The Sedimentary Record

Sedimentation Across the Tidal-Fluvial Transition in the Lower Fraser River, Canada

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ABSTRACT

The Fraser River is the largest undammed river on the west coast of North America. In its lower reaches, a saltwater wedge intrudes up to 30 km inland during mixed semi-diurnal tidal cycles that range up to 5.3 m in height. Sediments deposited in the lower reaches of the Fraser River show distinctive characteristics that reflect the relative control of river versus tidal processes, as well as the persistence of saline water at each point along the channel. Grain-size trends along the river are controlled by the hydrodynamics in each distributary. Mud deposition is concentrated in the zone of saltwater-freshwater mixing. Coarse-grained sand and mud/fine-grained sand deposition is largely seasonally controlled, wherein bed material (diameter > 0.177 mm) is deposited during the waning freshet, and washload transported mud and fine-grained sand (< 0.177 mm) is deposited during the late-stage waning freshet flow and during base flow.

The diversity and density of bioturbation changes according to the volume and residence time of brackish water at the bed. Higher salinity water and greater durations that saline water is sustained at any locale, supports a more diverse and uniformly distributed trace assemblage. With decreasing salinity, the trace assemblage decreases in diversity and bioturbation becomes more sporadically controlled, wherein bed material (diameter > 0.177 mm) is deposited during the waning freshet, and washload transported mud and fine-grained sand (< 0.177 mm) is deposited during the late-stage waning freshet flow and during base flow.

Understanding sediment deposition across the tidal-fluvial transition has received increasing attention in recent years (e.g., Dalrymple and Choi 2007) in large part because subsurface reservoirs of the bitumen-hosting middle McMurray Formation in northeast Alberta are interpreted as paleo-estuarine channel bars (Pemberton and Wightman 1992; Ranger and Pemberton 1997; Musial et al. 2012). The lateral and vertical extent of mud beds and muddy bedsets interbedded with sand in the channel bars is the dominant control on reservoir compartmentalization, and can strongly impact the economic viability of exploiting hydrocarbons contained in these deposits (Strobl et al. 1997; Hein and Cotterill 2006). To better understand mud distribution in tide-influenced river channels, a range of modern analogues are being evaluated across the spectrum from tide-dominated (Dalrymple et al. 2003; Choi et al. 2004; Pearson and Gingras 2006), to fluvially influenced, tide-dominated (Smith 1988; Gingras et al. 1999; Smith et al. 2009), to mixed tidal-fluvial (Johnson 2012), to tide-influenced, fluvially dominated (Sisulak and Dashtgard 2012) to fluvially dominated (Smith et al. 2009; Smith et al. 2011) settings.

The lower Fraser River (Fig. 1) is a natural laboratory for studying sediment deposition in tide-influenced, fluvially dominated channels and mixed tidal-fluvial channels. The availability of historical and real-time hydraulic data (e.g., Johnson 1921; Ages 1979; Thomson 1981), the fact that the Fraser River is undammed along its entire length, and the extensive studies of sediment transport in the river (e.g., Kostashuk and Luternauer 1989; Church and Krishnapan 1995; Kostashuk and Villard 1996; Kostashuk et al. 1998; McLean et al. 1999; Kostashuk and Best 2005) provide datasets that can be used to link sedimentological, ichnological, and architectural characteristics of the sediments to the hydrodynamic and chemical conditions under which they were deposited and colonized by infauna.

INTRODUCTION

With increasing interest in recognizing differences in the sedimentological and ichnological character of sediments deposited across the tidal-fluvial transition, it is necessary to study a variety of modern analogs subjected to varying degrees of fluvial and tidal input. One such analog is the Fraser River, British Columbia, Canada, which in its lower reaches is affected by strong tidal flow. The grain sizes of sediments deposited in the channel are strongly linked to the degree of tidal flow relative to river flow, and to the extent and duration of saltwater intrusion at sites of sediment deposition. Consequently, the sedimentological and ichnological character of the sediments reflects the depositional conditions under which they were deposited, and hence, can be used as a proxy for establishing the volume and duration of saline water intrusion and the relative input of tidal versus river flow.

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THE FRASER RIVER

The Fraser River drains 228000 km² of mountainous terrain and has a mean annual river discharge of 2710 m³s⁻¹ at Hope, BC, ~165 river km upstream of the delta front. Low flow rates in winter are ~1000 m³s⁻¹, and the annual peak flow ranges between 5130 and 15200 m³s⁻¹ with a mean of 8642 m³s⁻¹ (Water Survey of Canada, http://www.wateroffice.ec.gc.ca/, accessed Sept 7, 2012). At low flow, the saltwater wedge (SWW) intrudes ~30 km upriver (Kostashuk and Atwood 1990). During high river flows,
the SWW is displaced towards the mouth of the channel. At river flows between 5000 and 7000 m$^3$ s$^{-1}$ (at Hope), a SWW has been observed to penetrate only a few kilometers up the Main Channel (red line, Fig. 1) during spring high tides (Milliman 1980). At high peak flows (~8000 m$^3$ s$^{-1}$ at Hope), however, the SWW likely does not enter the Main Channel.

In its tide-influenced lower reach, the Fraser River bifurcates into two distributaries, the North Arm and the Main Channel (Fig. 1). The North Arm bifurcates again to form the Middle Arm. Observations made in 1970 at a flow rate close to the mean annual peak rate (8670 m$^3$ s$^{-1}$) indicated that the North and Middle arms carried ~7% and ~5% of channel flow respectively (WCHL 1977). The Main Channel carried 70% of the flow and its distributary, Canoe Pass, carried 18% of the flow (Fig. 1).

Sediment flux in the Fraser is washload dominated. Washload is sediment not present in the channel bed and lower banks of the river, and that stays in suspension through a defined river reach (Church 2006). In the Main Channel and the North Arm, the washload is composed of fine sand (< 0.177 mm), silt, and clay, whereas in the Middle Arm and probably Canoe Pass, similar grain sizes are deposited on the channel bed during non-peak flows (Johnson 2012). Landward of New Westminster, before the Fraser bifurcates into its various distributaries, McLean et al. (1999) reported that between 1966 and 1986, the total sediment load was $1.7 	imes 10^6$ t yr$^{-1}$.

The remaining 60 km of tide-influenced river is regularly inundated by brackish water. The Fraser River exhibits significant volumes of both sand and mud in the tidally affected portions of the bars contain significant volumes of both sand and mud (Fig. 2). The channels in this reach also show evidence of lateral and downstream migration (prior to the channel being diked) and tend to

Sedimentological trends in the lower Fraser River

There are pronounced sedimentological trends in the lower Fraser River (Church 1983; McLean 1990; Ham 2005) to a sinuous sand-bed channel (Ventditt et al. 2010) with in-channel (tidal) bars. The position of this transition is thought to be topographically controlled (Ventditt et al. 2010), although tides may play a secondary role. The wandering gravel-bed river occurs wholly in the freshwater, non-tidal reach, whereas the sand-bed channel extends through the freshwater-tidal and brackish water-tidal reaches.

In the brackish water-tidal reach, saltwater intrusion (brackish-water + tidal, Fig. 1) is periodic (depending on river discharge) and the tidally affected portions of the bars contain significant volumes of both sand and mud (Fig. 2). The channels in this reach also show evidence of lateral and downstream migration (prior to the channel being diked) and tend to
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2) The most significant change observed in the sedimentology between the freshwater-tidal reach and the brackish water-tidal reach is in the distribution of mud. In the freshwater-tidal reach, mud-dominated beds and bedsets are typically thin (< 10 cm thick) and are laterally continuous for meters to tens of meters. The channel bottom and intertidal banks are sand-dominated (Fig. 2), and mud deposited during base flow is typically eroded during the freshest. In the brackish water-tidal reach, mud deposition is increasingly widespread (Fig. 3). Mud beds and mud-dominated bedsets thicken (to > 1 m thick) and are laterally continuous for hundreds of meters to kilometers in the intertidal zone and likely the upper subtidal zone (Johnson 2012; Sisulak and Dashtgard 2012). The thickness and lateral continuity of muddy bedsets is linked, at least in part, to the persistence and duration of saline water and the development of a turbidity maximum, and in part to the relative influence of fluvial versus tidal processes on sediment deposition. This is best expressed in the differences in the mud content on bars in the Main Channel (South Arm Mashes (SAM) bar complex, Fig. 3B; Sisulak and Dashtgard 2012) and in the Middle Arm (Fig. 3C-E; Johnson 2012).

3) The cyclicity and architecture of bedding within bars changes with position along the channel, and reflects both the relative influence of fluvial and tidal processes, and the variability in the amount of mud deposited in and along the margins of the river. This, in turn, is linked to the position of the saltwater wedge. Johnson (2012) found significant uniformity in the thickness of sand beds and sand-mud interbeds (Fig. 4) in the admixed tidal-fluvial (i.e., tidal and fluvial processes equally control sediment deposition) Middle Arm. She attributed this uniformity in bedding to the relatively strong tidal influence on sediment deposition. In the tide-influenced, fluvially dominated Main Channel, Sisulak and Dashtgard (2012) found that along the margins of the SAM bar complex (Fig. 3B), sand beds were non-uniform in thickness, and sand-mud interbedding was non-rhythmic (Fig. 5). They attributed this relation to the fact that sand transport and deposition was dominated by river flow, which changes significantly from year to year. Mud beds, however, were deposited during lower flow and base-flow conditions, when estuarine circulation was re-established and the washload started to settle out of suspension. Landward of the maximum upstream position of the saltwater wedge, mud deposition is limited, and the seasonal cyclicity between sand and mud interbeds is not observed. Consequently, vertical bedding in the freshwater-tidal and freshwater-non-tidal reaches (Fig. 1) are either sand-dominated or gravel dominated, with rare thin and discontinuous mud interbeds.

4) The sedimentary structures preserved within bars along the Fraser River record tidal influence on sediment deposition. In the admixed tidal-fluvial Middle Arm, bars contain abundant mm- to cm-scale sand-mud laminasets that occasionally occur in full sets of 12-14 couplets and are interpreted as tidal rhythms. Tidal rhythms are still present in bars through the tide-influenced, fluvially dominated part of the Main Channel and Canoe Pass (Fig. 6B), but the number of rhythms is greatly reduced. Cross-bedding similar to sigmoidal cross-bedding (Kreisa and Moiola 1986) was also observed in sandy dunes developed in the intertidal zone in Canoe Pass (Fig. 6A), although this bedding style is attributed to tidal modification of fluvially formed dunes. Flaser bedding was
The ichnological character of sediments in the lower Fraser River is consistent with the expected trace assemblage for brackish-water settings (e.g., Pemberton and Wightman 1992; MacEachern and Gingras 2007), in that the trace assemblage on all bars in the tide-influenced part of the river is dependent upon the persistence of brackish water at each locale. In the freshwater-non-tidal and freshwater-tidal reaches of the Fraser River, bioturbation is very rare and is limited to sporadically distributed, thin (<2 mm diameter) oligochaete burrow networks. The trace assemblage in these zones is best described as a very low density (bioturbation index (BI) 0 with very rare occurrences of BI 1-2; Fig. 6F) of small diameter Planolites- to Thalassinoides-like, horizontal burrow networks. For reference, the bioturbation index is a non-linear scale, from 0 to 6, of biogenic reworking of the sediment; the scale is included in the legend in Figure 6.

With increasing saltwater intrusion and the persistence of brackish water conditions at any point along the channel profile, there is a corresponding increase in the diversity and density of bioturbation (Fig. 6B-E; Chapman and Brinkhurst 1981; Johnson 2012; Sisulak and Dashtgard 2012). In bars through the tide-influenced, fluvially dominated Main Channel, the trace density increases from BI 0-2 (Fig. 6D-E) to BI 0-4 (Fig. 6B-C), where the burrow density in individual bedsets is dependent upon both the persistence of saltwater and the sedimentation rate. The trace assemblage comprises a low diversity suite of Arenicolites-, Skolithos-, and Polykladichnus-like burrows (Fig. 6B-E), most of which are the vertical dwellings of polychaetes. In the tidal-fluvial Middle Arm, burrows produced by marine organisms are maintained year-round due to the persistence of brackish water and a reduced sedimentation rate resulting from lower river discharge. As such, Middle Arm sediments tend to exhibit a higher density (BI 2-6) and diversity of burrowing with the addition of both large and small Siphonichnus-like (bivalve-generated) traces (Johnson 2012). The traces in the tidal-fluvial Middle Arm are larger on average than those found in the tide-influenced, fluvially dominated Main Channel.

The increase in the density and diversity of traces with increasing brackish-water influence in the channels is relatively subtle when compared to the large increase in trace density and diversity from the channels onto the lower delta plain tidal flats of the Fraser River (Dashtgard 2011b), and to the nearly fully marine tidal flats in Boundary Bay (Fig. 1; Dashtgard 2011a). The brackish water-tidal reach of the Main Channel has an infaunal diversity of 3, which is 14% that of the nearly fully marine tidal flats of Boundary Bay. In the tidal-fluvial Middle Arm, the infaunal diversity of intertidal zone sediments doubles from 3 to 6 common animals. There is a significant increase in infaunal diversity from the intertidal zone of the Middle Arm to the active lower delta plain tidal flats, with an increase in infaunal diversity from 6 to 14 common animals. However, the lower delta plain tidal flats show a diversity reduction of 34% from the Boundary Bay tidal flats (Dashtgard 2011a; Dashtgard 2011b).

The most significant reduction in infaunal diversity occurs from the lower delta-plain tidal flats into the distributaries of the lower Fraser River. The low diversity and density of infauna observed in the channels is distinctive of the brackish-water reaches of the Fraser River, and provides a useful indicator of channel versus non-channel, marginal-marine facies. The upstream decrease in trace diversity and density is indicative of the relative persistence of brackish-water conditions along the channel profile, and can be used as proxy for determining salinity in the channel. The interbedding of bioturbated and non-bioturbated beds is indicative of seasonal changes in river discharge and the corresponding decrease in salinity and increase in the sedimentation rate.
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**IMPLICATIONS FOR SEDIMENT DEPOSITION ACROSS THE TIDAL-FLUVIAL TRANSITION**

The lower Fraser River is an excellent analog for studying changes in the sedimentology and ichnology of channel-associated deposits across the tidal-fluvial transition in a tide-influenced, fluvially dominated river. The character of sediments can be linked to the hydrodynamic conditions in the distributaries and to water salinity at various bars along the channel. Based on the results of our research, we make the following observations for the purpose of application to the rock record.

1) Grain-size distributions along the lower Fraser River are linked to tidal influence, and to flow reduction or flow reversal during the flood tide. The river is gravel-bedded upstream of the landward extent tidal effects. The river transitions to a sand-bedded upstream river - 15 km upstream of the freshwater-tidal reach, where tides may play some role in determining this transition. The Main Channel and most of the distributaries are also sand-bedded along the brackish water-tidal reach; however, mud is commonly deposited along the channel margins and in the upper part of in-channel bars in the Main Channel, and on the channel floors and bars of distributaries that carry lower volumes of the river water (e.g., Middle Arm).

2) Mud deposition is concentrated in the zone of freshwater-saltwater mixing (i.e., the turbidity maximum), such that the amount of mud preserved in the bars is linked to the persistence of saltwater at any point along the channel axis. In tidal-fluvial and tide-influenced, fluvially dominated settings, intertidally exposed mud beds are laterally continuous for up to 1 km (Johnson 2012). The lateral continuity of mud beds decreases rapidly landward of the zone of saltwater intrusion.

3) In the brackish-water influenced reaches of the lower Fraser River, coarse sand (> 0.177 mm) is deposited during the waning freshet. Clay, silt and fine sand (< 0.177 mm) are deposited during late-stage waning freshet flow and during base flow, although mud deposition in the Main Channel is restricted to the channel margins. This results in a seasonal cyclicity to sand-mud interbedding (Sisulak and Dashtgard 2012). Seasonal cyclicity is generally not discernable in sediments landward of the brackish-water influenced zone.

4) The diversity of infauna (and their traces) exhibits the greatest decrease from the lower delta plain tidal flats into the channels. In tidal-fluvial and tide-influenced, fluvially dominated channels, infaunal diversity is low: 14-28% of the diversity of the nearly fully marine tidal flats at Boundary Bay. Trace diversity across the tidal-fluvial transition decreases with decreasing saltwater intrusion, suggesting that trace diversity can be used to predict the salinity conditions under which the sediments were colonized.

5) Trace density is controlled by salinity and the sedimentation rate. Trace density decreases and becomes more sporadically distributed with decreasing salinity, although tidal-fluvial and tide-influenced, fluvially dominated upper bar and channel-margin deposits show BI values of 2-6 and 0-4, respectively. The sedimentation rate also exerts a major control on trace density in that high rates of sediment deposition translate into low density burrowing. In the bars in the tidal-fluvial Middle Arm, this is manifest as lower BI values in sand beds versus mud beds (Johnson 2012). In the tide-influenced lower reach of the Main Channel, the SAM bar complex, sand beds in the upper part of the bar tend to lack bioturbation or are burrowed from the top down, and mud beds show the highest levels of burrowing (Sisulak and Dashtgard 2012). The correlation between bioturbation and grain size further emphasizes the seasonal cyclicity recorded by interbedded sand and mud beds in brackish-water influenced channels.

Significant variability occurs between the distributaries of the lower Fraser River, such that one style of sedimentation cannot be applied to all channels. However, the sedimentological and...

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**Figure 6:** X-radiographs of box cores taken from bars along the lower Fraser River. The position of each box core is shown on the air photo at the bottom of the figure. The two vertical columns on the right-hand side of each x-radiograph show the general lithology and bioturbation intensity (recorded as the bioturbation index). In figures 6B and 6C, the solid horizontal black lines labeled 1,2 and 3 define the tops of seasonal cycles of deposition. Abbreviations for sedimentary structures (squares with arrows): current ripple lamination (cr); muddy current ripple lamination (mcr); planar lamination (pl); sigmoidal cross bedding (SXB); tidal rhythmites (tr); trough cross-bedding (txb). Abbreviations for ichnological/biogenic structures (circles with arrows): Arenicolites (Ar); bird footprint (fp); Polykladichnus (Pk); Skolithos (Sk): threadworm burrow (t); wood (wd).


