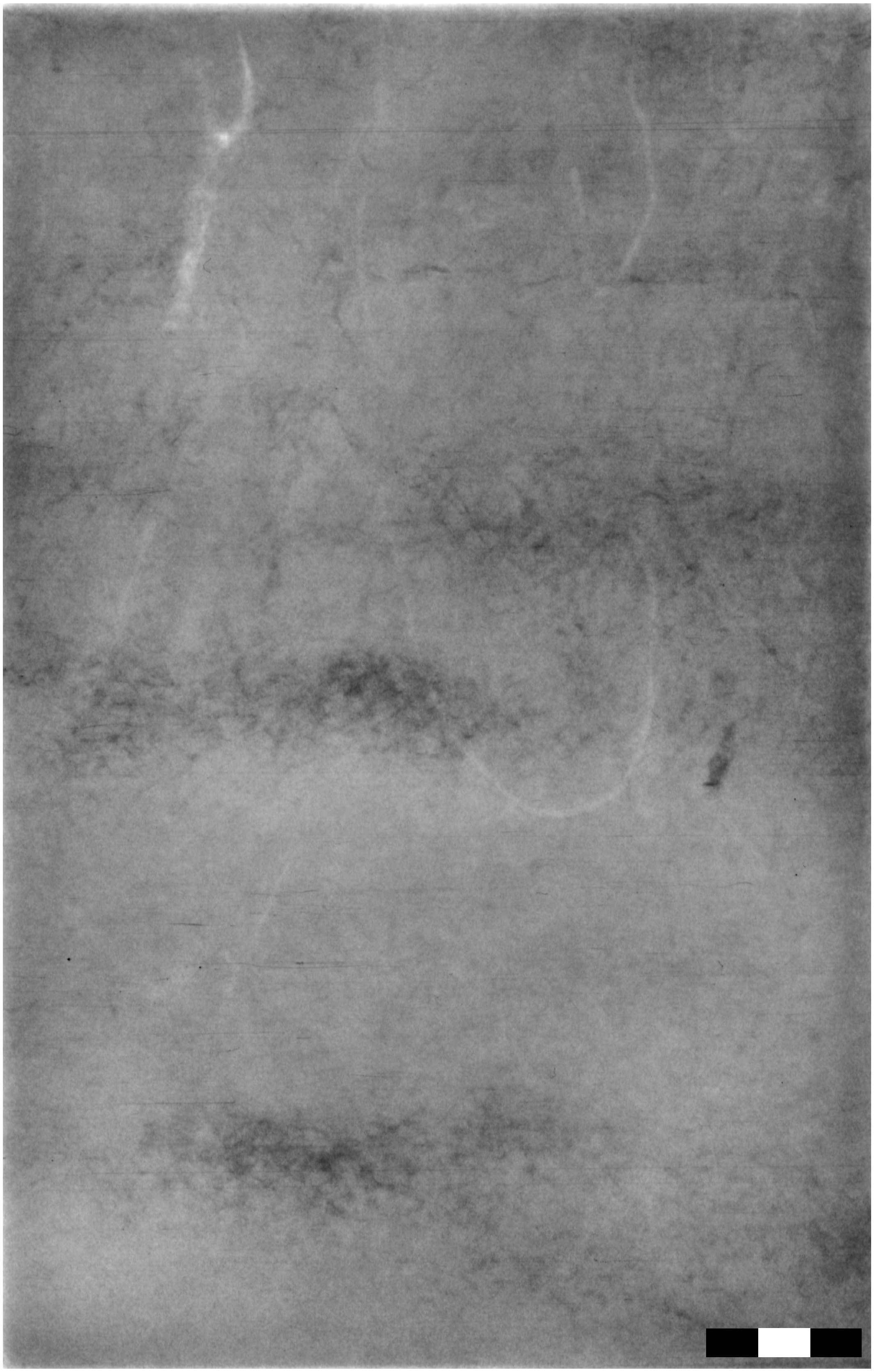
Fig. A-11: Sand flat on Taylor Sands. Salinity of 2 ppt.

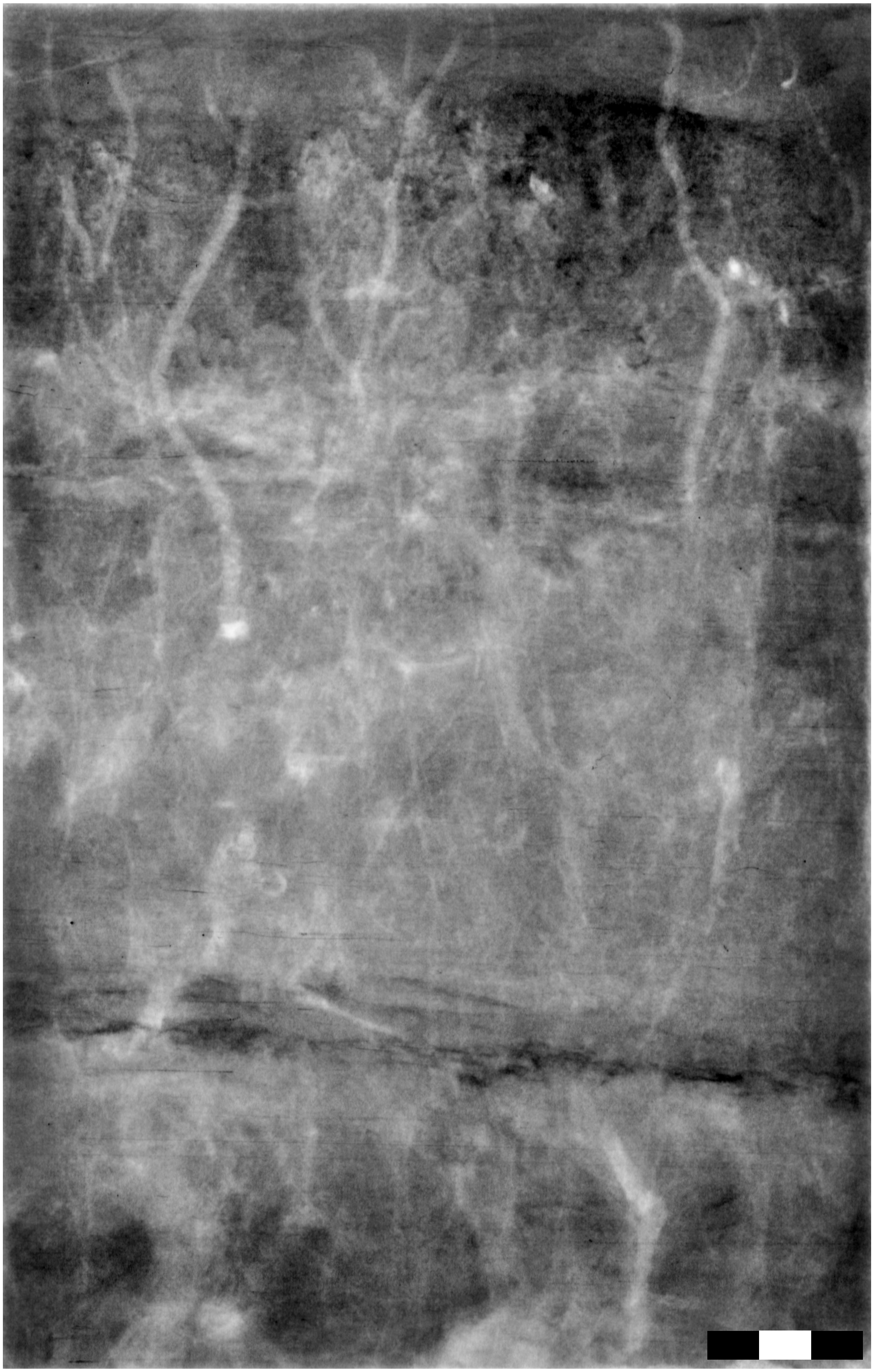

Fig. A-12: Sand flat on Lois Island at oceanward point. Salinity of 2 ppt.

Fig. A-13: Sand flat on Lois Island near oceanward point. Salinity of 1 ppt.

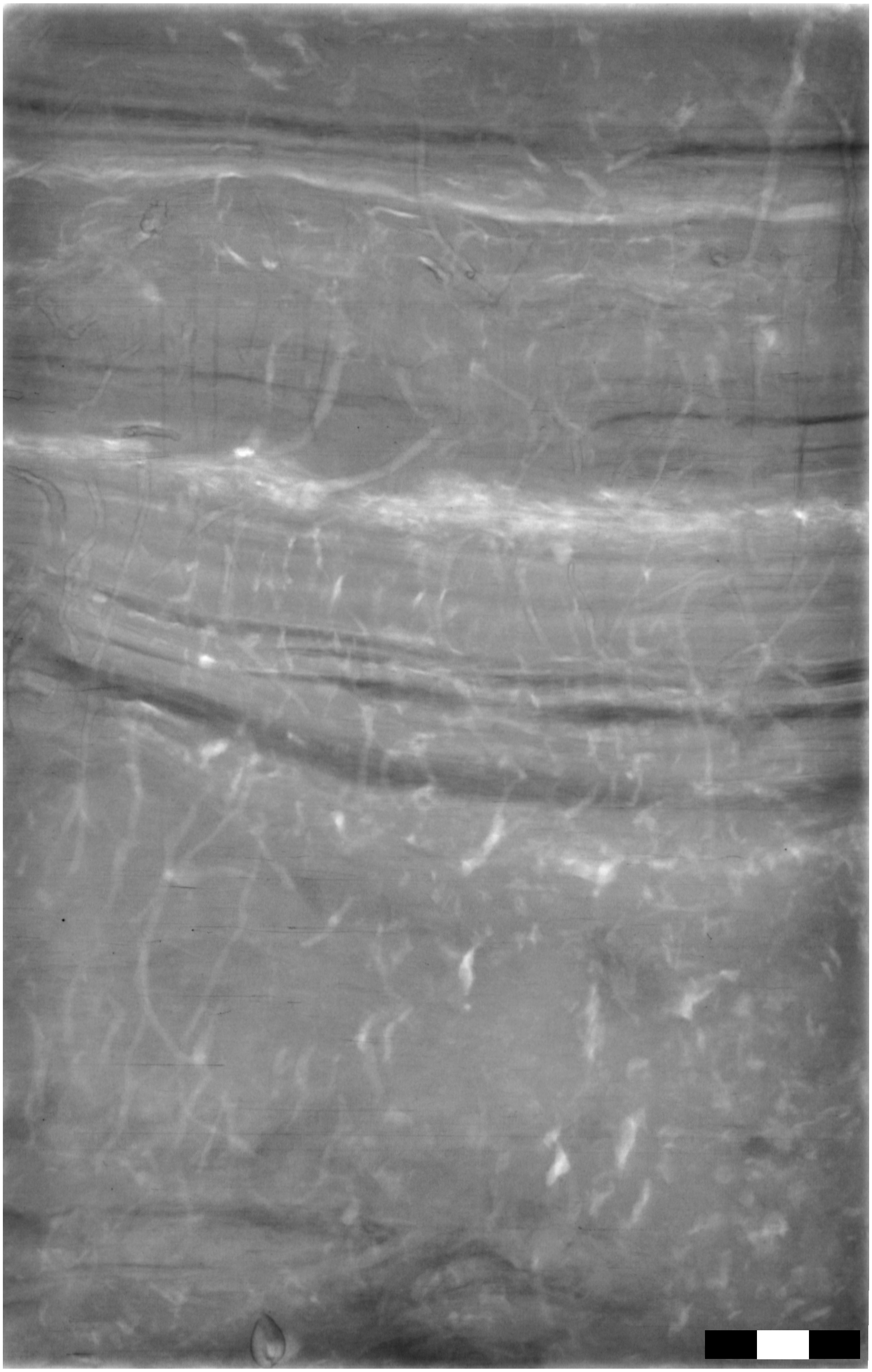

Fig. A-14: Mud flat on Lois Island near salt marsh transition. Salinity of 2 ppt.

Fig. A-15: Mud flat on Lois Island near salt marsh transition. Salinity of 2 ppt.

Fig. A-16: Mud flat on Lois Island within Cathlamet Bay. Salinity of 3 ppt.

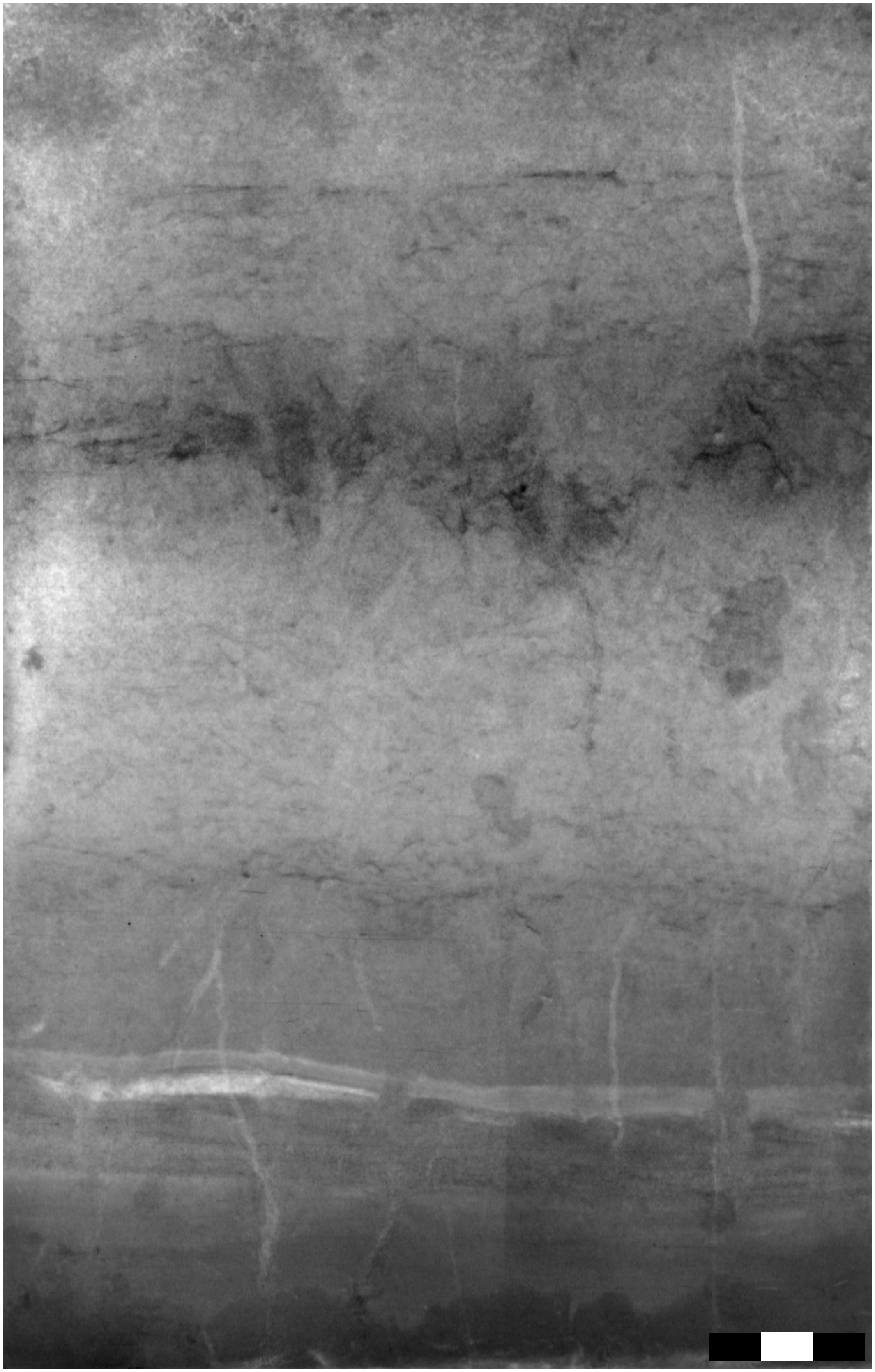

Fig. A-17: Sand flat on Lois Island. Salinity of 2 ppt.

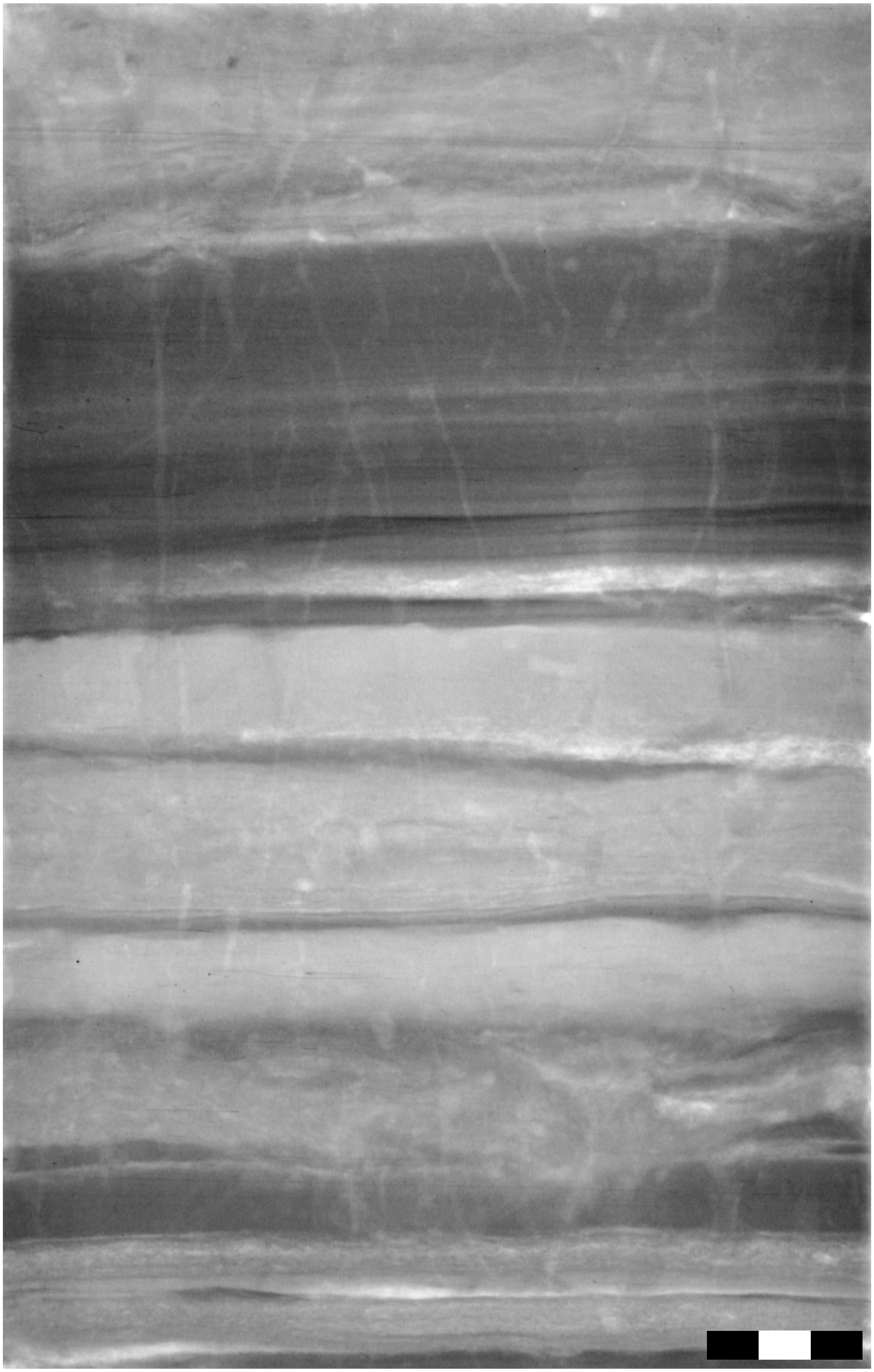

Fig. A-18: Mud flat on Lois Island within Cathlamet Bay. Salinity of 0.5 ppt.

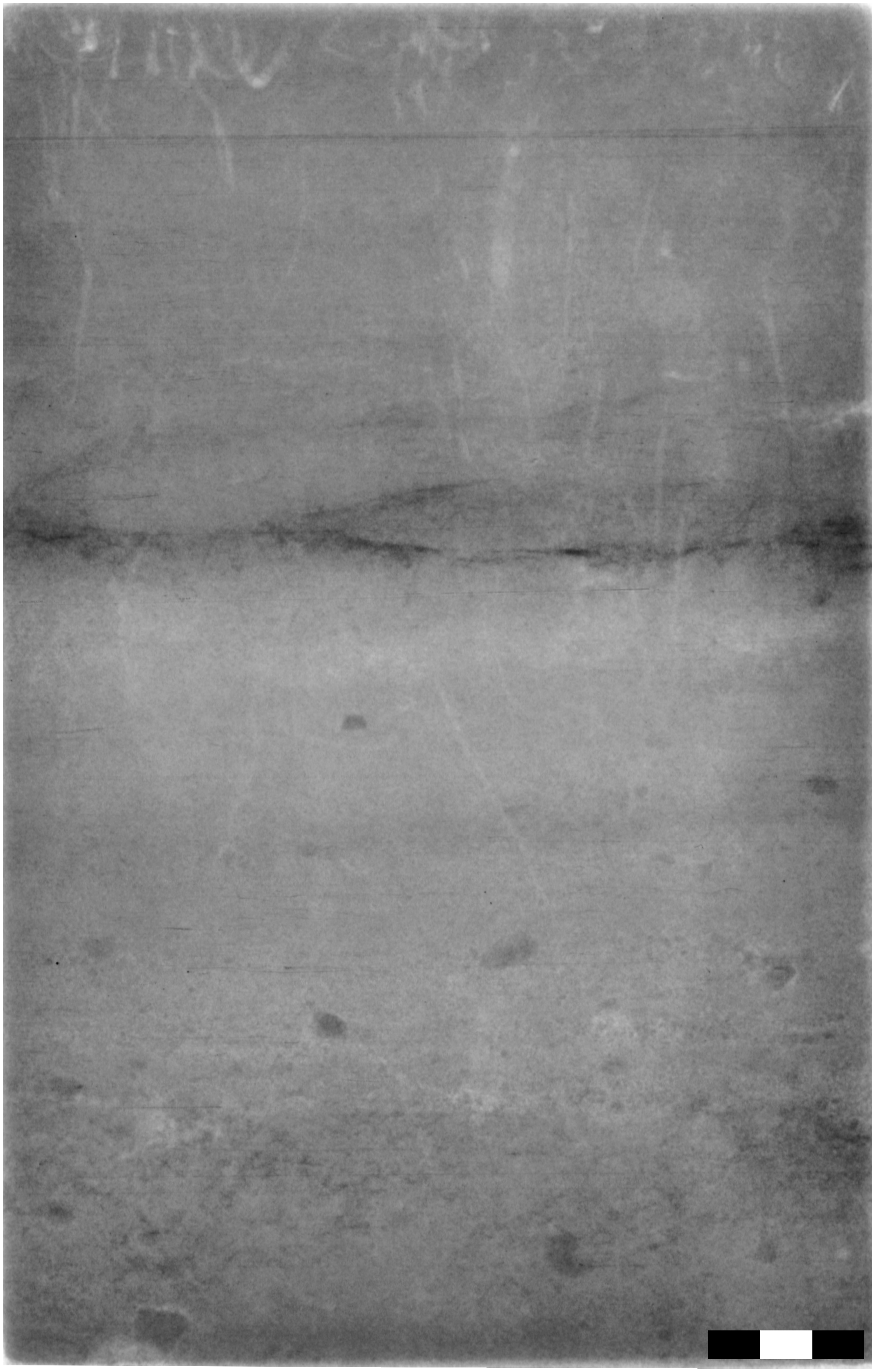

Fig. A-19: Muddy sand flat on Rice Island. Salinity 0 ppt.

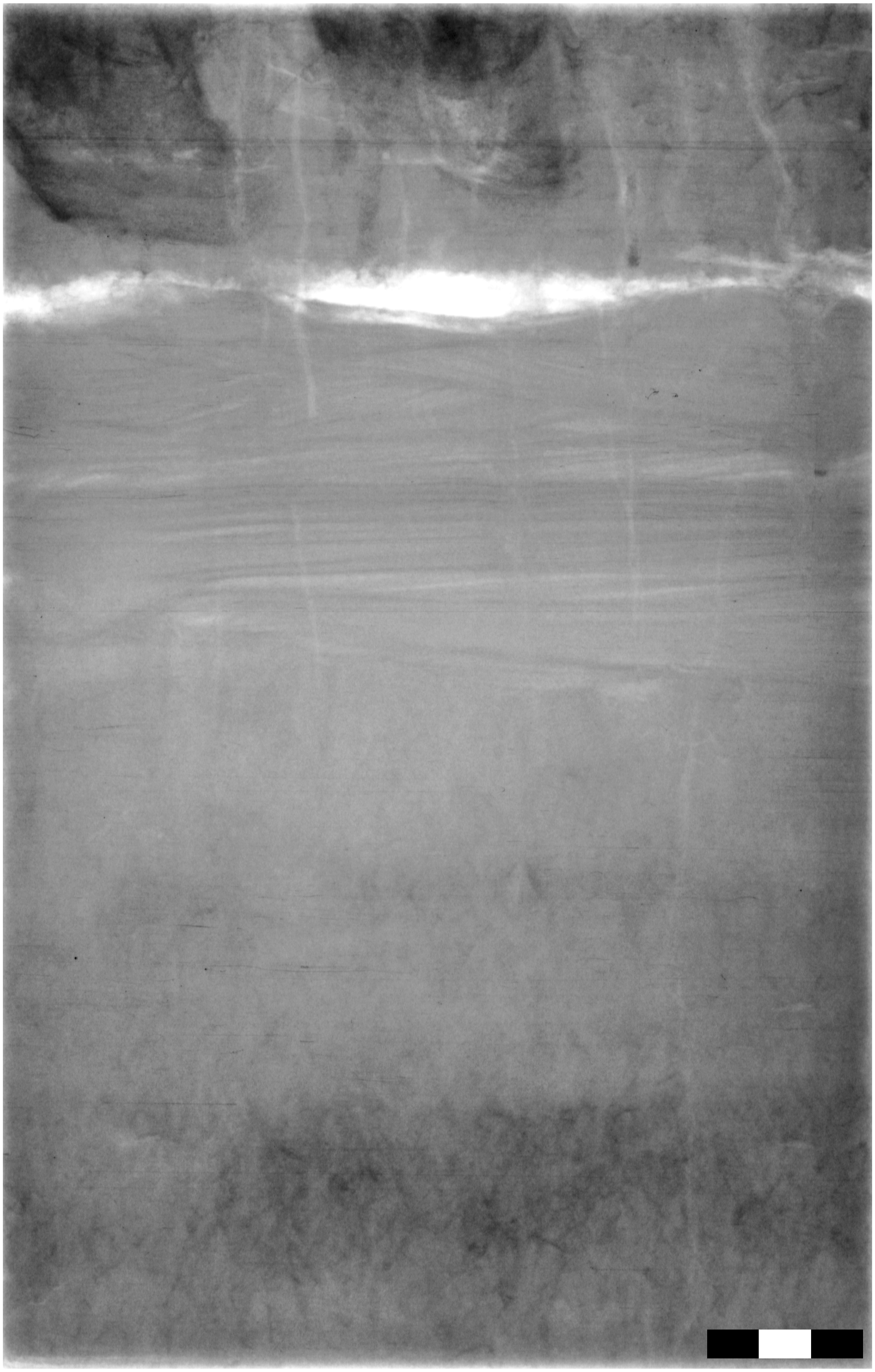

Fig. A-20: Sand flat with 1-2 mm mud layer on Miller Sands. Salinity of 0 ppt.

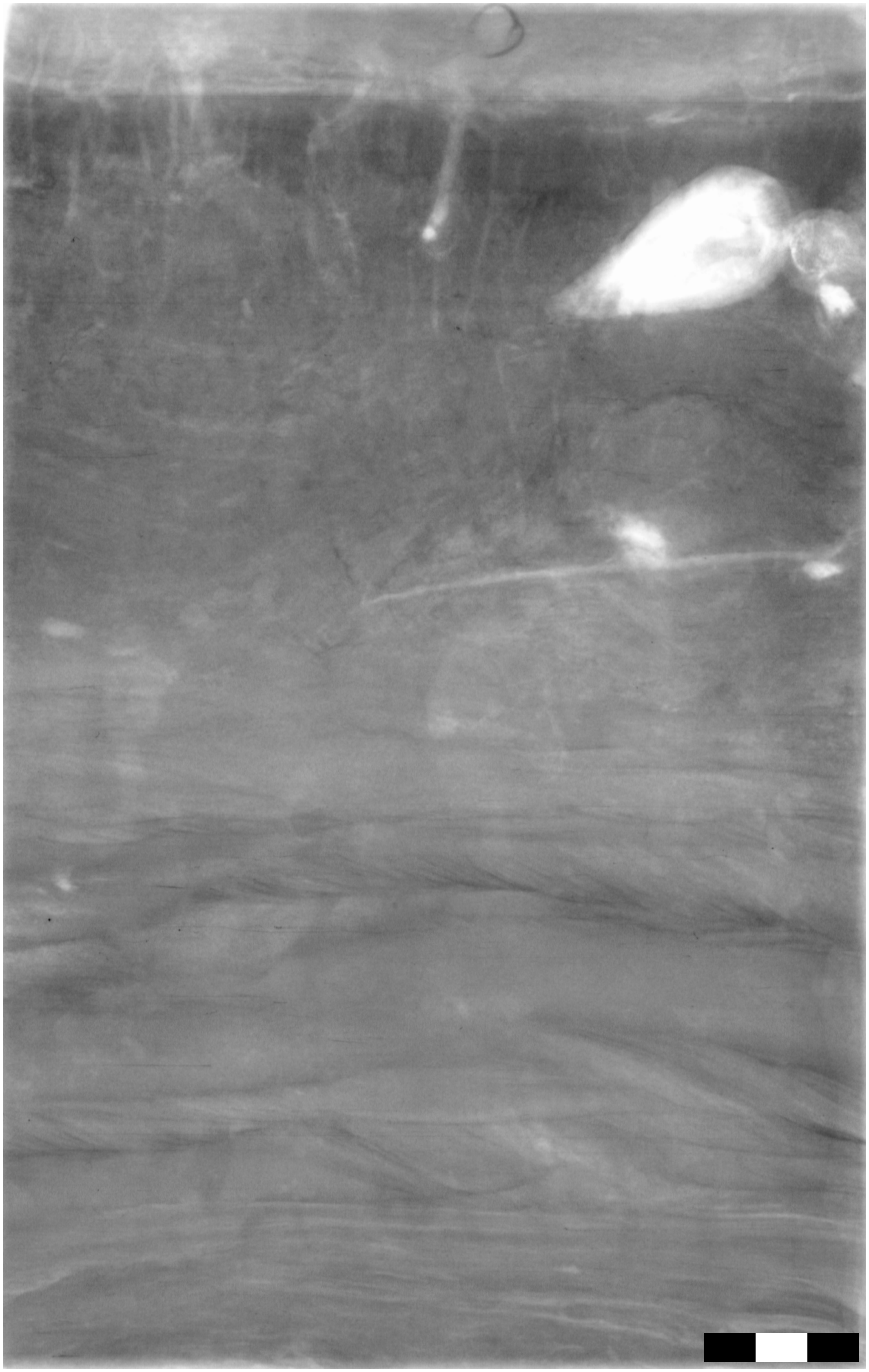

Fig. A-21: Muddy sand flat near salt marsh transition on Seal Island. Salinity of 1 ppt.

Fig. A-22: Muddy sand flat near salt marsh transition on Seal Island. Salinity of 1 ppt.

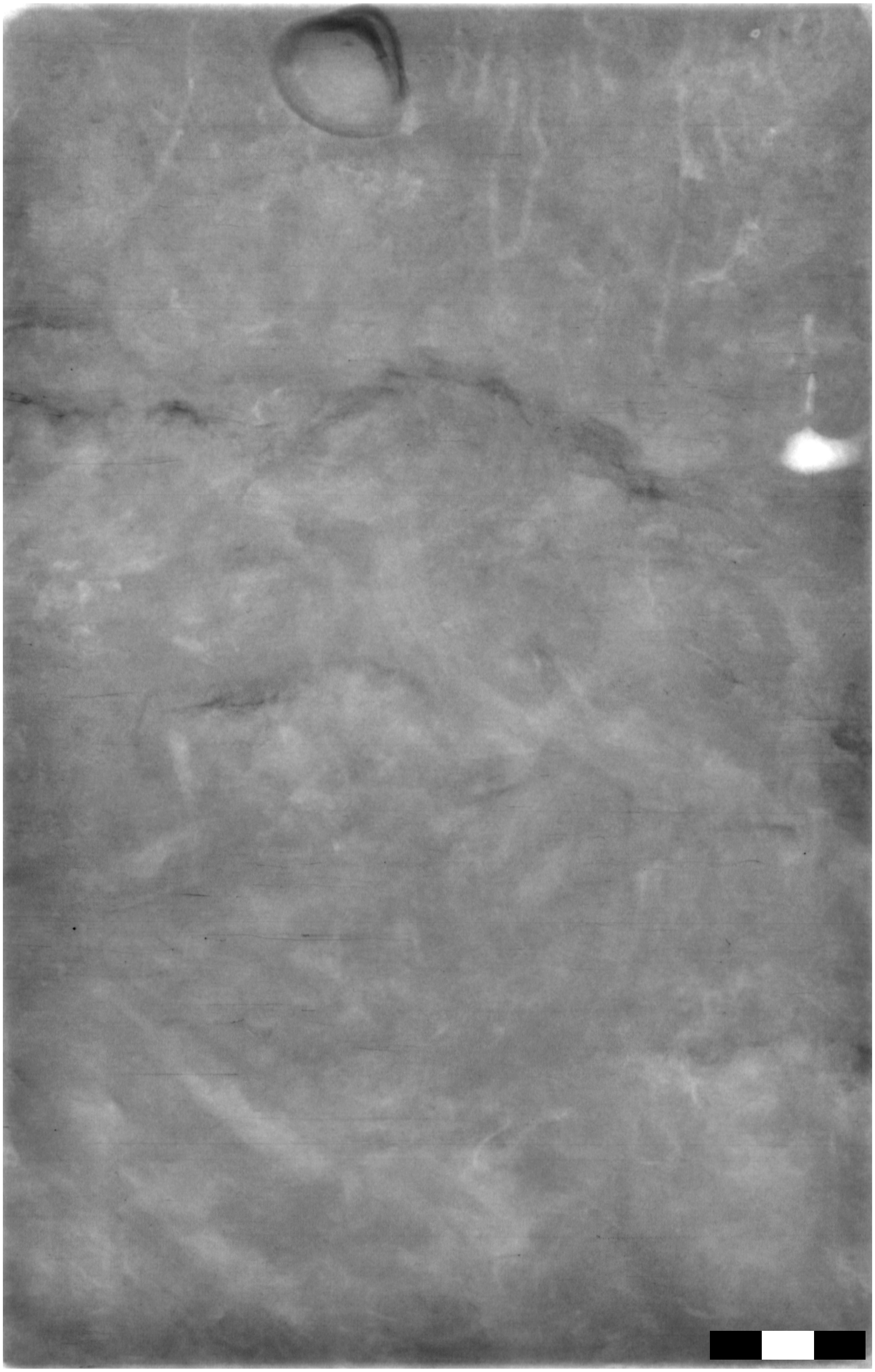

Fig. A-23: Muddy sand flat on Karlson Island. Salinity of 1 ppt.

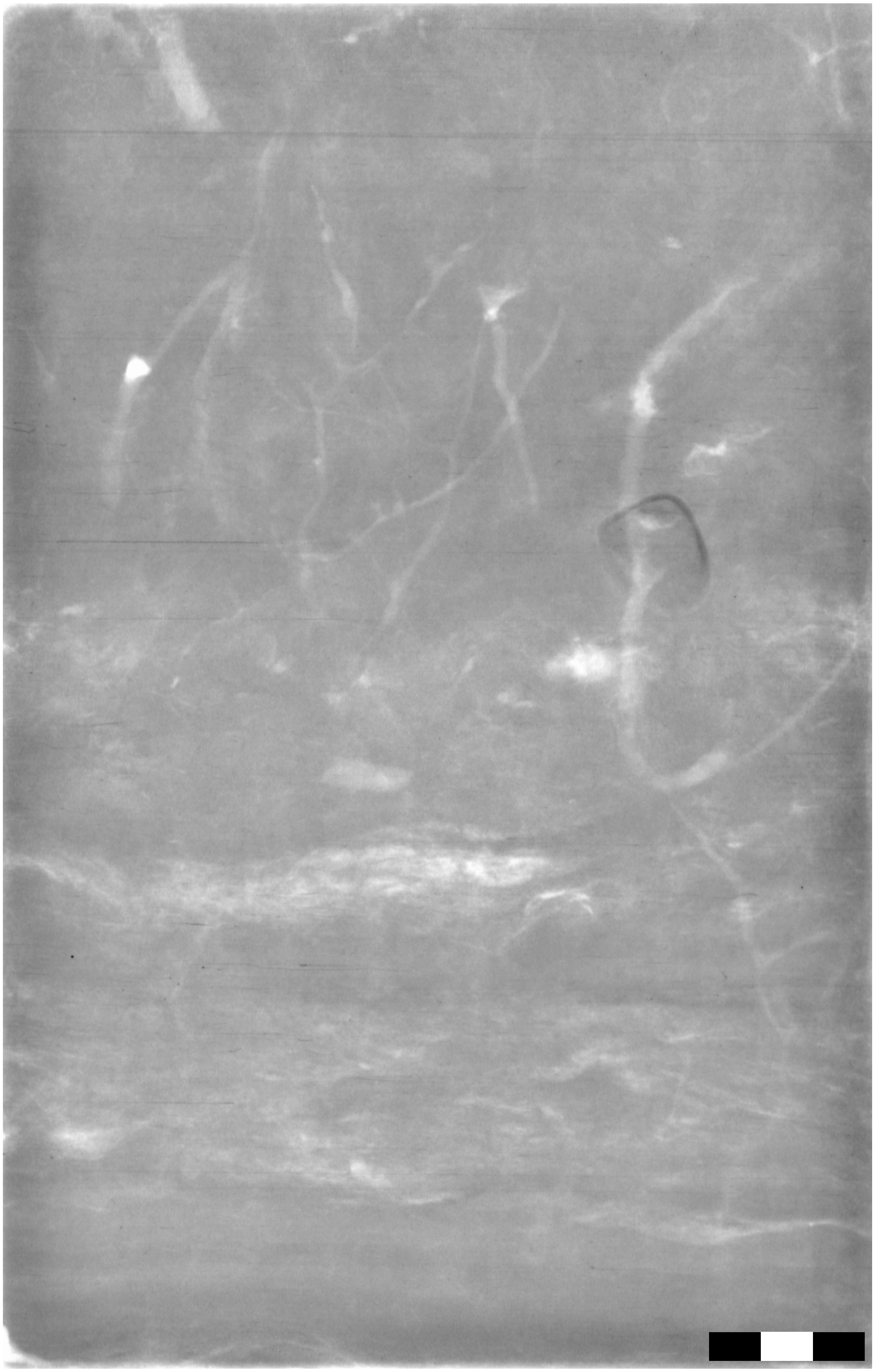

Fig. A-24: Sand flat on Karlson Island. Salinity of 1 ppt.

Fig. A-25: Sand flat near salt marsh transition on Marsh Island. Salinity of 1 ppt.

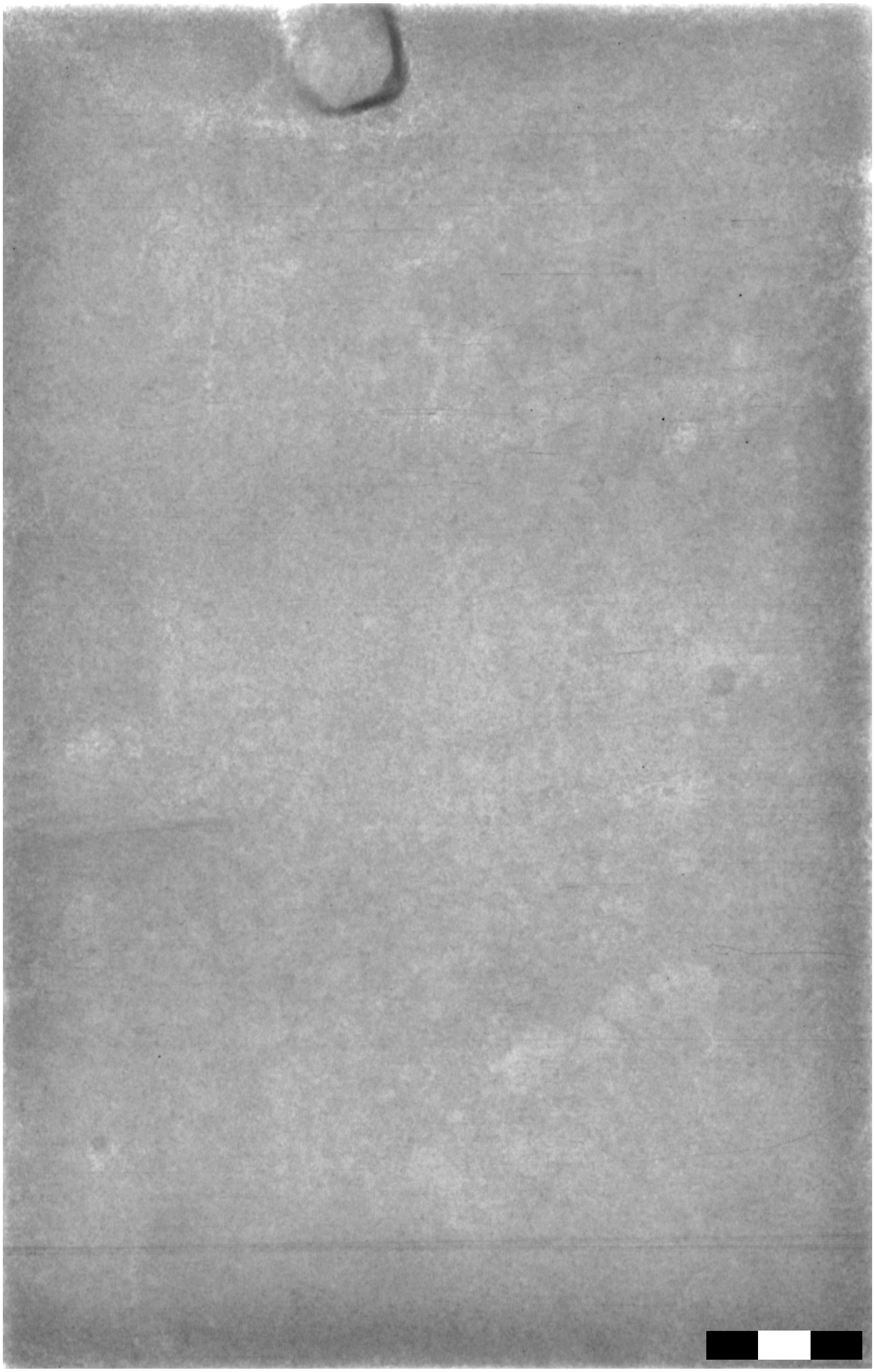

Fig. A-26: Sand flat on Woody Island. Salinity of 0.5 ppt.

Fig. A-27: Sand flat near salt marsh transition on Grassy Island. Salinity of 0.5 ppt.

Fig. A-28: Sand flat on Grassy Island. Salinity of 0.5 ppt.

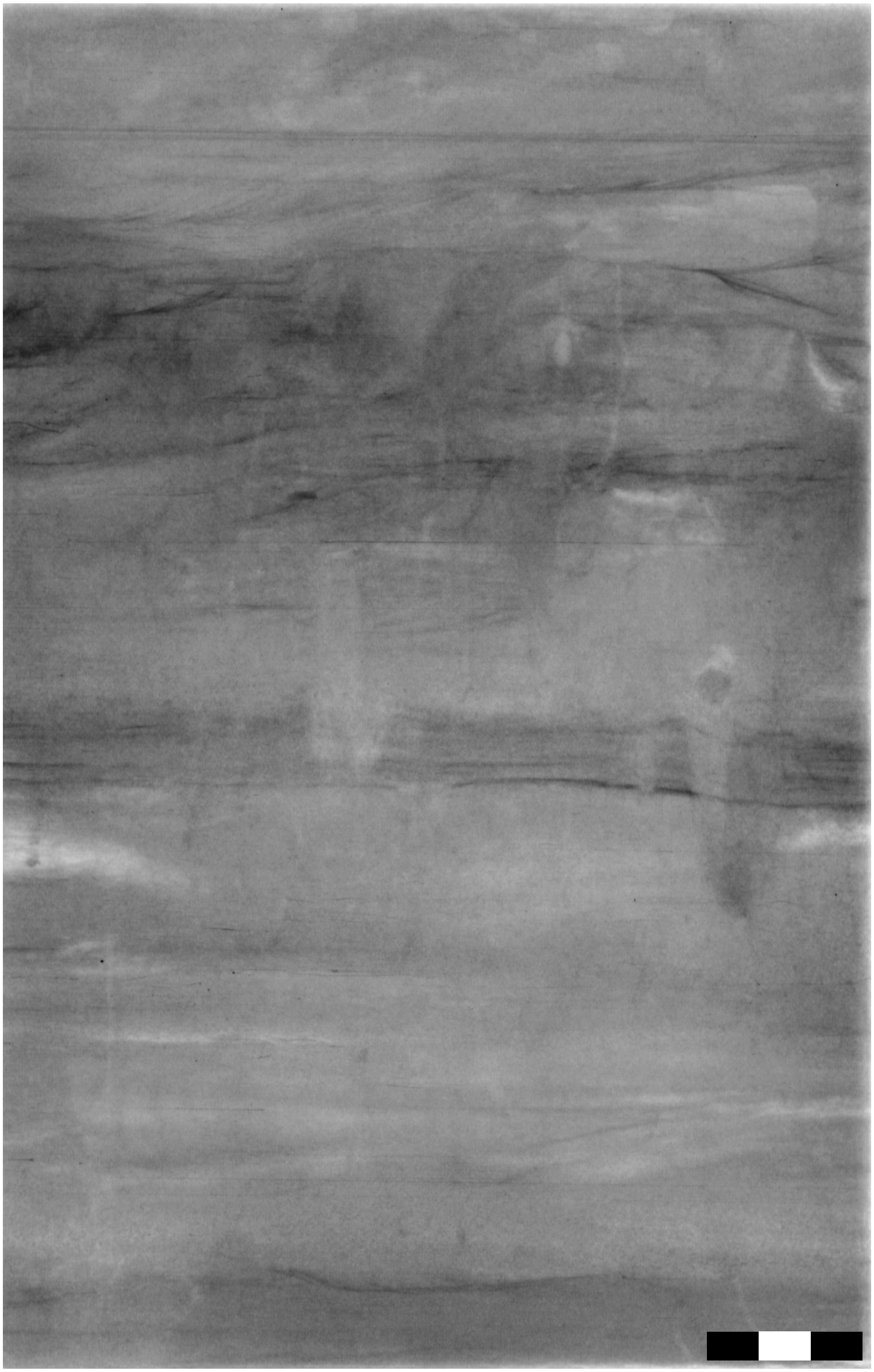

Fig. A-29: Sand flat on Fitzpatrick Island. Salinity of 0.5 ppt.

Fig. A-30: Sand flat near salt marsh transition on Fitzpatrick Island. Salinity of 0.5 ppt.

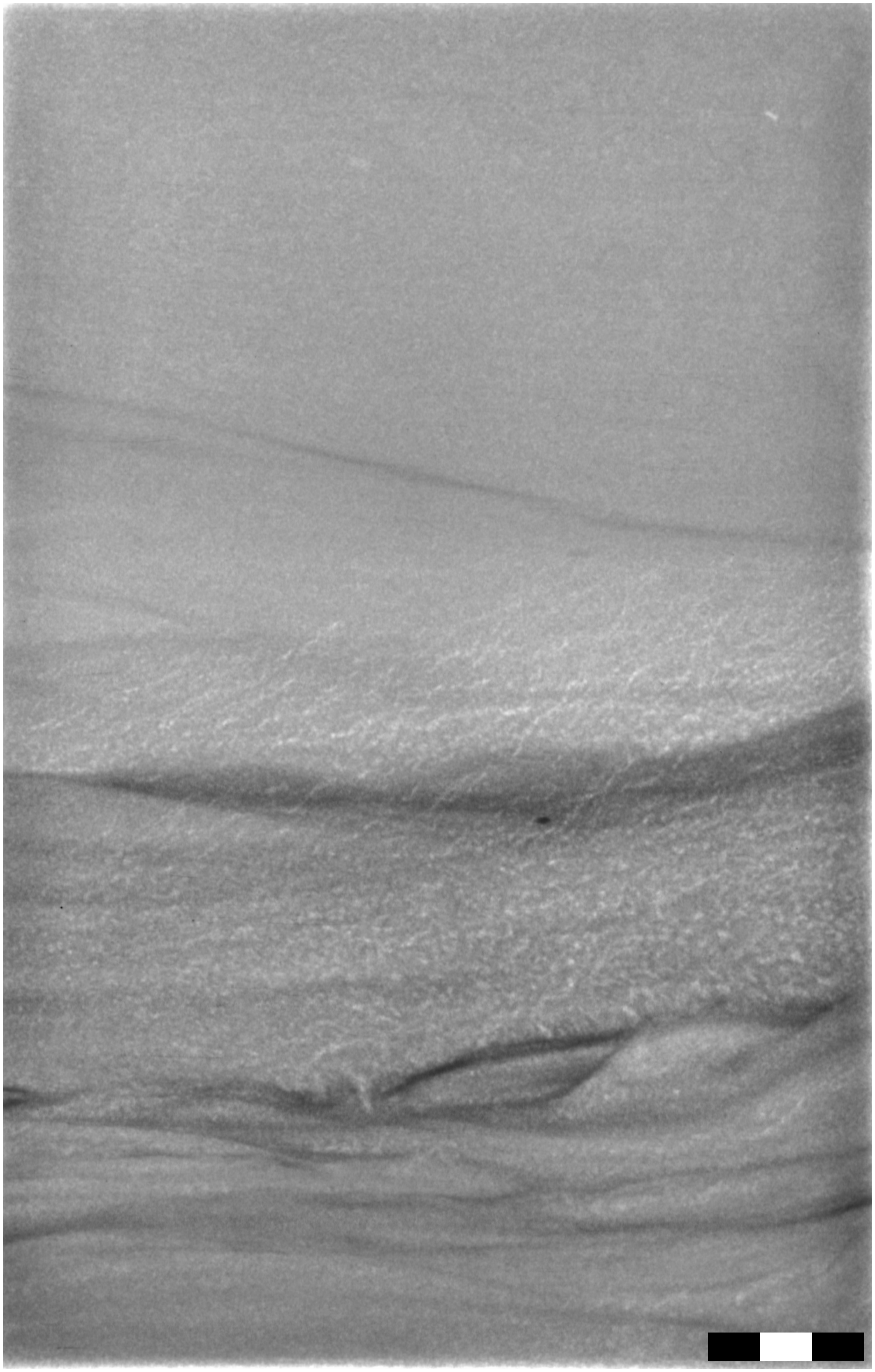

Fig. A-31: Heavy mineral-rich sand flat on Tenasillahe Island. Salinity of 1 ppt.

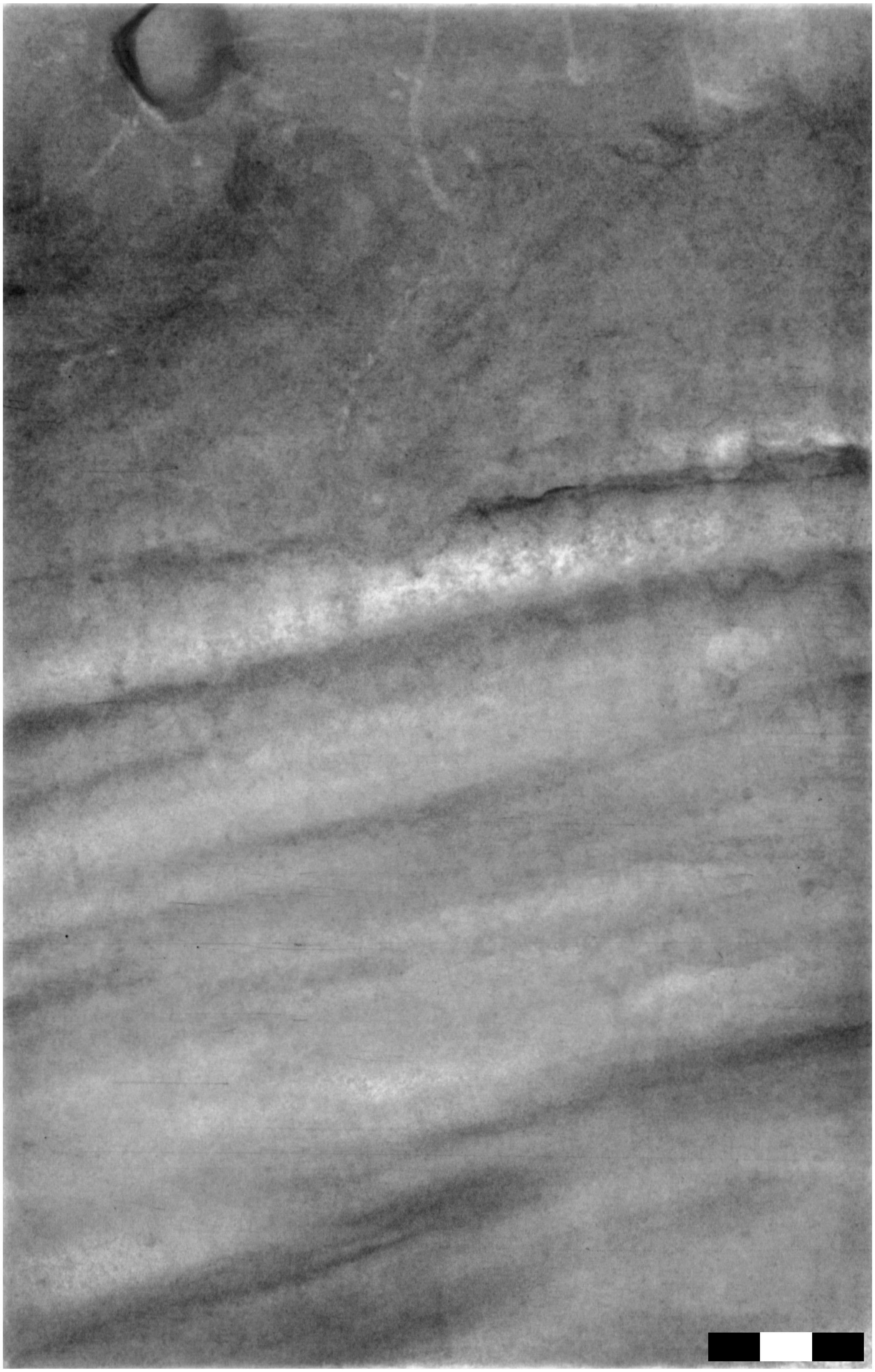

Fig. A-32: Sand flat with mud in ripple troughs on Coffee Pot Island. Salinity of 0.5 ppt.

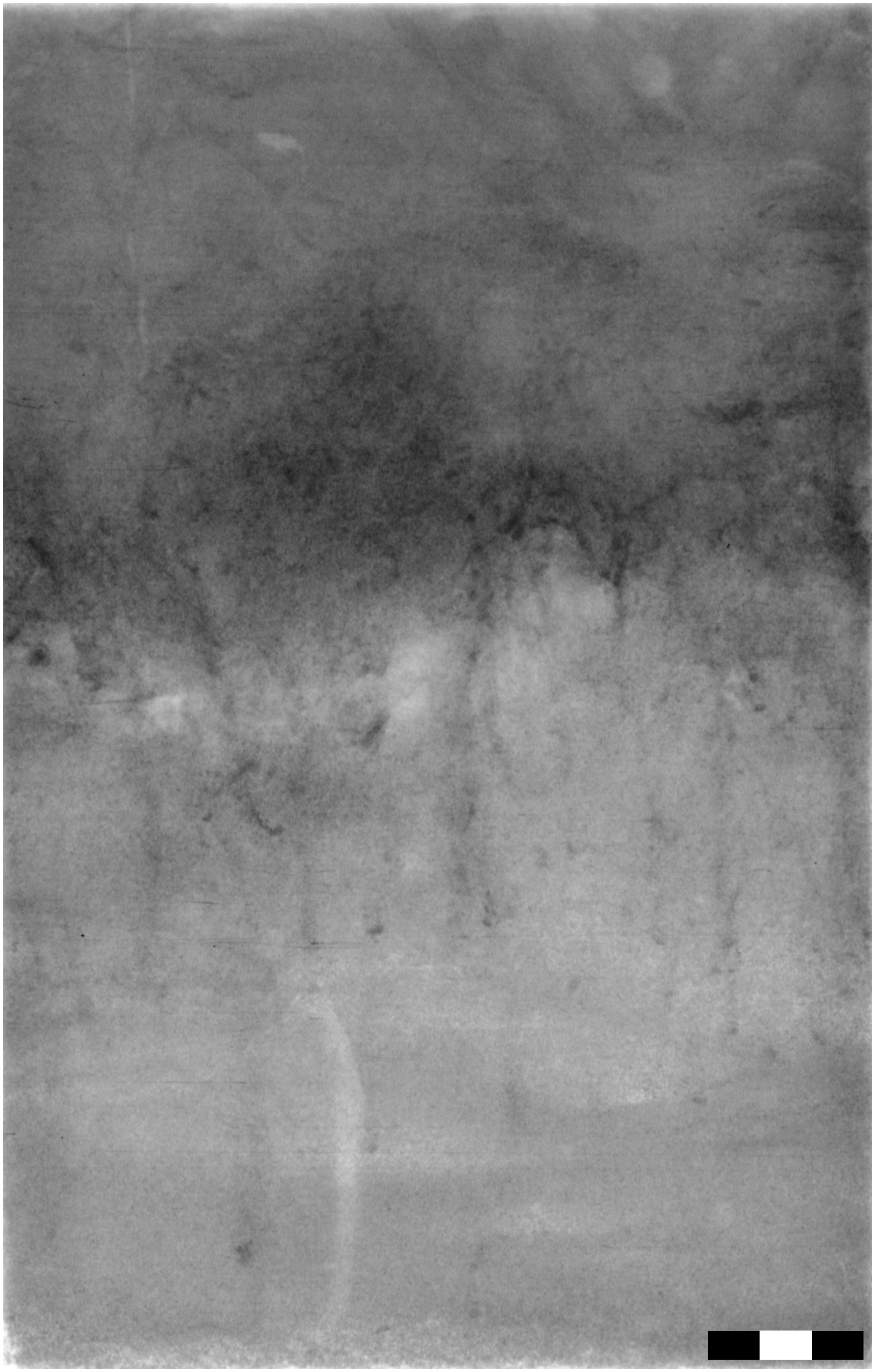

Fig. A-33: Sand flat on Coffee Pot Island. Salinity of 0.5 ppt.

Fig. A-34: Sand flat near salt marsh transition on Cooper Island. Salinity of 1 ppt.

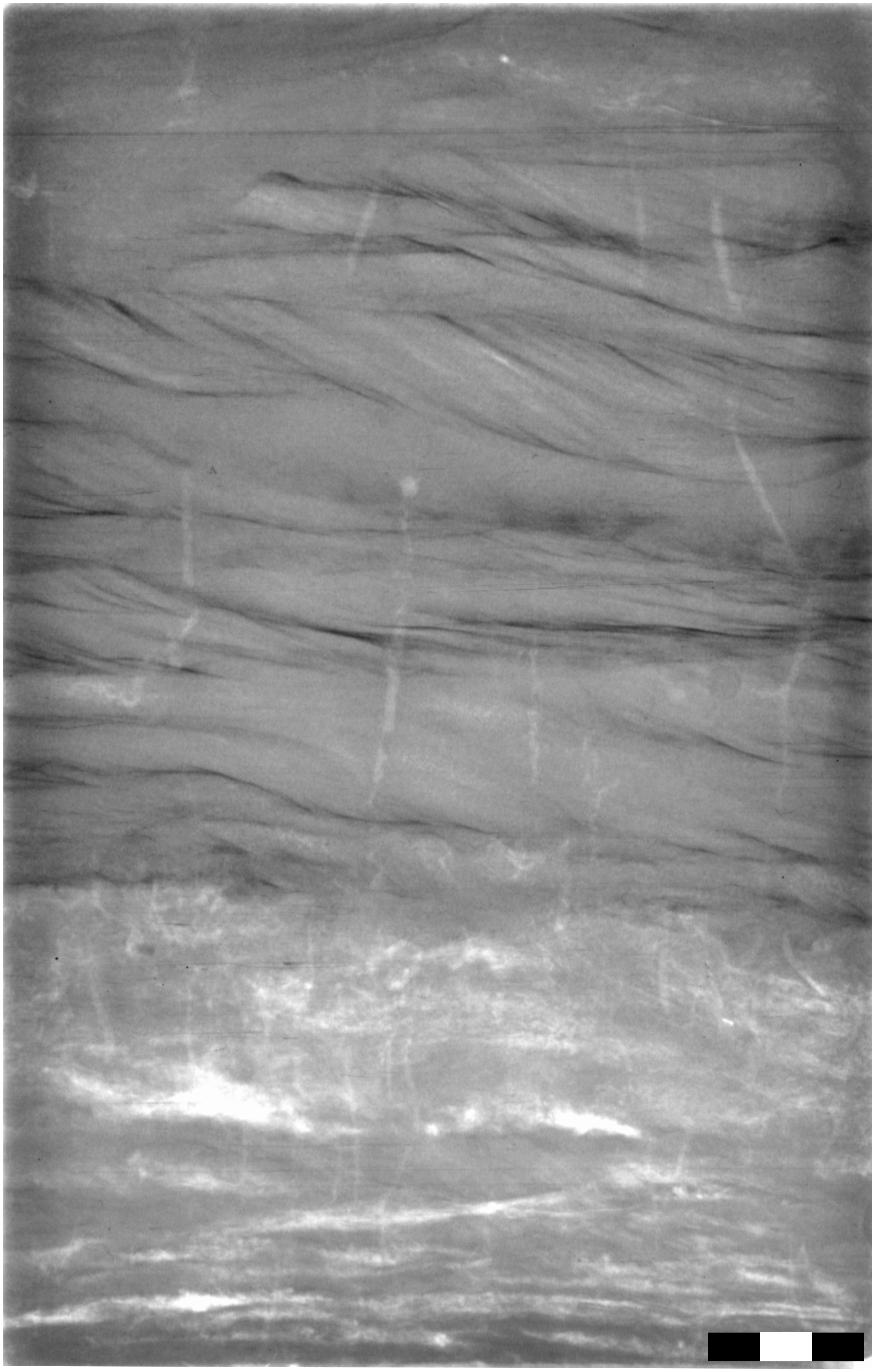

Fig. A-35: Sand flat with mud in ripple troughs on Cooper Island. Salinity of 1 ppt.

Fig. A-36: Muddy sand flat on Wallace Island. Salinity of 1 ppt.

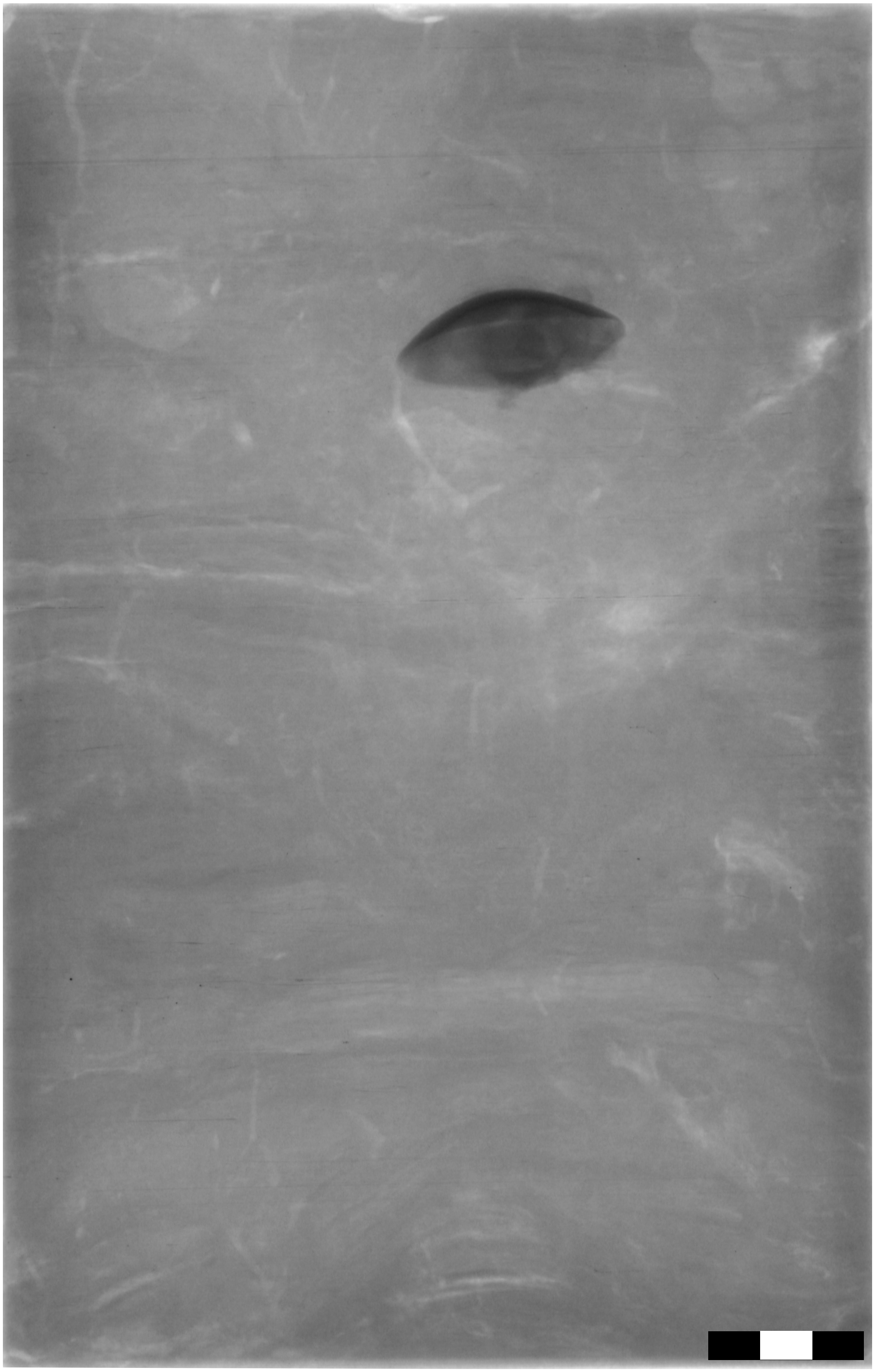

Fig. A-37: Mud flat along Oregon coast. Salinity of 1 ppt.

Fig. A-38: Sand flat on Gull Island. Salinity of 0.5 ppt.

Fig. A-39: Sand flat on Gull Island. Salinity of 0.5 ppt.

Fig. A-40: Slightly muddy sand flat on Crims Island. Salinity of 0.5 ppt.

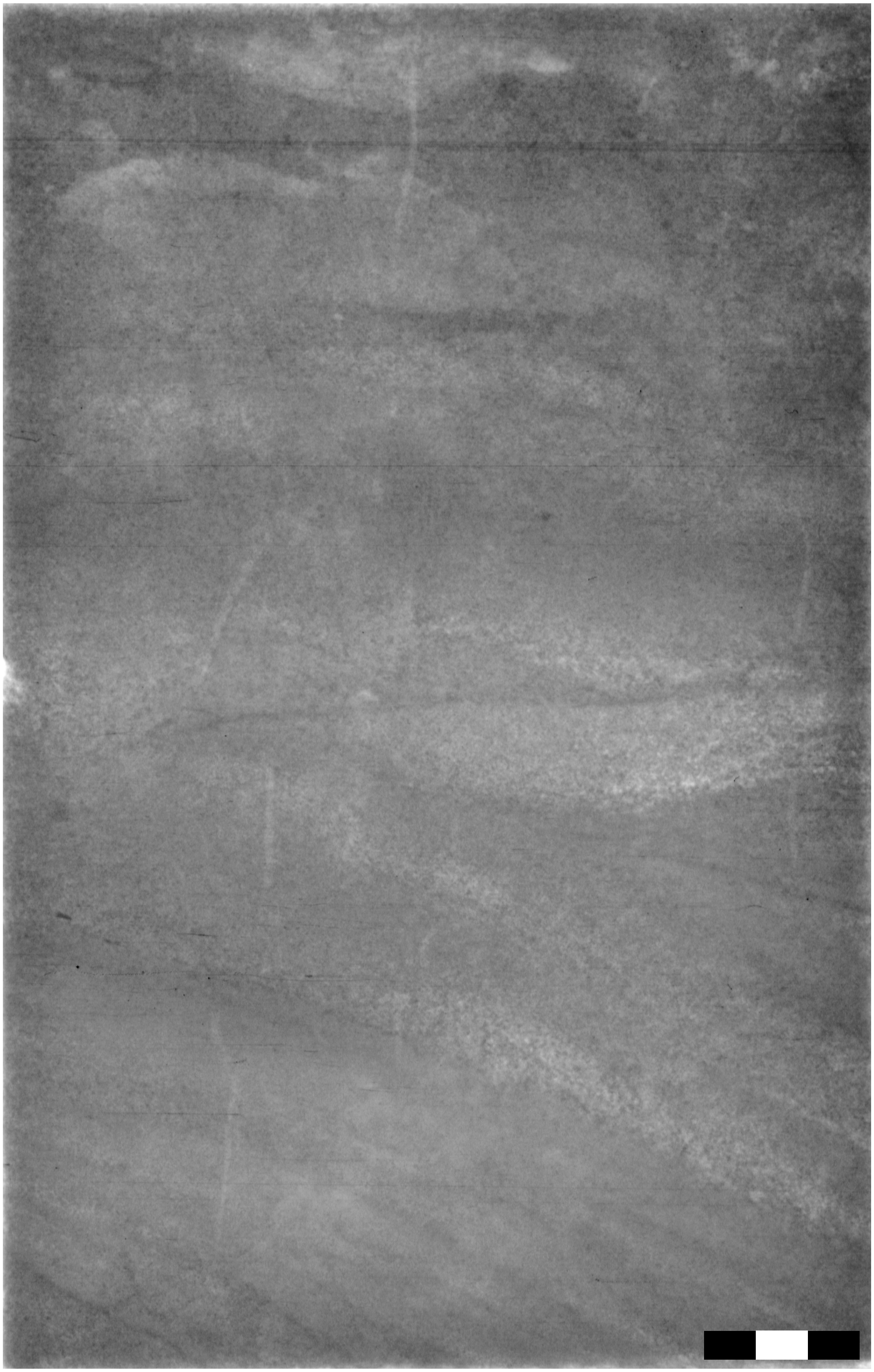

Fig. A-41: Slightly muddy sand flat on Crims Island. Salinity of 0.5 ppt.

Fig. A-42: Sand flat with mud in ripple troughs along Oregon coast. Salinity of 0 ppt.

Appendix B
Vibracore Data

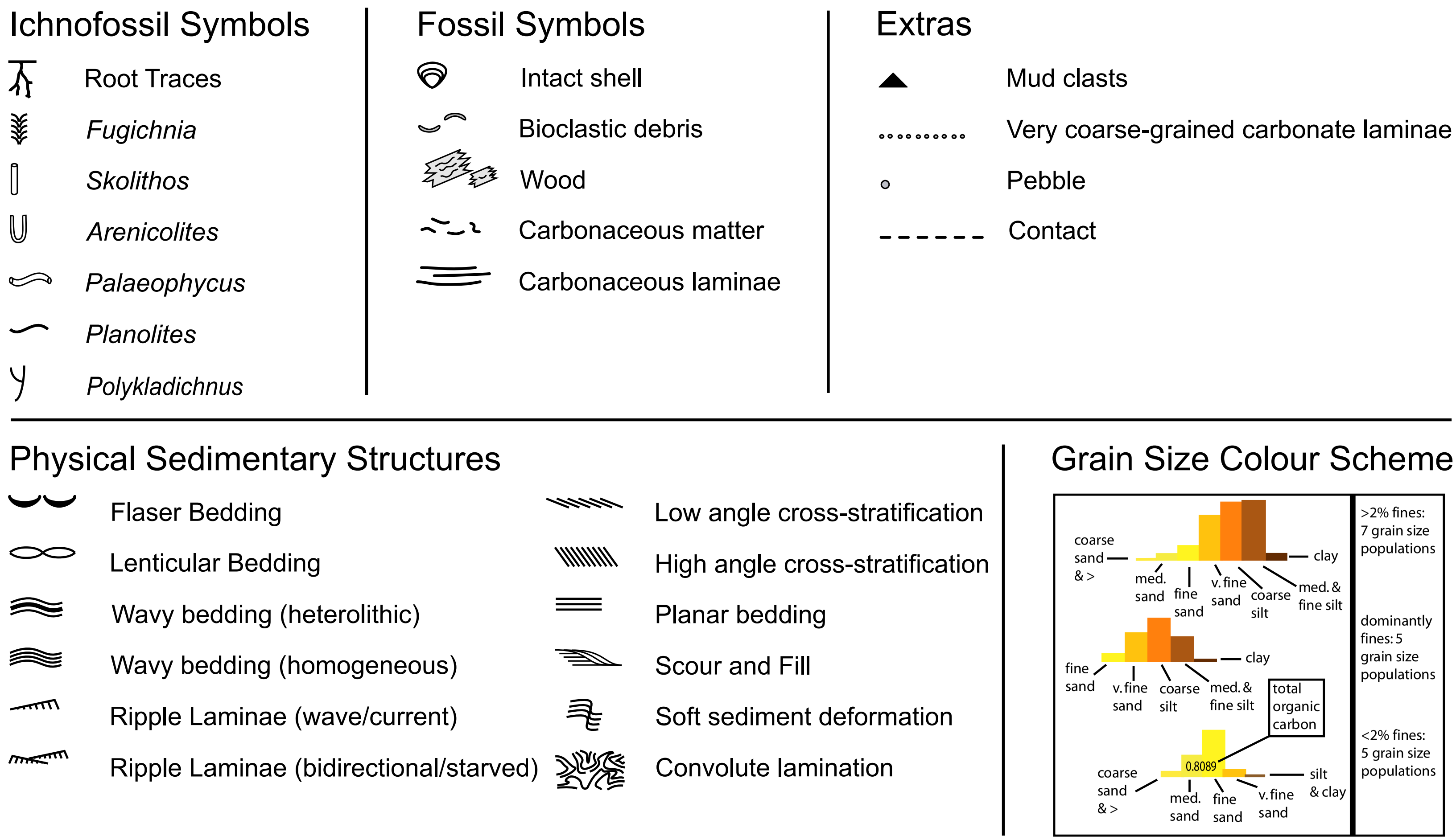

Fig. B-1: Legend of colours and symbols used.

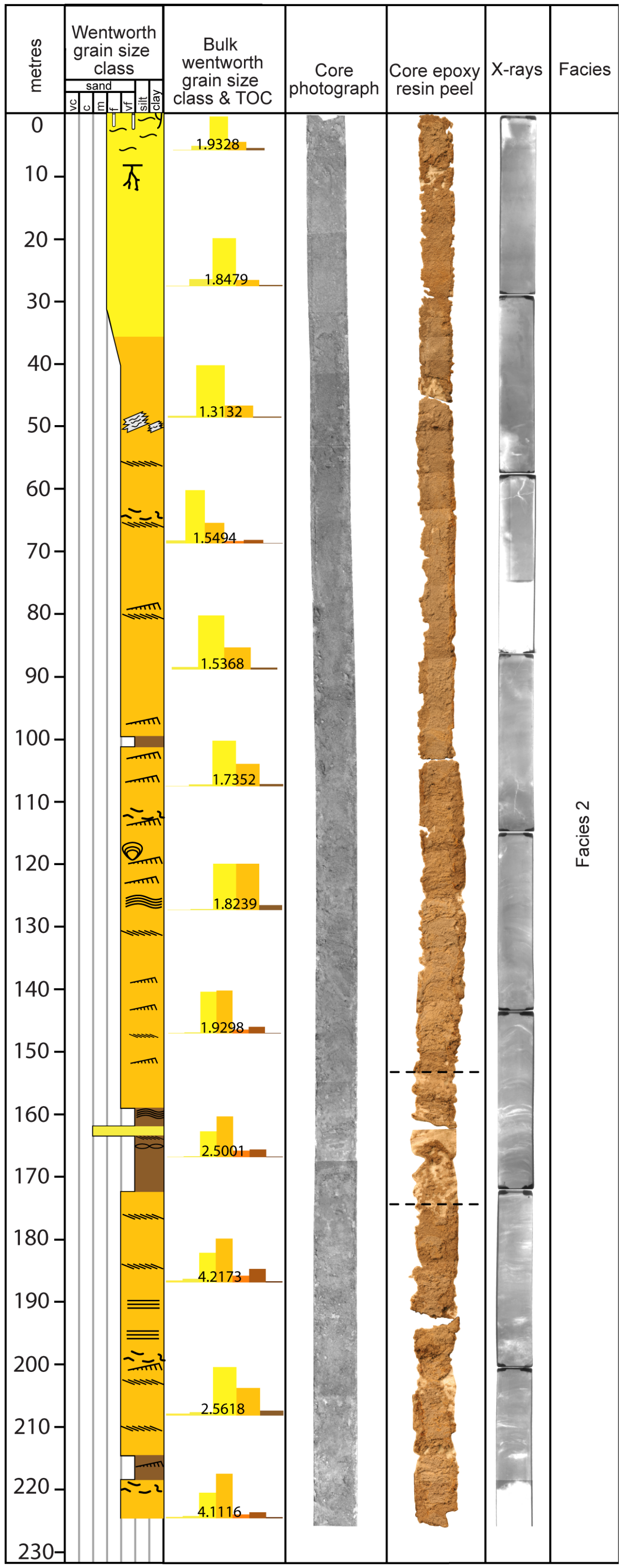

Fig. B-2: Vibracore 1 – Lois Island.

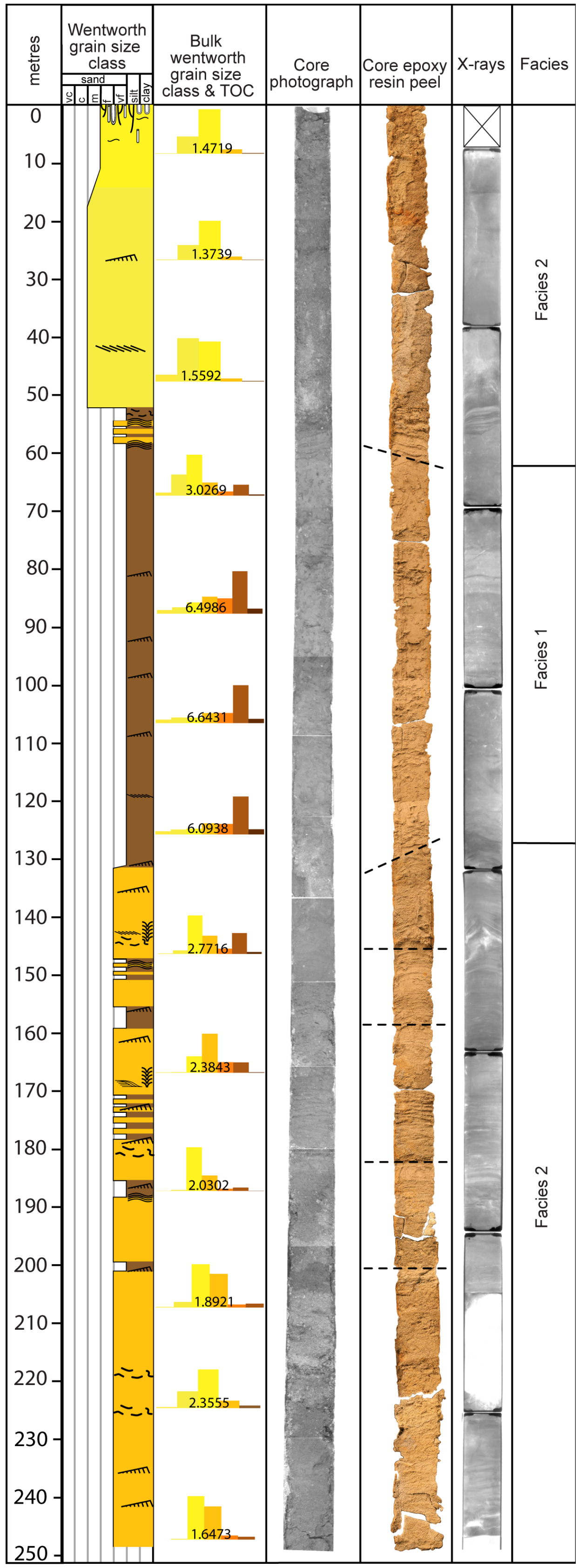

Fig. B-3: Vibracore 2 – Lois Island.

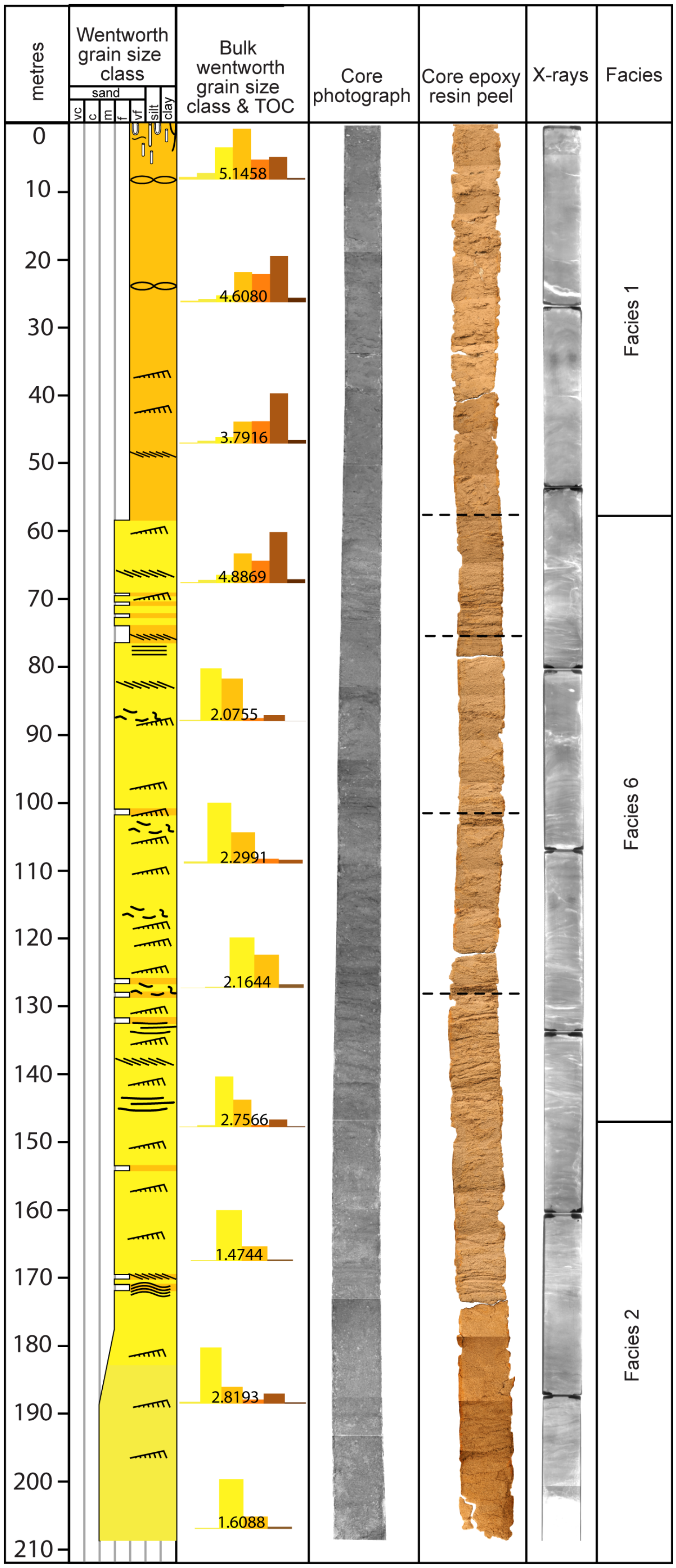

Fig. B-4: Vibracore 3 – Lois Island.

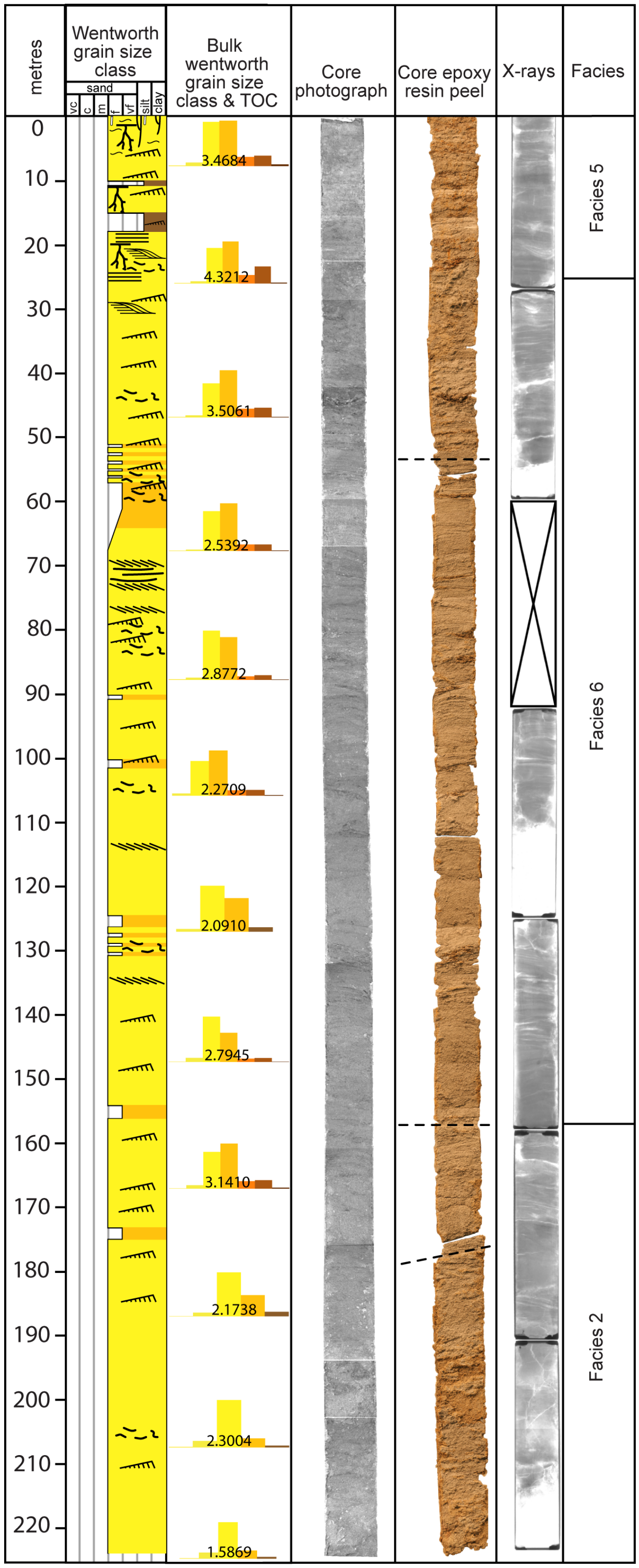

Fig. B-5: Vibracore 1 – Karlson Island.

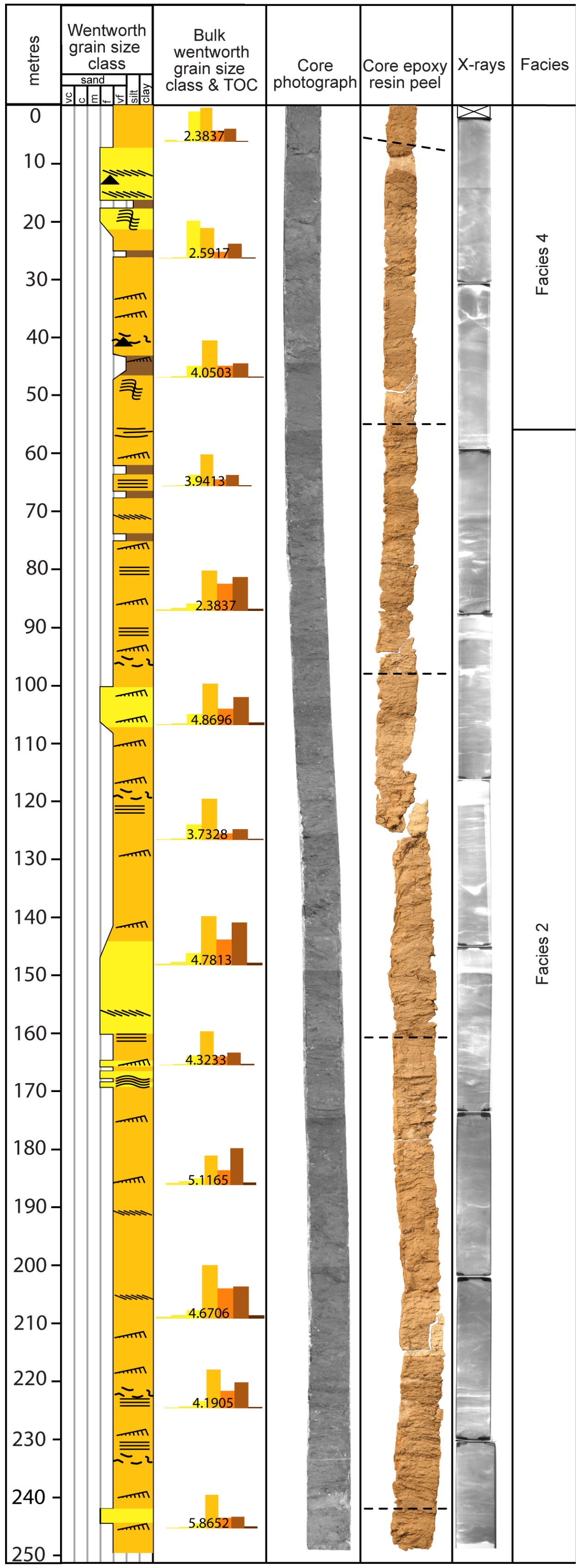

Fig. B-6: Vibracore 2 – Karlson Island.

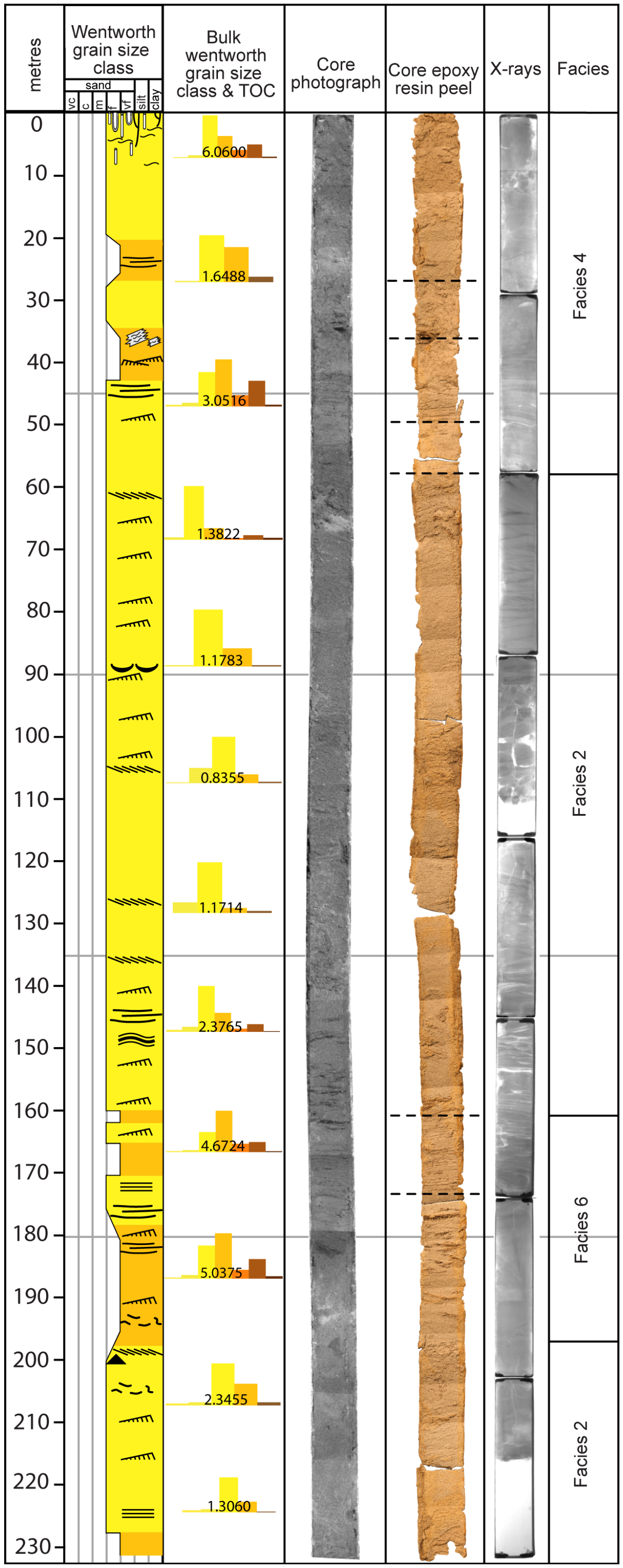

Fig. B-7: Vibracore 3 – Karlson Island.

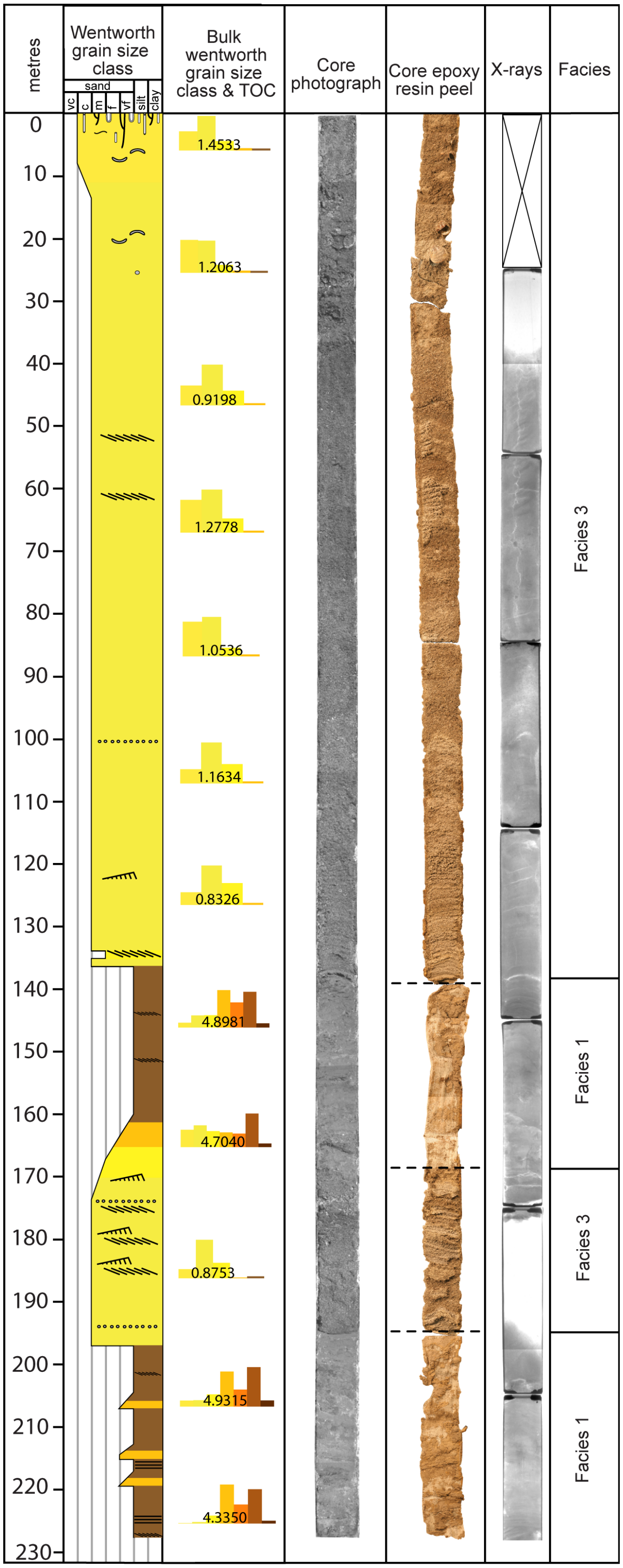

Fig. B-8: Vibracore 1 – Coffee Pot Island.

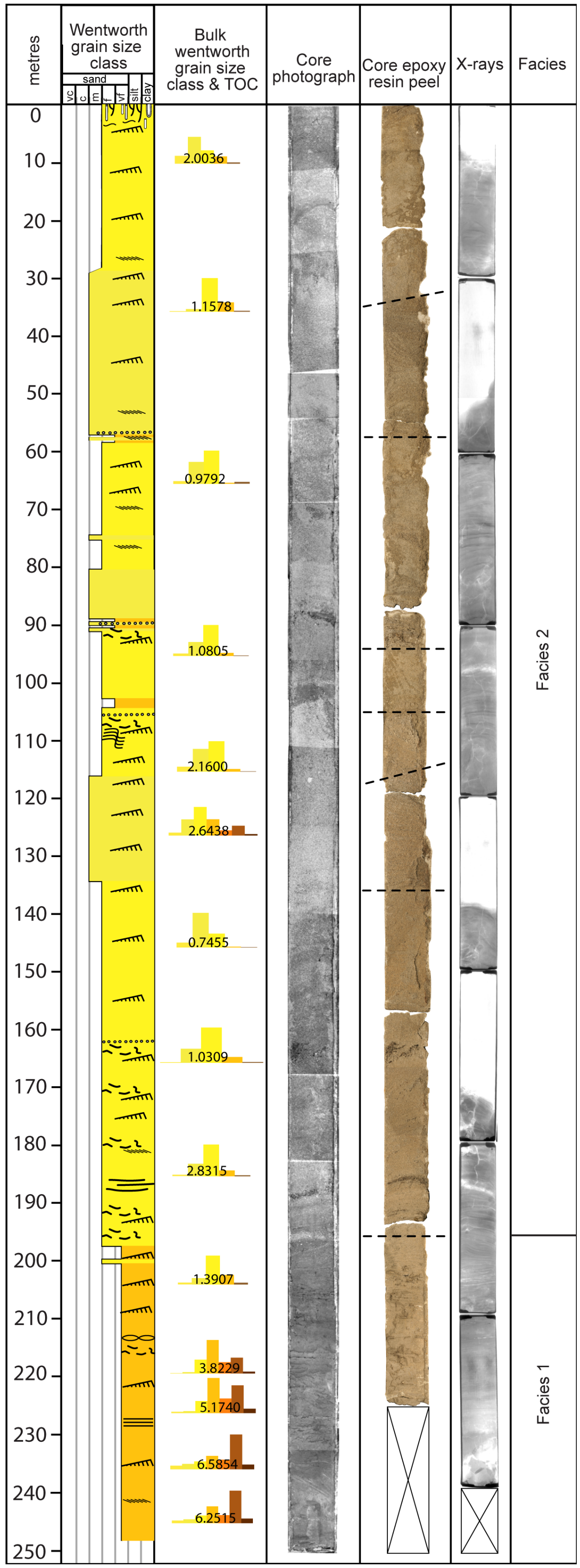

Fig. B-9: Vibracore 2 – Coffee Pot Island.

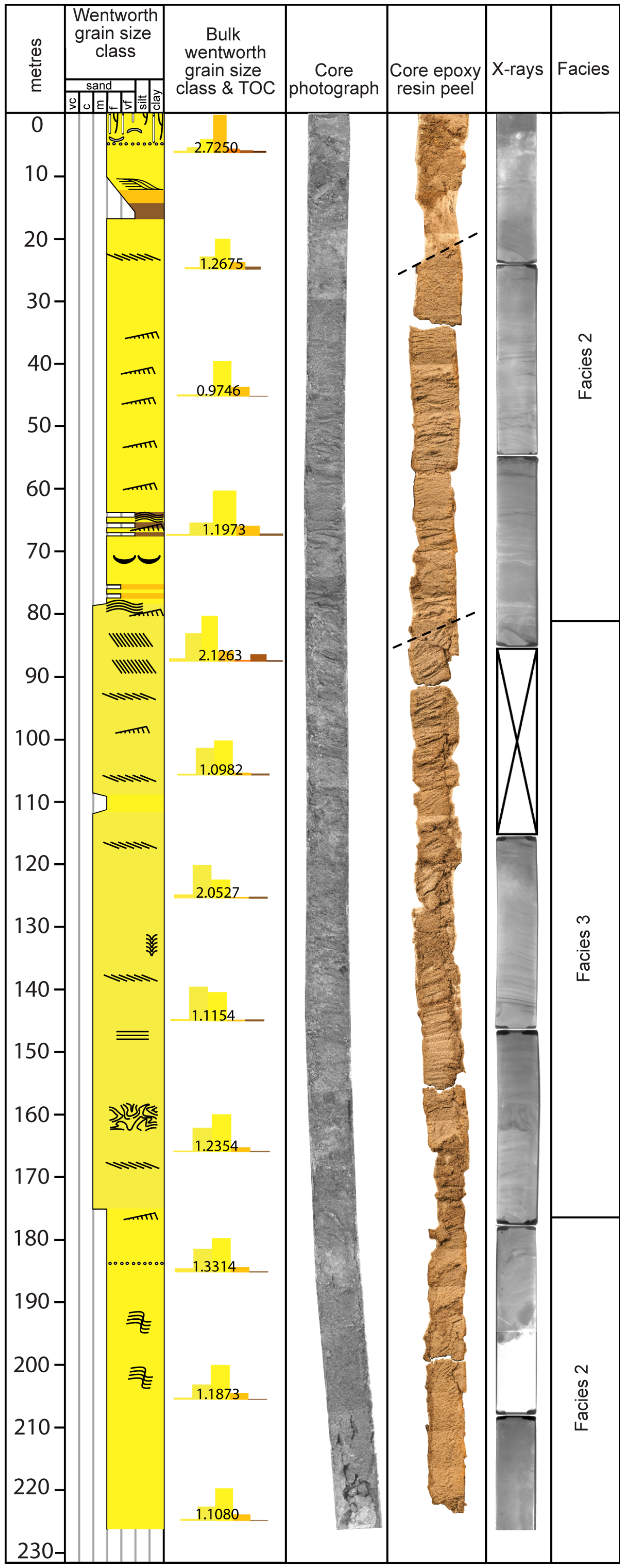

Fig. B-10: Vibracore 3 – Coffee Pot Island.