Scales of variability in bed material gravels: Sorting across river bars in relation to downstream fining

STEPHEN P. RICE[1] and MICHAEL CHURCH[2]

1. Department of Geography, Loughborough University, Loughborough, Leicestershire, LE11 3TU, UK. (s.rice@lboro.ac.uk)*.

2. Department of Geography, The University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z2.

Submitted to *Sedimentology*, March, 2009

Short running title: Bar-scale sediment sorting

* corresponding author

ABSTRACT

The grain-size variability of riverbed gravels at bar scales is poorly understood, as are the relations between variability at this scale and at reach and river scales. Surface and subsurface grain size distributions were therefore examined at reach, bar and bedform scales along lower Fraser River, British Columbia, Canada. Grain-size variations within compound bars are conditioned by longitudinal position, elevation and morphological setting. Surface and subsurface sediments tend to decrease in median size from bar head to bar tail by 33% and 17%, respectively. Higher elevations attract smaller particle sizes because of reduced flow competence during high stages. Unit bars have surface sediments that are finer and better sorted than the bed materials in bar-top channels and along the main bar edges. Secondary unit bars tend to have a lower sand content than other features, a consequence of sediment resorting. Individual unit bars and gravel-sheets exhibit streamwise grain-size fining and lee-side sand deposition. Through time, morphological adjustments, even significant amounts of cut and fill, do not *ipso facto* cause changes in surface grain sizes, yet sediment characteristics can change without any significant morphological adjustment taking place. At the reach-scale there is a clear downstream fining trend, but local variability is consistently high due to within-bar differences that result from sorting by position, elevation and morphology. The surface median grain size range on individual bars is, on average, 25% of that along the entire 50 km reach but is 68% on one bar. While the overall fining trend yields a downstream change in surface median size of 0.76 mm km^{-1}, the average value for head-to-tail size reduction on individual bars is 6.3 mm km^{-1}, an order of magnitude difference that highlights the effectiveness of bar-scale sorting processes in gravel-bed rivers. We discuss possibilities for modelling bar-scale variability and the interaction of the different controls that are identified.

(307 words)

Keywords: compound bar, fluvial sediment, grain size, gravel sheet, unit bar, wandering channel

INTRODUCTION

A large body of work has revealed how bed material grain-size varies in gravel-bed rivers at reach and river-length scales and has sought to explain the principal spatial features, including downstream fining (Sternberg, 1875; Church and Kellerhals, 1978) and the gravel-sand transition (Yatsu, 1955; Sambrook Smith and Ferguson, 1995). In comparison, the variability of river-bed grain size at bar scales has been the subject of fewer systematic measurement programs and modelling efforts despite the casual observation that many have made, that bar-scale sorting typically produces impressive within-bar grain size differences. Church and Kellerhals' (1978) analysis of replicate Wolman samples collected from 39 bar-head sites on Peace River, British Columbia showed that within apparently homogeneous textural units on single bars, between-sample variance was significantly greater than within-sample variance and that this added significant scatter to downstream (between bar) fining patterns. Bar-scale sorting and its relation to the larger-scale longitudinal trend have substantial implications for sedimentary geology and fluvial geomorphology in terms of explaining the character of alluvial fills and analysing controls on bed load sediment transport and channel hydraulics.

Distributed quantitative measurements have rarely been used to systematically examine grain size across gravel bars (but see Ashworth and Ferguson, 1986; Lunt and Bridge, 2004) but facies mapping of bar surfaces (Bluck, 1976; Forbes, 1983; Wolcott and Church, 1991), remote sensing of bar surface texture (Carbonneau *et al.,* 2004; Chandler *et al.,* 2004; Verdu *et al.,* 2005) and measurements of grain size along transverse transects across braid bar complexes (Mosley and Tindale, 1985; Dawson, 1988; Seal and Paola, 1995) reveal the patchy nature of textural variation. This patchiness arises from sorting of heterogeneous sediments by imperfectly understood mechanisms operating at various scales (Whiting, 1996; Powell, 1998). At grain scales, segregation by size occurs at entrainment because of size-dependent differences in inertia, protrusion (hence drag) and pivot angle, and during deposition because of size-dependent interactions between the bedload and the underlying bed surface texture - for example "like-seeks-like" phenomenon (Moss, 1963; Kuenen, 1966; Clifford *et al.,* 1993), congestion sorting (Iseya and Ikeda, 1987; Whiting *et al.,* 1988) and particle overpassing (Allen, 1983; Carling, 1990). At larger, bedform scales bedload is sorted during transport because of size-dependent differences in the response of particles to gravity effects – so called topographic sorting – (Paola, 1989; Lisle *et al.,* 1991) and to variations in near-bed forces induced by local flow patterns around bedforms (Brayshaw *et al.,* 1983), in bends and around bars (Ashworth, 1996a). The operation of processes like these at bar scales may have implications for larger scale sorting at reach scales, between bars. For example, in a sequence of alternate bars or bar-chute units, upstream trapping of relatively coarse materials in bar heads and pools may reduce the availability of those sizes downstream, forcing reach-scale longitudinal fining (Bluck, 1987). On compound bars the situation is further complicated because the unit bars and unit bar remnants that are the primary elements of bedform construction and that define an important scale at which many sorting phenomena operate, are arranged in complex vertical and areal patterns that reflect complicated depositional and erosional histories.

In this paper we describe and explain aspects of grain size variation across compound bars and discuss bar-scale patterns in relation to larger-scale downstream trends. First, we examine how bed material grain size varies with longitudinal position on the bar, with elevation of the bed surface and with the local morphological setting. Each of these factors is implicated in previous work as a potential cause of bar-scale variability. For example, the most widely reported bar-scale sorting phenomenon is the tendency for bar heads to be coarse relative to bar tails (Leopold and Wolman, 1957; Church, 1972; Bluck, 1974; Lewin, 1976; Ashworth and Ferguson, 1986; Lunt and Bridge, 2004;) but, although head to tail sorting has been measured on simple unit bars (Smith, 1974), there has not been any systematic quantification of head to tail fining on compound bars. Similarly, several investigators have noted the apparent influence of bar morphology for structuring bar-scale variations of grain size (Bluck, 1976; 1979; Lunt and Bridge, 2004) and drawn basic contrasts between channel and bar characteristics, but there has been relatively little explicit consideration of how grain size varies between morphological features or across the complex topography of compound bars. Second, we examine how grain size varies across unit bar surfaces because previous evidence is inconsistent. While Smith (1974) observed downstream fining of surface sediments on seven simple unit bars studied on the Kicking Horse River, British Columbia, Lunt and Bridge (2004) observed downstream coarsening of sub-armour layer sediments on unit bars of the Sagavanirktok River, Alaska. Examples of both downstream fining (Livesey *et al.,* 1998) and downstream coarsening (Iseya and Ikeda, 1987) are apparent in flume studies where sheets have been observed. Third, we consider the short-term temporal variability of bed material grain size as compound bars are modified by unit bar accretion and erosion. Finally, we compare our findings with the evidence for systematic downstream changes in bed sediment texture and examine the combined effects of bar-scale sorting relative to downstream fining rates. The field site is in the gravel reach of lower Fraser River, British Columbia, Canada.

FRASER RIVER GRAVEL REACH

The gravel reach extends for approximately 50 km from Laidlaw, where the river emerges from confinement between valleyside slopes and terraces, to Sumas Mountain, immediately upstream from the town of Mission, where there is a rapid gravel-sand transition (Figure 1). Through the gravel reach the river exhibits a wandering style within an active channel zone between one and two kilometres wide that is partially constrained by flood defences. Near Laidlaw, at the Agassiz gauge, the river is 512 m wide at mean annual flood stage, has a mean depth of 6.6 m, a mean velocity of 2.6 m s^{-1} and a gradient of 4.8 x 10^{-4}. Corresponding values at Mission are w = 540 m, d = 12.6 m, v = 1.5 m s^{-1} and S = 5.0 x 10^{-5} (McLean *et al.,* 1999). Most bed load transport, deposition and reworking occur during an annual snowmelt freshet in late spring and early summer. At Mission (Water Survey Canada, gauge 08MH024), the mean annual flow is 3410 m^3 s^{-1} and the mean annual flood is 9790 m^3 s^{-1} .

Rice et al. (2009) present a morphological typology for compound bars in wandering gravel-bed rivers that is primarily developed from observations in the gravel reach of Fraser River. The fundamental morphological unit is the familiar pool-riffle-bar triplet (Bluck, 1976; Lewin, 1976; Ferguson and Werrity, 1983): deposition grows a bar where flow diverges across an oblique riffle, while scour creates a pool that is constrained by the facing bank where flow converges below the riffle front. Several styles of bank-attached lateral or, less frequently, medial bars are the dominant macroforms (Jackson, 1975). The scale of the river is such that these bars may be up to 2.5 km in length and may exceed a kilometre in width. The compound bars record vertical and lateral accretion of unit bars and their subsequent modification by cut and fill processes in secondary channels, seasonal anabranches and smaller bar-top channels that are progressively occupied as stage rises during flood events. Unit bars, built by the stacking of gravelly bedload sheets, are the basic building blocks that record individual sediment depositing episodes and dominate the process of morphological change. The characteristic length scale varies between 10^1 and 10^3 m. Primary unit bars are those which deliver sediment to the bar complex from the principal channel whereas secondary unit bars are the product of dispersal of sediment from the primary accretion sites into and through the bar complex via secondary channels, seasonal anabranches and smaller bar-top channels. Figure 2 illustrates these various supraplatform features for one bar on Fraser River (see Rice et al. (2009) for additional illustrations, particularly Figures 6, 7, and 9 therein). Analysis of bar development on decadal timescales shows that compound bar formation is controlled by shifts in the position of the principal channel and, therefore, loci of erosion and unit-bar deposition, but long-term histories reveal the potential for long sequences (approaching 100 years) of persistent accretion.

METHODS

To characterise bar sediments along the gravel reach, 53 surface (Wolman) and 48 subsurface samples were collected from nineteen compound bars between Wahleach bar near Laidlaw and Yaalstrick bar close to Mission during the winter of 2000. To evaluate gross within-bar variability, two or more samples were collected from sites within the upper, middle and lower thirds of most bars. Bulk samples that met the 1% criterion of Church et al. (1987) were collected by pooling small sub-samples from across a larger area, e.g. the bar head. Wolman samples were positioned at a representative site within the larger unit and consisted of approximately 400 grains collected from a 20 x 5 m grid with 0.5 m spacing.

To investigate bar-scale variability in greater detail, an additional 87 surface samples and four subsurface samples (in this case, from single pits) were collected from Queens Bar in April 2000 (before the freshet). Samples were located in a quasi-systematic manner to cover the entire survey area and ensure representation of the major morphological features. Wolman samples of 360-400 grains were collected from homogeneous units at 41 sites and a photo-count method (see below) was used at 46 sites. In September 2000 (after the freshet), 21 of these sampling positions were reoccupied and Wolman samples were again collected. In September 2004, 17 positions were reoccupied and sampled again, and 20 new sites were established. On this occasion, 19 Wolman samples were collected and the AGS (automated grain-sizing) photographic method (Graham *et al.,* 2005a; 2005b) was employed at 18 sites. Additional surface samples were collected from several other sites where features of interest were surveyed, including 51 photo-count samples on Spring Bar and Gill Island during September 2001.

During the collection of Wolman samples, templates were used to sort grains more than 8 mm in diameter into half-psi size classes. Smaller grains were classified as 4 to 8 mm or as less than 4 mm, which we define as the ‘sand’ fraction. From the Wolman samples we obtained a percentage sand cover value and could also derive either coarse-fraction percentiles from a distribution truncated at 4 mm or percentiles for the entire distribution including sand. Clean and sandy gravels (those obscured by a thin, discontinuous veneer of sand) dominate the active portions of the bed. Although the sand cover is of interest, it is sometimes of interest to establish the size distribution of the coarser fraction without the sand component because the sand veneer is quickly flushed away during floods and it is the gravel component that ultimately determines the stability of the bar surface and reflects the peak entrainment stresses at a site.

The photo-count method is based on a simple calibration between particle size and the number of particles per unit area (Rice and Church, 1998). At 83 sites where Wolman data were collected (on ten bars along the reach) a vertical photograph was taken of a 0.5 by 0.5 m quadrat laid down at random within the Wolman grid. After correction for sand coverage and obscuration by shadow, calibration relations were established between count greater than 4 mm and Wolman-derived D_{50} and D_{95} (truncated to exclude the < 4 mm sand fraction). Sites with more than approximately 5 % exposed sand degraded the quality of the relations and were excluded. The resulting calibrations yield prediction limits ($\alpha = 0.05$) for mean D_{50} and D_{95} estimates of ±5 and ±17 mm respectively, and were used to estimate coarse grain percentiles at 38 sites where only photographs were collected (estimates were not obtained at 8 of the original 46 sites where sand cover was greater than 5%). The AGS method employed in 2004 uses robust image processing tools to automatically identify and measure surface grain sizes. Wolman samples were collected at eleven sites and provide a check on the method’s application on Fraser River. Comparison of Wolman with AGS D_{50} and D_{95} estimates revealed no significant bias and root mean square differences of ±3 mm and ±9 mm, respectively.

In addition to grain size information, bed structure was described using the “loose”, “underloose”, “normally loose” classification suggested by Church (1978) and the degree of embeddedness and strength of imbrication were evaluated qualitatively. Finally, high-stage flow direction was estimated by measuring the orientation of imbricated clasts. Ten measurements were made at each sediment sampling site.

OBSERVATIONS

Down-Bar position and grain size

During sampling in 2000, at least one surface sample was collected from the upstream and downstream thirds of nine bars, and at least one subsurface sample from the upstream and downstream thirds of fourteen bars along the reach (in a population of 20 bars). For these cases, the ratio of upstream to downstream median grain sizes (untruncated samples) was calculated as $\Delta_{50} = D_{50U} / D_{50D}$, where the subscripts U and D refer to upstream and downstream positions respectively. In eight of the nine surface cases and ten of the fourteen subsurface cases, $\Delta_{50} > 1.0$ indicating that bed material size tends to be coarser in the upstream thirds of compound bars than in the downstream thirds. Mean surface and subsurface Δ_{50} values are 1.47 and 1.19 respectively, indicating 33% and 17% decreases in median size from bar head to bar tail. This bar-scale longitudinal differentiation decreases with distance downstream (Figure 3) presumably because of an overall improvement in bed material sorting due to downstream fining.

Surface elevation and grain size

Across Queens Bar, sites at higher elevations are associated with smaller maximum particle sizes (Figure 4), presumably because water depth at high-stage and, therefore, maximum shear stress decline as elevation increases. General competence considerations suggest that maximum grain size should be related to water depth by

$$D_{\max} = Y \frac{S}{\tau^{*} \cdot \gamma_s} \qquad (1)$$

where $D_{\max}$ is maximum particle size, Y is water depth, S is the energy slope, γ_s is submerged specific weight (=1.65) and τ^* is Shields' dimensionless critical shear stress (≈ 0.03 for dis-entrainment). The D_{95} values plotted in Figure 4 are for 87 surface samples collected along the flank and through the main anabranches of Queens bar in April 2000. During moderate discharge at that time, average water surface slope across the sampled area was 0.0004 yielding a first approximation of $D_{\max} / Y = 0.008$ (m m^{-1}), the rate at which maximum grain size should increase as water depth increases. When expressed in terms of the decrease in grain size per unit increase in bed surface elevation, the appropriate slope is –0.008. The bulk of the data plotted in Figure 4 is neatly contained by an envelope curve with this slope, supporting the argument that variations in particle size with elevation are caused by differences in imposed shear stresses.

Morphological setting and grain size

The 87 surface samples from Queens bar were classified according to their site morphology as primary unit bars, secondary unit bars, bar-top channels and principal channel edge. The surface sediment characteristics of each group are reported in Table 1a. Although individual sites in different categories share common surface characteristics, sorting processes do produce some significant between-group differences. Primary and secondary unit bars have mean D_{50} and D_{95} values that are very similar and significantly finer than those for the bed materials in bar-top channels and along the main bar edge (t-tests, $p < 0.001$; Figure 5A). Unit bar gravels are marginally better sorted and the difference in sorting between primary unit bars and erosional bar edges is significant (Mann-Whitney U test, $p = 0.033$). These basic distinctions are explained by the greater mobility and simple depositional history of the unit bar sediments and their higher elevations (t-tests, $p < 0.001$; Figure 5B), and therefore lower entrainment stresses at high stage. Some sites on the unit bars were 'over-loose' and the majority of sites were 'normally' loose (Table 1a). In contrast, 'under-loose' sediments dominated the bar-top channels (62%) and no sites were classed as 'over-loose'. This reflects the relative mobility and ephemeral flow across unit bars in contrast to the structural consolidation achieved by longer-lived competent flows in the surrounding channels. Secondary unit bars were the only setting where surface censoring was observed, typically at those sites close to the edge of a leading avalanche face. This presumably reflects the development of a steep energy gradient and, therefore, strong hydraulic winnowing of matrix fines across the avalanche face as stage falls.

Average percentage sand is significantly lower on secondary unit bars than in the other three settings (Mann-Whitney U tests, $p < 0.001$), each of which exhibits a wide range of sand cover from zero to over 48 % (Table 1a). While 67 % of secondary unit bar sites had 'clean' surfaces and none were 'heavily' embedded, in bar-top channels only 17 % were 'clean' and 48 % were 'heavily' embedded. The high proportion of sand in bar-top channels is caused by proximal disconnection as stage falls. Fines settle out of suspension or stall as they move along the bed to partially or completely veneer the gravel surface with sand and then silt. At distal locations, where connections to the principal or secondary channel are maintained for long periods so that sediment laden waters are refreshed, these veneers may be several centimetres thick. In contrast, the low proportion of sand on secondary unit bar surfaces reflects the high relative position of their surfaces, which means that they are less likely to be inundated by deep, slack water from which a significant amount of fine sediment can be deposited. High proportions of sand at some sites on primary unit bars reflect local hydraulic conditions. For example where a unit is being overridden by a fresh bar the surface of the lower, older unit is prone to fine sedimentation in the lee of the advancing avalanche face.

Single subsurface samples collected from each type of morphological setting on Queens bar show that subsurface grain-size characteristics also vary between morphological settings within bars. These samples provide good evidence that the degree of variability in subsurface sediment characteristics is similar to that of the corresponding surface sediments (Figure 6A) and, therefore, that the sorting processes that produce diverse surface textures affect the associated bulk deposits too. Again, a primary distinction can be drawn between the characteristics of unit bar and channel samples. Samples from the two unit bars yielded similar grain-size distributions that were deficient in coarse gravels and cobbles relative to the bar-top and bar-edge channel samples (Table 1b; Figure 6B). Armour ratios (= surface D_{50}/subsurface D_{50}) were calculated for these four sites using untruncated surface and subsurface GSDs. Values are low for the unit bars (= 1.3 in both cases) which reflects their mobility and ephemeral flow regime. In contrast, the bar-edge site has an armour ratio approaching 3.0, which reflects surface winnowing of fine sediment and is consistent with the greater structural consolidation of channel surfaces noted above. The bar-top channel site has a low armour ratio (< 1) because the surface at the sampling location was heavily embedded. This is common (14 of 29 bar-top channel sites were heavily embedded) and reflects the propensity for fine sedimentation from still water or slackening flows as bar-top channels are isolated from the principle and secondary channels by falling stage during the receding limb of the freshet.

A further source of variability is the degree of bimodality in the subsurface sediments. Each of the bulk grain size distributions is bimodal with a gap in the 0.5 mm to 5.0 mm range. However, bimodality is notably stronger in the two unit bar sediments and is weakest in the bar edge sample (Figure 6B). This suggests that bimodality is preferentially generated by active transport and deposition or preferentially restricted in high-energy erosive environments where sand fractions are more mobile.

Grain-size variations across sheets and unit bars

Grain size variations across individual unit bars and the gravel-sheets which build them tend to exhibit streamwise grain-size fining and lee-side sand deposition (Figure 7). On Spring bar, bar-head unit-bar accretion occurs across the full channel width under a relatively simple flow field that is uncomplicated by islands or channel anabranches. Numerous gravel sheets and stalled unit bars are evident on the bar platform. At each of seven sheet fronts, four photographic grain-size samples were obtained, two upstream of the crest and two downstream on the lower, partly over-ridden unit in front. All samples were collected within 10 m of the sheet crests which were, on average, 0.11 m high. Sand cover was greater downstream in six of the seven cases and, on average, there was 5.8 times more sand area on the surface downstream than upstream. This lee-side sand cover is discontinuous but reached 33% in one case (Figure 7A). Beneath the sand, the lee-side gravels tend to be coarser than in the advancing sheet and in all seven cases, gravel sizes on the crest were finer than those downstream (Figure 7B and C). On average, the ratio of upstream to downstream D_{50} was 0.70 (range, 0.49 to 0.93). The relatively coarse bed material in the lee of each advancing unit belongs to the tail of the underlying sheet so that the differences in gravel size across each crest suggest that there is a streamwise decrease in framework grain size toward the sheet crest (Figure 7D). It appears that, on Spring bar, streamwise sorting occurs within each individual sheet as it climbs up onto the back of the underlying unit. Similar streamwise fining is apparent on the surface of flat-topped unit bars, for example flank bars on Gill Island where D_{50} declines from 46 mm to 28 mm in 130 m. Fining is not ubiquitous and where the flow field is complex grain size variations across unit bars are less consistent. Figure 7E shows D_{95} values across two unit bars that were deposited on Queens during the 2002 freshet. Along high-flow paths indicated by clast orientation, gravels more often fine downstream (e.g. X to X') but streamwise coarsening is sometimes apparent (e.g. Y to Y').

The tendency for streamwise fining is consistent with some previous flume observations (Livesey *et al.,* 1998) but inconsistent with the observations of Whiting *et al.* (1988) on Duck Creek, where gravel sheets had a relatively coarse leading edge. The material in motion on Duck Creek is much finer than that on Fraser River ($D_{50} \approx 5$ mm) and laboratory observations have demonstrated the importance of a high sand content for the leading-edge congestion and over-passing process that is associated with this type of sheet migration (Iseya and Ikeda, 1987; Dietrich *et al.,* 1989). Fining on the Fraser River unit bars might simply reflect the dominance of size-selective sorting where the bed load grain-size distribution is generally more coarse with less sand content and where the relief of the unit bars and sheets is greater such that depth and therefore competence vary significantly along the streamwise axis. That is, the streamwise fining reflects the increasing downstream height of sheets that are climbing onto existing bars.

Morphological development and temporal grain size changes

The emplacement of individual unit bars can be responsible for significant local changes of grain size (Figure 8). For example, the flank unit bar that formed the bar edge at Calamity before the 2002 freshet had a mean surface D_{50} of 32 mm (n = 9). The overriding unit that became attached during the 2002 freshet consisted of coarser gravels with an average D_{50} of 44 mm (n = 5), a significant difference (t-test, $\alpha = 0.01$). Despite such spectacular local events and the general associations between morphological elements and grain size, analyses of bed material samples from Queens bar suggest that local grain size modification can also occur in the absence of topographic change and that topographic change does not necessarily produce changes in grain size.

In September 2000, grain size samples were collected at 21 positions on Queens bar that had previously been sampled in April. The freshet that occurred during the intervening period (maximum daily discharge = 8470 $m^3 s^{-1}$, less than the mean annual flood) caused small-scale reworking of bar morphology (Rice *et al.*, 2009). Topographic surveys indicate that eight of the sampled positions had experienced either a significant change in elevation or are likely to have experienced the passage of a large unit bar. The remaining 13 positions underwent no significant morphological change and were unlikely to have been affected by the passage of unit bars. Seven of the same positions were reoccupied in September 2004 and all sites had undergone significant changes during large-scale modification of the bar in the 2002 freshet (maximum daily discharge = 11 000 $m^3 s^{-1}$, the fifth largest in the 40-year measured record). Replicate Wolman samples yield a 95% confidence interval on D_{50} estimates of ±1.8 mm. Figure 9 plots D_{50} for the surveys before and after the 2000 freshet (April and September 2000) and before and after the 2002 freshet (September 2000 and September 2004). The solid lines indicate the region within which differences could be due to sampling imprecision (± 2.55 mm $= \sqrt{(1.8^2 + 1.8^2)}$). It is clear that that there is a good deal of temporal consistency such that sites are characterised by similar D_{50} grain-sizes before and after each flood. It is somewhat surprising in Figure 9A, that there is not a clearer distinction between sites experiencing significant cut and fill or the passage of unit bars and those where no morphological adjustment was apparent.

On the one hand this suggests that morphological adjustments, even significant amounts of cut and fill, do not *ipso facto* cause changes in surface grain sizes and, on the other hand, that sediment characteristics can change without any significant morphological adjustment taking place. The former may reflect the relatively well-sorted nature of the sediments on this part of the river, such that local sorting during cut and fill can produce only small changes in median size (which is in any case a relatively insensitive measure of change). The latter may indicate that the magnitude of grain size change due to deep incision or burial beneath active gravel sheets is no greater than that which can be accomplished in the surface layer by, for example, winnowing or the discontinuous diffusion of mobile materials.

The limited changes that took place at particular locations on Queens bar are consistent with the similarity of average bar-scale grain-size characteristics during the study period. When the mean and variance of the 79, 21 and 17 D_{50} values obtained on Queens in April 2000, September 2000 and September 2004 were compared, there were no significant differences (F- and t-tests, $\alpha > 0.10$).

The downstream trend

The dominant large-scale trend in many alluvial rivers is downstream fining caused by sorting and abrasion processes (Russell, 1939; Parker, 1991; Ferguson *et al.,* 1996; Rice, 1999; Lewin and Brewer, 2002), punctuated by positive grain-size steps at coarse-sediment recruitment points such as some tributaries (Sternberg, 1875; Miller, 1958; Knighton, 1980; Rice and Church, 1998). This model may be disrupted to varying degrees by low sediment supply (Singer, 2008), diffuse lateral sediment sources (Heller *et al.,* 2001; Davey and Lapointe, 2007) and local factors that include hillslope-channel coupling (Rice and Church, 1996), anthropogenic channel modifications (Surian, 2002) and variations in gravel mobility due to lithological control of channel morphology (Constantine *et al.,* 2003).

Overall downstream fining is present along the gravel reach of Fraser River, beyond which there is a transition to sand. In 2000, multiple samples were collected from homogenous patches on twenty individual bars. Surface D_{50} declined from approximately 50 to 20 mm (Figure 10) along the gravel reach, and D_{90} declined from approximately 100 to 30 mm. Corresponding values for subsurface sediments were 25 to 10 mm and 90 to 30 mm. Despite these general trends, local variability is consistently high (on the order of 1 to 1.5 psi units or $\log_2$ cycles) and, in common with many published downstream fining datasets, scatter is a dominant characteristic. It is clear from Figure 10A, where data for individual bars are differentiated, that much of this scatter is due to within-bar variability rather than between-bar differences. Indeed, both surface and subsurface sediments can exhibit almost as much variation within the limits of an individual compound bar as does the entire gravel reach. For the nine bars where head and tail Wolman samples are available, and where we might therefore presume to have captured a reasonable amount of the bar-scale textural variability, the average surface D_{50} range is 20 mm, the maximum is 51 mm (Wahleach Bar) and the minimum is 4 mm (Carey Bar). These contrast with the surface D_{50} range of 90-15 = 75 mm for the entire set of gravel bars along the 50 km reach. This indicates that the grain size range on individual bars is, on average, approximately 25% of the overall range in the reach but can be as high as 68%.

An alternative expression of this pattern takes into account the distance over which sorting is apparent at reach and bar scales. For the entire reach, the linear least-squares downstream fining model yields a diminution rate of 0.76 mm km^{-1}. For the nine bars with head and tail samples (excluding the one bar where the bar tail was coarser) the rate of decline in median grain size from head to tail ranges between 0.56 mm km^{-1} at Yaalstrick and 15.08 mm km^{-1} at Gill, with an average of 6.31 mm km^{-1}.

To examine temporal stability of the downstream fining trend, grain-size data from 2000 can be compared with an earlier data set of bar-head samples collected in 1983/84 (n = 53). Surface (Wolman) samples collected in the earlier program were only 100 clasts in size, but that is sufficient to return a reliable estimate of the median grain size (Rice and Church, 1996). The comparison of surface materials indicates that bed materials have become finer in the sub-reach common to both sampling programmes (between river km 108 and 140). Over that period, mean surface D_{50} in the sub-reach appears to have declined significantly from 35 to 29 mm (t-test, $p = 0.05$). Overall fining trends remain consistent, however, with no significant difference in the regression slopes for linear fining models for the two years (Ancova, $p = 0.83$; Figure 10B). There is a possibility that differences between the two sampling programs in sample protocol with respect to the finest grains may have induced the result. However, reach-scale changes are presumably dominated by patterns of sediment supply and transport capacity; a long run of below normal freshets between the two sampling dates may very well have effected such a change.

Combined effects

The question arises whether the sedimentological effects described above act in combination to affect grain size. Because downstream fining effects impose a systematic difference in expected mean grain size from bar to bar, we ask whether the bar-scale variations we have studied may affect that trend locally. Down-bar fining – also a systematic spatial effect – needs to be averaged away in a representative way in order to study downstream fining from bar to bar, while grain size variations associated with morphological setting, which vary spatially within bars, also needs to be averaged. We also know that surface elevation affects sediment size within bars and we do know bar platform elevation (see Church and Rice, in review), that is, the elevation of the gravel surface above the main channel bed. Hence, using the spatially averaged mean grain size for each bar, we may ask whether bar platform elevation explains any of the substantial scatter of data about the mean downstream trend. We examine this question by computing the downstream trend for data averaged across individual bars and then examining the correlation between bar platform elevation and the residuals from that trend. Surface and subsurface data of 12 bars are available for analysis.

Some results are displayed in Figure 11. To compute the trend line, data of Foster Bar were excluded. Foster Bar presents a large anomaly, a circumstance that probably is related to a large gravel extraction that occurred on the bar 4 years before sampling. The residuals do correlate with bar thickness, except that Big Bar again presents a significant anomaly. Big Bar is a relatively recently established bar (45 years) that has formed on top of a long diagonal riffle in the river. The bar tail sits astride the riffle and there is a large, perennially flowing chute channel below the riffle. With this morphology, there is little bar tail deposition of finer sediments, which serves to elevate the mean grain size for the bar. For the remaining bars the correlation of the residuals with bar thickness is significant ($p = 0.06$; for exploratory purposes we adopt $\alpha = 0.10$ as the threshold for a significant result). We tentatively conclude that bar thickness influences grain size downstream and helps to explain residual scatter about the reach-scale fining trend. The results displayed in Figure 11 are for surface D_{50}. Variance reduction in the same analysis is marginally superior for surface D_{90} and the pattern is identical, but no significant effect was found for subsurface sediments.

Given this effect and the general expectation that bars thicken as they grow, the further question arises whether bar age is correlated with grain size (in the absence of the fining trend and other local effects). We know the ages of the bars, but we found that bar age did not correlate with the residual variance from the downstream fining trend line and conclude that there is no age effect. This is explained by the observation that once established, bars rapidly assume a surface elevation that is close to the final elevation (Church and Rice, in review) such that bar thickness is essentially independent of bar age.

DISCUSSION

We have demonstrated grain size variations in a gravel-bed river at scales varying from individual sedimentary units (unit bars) within bar, through the dominant bar scale, to whole reach scale. Within sedimentary units, size gradation is associated with distance along a flowline and with elevation, themselves correlated so that fining occurs upward and downstream. Overall, fining is associated with flow divergence and sediment depositional gradient. Secondary sorting in bar top channels and resedimented units complicates the local pattern of grain size variation so that a somewhat palimpsestic pattern of repeated local fining gradients occurs on a compound bar.

An overall pattern of down-bar fining at the bar scale is the strongest individual gradient at any scale. This gradient is the consequence of sediment sorting associated with steering of the river current by the developing barform. The major sediment body dominantly grows laterally (Rice et al., 2009; Figure 8, herein), so the lee-side regions become shadow zones into which sediment moves over the bar-top, primarily through bar-top channels, or diffuses laterally from the displaced main current. Predominantly finer sediment is deposited in this shadow zone. While this bar-scale gradient is strongest, clearly demonstrating that sorting on individual gravel bars is highly effective, this remains the aspect of bar-scale sedimentation that is perhaps least well understood in its details.

This explanation has an affinity with Ashworth's model of bar formation in braided rivers in terms of the focus on mobile units and their different local transport pathways and sinks (Ashworth *et al.* 1992a,b; Ashworth, 1996). In that model, the relatively small impact of secondary flows on coarse bedload and flow divergence at emergent bar heads is thought to lead to the concentration of relatively coarse material there, while finer sediments moved laterally by secondary currents are thought to be more easily deflected around bar heads into distributary channels, where topographic sorting promotes bar-tail deposition. Bluck (1976; 1979) emphasised the stage dependence of depositional positions across a bar platform, suggesting that coarser bar heads are formed at high stages and finer tails in the lee of these deposits during falling stages. Thick sandy facies are commonly deposited on Fraser River bar tails during the receding limb of the annual hydrograph so this process is probably part of the explanation too. It is unlikely that bar-scale fining reflects the operation of a “turbulence template” whereby relatively coarse bar head materials generate hydrodynamics that only relatively coarse bedload grains can tolerate, such that incoming finer grains are rejected and transported to downstream positions (Bluck,1987; Clifford *et al.* 1993), because such a process does not operate at the kilometre scale of the compound bars.

Local sorting across bars and individual bedforms produces grain size variations at the scale of the channel width that are equivalent to those observed longitudinally over much greater distances. In practice, this means that downstream fining patterns are revealed most clearly when sediment variability at a local scale is minimised, usually by limiting sampling to a particular bar-scale unit (typically the bar head) or by lumping together observations to provide a spatial average. The usefulness of downstream fining models for prediction is then limited to reach scale applications, while predictions of bar-scale variability require an additional term to express the local grain-size range that can be anticipated.

Our analysis of Fraser River sediments suggests two potential means of providing such an expression. First there is, on average, a 33% reduction in median surface grain size between bar-head and bar-tail (defined as the upper and lower third of the compound bar surface, respectively). Bar-scale variability on this river might be approximated by reducing a prediction of bar-head grain size (D_{50U}) from a downstream fining model by a proportion P (= 0.33 on Fraser River) to estimate the bar-tail grain size and thence the bar-scale range = D_{50U} $(1- P)$. This simple model and the value of P requires further investigation because other rivers are likely to exhibit different ratios; for example, the maximum particle size delivered to bar heads presumably limits the possible magnitude of downstream bar change because the lower limit is essentially fixed. Indeed, this example suggests a second means of estimating bar-scale variability that relies on the possibility that the value of P may vary systematically along a fining trend. We note that along the reach-scale fining sequence, there is a weak decline in within-bar (between-patch) variability ($R^2 = 0.55$ for the relation between distance downstream and within-bar D_{50} range; Figure 10A), suggesting that patch textures become less diverse as a systematic function of position along a fining trend. This is consistent with the progressive downstream exclusion of coarse grains during downstream fining, leaving available a reduced mixture of sizes for bar-scale sorting (cf. Bluck, 1987). We hesitate to define the nature of this relation here, but a larger data set designed to establish within-bar, between-patch variability along a number of fining sequences, may yield useful empirical models.

At bar scales, however, there is no equivalent means of modelling textural change through time, even though such information is important for understanding the details of alluvial stratigraphy and the impact of river change on lotic habitats. Developing a better spatial and temporal understanding of textural variability at even finer sub-width scales is also important, for example, for validating and calibrating 2-D models of channel hydraulics, sediment transport and patchy lotic habitats. Repeated plane table mapping and sediment-size analysis of bars on the River Tulla, Scotland by Bluck (1987) revealed that most bars coarsen as they age, which Bluck suggested was due to *in situ* modification by the turbulence template mechanism (Clifford *et al.,* 1993). We do not have a sufficiently long data set to test these ideas, but our examination of grain size responses to mobile bed events across Queens Bar, does show that morphological change may or may not cause local grain size changes and that morphological stability may or may not be associated with grain size change. Moreover, we found no correlation between bar age and residuals from the downstream fining trend.

CONCLUSIONS

We have demonstrated that sediment grain sizes found on bar surfaces in a 50-km gravel bed reach of a large wandering gravel-bed river vary systematically with down-bar position, with morphological setting, and with bar surface elevation. In addition, sediment texture can be modified by secondary resedimentation on a bar but, on the bars found in this large river, representative grain size does not necessarily change systematically, at a particular position, over a period of years that includes repeated seasonal inundation.

The qualitatively well-known down-bar variation is by far the greatest source of variation, quantitatively larger locally than the overall downstream fining of fluvial gravels. On lower Fraser River, the difference amounts to an order of magnitude (6.3 mm km^{-1} vs. 0.76 mm km^{-}

[1]). Its occurrence is mediated by the mutual effect of bar growth and river current steering, which determines the developing pattern of sedimentation. Local variation in grain size due to the surface elevation of the bar surface above the main channel bed contributes to the observed variance in overall downstream fining.

This finding carries important implications for representative sampling of fluvial bed material grain size along gravel-bed rivers and for both the calibration of 2-D morphodynamic models and the interpretation of bed material grain size predicted by those models. High bar-scale variability means that large-scale trends can only be revealed when local-scale variability is removed; for example, by consistently sampling from a single depositional environment, like bar-heads. While this is well-established practise amongst most geomorphologists and sedimentologists dealing with modern sediments, it is clearly difficult to achieve when examining limited exposures in alluvial fills or lithified gravels. High local variability also means that single bed material samples cannot be representative of the grain sizes apparent on a bar or across a channel width. This is problematic when trying to establish grain roughness parameters in morphodynamic models of gravel-bed rivers and when comparing model predictions of bed material grain size with field data (e.g., Ferguson and Church, in review).

Notwithstanding the explanations of bar-scale variability described herein, it is clear that the complexity of sediment sorting across compound bars will continue to hinder the identification of simple predictive models of bar-scale grain-size. In this context, empirical information remains important, both for improving understanding of bar-scale sedimentation and for providing calibration and test data for morphodyamic models. Recent technical advances in distributed measurement tools (Carbonneau *et al.,* 2005; Graham *et al.,* 2005b; Verdu *et al.,* 2005) will improve our ability to document the spatial and temporal variability of river bed sediments at bar and reach scales. Both automated airborne and ground-based image-analysis systems now make it feasible to collect high-resolution grain size information over large areas and, where long-term archives of air photography are available, to unlock histories of grain-size change

Acknowledgments

Work on lower Fraser River is supported by the Natural Sciences and Engineering Research Council of Canada through a Discovery Grant to M.Church. A host of assistants and colleagues made major contributions in the field and laboratory, including Jim Chandler, Erica Ellis, Nick Manklow, Laura Rempel, Hamish Weatherley and André Zimmermann. The 1984 sediment data were collected by David McLean.

References

Allen, J.R.L. (1983) Gravel overpassing on humpback bars supplied with mixed sediment - Examples from the Lower Old Red Sandstone, Southern Britain. *Sedimentology,* **30**: 285-294.

Ashworth, P.J. (1996a) Mid-channel bar growth and its relationship to local flow strength and direction. *Earth Surface Processes and Landforms,* **21**: 103-123.

Ashworth, P.J. and Ferguson, R.I. (1986) Interrelationships of channel processes, changes and sediments in a proglacial braided river. *Geografiska Annaler,* **68 A**: 361-371.

Ashworth, P.J., Ferguson, R.I. and Powell, M.D. (1992a) Bedload transport and sorting in braided channels. In: *Dynamics of Gravel-bed Rivers* (Eds P. Billi, R.D. Hey, C.R. Thorne and P. Tacconi), pp. 497-515. John Wiley & Sons Ltd, Chichester.

Ashworth, P.J., Powell, D.M., Prestegaard, K.L., Ferguson, R.I., Ashmore, P.E. and Paola, C. (1992b) Measurements in a braided river chute and lobe. 2. Sorting of bed load during entrainment, transport, and deposition. *Water Resources Research,* **28**: 1887-1896.

Bluck, B.J. (1974) Structure and depositional properties of some valley sandur deposits in southern Iceland. *Sedimentology,* **21**: 533-554.

Bluck, B.J. (1979) Structure of coarse grained braided stream alluvium. *Transactions of the Royal Society of Edinburgh,* **70**: 181-221.

Bluck, B.J. (1976) Sedimentation in some Scottish rivers of low sinuosity. *Transactions of the Royal Society of Edinburgh,* **69**: 425-455.

Bluck, B.J. (1987) Bed forms and clast size changes in gravel-bed rivers. In: *River Channels: Environment and Process* (Eds K. Richards), pp. 391. Blackwell, Oxford.

Brayshaw, A.C., Frostick, L.E. and Reid, I. (1983) The hydrodynamics of particle clusters and sediment entrainment in coarse alluvial channels. *Sedimentology,* **30**: 137-143.

Carling, P.A. (1990) Particle over-passing on depth-limited gravel bars. *Sedimentology,* **37**: 345-355.

Chandler, J.H., Rice, S.P. and Church, M. (2004) Colour Aerial Photography for riverbed classification. *Archives of the International Society for Photogrammetry and Remote Sensing,* **XXXV**

Church, M. (1972) Baffin Island sandurs: a study of Arctic fluvial processes. *Geological Survey of Canada, Bulletin,* **216**: 208.

Church, M. (1978) Paleohydrological reconstructions from a Holocene valleyfill. In: *Fluvial Sedimentology (Proceedings, 1st International Symposium on Fluvial Sedimentology)* (Eds A.D. Miall), Canadian Society of Petroleum Geologists *Memoir* **5**: 743-772.

Church, M. and Kellerhals, R. 1978. On the statistics of grain size variation along a gravel river. *Canadian Journal of Earth Sciences,* **15**: 1151-1160

Church, M., McLean, D.G. and Wolcott, J.F. (1987) River bed gravels: sampling and analysis. In: *Sediment Transport in Gravel Bed Rivers* (Eds C.R. Thorne, J.C. Bathurst and R.D. Hey), John Wiley & Sons Ltd, Chichester.

Clifford, N.J., Hardisty, J., French, J.R. and Hart, S. (1993) Downstream variation in bed material characteristics: a turbulence controlled form-process feedback mechansism. In: *Braided Rivers; Geological Society Special Publication no. 75* (Eds J.L. Best and C.S. Bristow), pp. 89-104. The Geological Society, London.

Constantine, C.R., Mount, M.F. and Florsheim, J.L. (2003) The effects of longitudinal differences in gravel mobility on the downstream fining pattern in the Cosumnes River, California. *Journal of Geology,* **111**: 233-241.

Davey, C. and Lapointe, M. (2007) Sedimentary links and the spatial organization of Atlantic salmon (Salmo salar) spawning habitat in a Canadian Shield river. *Geomorphology,* **83**: 82-96.

Dawson, M. (1988) Sediment size variation in a braided reach of the Sunwapta River, Alberta, Canada. *Earth Surface Processes and Landforms,* **13**: 599-618.

Dietrich, W.E., Kirchner, J.W., Ikeda, H. and Iseya, F. (1989) Sediment supply and the development of the coarse surface layer in gravel-bedded rivers. *Nature,* **340**: 215-217.

Ferguson, R.I. and Werrity, A. (1983) Bar development and channel changes in the gravelly River Feshie, Scotland. In: *Modern and Ancient Fluvial Systems* (Eds J.D. Collinson and J. Lewin), pp. 181-193. Blackwell Science, Oxford, UK.

Ferguson, R.I. (2003) Emergence of abrupt gravel to sand transitions along rivers through sorting processes. *Geology,* **31**: 159-162.

Ferguson, R. I. and Church, M. in review. A critical perspective on 1D modelling of river processes: gravel load and aggradation in lower Fraser River. *Water Resources Research.*

Ferguson, R.I., Hoey, T., Wathen, S. and Werrity, A. (1996) Field evidence for rapid downstream fining of river gravels through selective transport. *Geology,* **24**: 179-182.

Forbes, D.L. (1983) Morphology and sedimentology of a sinuous gravel-bed channel system: lower Babbage River, Yukon coastal plain, Canada. In: *Modern and Ancient Fluvial Systems* (Eds J.D. Collinson and J. Lewin), pp. 195-206. Blackwell Scientific, Oxford, UK.

Graham, D., Reid, I. and Rice, S. (2005a) Automated Sizing of Coarse-Grained Sediments: Image-Processing Procedures. *Mathematical Geology 37, no.1,*

Graham, D.J., Rice, S.P. and Reid, I. (2005b) A transferable method for the automated grain sizing of river gravels. *Water Resources Research,* **41**: 1-12.

Heller, P.L., Beland, P.E., Humphrey, N.F., Konrad, S.K., Lynds, R.M., McMillan, M.E., Valentine, K.E., Widman, Y.A. and Furbish, D.J. (2001) Paradox of downstream fining and weathering-rind formation in the lower Hoh River, Olympic Peninsula, Washington. *Geology,* **29**: 971-974.

Iseya, F. and Ikeda, H. (1987) Pulsations in bedload transport rates induced by a longitudinal sediment sorting: a flume study using sand and gravel mixtures. *Geografiska Annaler,* **69 A**: 15-27.

Jackson, R.G. and II (1975) Hierarchical attributes and a unifying model of bedforms composed of cohesionless material and produced by shearing flow. *Geological Society of America Bulletin,* **86**: 1523-1533.

Knighton, A.D. (1980) Longitudinal changes in size and sorting of stream bed material in four English Rivers. *Geological Society of America Bulletin,* **91**: 55-62.

Kuenen, P.H. (1966) Experimental turbidite lamination in a circular flume. *Journal of Geology,* **74**: 523-&.

Leopold, L.B. and Wolman, M.G. (1957) River channel patterns - braided, meandering, and straight. *US Geological Survey Professional Paper,* **282-B**: 39-85.

Lewin, J. (1976) Initiation of bed forms and meanders in coarse-grained sediment. *Geological Society of America Bulletin,* **87**: 281-285.

Lewin, J. and Brewer, P.A. (2002) Laboratory simulation of clast abrasion. *Earth Surface Processes and Landforms,* **27**: 145-164.

Lisle, T.E., Ikeda, H. and Iseya, F. (1991) Formation of stationary alternate bars in a steep channel with mixed size sediment: a flume experiment. *Earth Surface Processes and Landforms,* **16**: 463-469.

Livesey, J.R., Bennett, S., Ashworth, P.J. and Best, B.J. (1998) Flow structure, sediment transport and bedform dynamics for a bimodal sediment mixture. In: *Gravel-Bed Rivers in the Environment* (Eds P.C. Klingeman, R.L. Beschta, P.D. Komar and J.B. Bradley), pp. 149-176. Water Resources Publications, Colorado, USA.

Lunt, I.A. and Bridge, J.S. (2004) Evolution and deposits of a gravelly braid bar, Sagavanirktok River, Alaska. *Sedimentology,* **51**: 415-432.

McLean, D.G., Church, M. and Tassone, B. (1999) Sediment transport along lower Fraser River: 1. Measurements and hydraulic computations. *Water Resources Research,* **35**: 2533-2548.

Miller, J.P. (1958) High mountain streams: effects of geology on channel characteristics and bed material.

Moss, A.J. (1963) Physical Nature of Common Sandy and Pebbly Deposits .2. *American Journal of Science,* **261**: 297-343.

Mosley M.P. and Tindale, R.S. (1985) Sediment variability and bed material sampling in gravel-bed rivers. *Earth Surface Processes and Landforms* **10**: 465–482.

Nicholas, A.P., Ashworth, P.J., Kirkby, M.J., Macklin, M.G. and Murray, T. (1995) Sediment slugs: large-scale fluctuations in fluvial sediment transport rates and storage volumes. *Progress in Physical Geography,* **19**: 500-519.

Paola, C. (1989) Topographic sorting. *EOS, Transactions of the American Geophysical Union,* **70**: 332.

Parker, G. (1991) Selective sorting and abrasion of river gravel. I; Theory. *Journal of Hydraulic Engineering,* **117**: 131-149.

Powell, D.M. (1998) Patterns and processes of sediment sorting in gravel-bed rivers. *Progress in Physical Geography,* **22**: 1-32.

Rice, S.P. (1999) The nature and controls on downstream fining within sedimentary links. *Journal of Sedimentary Research,* **69**: 32-39.

Rice, S.P. and Church, M. (1996) Bed material texture in low order streams on the Queen Charlotte Islands, British Columbia. *Earth Surface Processes and Landforms,* **21**: 1-18.

Rice, S.P. and Church, M. (1996). Sampling surficial fluvial gravels: the precision of size distribution percentile estimates. Journal of Sedimentary Research, 66: 654-665.

Rice, S.P. and Church, M. (1998) Grain size along two gravel-bed rivers: statistical variation, spatial pattern and sedimentary links. *Earth Surface Processes and Landforms,* **23**: 345-363.

Rice, S.P., Church, M., Wooldridge, C.L. and Hickin, E.J. (2009) Morphology and evolution of bars in a wandering gravel-bed river; lower Fraser river, British Columbia, Canada *Sedimentology,***56**: 709-736.

Russell, R.D. (1939) Effects of transportation on sedimentary particles. In: *Recent Marine Sediments* (Eds P.D. Trask), pp. 33-47. American Association of Petroleum Geologists, Tulsa.

Sambrook Smith, G.H. and Ferguson, R.I. (1995) The gravel sand transition along river channels. *Journal of Sedimentary Research Section A-Sedimentary Petrology and Processes,* **65**: 423-430.

Seal, R. and Paola, C. (1995) Observations of downstream fining on the North Fork Toutle River near Mount St. Helens, Washington. *Water Resources Research,* **31**: 1409-1419.

Singer, M.B. (2008) Downstream patterns of bed-material grain size in a large, lowland alluvial river subject to low sediment supply. *Water Resources Research*, doi:10.1029/2008WR007183

Smith, N.D. (1974) Sedimentology and bar formation in the Upper Kicking Horse River, a braided outwash stream. *Journal of Geology,* **82**: 205-223.

Sternberg, H. (1875) Untersuchungen über längen- und Querprofil geschiebeführender Flüsse. *Zeitschrift für Bauwesen,* **25**: 483-506.

Surian, N. (2002) Downstream variation in grain size along an Alpine river: analysis of controls and processes. *Geomorphology,* **43**: 137-149.

Whiting, P.J. (1996) Sediment sorting over bed topography. In: *Advances in Fluvial Dynamics and Stratigraphy* (Eds P.A. Carling and M.R. Dawson), John Wiley & Sons Ltd, Chichester.

Whiting, P.J., Dietrich, W.E., Leopold, L.B., Drake, T.G. and Shreve, R.L. (1988) Bedload sheets in heterogeneous sediment. *Geology,* **16**: 105-108.

Wolcott, J.F. and Church, M. (1991) Strategies for sampling spatially heterogeneous phenomena: the example of river gravels. *Journal of Sedimentary Petrology,* **61**: 534-543.

Yatsu, E. (1955) On the longitudinal profile of the graded river. *American Geophysical Union Transactions*, 36: 655-663.

Table 1. (a) Surface and (b) subsurface sediment characteristics of morphological units on Queens bar.

	Primary unit bars	Secondary unit bars	Bar-top channels	Erosional bar edge
a) Surface layer				
Number of samples[1]	21 [19, 9]	30 [29, 14]	29 [24, 12]	7 [7, 6]
Sand (%)	6 (0-75)	1 (0-16)	17 (0-79)	9 (0-48)
Coarse-fraction[2] D_{50} (mm)	25 (18-30)	26 (18-32)	34 (27-34)	35 (22-43)
Coarse-fraction D_{95} (mm)	59 (43-72)	60 (41-76)	79 (61-99)	81 (54-97)
Sorting of coarse fraction[3]	0.72 (0.58-0.86)	0.76 (0.62-1.00)	0.81 (0.64-1.10)	0.89 (0.56-1.02)
Structure: overloose, normal, underloose	4, 12, 5	4, 17, 9	0, 11, 18	0, 4, 3
Embeddedness: clean, slight, moderate, heavy	8, 5, 6, 2	20, 7, 3, 0	5, 10, 0, 14	0, 3, 2, 2
Imbrication: none, weak, strong, very strong	1, 9, 9, 2	1, 10, 14, 5	0, 11, 12, 6	0, 3, 3, 1
Censored surface layers?	none	5 sites	none	none
b) Subsurface bulk				
Number of samples	1	1	1	1
Sand (%)	18	13	21	27
D50 (mm)	19	20	23	13
D95 (mm)	63	62	78	71
Armour ratio[4]	1.3	1.3	0.2	2.9

Entries for surface D_{50}, D_{95}, sorting and percentage sand are group means with minimum and maximum values in parentheses. (1) Sample size refers to the total number of samples in each group. Sorting values were calculated only for grain size distributions based on Wolman sampling and eight photographic samples that contained more than 5% sand were not used to estimate gravel D_{50} and D_{95}. Values in square parentheses therefore indicate the group sizes for gravel percentile and sorting calculations, respectively. (2) Coarse-fraction refers to grain-size distributions truncated at 4mm. (3) sorting was calculated as $(\Psi_{84} - \Psi_{16})/2$ (Inman, 1952). Armour ratios are for the four individual sites where subsurface data are available and were calculated using corresponding untruncated surface and subsurface GSDs.

Figure captions:

Figure 1. Fraser River gravel reach between Laidlaw and Mission, British Columbia, Canada. River kilometres are measured from Sand Heads (mouth of the river); the major bars are named.

Figure 2. Supraplatform features of a large lateral compound bar (Wellington Bar) on Fraser River.

Figure 3. Ratio of median grain sizes (no truncation) in the upstream third to downstream third of individual lower Fraser River bars plotted against distance downstream (measured from river km 155). Filled circles represent surface bed materials and open circles represent subsurface materials. Points above the dashed line are those where coarser bed materials are found toward the bar head.

Figure 4. D_{95} of the coarse fraction (> 4 mm) of the surface grain size distribution plotted against site elevation for 87 samples from Queens bar. The dashed line, which has a slope of –0.008 is an appropriate envelope that constrains the relation between particle size and elevation for the local channel slope (see text for details).

Figure 5. Distributions of (A) coarse-fraction (> 4mm) D_{95} and (B) site elevation grouped by site morphology. Queens bar sites, details in Table 1.

Figure 6. (A) Truncated (> 4 mm) subsurface grain-size distributions compared with the surface grain-size distributions (> 4mm truncation) at the same four sites on Queens bar. (B) Full subsurface grain-size distributions of samples collected from each morphological setting on Queens bar.

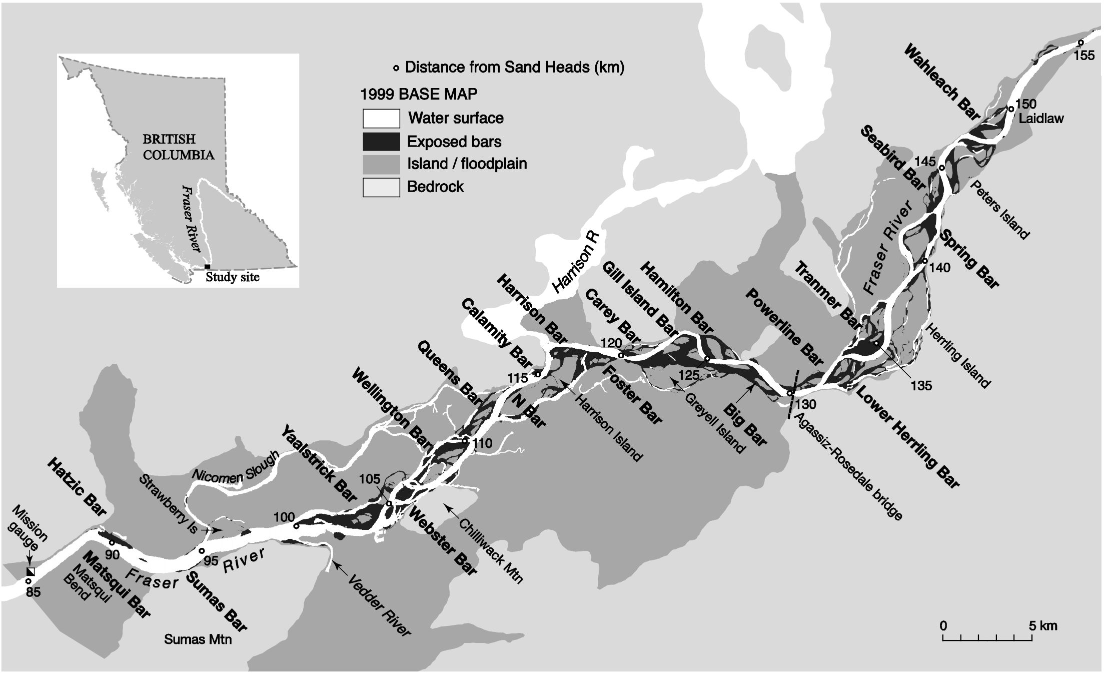
Figure 7. Grain-size variations across unit bars and sheets: (A) discontinuous sand deposition in the lee of a sheet crest on Spring Bar; (B) and (C) gravel bed materials upstream and downstream of a sheet crest on Spring bar – quadrat is 0.50 by 0.50 m; (D) tail to crest fining of bed material across a series of climbing sheets on Spring bar – circles represent coarse-fraction (> 4mm) D_{50} and the locations of photographs B and C are indicated; (E) coarse-fraction (> 4mm) D_{95} variations and high-flow current directions across two unit bars on Queens – dashed lines indicate avalanche faces and symbol 'handles' point downstream.

Figure 8. Flank unit bar accretion on Calamity Bar during the 2002 freshet. Total station surveys of (A) March 2002 and (B) April 2003. Arrows indicate flow direction in the principle channel. Colours indicate bed elevation from low in deep blue through brown, yellow and white to green at the highest elevations.

Figure 9 Median grain size changes at reoccupied sampling positions on Queens bar between (A) April and September 2000 and (B) September 2000 and September 2004. Sites where there was net aggradation or erosion or that are likely to have experienced the passage of a significant sediment unit (closed circles) are differentiated from sites where there was no morphological change (open circles). The diagonal lines define a zone within which differences may be due to sampling error (see text for details).

Figure 10. (A) Median surface grain size (no truncation) plotted against distance downstream (measured from river km 155) for the entire gravel-bed reach of lower Fraser River. Data of individual bars are indicated by the different symbols. The majority of scatter within the general downstream fining trend is caused by within-bar variability. Within-bar variability (between homogeneous patches) declines downstream. (B) Median surface grain size (no truncation) plotted against distance downstream (measured from river km 155) for the sub-reach common to sampling programmes conducted in 2000 and 1983/84 (between river km 108 and 140). There has been some general fining, but slopes in the linear regression models are not significantly different (Ancova, $p = 0.83$).

Figure 11. Departures from the downstream trend correlated with bar thickness. See text for explanations concerning the two named, anomalous bars.



Distance from Sand Heads (km)
1999 BASE MAP
Water surface
Exposed bars
Island / floodplain
Bedrock
BRITISH COLUMBIA
Fraser River
Study site
Wahleach Bar
155
150
Laidlaw
Seabird Bar
145
Peters Island
Spring Bar
140
Fraser River
Tranmer Bar
Herrling Island
135
Lower Herrling Bar
Powerline Bar
130
Agassiz-Rosedale bridge
Big Bar
Greyell Island
125
Hamilton Bar
Gill Island Bar
Carey Bar
120
Foster Bar
Harrison Island
Harrison R
Harrison Bar
Calamity Bar
115
N Bar
Queens Bar
Wellington Bar
110
Yaalstrick Bar
105
Webster Bar
Chilliwack Mtn
Nicomen Slough
Strawberry Is
100
Vedder River
95
River
Fraser
Sumas Bar
Sumas Mtn
Hatzic Bar
90
Matsqui Bar
Matsqui Bend
Mission gauge
85
0
5 km

Figure 1

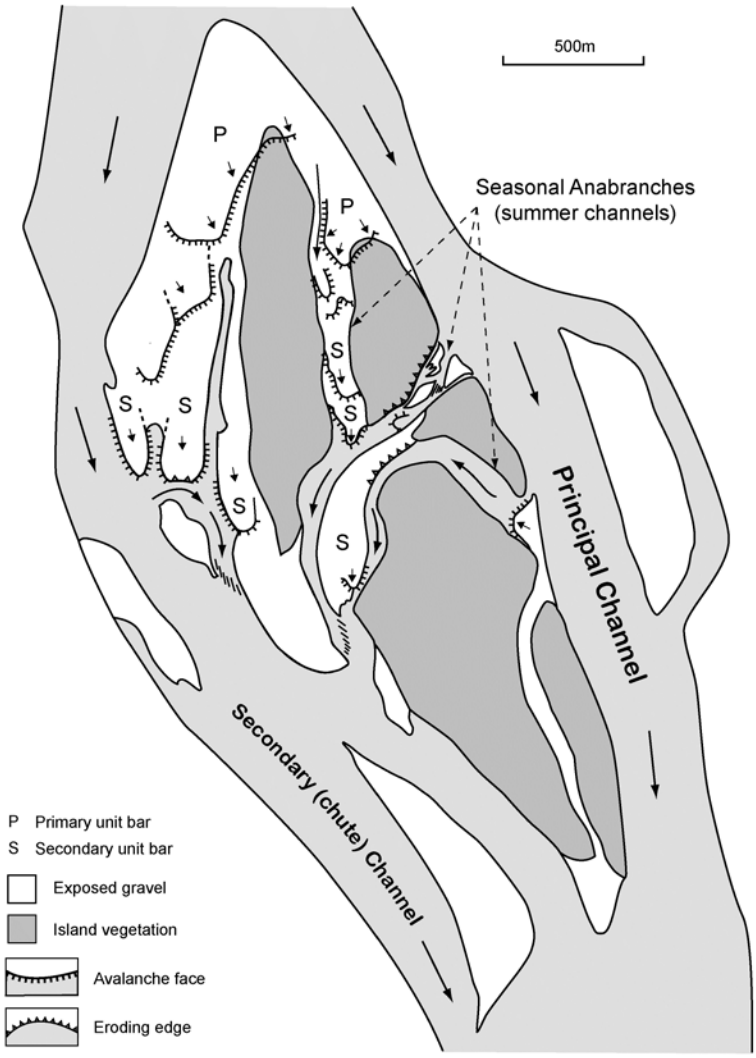
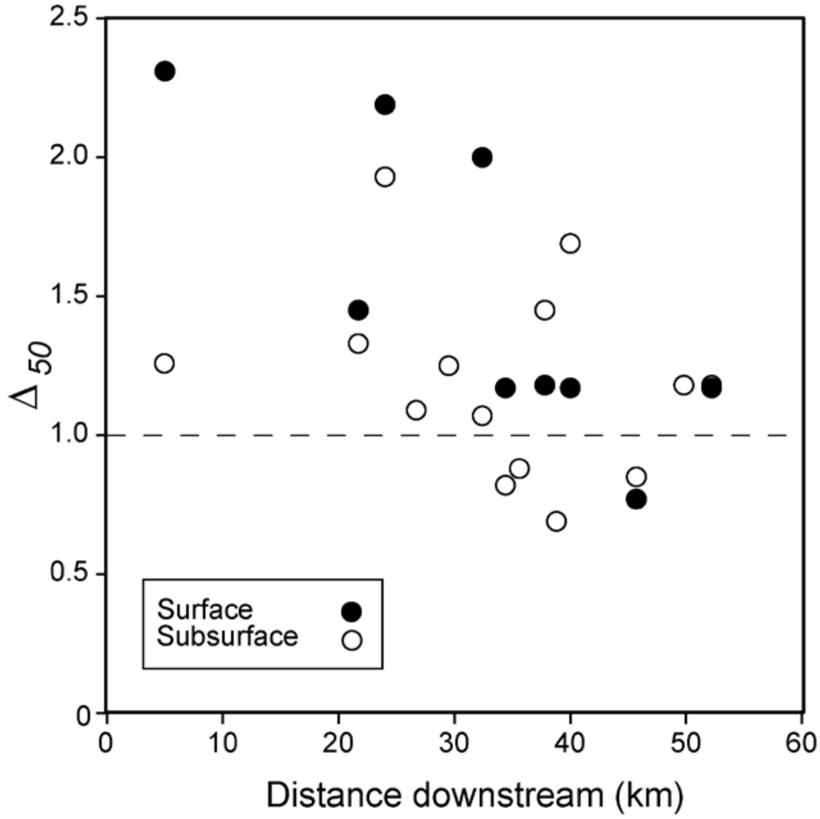

500m
Seasonal Anabranches
(summer channels)
P
P
S
S
S
S
S
S
S
Principal Channel
Secondary (chute) Channel
P Primary unit bar
S Secondary unit bar
Exposed gravel
Island vegetation
Avalanche face
Eroding edge

Figure 2



2.5
2.0
1.5
1.0
0.5
0
Δ 50
Surface
Subsurface
0
10
20
30
40
50
60
Distance downstream (km)

Figure 3

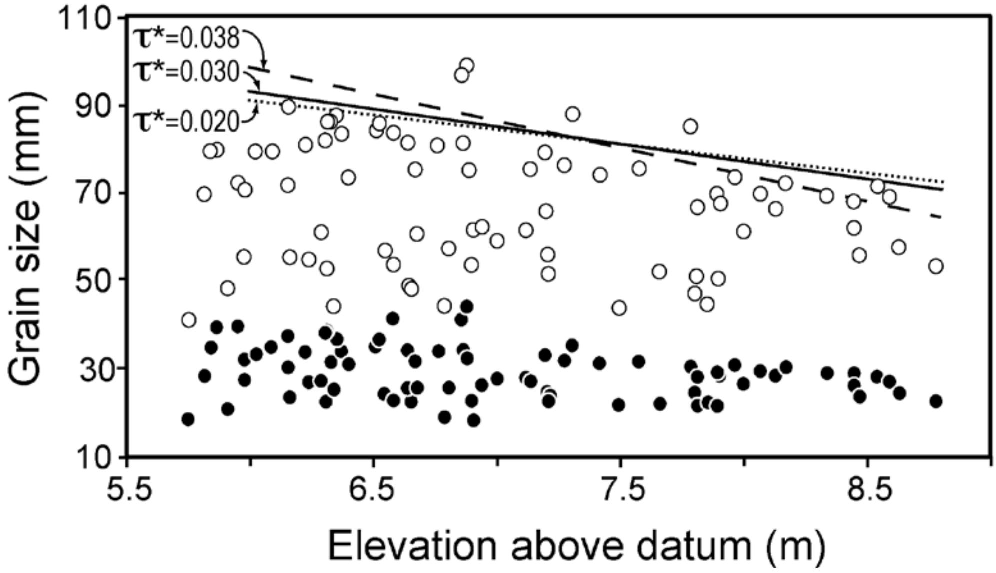

τ*=0.038
τ*=0.030
τ*=0.020
Grain size (mm)
10
30
50
70
90
110
5.5
6.5
7.5
8.5
Elevation above datum (m)

Figure 4

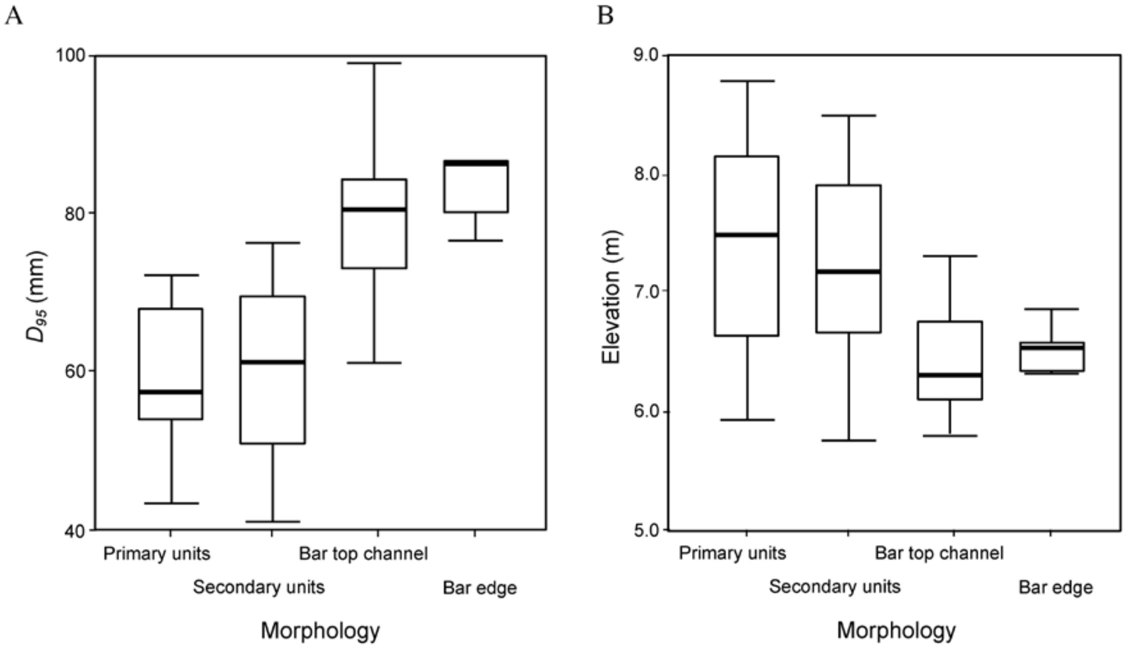
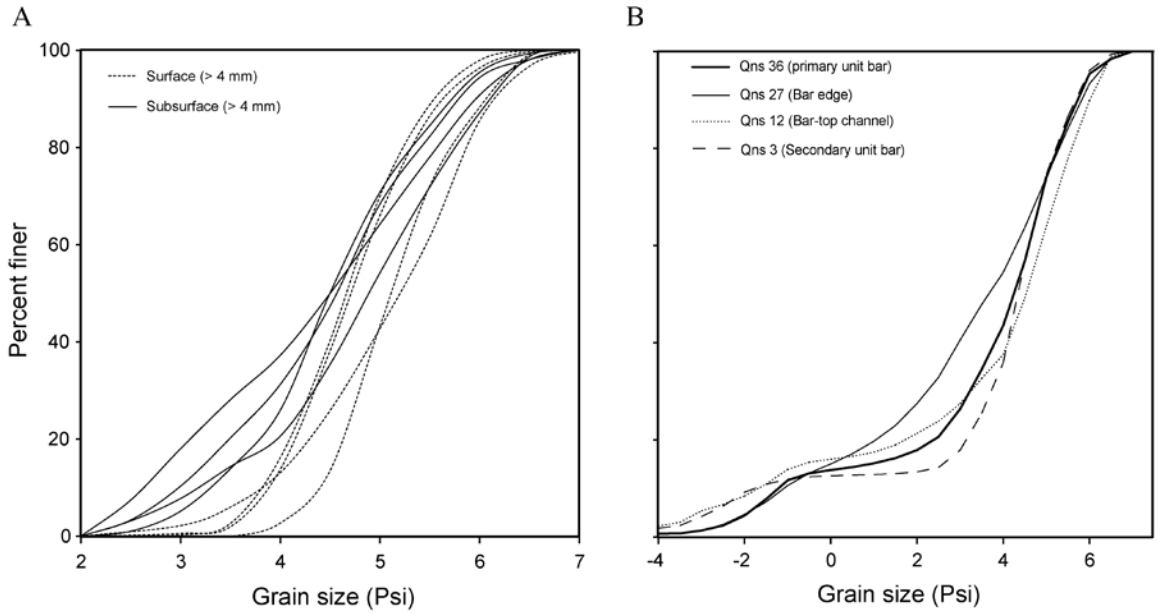

A
B
100
80
60
40
D95 (mm)
9.0
8.0
7.0
6.0
5.0
Elevation (m)
Primary units
Secondary units
Bar top channel
Bar edge
Morphology

Figure 5


A
Surface (> 4 mm)
Subsurface (> 4 mm)
Percent finer
Grain size (Psi)
B
Qns 36 (primary unit bar)
Qns 27 (Bar edge)
Qns 12 (Bar-top channel)
Qns 3 (Secondary unit bar)
Grain size (Psi)

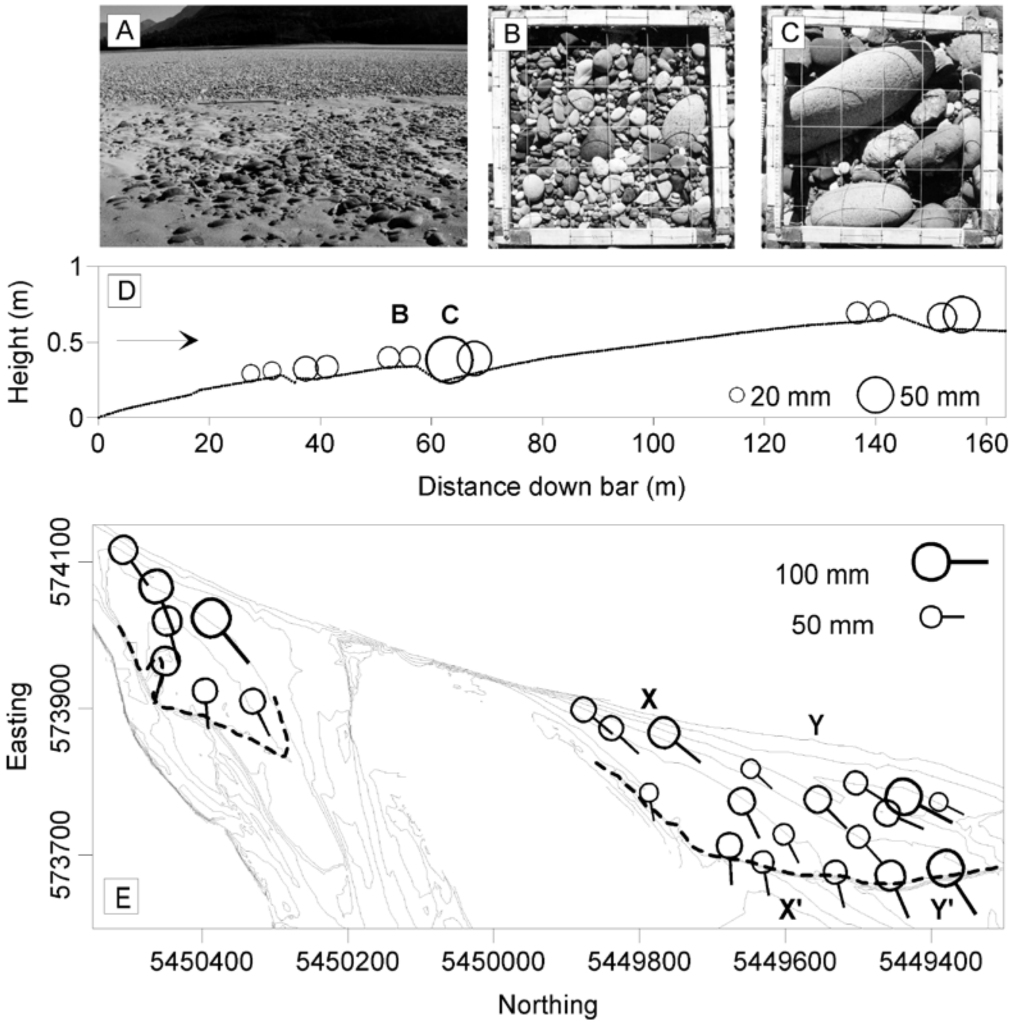

A
B
C
D
Height (m)
1
0.5
0
B
C
20 mm
50 mm
0
20
40
60
80
100
120
140
160
Distance down bar (m)
E
Easting
574100
573900
573700
100 mm
50 mm
X
Y
X'
Y'
5450400
5450200
5450000
5449800
5449600
5449400
Northing

Figure 7

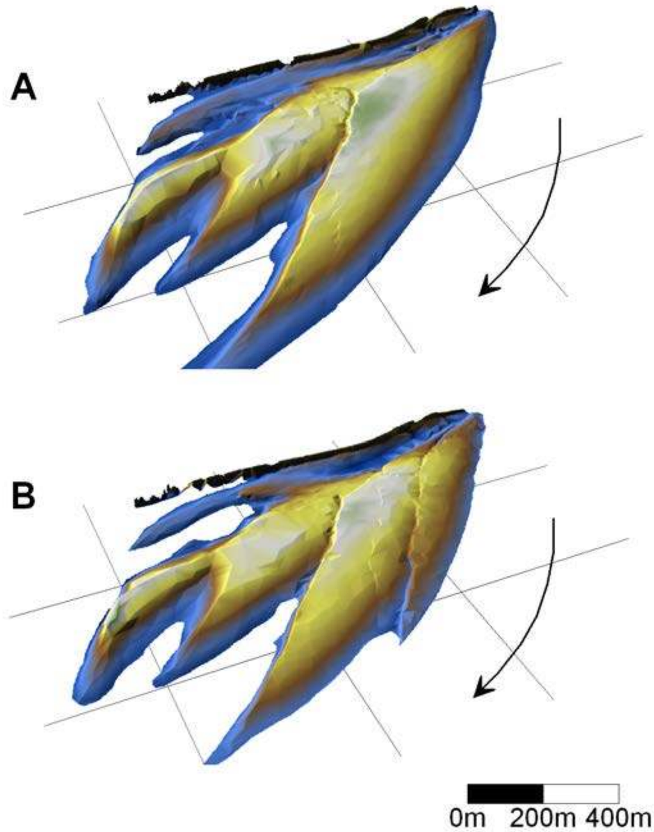


Figure 8

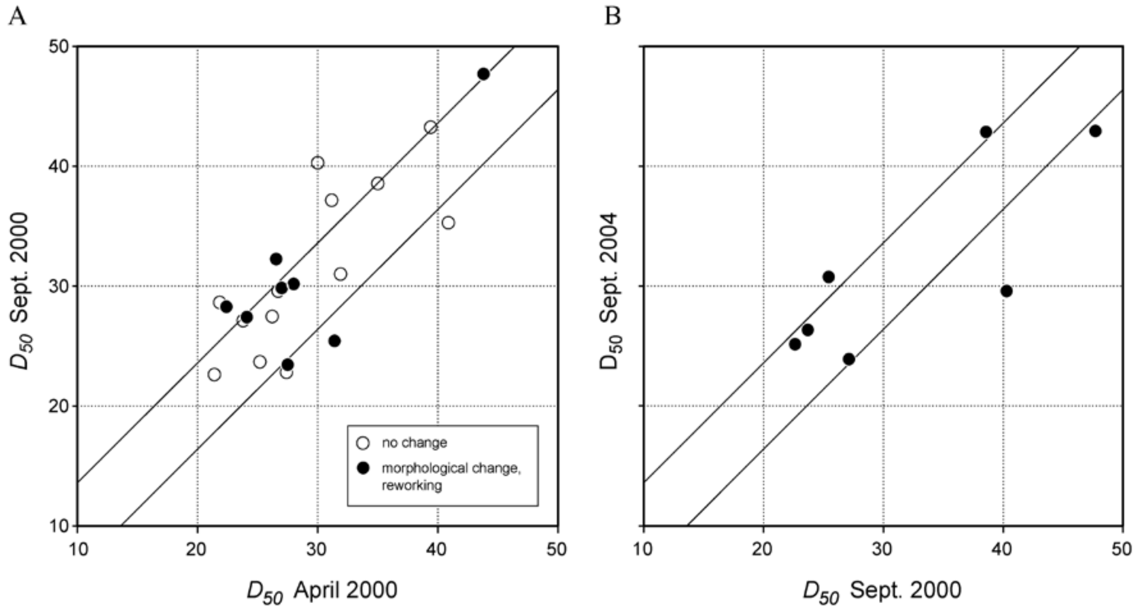

A
B
D_{50} Sept. 2000
D_{50} April 2000
D_{50} Sept. 2004
D_{50} Sept. 2000
no change
morphological change, reworking
10
20
30
40
50

Figure 9

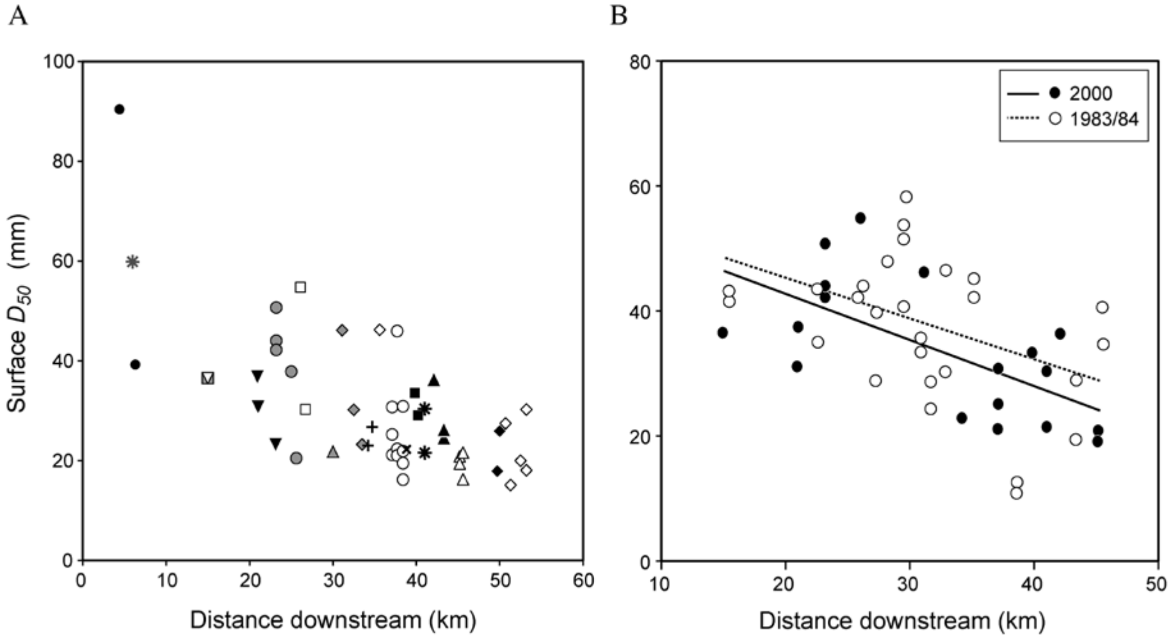

A
B
Surface D_{50} (mm)
Distance downstream (km)
Distance downstream (km)
2000
1983/84
100
80
60
40
20
0
0
10
20
30
40
50
60
80
60
40
20
0
10
20
30
40
50

Figure 10

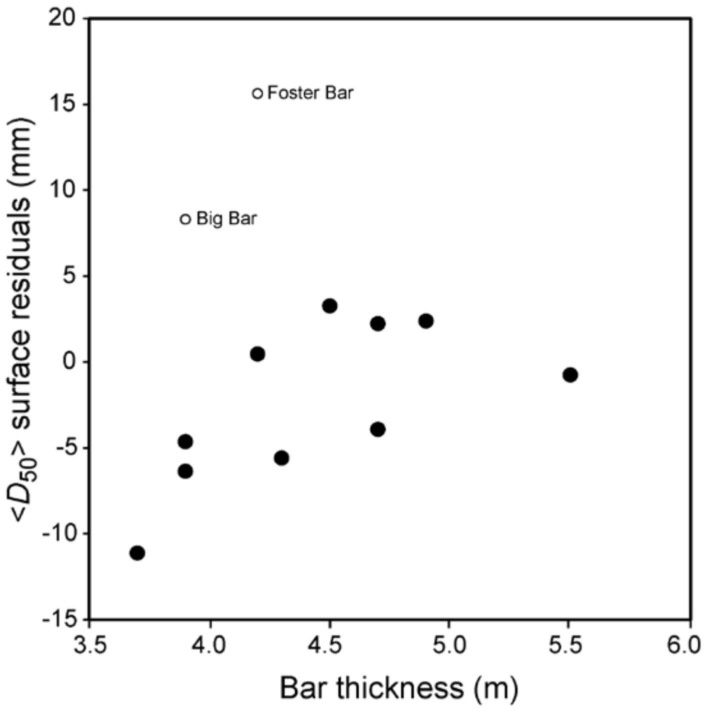

Foster Bar
Big Bar
<D_{50}> surface residuals (mm)
Bar thickness (m)
20
15
10
5
0
-5
-10
-15
3.5
4.0
4.5
5.0
5.5
6.0

Figure 11