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MORPHOLOGY AND DYNAMICS OF A GRAVEL-SAND TRANSITION

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Abstract: The beds of alluvial river channels become finer grained moving downstream and often exhibit an abrupt transition from gravel to sand-bedded conditions. Most previous work documenting this phenomenon has focused on small upland streams where sediment supply to the channel is strongly connected to sediment delivery from hillslopes. Fewer studies have focused on the gravel-sand transition in large alluvial channels and none have documented the spatial variability through reaches where transitions occur. The downstream fining pattern observed in the Fraser River is widely cited as a classic example of an abrupt gravel-sand transition in a large alluvial channel. However, important questions regarding the exact location of the transition, its morphology, and what controls its location remain unanswered. Here, we present detailed observations of bed material grain size and river bed topography through the reach where the transition is widely thought to occur in the Fraser River. Some limited bed material sampling was done at high flow (11 000 m^3s^{-1}) with more detailed sampling at low flows (~1000 m^3s^{-1}). These observations indicate that there is little gravel material on the active channel bed downstream of Yaalstrick Bar, the last bar along the river dominated by gravel (> 75% of the bar material > 2 mm). However, sorting patterns caused by the superior mobility of gravel over sand have led to gravel patches on the upstream sides and surfaces of sand bars. There are also gravel patches along the thalweg through the apex of some river bends. There is a dramatic increase in bar amplitude downstream of Yaalstrick Bar, suggesting greater sand composition. Our observations suggest the gravel-sand transition in the Fraser River is abrupt, forming a gravel front at Yaalstrick Bar as is commonly observed in smaller channels.

INTRODUCTION

The beds of alluvial river channels become finer moving in the downstream direction. It is widely accepted that bed material size declines exponentially with distance downstream in the absence of lateral sediment inputs (Sternberg, 1875; Yatsu, 1955; Shaw and Kellerhals, 1982; Rice and Church, 1998). In many channels, there is a significant discontinuity in the bed material grain size fining trend that occurs over relatively short downstream distances (Yatsu, 1957; Howard, 1980; Shaw and Kellerhals, 1982; Brierley and Hickin, 1985; Sambrook Smith and Ferguson, 1995; Dade and Friend, 1998; Cui and Parker, 1998; Parker and Cui, 1998; Knighton, 1998; Ferguson, 2003; Singer, 2008). The phenomenon is characterized by a change in the bed material from gravel to sand through an intervening reach where bed material is a bi-modal mixture of sand and gravel (Sambrook Smith and Ferguson, 1995).

A variety of explanations for this discontinuity have been proposed including 1) the disintegration of fine gravel particles of certain lithologies into sand sized particles during the transport process (c.f. Yatsu, 1957; Kodama, 1994) and the existence of a grain size gap between 1 and 10 mm (Wolcott, 1988), 2) selective transport caused by a decline in the capacity of the river to carry larger particles (c.f. Brierley and Hickin, 1985; Ferguson et al., 1996; Ferguson et al., 1998; Wilcock, 1998; Ferguson, 2003) and 3) external base-level control that generates a backwater effect and a rapid decline in transport capacity (c.f. Pickup, 1984; Sambrook Smith and Ferguson, 1995). It is likely that some combination of these processes lead to gravel-sand transitions, although the relative importance of these controls in a given river system may vary.

In spite of the wide variety of explanations for the gravel-sand transition, there is a paucity of detailed studies of grain size change through these transitions, particularly in large channels. Indeed, the most detailed studies of grain size change have focused on small upland streams with widths on the order of meters and depths on the order of tens of centimeters or even smaller scale laboratory flumes (Sambrook Smith and Ferguson, 1996; Ferguson et al., 1996; Wilcock, 1998). Fewer studies have focused on the gravel-sand transition in large alluvial channels with widths on the order of hundreds of meters and flow depths of tens of meters, although gravel-sand transitions have been noted to occur in these larger scale channels (c.f. Mclean et al., 1999; Singer, 2008).

Investigations in small channels and flumes have suggested that the gravel-sand transition is abrupt and characterized by a gravel front (c.f. Sambrook Smith and Ferguson, 1995). However, sampling in larger channels is generally too sparse to assess the abruptness of the transition or to draw conclusions as to its cause. This is a problem because larger scale channels can accommodate changes in bed material supply from upstream though lateral variability in grain size that is often not possible in small channels or flumes. Also, the role that variability in bed topography plays in the transition cannot be assessed in small channels or flumes where topographic variability and the range of sedimentary environments are limited.

The Fraser River in British Columbia (BC) is often evoked as a classic example of a gravel-sand transition in a large channel, but this is based on only three samples obtained over a few tens of kilometers of the river reported by Mclean et al. (1999). Here, we report on a bed material sampling program undertaken to identify the exact location of the gravel-sand transition, the morphology of the transition and linkages between sediment dynamics and river bed topography in the Fraser River. We find that the transition is indeed abrupt, and that there is a strong topographic control on the occurrence of gravel downstream of the abrupt gravel front.

FIELD SITE

The Fraser River drains 228 000 km^2 of central British Columbia into the Strait of Georgia. The river begins in the Rocky Mountains and flows across the interior plateau of British Columbia. About 486 km from the sea, the river enters a 270 km bedrock canyon, funneling sediment from the British Columbia interior plateau and mountains to the Lower Mainland of British Columbia. The lower portion of the river begins at the exit of the Fraser Canyon (upstream of Hope, BC) where the river becomes alluvial and starts to deposit its gravel load ~185 km upstream of the sea. The river undergoes a 10x reduction in water surface slope from Hope (river km, RK 165) to Mission, BC (RK 86), causing a transition from gravel-bedded to sand-bedded conditions (Figure 1).

The Fraser is dominated by a snowmelt hydrograph that begins to rise in April with high flows through May, June and July, and that falls in August and September. The mean annual flow at Hope is 3410 m^3s^{-1} and the mean annual flood is 9790 m^3s^{-1} (McLean et al., 1999). Winter flows are typically ~1000 m^3s^{-1}. The largest flood at Hope is estimated at 17,200 m^3s^{-1} and occurred in 1894, prior to establishment of the Water Survey of Canada (WSC) gauge. The WSC flood of record occurred in 1948 and reached 15,200 m^3s^{-1} at Hope. There is also a WSC gauge at Mission where water levels are monitored, but the stage-discharge relation is complicated because the river is tidally-influenced. There are no major tributaries between Hope and Mission, so flows at Mission are estimated by the WSC from a regression model using flows at the Hope gauge and tidal elevations at Point Atkinson in the Strait of Georgia. The model is only used when discharge at Hope exceeds 5000 m^3s^{-1}. Weak upstream flows can occur at Mission during exceptionally high ebb tides during the winter months. Salt-wedge intrusion does not penetrate inland further than New Westminster BC (RK 45). At high flows, the tidal influence is relatively minor, but still causes diurnal fluctuations of a few hundred to 1000 m^3s^{-1} in discharge at Mission during freshets, depending on the upstream flow and tidal conditions.

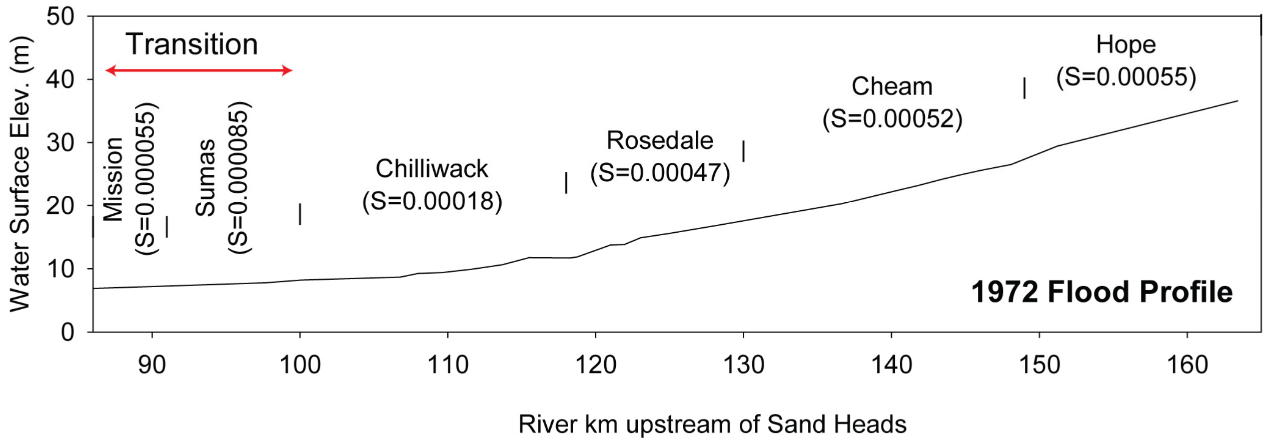

Figure 1: Water surface elevation of the 1972 flood profile in the Fraser River. The water surface slope (S) of the various reaches between Hope and Mission are provided. The reaches where the gravel-sand transition is thought to occur are marked 'Transition'.

OBSERVATIONS

The data presented here were collected during the 2007 and 2008 freshet and the intervening low flow period in winter 2008 (Figure 2). During the 2007 freshet, flows peaked on June 10. At Hope flows peaked at ~10 800 m^3s^{-1} (return interval of ~12 years) while at Mission, flows peaked at ~11 900 m^3s^{-1}. After this peak, flows at Mission remained at ~8000 m^3s^{-1} through the end of July, after which flows declined though the low flow season. The size of this flow ensures that the transport processes responsible for the gravel-sand transition were active during the sampling period.

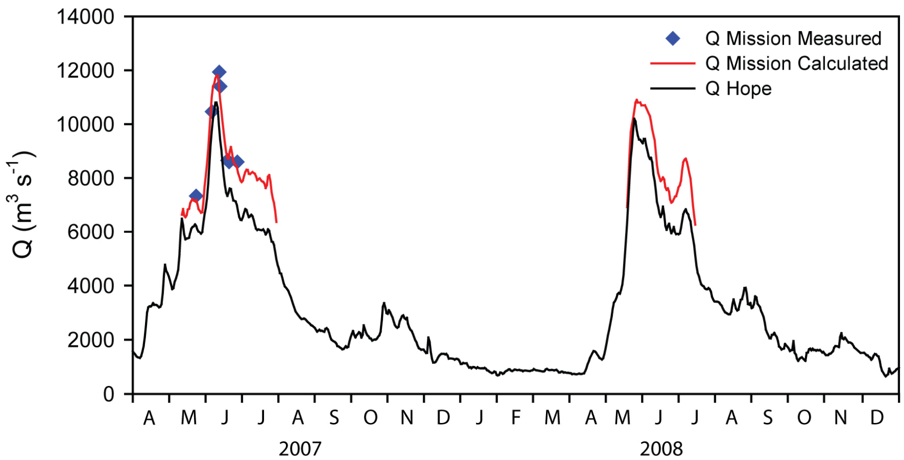

Figure 2: Hydrograph for the Fraser River at Hope (WSC Gauge 08MF005) and Mission (WSC 08MH024) for the 2007 water year.

We present bathymetric data provided by Public Works and Government Services, Canada collected during the 2008 freshet, which was similar to the 2007 flow. Survey lines were spaced roughly 100 m apart and elevations were obtained at sub-meter spacing along each line. This data was collected at high water, so it provides bank-to-bank spatial coverage. This data is not detailed enough to observe bedforms in the channel, but does provide complete topographic information about channel-scale bed topography and bar morphology.

During the 2007 freshet, bed material samples were recovered using a Shipek bed sampler. These sampling locations were reoccupied in the winter of 2008 at low flows and samples were obtained using a dredge sampler. The Shipek and dredge samplers collect roughly the same volume of bed material, but the collection methods are slightly different. The Shipek uses a weight and spring mechanism to scoop sediment at-a-point upon impact with the bed. The dredge sampler is dragged along the bed until it fills. The retrieved material may be from a point where the dredge excavated the bed surface, a series of points along the drag line, or particles collected as the sampler skidded along the surface of the drag line. As such, the dredge samples should then be considered as a line sample with a length not exceeding ~20 m. As indicated below, the sampling method does not appear to have affected the recovered grain size distributions.

RESULTS

The 2008 river bed topography through the reach where the gravel-sand transition is thought to occur is shown in Figure 3. The river is gravel-bedded to Yaalstrick Bar. A sediment transport sampling program undertaken by the Water survey of Canada and analyzed in detail by McLean, et al. (1999) suggests that in the gravel-bedded part of the river, upstream of Yaalstrick Bar, sand is carried in suspension. At Mission, the river is known to be sand-bedded across its width, suggesting that some of the suspended sand load has been deposited on the bed. Using these observations and a bimodal sediment sample from the upstream end of Hatsic Bar, McLean, et al. (1999) suggested that that gravel-sand transition must lie somewhere between Yaalstick Bar and Mission.

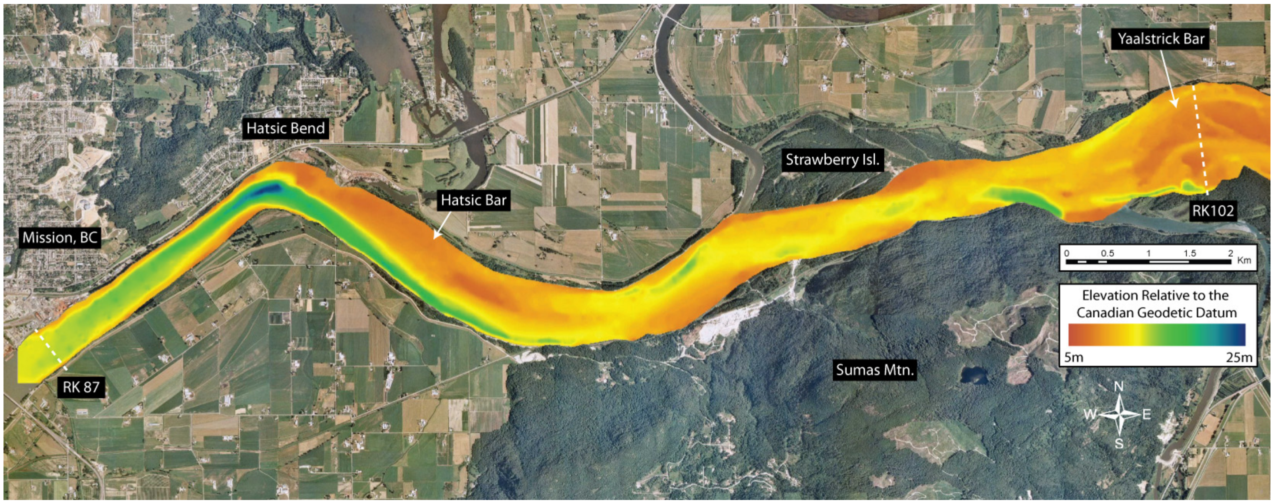

Figure 3: Bed topography observed during the 2008 freshet.

The 2008 river bed topography highlights a number of prominent features of the transition reach. Yaalstrick Bar tapers downstream and there are multiple sub-aqueous channels with two prominent channels on either side of the center channel bar. There is a sinuous thalweg downstream of Yaalstrick Bar between Sumas Mountain and Strawberry Island. Hatsic Bar is a large concave back bench bar (sensu Hickin, 1979) formed by flow separation that occurs in the first major bend downstream of Yaalstrick Bar. The river is confined against the southern bank by bedrock and rip-rap through most of the reach, until the river exits Hatsic Bend where it is essentially unconfined (Ham, 2005). Here, the bed is deeply scoured. Moving downstream from Yaalstrick Bar to Mission, the river generally becomes deeper and narrower. Church and Rice (2009) measured bar heights through the gravel-bedded part of the river and found that bar amplitude doubles downstream of Yaalstrick Bar.

Figure 4 shows the grain size distributions from the sampling program. There is no apparent difference between the high and low flow grain size samples, so we combined the data sets. The majority of the samples are sand, but there are many bimodal distributions and a few samples that are pure gravel. The sand mode is centered at ~0.3 mm throughout the reach. Gravel samples from the thalweg are generally too small to accurately represent the grain size distributions (see Church et al., 1987), so we focus on the percent gravel, sand and silt/clay in each sample.

There are strong spatial patterns in bed surface grain size through the reach (Figure 5). As expected, samples from Yaalstick Bar are gravel. The channel north of Yaalstrick Bar is a backwater channel, and consequently is sand bedded. Downstream of Yaalstrick Bar, the channel is almost entirely sand-bedded with gravel appearing in some of the deeply scoured pools and on the bar heads that are immediately downstream of these pools. The remainder of these bars is composed of sand. This pattern is well developed immediately upstream of Strawberry Island, where a scoured pool occurs on the southern side. The bed of the pool is a gravel-sand mix that grades into a gravel bar head against the north bank. The along bar fining is particularly strong on Hatsic Bar, where the gravel head grades smoothly downstream into sand on the bar surface. Samples of the subsurface material indicate it is ~30% sand. Shallow trenches (~1 m deep) revealed the gravel surface grades to a gravel-sand mix with increasing sand content at depth, suggesting the gravel is largely a veneer deposit.

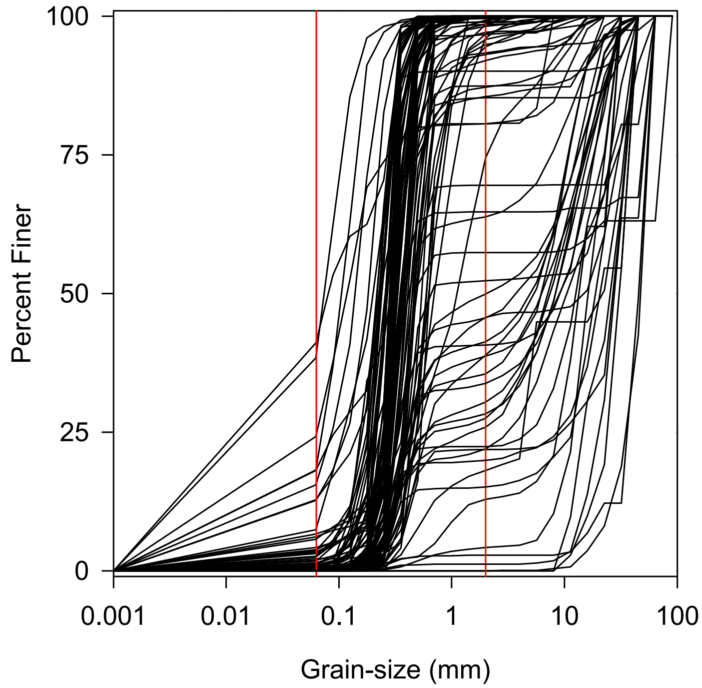

Figure 4: Grains-size distributions from the gravel-sand transition reach.

Gravel is also found in the thalweg adjacent to Hatsic Bar and along the north bank downstream of Hatsic Bend. At least one sample from the deepest part of the bend (not shown here) is composed of a packed marine mud that underlies the Fraser River sediments. This suggests that Hatsic Bend is scouring to the base of the modern river sediments at high flows. It is not clear whether the gravel in the thalweg is a lag deposit or an active gravel bed.

The downstream change in bed material through the lower Fraser River is shown in Figure 6 where the cumulative percent of silt/clay, sand and gravel are plotted. Data between Hope and Yaalstrick Bar are drawn from McLean (1990) and Ham (2005). Between Yaalstrick Bar and Mission, the data from the present sampling program are plotted. There is no data available between RK 50 and RK 86 (at the time of writing). Data from RK 50 to the sea is from McLaren and Ren (1995). Each point from McLaren and Ren (1995) represents cross-sectional average of 5-8 samples. Figure 6 reveals that a strong change in the composition of the bed material occurs at Yaalstrick Bar. Bed material goes from being composed of ~70% gravel and ~30% sand to being entirely sand over less than a kilometer. Downstream of Yaalstick Bar, the river is essentially sand bedded. Beyond Mission, the river bed is composed of 0.3 mm sand until it reaches the Strait of Georgia (McLean et al., 1999). Although some gravel patches appear between Yaalstick Bar and Mission, they are limited in size. The silt/clay content of the bed material is generally much greater downstream of Mission and it rises to >80% of the bed material as the river transitions to the delta front beyond Sand Heads at RK 0 where the river enters the Strait of Georgia.

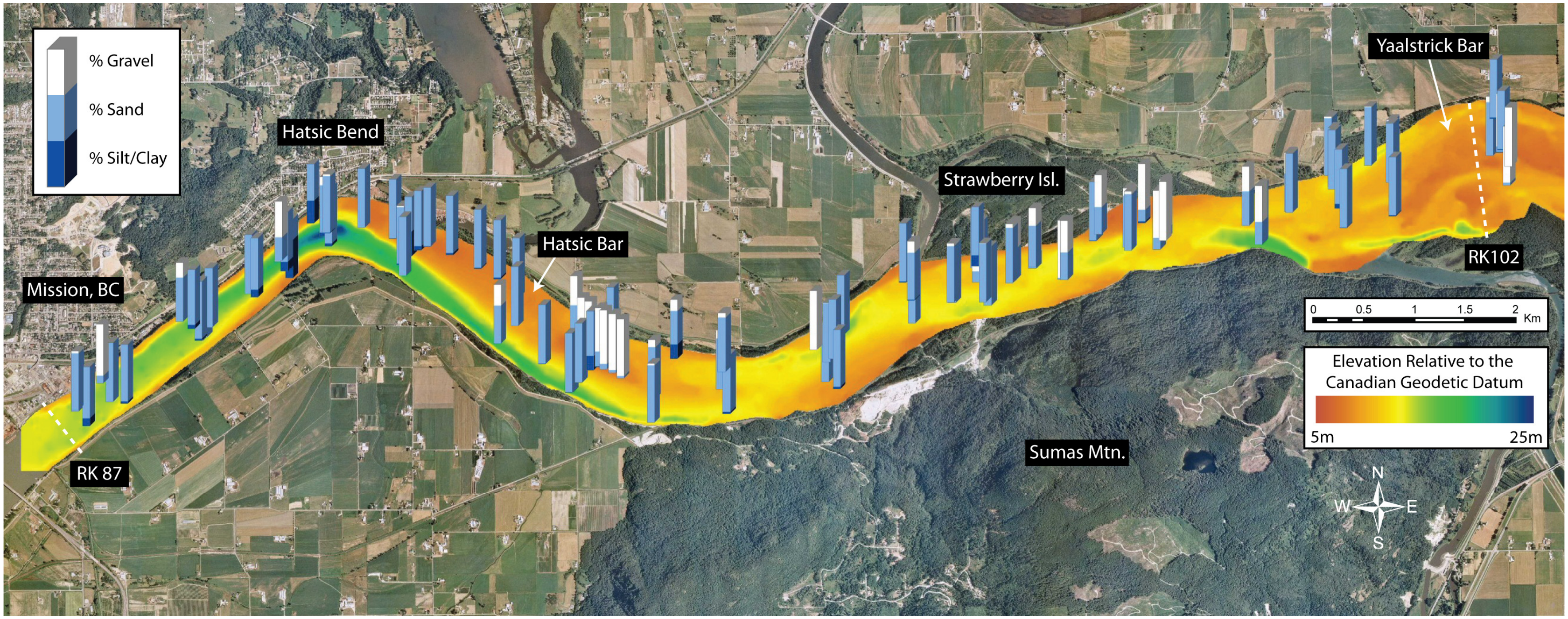

Figure 5: Percent gravel, sand and silt/clay on the surface through the gravel-sand transition reach. Each tricolor (dark blue, light blue, white) bar represents one grain size sample. The proportion of a color on the bar indicates the percent of the sample composed of a particular size class. For example, the tricolor bar in the legend is 33.3% gravel, 33.3% sand and 33.3% silt/clay.

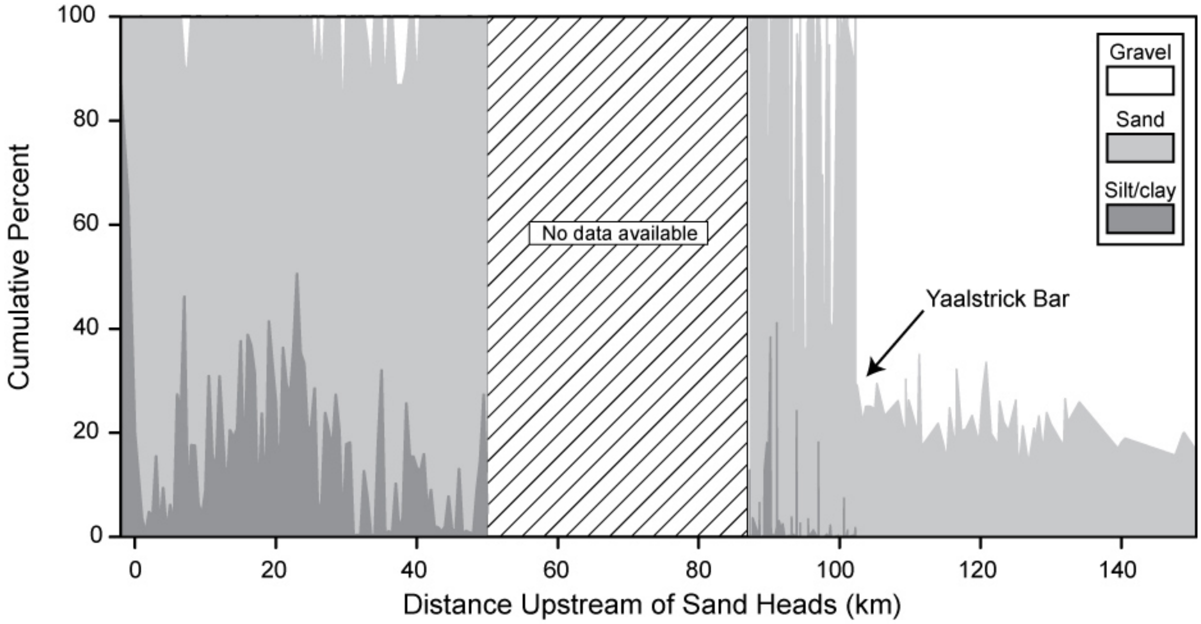

Figure 6: Cumulative percent of bed material composed of a particular grain size class between Hope, BC (where the river exits the Fraser Canyon) and Sand Heads (where the river enters the Strait of Georgia)

CONCLUDING DISCUSSION

The gravel-sand transition in the Fraser River appears as a gravel front at the downstream end of Yaalstrick Bar. As the river approaches and passes Yaalstrick Bar, we expect that sand comes out of suspension, forming sand patches on the bed and that general gravel-bed motion ceases in response to the drop in shear stress caused by the decline in bed slope. This results in the gravel front.

The gravel-sand transition in the Fraser coincides with a dramatic change in slope that occurs at Sumas Mountain and with the upstream extent of the backwater effect caused by the ocean tides. As such, the location of the transition is externally controlled. There is no evidence that the location or morphology of the gravel-sand transition is linked to the abrasion of particles in the gravel-bedded portion of the river. The gravel mode of the grain size distributions at the gravel front has a size much larger than 10 mm, which is the size that is usually described as being unstable and breaking down to sand sized particles in some lithologies. The 0.3 mm sand that is downstream of the gravel front is present throughout the Fraser Canyon as well, suggesting its source may be several hundreds of kilometers upstream of the gravel-bedded reach of the lower river between Hope and Yaalstrick Bar.

In light of the dramatic decrease in bed slope, it is likely that the morphology of the transition – an abrupt gravel front – is controlled by sorting processes. Ferguson and collaborators (see reference throughout) argue that abrupt gravel transitions occur because the relation between shear stress and sediment transport is non-linear. Ferguson et al., (1998) in particular, argue that as shear stress declines, coarser particles are deposited and finer particles are selectively transported. The bed becomes finer moving downstream as the coarser particles are removed from the upstream sediment supply. Ferguson (2003), building on a suggestion by Wilcock (1998), argues that the abruptness arises because sand coverage is increasing. As sand makes up a greater portion of the bed surface, transport rates of both sand, and to a lesser extent gravel, increase. This increases the downstream sand supply relative to gravel. The shift occurs where a critical sand coverage on the gravel bed occurs. So where there is a strong downstream gradient in the sand coverage, the transition will be abrupt.

There are a number of gravel deposits downstream of the gravel front in the Fraser River, but they appear limited in size. Some bar heads between Yaalstrick Bar and Mission have gravel veneers, but the bar sediments grade from gravel to sand in the downstream direction. Where we examined the gravel deposits, we found a coarse surface layer composed of gravel and a subsurface that graded to sand with depth. Systematic measurements of the bar subsurface sediments were not undertaken, but our observations suggest that the bars are largely composed of sand. This is consistent with the doubling of bar amplitude downstream of Yaalstrick Bar observed by Church and Rice (2009).

We strongly suspect that the deposits formed on the bar heads are caused by the superior mobility of gravel over sand. When general gravel-bed movement ceases, gravel may still be carried as bedload on top of the sand. Sand has a hydraulic smoothing effect on river beds that can accelerate near bed fluid velocities sufficiently to move gravel sized particles, even though general movement of a gravel bed has ceased due to lower shear stresses (Venditti et al., in press). This gravel continues to move over the sand bed due to a lack of distrainment sites.

We suspect that sand present on the bed upstream of Yaalstrick Bar maintains a small gravel load that rides over the sand beyond the gravel front. This gravel is gravitationally sorted into the pools where it may stop because there are like-sized particles whose packing provides ample distrainment sites. At high flows, these deposits in the pools can be entrained either by greater shears stresses or because sand has been deposited into the pool during low flows, lowering the critical shears tress for entrainment of the gravel-sand mix. Once entrained, this sediment may continue downstream overriding sand, moving to a subsequent downstream pool along the thalweg or depositing on bar heads where shear stresses decline and like-sized gravel particles provide distrainment sites.

As such, we suggest that the gravel deposits downstream of the gravel front are formed by gravel particles 'leaking' out of the gravel-bedded part of the river and preferentially moving into the deep scour holes and bar heads. Through time, these bars exist without passing the gravel load by the channel shifting laterally, leaving the gravel veneers formed at high flow in the floodplain. If the channel is constrained laterally, the bars must become coarser through time, which will shift the gravel-sand transition downstream.

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