[PS] # The Nature of Inclined Heterolithic Stratification in a Mixed Tidal-Fluvial Setting, Fraser River, British Columbia, Canada*

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Search and Discovery Article #50657 (2012)**
Posted July 23, 2012

*Adapted from poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012

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Abstract

Inclined Heterolithic Stratification (inclined interbeds of sand and mud; IHS) is a commonly observed stratal architecture in mixed tidal-fluvial channels, both in the modern and in the rock record. However, the character of IHS varies along strike depending upon the dominant depositional process within the channel (i.e., fluvial, mixed tidal-fluvial, tidal). To assess the nature of IHS in subequally mixed tidal-fluvial channels, research was conducted on three deposits in the Middle Arm of the lower Fraser River, British Columbia, Canada, including a channel-margin deposit, an in-channel bar, and a point-bar. The channel margin deposit is situated in the most landward position, and the point bar in the most seaward position.

Sedimentologically the IHS in the mixed tidal-fluvial Middle Arm varies as a function of position within the channel. The most landward deposit (8 km inland from the delta front), the channel margin IHS is mud-dominated. Three kilometers seaward of the channel-margin deposit, the in-channel bar is predominantly sand-rich. Finally, the most seaward bar, the point-bar (within the intertidal zone; 4 km from the delta front), shows significant variability with higher sand percentages on the seaward end of the bar. Ichnologically, burrow diversity, burrow density, and trace size increases in the seaward direction. The channel-margin and in-channel bar deposits contain Polykladichnus, Skolithos, Arenicolites, Siphonichnus and Palaeophycus. The point-bar at the downstream end of the channel has the same traces as above, in addition to an abundance of large Siphonichnus produced by large resident bivalves.

By comparing the sedimentologic and ichnologic character of IHS within the various deposits of the Middle Arm to hydraulic conditions in the channel, a number of conclusions are drawn: (1) At the seaward end of the system, where tidal input exceeds fluvial input, sand is more abundant in the seaward direction, (2) at the landward end of the study area, where fluvial input appears to match tidal input, mud is dominant, possibly marking the position of the turbidity maximum zone, (3) in-channel bars tend to be more sand-rich than channel-margin deposits and point bars, and (4) the degree of marine (saltwater) influence in the system is best-expressed ichnologically. Higher salinity and prolonged residence time of saltwater within the channel is marked by an increase in trace diversity and density, and by an overall increase in burrow size.

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Acknowledgments

We thank the following organizations for generously providing funds for this research.

SUNCOR ENERGY, Statoil, Esso Imperial Oil, NSERC CRSNG, nexen

① Abstract

Inclined heterolithic stratification (IHS) is a common stratal architecture developed on bars in mixed tidal-fluvial channels, both in the modern and in the rock record. The dynamic interplay of hydrodynamic processes control deposition, and the sedimentological and ichnological character of IHS. This is indeed the case for the subequally mixed tidal-fluvial, Middle Arm of the lower Fraser River, British Columbia. The results of this study are considered as a process-response analog for IHS deposited in admixed tidal-fluvial environments.

Four sedimentological trends are identified that largely determine the character of IHS in the admixed tidal-fluvial Middle Arm. These trends can be used in concert to identify tidal versus fluvially generated IHS. (1) Grain size fines from medium- to coarse-grained sand in the middle of the channel to mainly mud on the flanks. (2) Intertidal zone and upper subtidal zone sediments are deposited in mm- to cm-scale, rhythmically alternating sand and mud beds (IHS), and this trend appears to continue to the lower bar. The distribution of sand and mud on the Middle Arm bars indicates that tidal cyclicity exerts a major control on deposition in this admixed tidal-fluvial system. (3) Surface samples from the intertidal zone indicate that mud dominates on the upstream and downstream ends of each bar and the center of each bar is sandy, such that bars exhibit a mud-sand-mud profile. (4) Muddy bedsets in the intertidal zone are laterally extensive for up to 1 km in the along-strike direction.

Ichnological trends reflect the relative input and persistence of brackish-water in the channel. Burrow diversity, burrow density, and trace size increases in the seaward direction reflecting the downstream increase in salinity. The deposits contain a low diversity assemblage of mainly vertical traces (*Polykladichnus*, *Skolithos*, *Arenicolites*, *Siphonichnus* and *Palaeophycus*). At the most seaward end of the system, the trace assemblage above is accompanied by abundant large *Siphonichnus* produced by large resident bivalves, whereas landward the *Siphonichnus* burrows are all produced by a smaller species of bivalve. The year-round persistence of infaunal organisms during the freshet differs significantly from other more fluvially dominated (persistent freshwater) deposits of the lower Fraser River, where burrows are abandoned during the freshet, and freshet-deposited sediments are generally devoid of bioturbation.

② Study Area

The Fraser River is the largest river in Western Canada with an extent of ~1 370 km (Fig. 1A). The Middle Arm of the Fraser River is a branch of the main river that is ~ 8 km long and recieves 5% of total Fraser River flow (Fig. 1B).

Three bars were studied: A channel-margin bar (CMB); an in-channel bar (ICB); and a point-bar (PB) (Fig. 1C). Within the study area, the average depth is 5.3 m (from AMHT) and the average width is 300 m (Fig. 2).

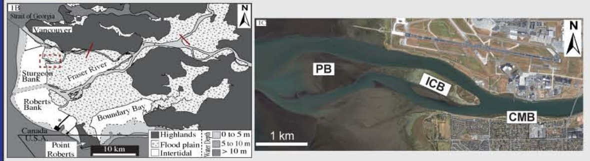


Figure 1: (A) The location of the Fraser Delta. (B) The location of the Middle Arm study area is in the dashed red box. The maximum landward extent of saltwater incursion is marked with red lines. (C) The location of the three bars within the study area (Image source: Google Earth).

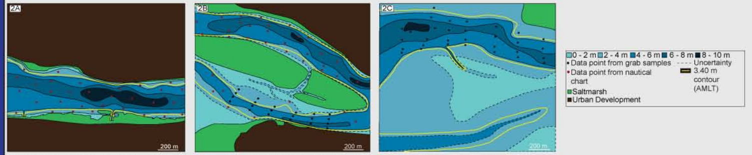
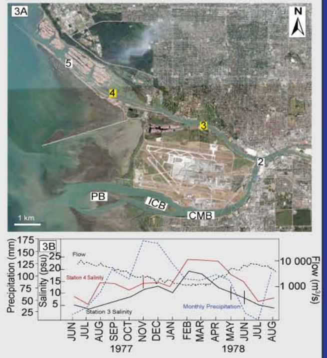


Figure 2: Bathymetric profiles of the channel adjacent to: (A) CMB; (B) ICB; (C) PB. Depths are recorded relative to the average maximum high tide in 2011 (AMHT; 4.30 m relative to chart datum). The yellow contour marks the average minimum low tide (AMLT; 3.40 m relative to AMHT), which is the approximate intertidal/subtidal zone boundary.

③ Tidal and Fluvial Processes

The Fraser River has a mean flow of 3 400 m^3/s, with flow ranging from 6 000 - 12 000 m^3/s during the spring freshet and flow less than 3 000 m^3/s for the remainder of the year. In the study area, interstitial salinities range from ~ 5 - 24 psu, where minimum salinities occur during the spring freshet, when fluvial discharge is the greatest.

Tidal influence reaches up to 120 km upstream from the Strait of Georgia. Tides are mixed semi-diurnal and have a mean tidal range of 3 m.



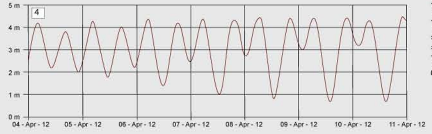


Figure 4: Tide chart for seven days. The amplitude of the tidal range increases as the tide cycle transitions from neap to spring.

Figure 3: (A) Location of stations 2 - 5 from the Chapman and Brinkhurst (1981) study on the North Arm. Stations 3 and 4 are used as analogues for the Middle Arm study area. (B) Interstitial salinity and flow measurements from station 3 and 4, as well as monthly precipitiation. (Modified from Chapman and Brinkhurst, 1981)

④ Sedimentology

Figure 5: (A) Ebb-oriented sand dunes with lingoid current ripples on the crests. Located mid-bar on the ICB. (B) Mud from the upstream end of the PB. (C) Lenticular bedded current ripples from the lower intertidal zone at the upstream side of the PB. (D) Ebb-oriented, upper fine-grained sand current ripples mid-bar at the PB. Small wave ripples obliquely cut the current ripples to form interference ripples. (E) Sinusoidal ripple crests of ebb-oriented, upper fine grained sand ripples from the middle intertidal zone, located mid-bar at the PB.

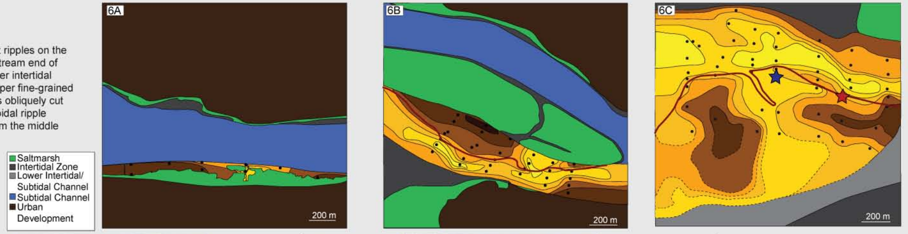


Figure 6: Grain size contour maps of: (A) CMB; (B) ICB; and (C) PB.

0 - 1.0 phi (coarse-grained sand)
1.0 - 2.0 phi (medium-grained sand)
2.0 - 3.0 phi (fine-grained sand)
3.0 - 4.0 phi (very fine-grained sand)
4.0 - 5.0 phi (silt)
5.0 - 6.0 phi (silt)
6.0 - 7.0 phi (clay)
Uncertainty
3.40 m depth contour (intertidal/subtidal zone boundary)

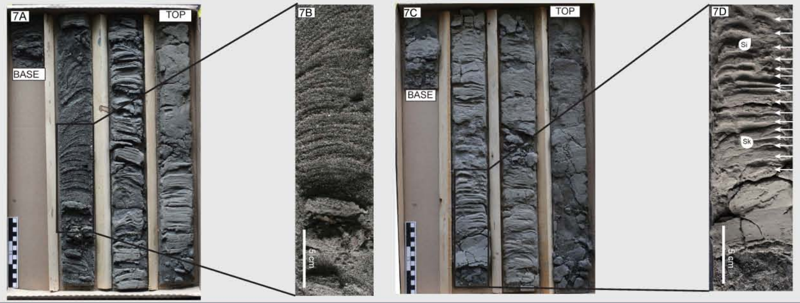
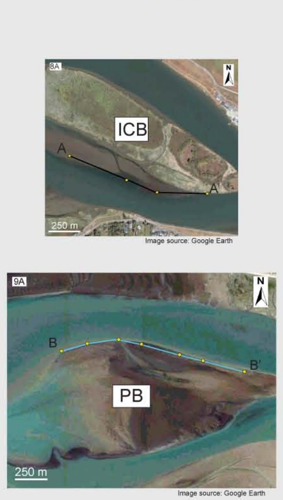
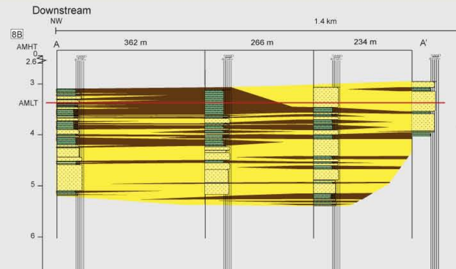


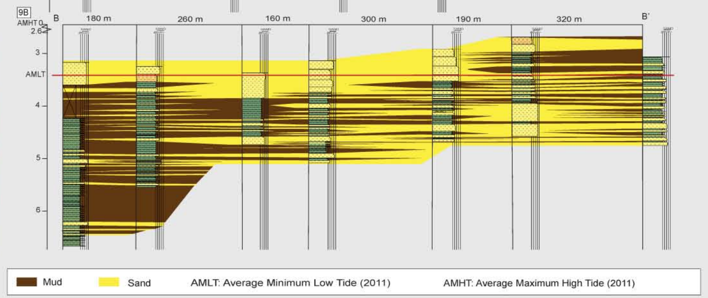
Figure 7: (A) The location of this core is marked by a red star in figure 6C. (B) Planar to gently inclined parallel laminated medium-grained sand. (C) Vibracore taken from the location indicated on Figure 6C with a blue star. (D) IHS with mm- to cm-scale mud laminations interbedded with upper very fine-grained sand laminations. Rhythmic alternation of sand and mud is indicated by white arrows. Two sand filled burrows are indicated: *Siphonichnus*-like'Si' and *Skolithos*-like 'Sk'.

⑤ Cross-Sections





All of the cores comprise mainly of muddy IHS. The ICB displays a discernible fining-upward trend on the downstream end of the bar (Fig. 8B). The PB contains more beds and displays and increased rhythmicity in bedding style compared to the ICB (Fig. 9B). This corresponds to increased tidal influence in the seaward direction.



⑥ Ichnology

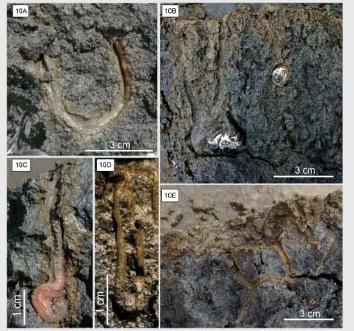
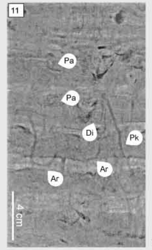


Figure 10: (A) Nereid polychaete inside a mud-filled *Arenicolites*-like burrow. (B) *Nutallia obscurata* on the left side of the photo with *Macoma balthica* on the right, burrowing in sediment from the intertidal zone of the PB. Both bivalves produce *Siphonichnus*-like structures. (C) Nereid polychaete inside a *Skolithos*-like burrow . D) *Corophium* generated *Arenicolites*-like burrow from the PB. E) Complex, mud-lined *Polykladichnus*-like burrow produced by a nereid polychaete.



Both sand and mud beds are colonized year round, but mud beds tend to display higher bioturbation intensity. There is an increase in bioturbation intensity from the landward CMB to the PB, the most seaward bar (Fig. 12).

Figure 11: X-ray radiograph of sediment from the downstream end of the ICB.

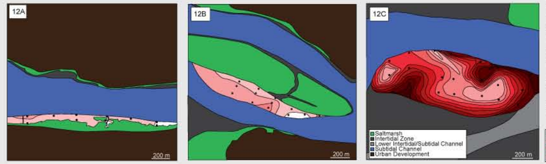


Figure 12: Bedding plane bioturbation intensity expressed as sediment disruption in maps for: (A) CMB; (B) ICB; and (C) PB. Values are determined by multiplying the average cross-sectional area of an organisms burrow by the number of individual infauna found in a m^2. The sediment disruption values of each organism are totalled at each site to get sediment disruption caused by all infauna present.

No disruption; 0.0 - 10 cm^2/m^2; 10 - 20 cm^2/m^2; 20 - 30 cm^2/m^2; 30 - 40 cm^2/m^2; 40 - 50 cm^2/m^2; 50 - 60 cm^2/m^2; 60 - 70 cm^2/m^2; 70 - 80 cm^2/m^2; 80 - 90 cm^2/m^2; 90 - 100 cm^2/m^2; 100 - 110 cm^2/m^2

⑦ Conclusions

- Tidal cyclicity is a major control on deposition in the admixed tidal-fluvial Middle Arm of the Fraser River. This is manifest as mm- to cm-scale rhythmic alternations of sand and mud. This is in contrast to the Main Arm of the Fraser River, where seasonal fluctuations in river discharge is the main control on deposition.

- The degree of saltwater incursion in the Middle Arm is reflected ichnologically. Salinity is high enough throughout the year that continuous infaunal colonization occurs, resulting in evenly distributed bioturbation.

- Burrow diversity, intensity and size increases seaward where salinity is greatest. Overall, the burrow suite consists of a low diversity of simple dwellings of deposit and suspension feeding organisms, and mobile deposit feeding structures. This is consistent with a typical brackish-water trace assemblage.

- Each bar displays a mud-sand-mud trend. This suggests that the middle of the bar should be targeted for subsurface units deposited in a similar depositional environment. However, mud beds are predominent and laterally continuous (> 1 km), and would be considered poor reservoir quality.