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Placer Mining Along the Fraser River, British Columbia: the Geomorphic Impact

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Abstract

We investigate the geomorphic impact of 19th century placer mining along the Fraser River, British Columbia, by estimating the volume and grain-size distribution of excavated sediment, evaluating the transport potential for the sediment in the river, and discussing the relation between placer waste sediment and observed morphodynamics of the Fraser River channel. Volume-by-area regression relations applied to 456 mapped mines estimate the total volume of material excavated to be about 58×10^6 m^3 (bulk volume). Sampling of mine scarp and mine lag sediments indicates that the discharged tailings consisted of 54% sand and finer and 46% gravel and small cobbles. Modern observation and historical narratives indicate that the channel of the Fraser between Quesnel and Laidlaw has been generally stable following placer mining. Application of a sediment transport function indicates that the river is capable of moving annually an amount of sediment comparable to the maximum loading from placer mining. By applying established relations between channel scale and sediment virtual velocity, we estimate the rate of downstream movement of the placer-waste slug to be between 1 and 6 km a^{-1}. The predicted rates of sediment migration indicate that peak delivery of placer waste to the lower river below Laidlaw likely occurred early in the 20th century. This predicted behavior agrees well with observed aggradation on the lower river. The result emphasizes the importance of historical legacy in the appraisal of recent geomorphological processes and shows that widespread small-scale disturbance has affected the Fraser River, with the effect concentrated where the gradient of the river is reduced.

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Introduction

In the middle to late 19th century placer gold was extracted from along the Fraser River and its tributaries (Figure 1). Large volumes of sediment were excavated from the banks and terraces along the river in pursuit of gold, with consequences for the river that we investigate in this paper.

Placer mining is one of the most frequently cited geomorphic disturbances caused by humans (e.g. Marsh 1874 , Nir 1983) . During the 19th and early 20th centuries placer mines used flowing water to mobilize large volumes of sediment. This sediment was processed through sluice boxes and commonly disposed of in streams or rivers, resulting in downstream aggradation and instability. The geomorphic impact of concentrated, large-scale placer mining has been well documented in several regions including California (e.g. Gilbert 1917; Rohe, 1986; James 1997, 2006, 2010), New Zealand (e.g. Barker 2001, Otago Regional Council 2008,) and Australia (e.g. Knighton 1989). However, the geomorphic impact of widespread, small to medium scale mining has not been quantitatively studied (Rohe 1986).

The introduction of placer waste to river systems results in sediment slugs that may spatially translate the impact of mining activity. Previous work (e.g. Nicholas et al. 1995) considering the evolution of sediment 'slugs' provides a basis for evaluating possible connectivity between locations of placer mining and downstream aggradation. However, such work has generally been restricted to studies at relatively local and detailed scales (e.g. Lisle et al. 2001). Other studies have considered the complementary problems of sediment virtual velocities (the downstream rate of sediment movement including periods when the sediment is at rest, e.g. Beechie 2001) and movement of sediment through complex channel networks (e.g. Hooke 2003). The longest wavelength sediment slug studied hitherto was documented by Knighton (1989). That slug originated from placer tin mining along many reaches of the Ringarooma River, Tasmania, impacted a long (75 km) study reach, and was considered over a

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long (110 year) time period.

In geomorphic systems where such historical anthropogenic disturbance is known, a historical legacy may influence current processes. Without historical context, modern process studies might reach erroneous conclusions regarding natural processes, because the observed event sequences on which the conclusions are based are frequently much shorter than the timescale of trends in geomorphic systems (Church 1980). Historical study and observation of legacy effects in geomorphic systems have the potential to provide context for the geophysical event sequences on which modern process studies are based (James 2010).

We investigate the suggestion of Church and Ham (2004) that the recent sedimentation history in the gravel bed reach of the lower Fraser River may be a legacy effect. They speculated that 20th century sedimentation was associated with neoglaciation, placer gold mining along the river, and railway construction projects along Fraser and Thompson rivers. We propose that widespread, small- to medium-scale placer mining along the Fraser River contributed a significant amount of sediment to that river, which has been transported downstream and is impacting modern processes in the lower Fraser. Placer mining in the Fraser drainage basin began in 1858 and continued through the first decade of the 20th century (with limited activity up to World War II) (British Columbia Department of Mines 1946). Along the Fraser River, Miners worked surficial alluvial deposits, the locations of which have been documented by Nelson and Kennedy (in press) and Nelson et al. (in press). Bowman (1887) mapped the locations of many additional mining excavations along the upper part of the Fraser tributary Quesnel River and many streams of the Cariboo mining district (Figure 1), and Galois (1970) addressed the general environmental impact of placer mining in the Cariboo. However, quantitative estimates of the geomorphic impact of placer mining in British Columbia have not previously been made.

Our objectives in this paper are to document the total volume and nature of material excavated

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by mining along the Fraser River and to consider probable geomorphological effects of mine tailings discharged into the river. We approach this by surveying a subset of mines to establish a volume-by-area regression relation that is applied to all mines mapped along the river, sampling grain size distributions of material removed from mines, applying empirical sediment transport functions, and considering observations of river morphodynamics over the past century. The geomorphic response to mining disturbance of the Fraser River demonstrates the importance of cumulative impacts of small scale mining. It also underscores the importance of placing process studies and management plans based on them into basin-scale historical context.

Placer Mining Impacts on Geomorphic Systems

Recognition of the magnitude of human impacts on geomorphic systems over the past several thousand years (e.g. Higgitt and Lee 2001) provides impetus to integrate the study of geomorphic systems and human history. Many observers have chronicled some of the extensive geomorphic effects of human activity including Marsh (1874), Nir (1983), Turner et al. (1990), Goudie (1995, 2000), Simmons (1996), Roberts (1998), and Hooke (2000).

Placer mining is a significant means by which humans have modified fluvial geomorphic systems. Three common 19th century approaches to placer mining have had particularly important effects: sluicing, ground sluicing, and hydraulic mining. At mines operating by means of sluicing, sediment is shoveled into sluice boxes; at ground sluices, a stream is diverted to erode material that is then flushed into a sluice box; and at hydraulic mines high pressure water is sprayed against the walls of a mine to excavate sediment. Lindström et al (2000) and Kennedy (2009) describe in detail the local effect of these placer mining techniques. All techniques wash fractions (generally sediment equal to or finer than small cobbles) of the waste away from the site, often directly into the river, sometimes into

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tailings piles. Lag deposits (usually cobbles and boulders) are left behind. Different mining techniques leave distinctive excavations (Figure 2).

Downstream sedimentation is a common result of mining activity if tailings are not carefully managed. Knighton (1989) described $40x10^6$ m^3 of debris resulting from the mining of alluvial tin that was released into the Ringarooma River, resulting in aggradation, development of a braided pattern, and a 300 percent increase in channel width. After mining ceased, these changes were followed by vertical incision at rates reaching 0.5 m a^{-1}, which began upstream and progressed downstream, and channelization into a single thread. Knighton predicted that it will take about 150 years for the stream to regain equilibrium.

Classic studies have been made in California, where placer mining introduced a very large volume of sediment into the Sacramento River and its tributaries. Shortly after an initial phase of mining (1849-1884) ceased, Banyaurd (1891) estimated that $0.8.x10^9$ m^3 of sediment were produced (cited in Gilbert 1917). Gilbert assumed that this figure was determined by collecting records of mining water use and assigning an approximate "duty of gravel" moved per unit volume of water. Gilbert (1917) undertook a surveying effort to independently estimate the total volume of gravel produced. He found that his estimate of the total volume exceeded earlier estimates by 51%, and presented a summary figure of $1.3x10^9$ m^3 of sediment produced by mining on tributaries of the Sacramento River. A second phase of licensed hydraulic mining occurred from 1893 to 1953 and resulted in production of at least $24x10^6$ m^3 of sediment (James 1997). Mining-waste sediment moved rapidly downstream causing several meters of aggradation and destruction of farmland along the Sacramento River. Channel degradation followed aggradation (Gilbert 1917), though large amounts of sediment remain stored in overbank deposits and continue to affect the river system (James 1997, 2006, 2010).

Substantial placer mining has occurred in other areas of North America, including northwestern

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Mexico, northwestern California, southwestern and northeastern Oregon, north-central Colorado, central Idaho, southwestern Montana, central and northern British Columbia, the Yukon, and interior Alaska (Koshmann and Bergendahl 1968, Sutherland 1985, Rohe 1986). Rohe (1986) contends that "traditional methods" of mining in North America, including panning, rocker box work, and sluicing, created very small scale but widespread disturbance having limited geomorphic impact, whereas important geomorphic disturbance was caused primarily by hydraulic mining. He acknowledged, however, that no statistics exist regarding the extent of impact from small-scale mining activity.

The New Zealand gold rush included significant ground sluicing, hydraulic mining, and extensive dredging (Barker 2001). Placer gold mining in the Clutha catchment on the South Island began in 1861 and continued into the first half of the 20th century. The Rivers Commission in 1920 estimated that $230x10^6$ m^3 of material were moved in the Clutha catchment by placer mining (Otago Regional Council 2008). They estimated that, as of 1920, $31x10^6$ m^3 had washed through the system, 46 $x10^6$ m^3 were currently passing through the river, and 153 $x10^6$ m^3 had not yet entered the river. Three meters of aggradation occurred as a result of this sediment input. Degradation began with the cessation of placer mining in the region in the 1920s and propagated downstream through the 20th century.

The examples of the impact of placer mining outlined above support the notion that human activities associated with placer mining have been a key driver of river disturbance in some regions of the world in recent time. Furthermore, the case studies reveal sluglike sediment movement through river systems following placer mining, with significant aggradation advancing from sediment inputs followed by subsequent degradation and a return to relative stability. However the effects of widespread, small-scale activity – as along the Fraser River – remain to be established.

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Mined Sediment: methods

We quantified the volume of sediment removed by placer mining from the banks along the Fraser River by surveying the topography of a subset of 51 mines. For each surveyed mine we calculated the volume excavated. We then applied regression relations developed from these data to predict the volume of all mapped mines using mine area as the independent variate. Nearly all excavated sediment was discharged directly into the river. Because the grain-size distribution of discharged sediment controls its geomorphic impact on the river, we estimated the grain-size distribution of the worked placer deposits. This was done by bulk sampling sediment from the scarps of mines and comparing the grain-size distribution (GSD) of these samples to Wolman pebble-count samples of lag deposits left at mine sites. Finally, the effect of the discharged sediment on the Fraser River was evaluated through application of a sediment transport formula to evaluate the capacity of the river to move the tailings sediment downstream, and comparison of the transport results with both historical descriptions of the river's geomorphology and quantitative measures of the river's historical aggradation rate in a distal gravel-bed reach. We did not investigate mining that occurred on river bars within the channel. This activity merely disturbed the bed sediment of the river and did not represent a net addition to the sediment load.

Mine site surveys

Physical evidence of 456 individual placer mine sites was mapped along the main stem of the Fraser River between Hope and Cottonwood Canyon, north of Quesnel, by Kennedy (2009), Nelson and Kennedy (in press), and Nelson et al (in press) (figure 1). Nelson and Kennedy (in press) located mines by air photo interpretation, interpretation of historical documents, and field reconnaissance. They classified mapped mine morphologies as sluice, groundsluice, or hydraulic according to the relict morphology (Figure 2). They additionally classified each mapped site by confidence in the mapping as nearly certainly mined, probably mined (with poorly defined boundary), or possibly mined. The mapping error in determining the ground area of the first class is limited to resolution of air photos or ground survey. The mapping error in the second class may be substantial as the boundaries were defined by remote-sensing methods and may have been obscured by vegetation or post-mining sediment deposition. The mapping error in the third class is variable but less important than the possibility that no mining actually occurred at the location. Because of variation in topography and vegetation cover, they did not access all areas along the river, and we suspect some sites remain unmapped. Though the total number of unmapped sites cannot be known it is not likely more than 40 or 50 locations (on the basis of the extent of unreconnoitred areas) and all must be relatively minor. Areas of mapped mine sites are used as the basis for the volumetric estimates of material excavated presented in this paper.

Fifty-one mines were surveyed in order to establish a relation between mine area and volume excavated. Surveys were completed utilizing a variety of methods including robotic total station (28), tape and level (1), partial survey with total station (6), staff mounted clinometer and tape (7) and point-based visual estimation of excavation depth (8), or topographic map (1). Details of each of these methods are described in Nelson (2011). Surfaces created using the total station and tape-and level/clinometer methods are precise (errors on the order of cm to tens of cm) relative to typical excavation depths of 3 to 10 m. Errors in point based visual estimation of excavation depth are likely to be ±25%.

Survey data were plotted and analyzed in ArcMap® 9.3 to determine the volume of excavated material utilizing the 3D analyst®, Geostatistical Analyst®, and Spatial Analyst® extensions (ESRI 2008), and the TIN Editor Toolbar (ESRI 2010). Where excavation depth had been directly estimated during survey, points were interpolated to produce a continuous surface of excavation depth. Where

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surveys had collected topographic information, surfaces representing the current topography were created as triangular irregular networks (TINs). This surface was subtracted from a reconstructed pre-mining surface to give excavation depth. Pre-mining surfaces were created by interpolating and/or extrapolating elevations of surfaces from around the mine over the surface of the mine. In the simplest cases — where the surface into which the mine was cut is approximately planar and is preserved on at least three sides of the mine — a second TIN was created based solely on surveyed points surrounding the mine. In cases where three sides of the mine were not preserved or the surface was slightly more complex, but could be approximated by a plane or other polynomial surface (for example where the pre-mining surface was a terrace or alluvial fan), polynomial interpolations were performed to project the remnant surface over the top of the mine. In some cases these two procedures were inadequate to produce a plausible surface. In such cases a TIN was created using all survey points from outside the mine and nodes were manually added to the TIN to represent the pre-mining surface. Frequently, high remnant surfaces within the mine or preserved remnant "buttes" were used as guides. Nelson (2011) describes in detail the methods used in pre-mining surface estimation. The Digital Elevation Models of estimated depth (resulting from both survey and direct estimation methods) were clipped to the extent of the mine as determined by air photo interpretation and field survey notes Figure 3 shows examples of mine surveys and excavation depth calculation. Errors in estimates of mine depth (which propagate directly into estimates of mine volume) arise mostly from errors in estimation of the pre-mining surface, and are typically less than 1 m, or approximately 10-25% of actual mine depth.

Regression relations predicting excavated mine volume (that is, material lost from the site) from mine area (that is, the two-dimensional area from which material was removed) and mining method were developed as a means to estimate volume for all mapped mines so that a system-wide estimate of the total volume of mined material could be made. Mining method is a class variable. Because mine

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area is precisely known relative to mine volume and because the objective is prediction of mine volume from mine area, forward regression is the appropriate statistical procedure (Mark and Church, 1977). The regression relations were developed using the statistical package R® 2.9 (R Development Core Team, 2011). The variables 'mine area' and 'mine volume' appear, on the basis of limited data, to be approximately log-normally distributed for sluice sites and for aggregated groundsluice and hydraulic sites that were used to build the regression relation (Figure 4). In order to meet the assumptions of linear regression, both mine area and volume were log-transformed before performing the regressions. The back-transform bias correction method of Miller (1984) was applied when re-transforming the regression equations.

Areas of the mines mapped by Nelson and Kennedy (in press) were then applied to the regression relation to predict individual mine excavation volumes. At surveyed sites, the volume of the mine as determined by the survey was adopted rather than the result from regression. The differences between these values are the residuals from the regression; therefore, due to the nature of regression, this decision has no effect on the summary volume calculated. Also, during the field work, fifteen mines that were not surveyed were observed to be unusually shallow for their extent and notes were taken regarding the estimated average depth (typically 0.5-2 m) of the mine. These shallow mines were typically observed locally (not in air photos) and it is not likely that the regression relation was applied to many other anomalously shallow sites. The depth estimated during the mapping effort was used rather than the depth predicted by the regression relation in order to produce a conservative estimate of the total volume of gravel produced by the mining while including historically interesting but geomorphically less significant mines in the mapping effort.

Sediment texture

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The GSD of placer waste was determined by defining four facies (loess, fluvial sand, fluvial gravel and mass wasting).of material that were removed at the mines, evaluating the relative volume of each facies at surveyed mines, bulk sampling of sediment to characterize the facies, and sampling lag deposits left at mine sites to understand censoring processes that occurred during mine excavation.

The proportion of each surveyed mine's volume that belonged to each facies was estimated by measuring (with a Jacob's Staff or visually) the depth of each facies in scarps surrounding the mine. Errors in these estimates are likely on the order of ±10-50%. It is impossible to sample the missing material actually excavated from mines, but no observations suggest that the composition or proportion of facies in excavated parts of mines were substantially different from material in deposits surrounding the mine. The volume of each facies that was affected by mining was estimated by multiplying the total volume of each surveyed mine by the proportion of that mine assigned to each facies and summing the results by facies.

Because bulk sampling of coarse sediments is labor intensive and required special permission of property owners who were sometimes concerned that the researchers were prospecting for gold, only twelve bulk samples were taken. Bulk samples were taken from deposits in reasonably accessible locations that were visually judged to be representative of each facies. For facies having substantial variability, samples were taken over the range of conditions observed for the facies. Composite, depth-integrated samples (cf. Wolcott and Church 1991) were taken from terrace scarps at four sites. All of these samples included loess and only one other facies. Samples were integrated as volume-by-depth rather than weight-by-depth, and the loess horizon was small (it typically represented one-fifth or less of the total scarp height) and of low bulk density (~ <1 to 1.5 t m^{-3} e.g. Bettis et al. 2003) as compared to gravel (~1.75 t m^{-3} e.g. Church et al. 2001). Therefore these composite samples are considered to be samples of the dominant facies slightly diluted by the addition of a fraction of loess. Sample size was

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determined according to the 1% criterion of Church et al. (1987), so that the largest stone in the deposit weighed 1% or less than the total sample weight, up to a maximum sample weight of 500 kg. Material was templated and weighed down to a size of 64 mm and then sieved and weighed down to a sub-22 mm sample, of which a split was taken back to the lab for further sieving down to 0.063 mm.

Wolman pebble counts were conducted to sample mine-site lag deposits at all except two sites where bulk samples had been collected, and at most sites where surveys were done. These lag deposits are the result of sorting during the process of mining. Cobbles and boulders were manually or mechanically excluded from sluices and left behind on the floor of the mine in fields, piles, or neatly stacked rows with little or no fines filling void spaces (Figure 5). Approximately 100 clasts were sampled and recorded in half-psi intervals. The distributions from Wolman counts give information on the coarse (~128 mm and larger) fraction of grain sizes present in the original, unaltered deposit and insight into sorting processes that occurred at the mine site, so that size fractions present in the mined deposit but not washed into the river could be defined.

Representative grain-size distributions were defined by combining bulk distributions and Wolman counts of the lag material. For paired samples, Wolman counts of lag deposits, on average, included stones that were 1.7 psi (psi = $\log_2 D$ = -phi, in which D is grain diameter) units larger than the largest stone encountered in bulk sampling reflecting the propensity for feasible samples not to capture the sparsely distributed coarsest clasts in cobble and boulder gravels. The observed correlation between the maximum size of lag stone and the maximum size of stones in the bulk distribution allows the best estimate of typical maximum grain size in each facies to be anchored in a more extensive sampling than is represented only by bulk samples. The balance of the distributions was estimated by visually fitting a reasonable line that approximates the median value for each grain size in the observed curves. Figure 8 illustrates the result of applying this method.

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Once volumes and grain-size distributions of mine inputs to the Fraser River were determined, probable effects on the river were considered by evaluating the capacity of the river to transport sediment, probable rates of downstream translation of the sediment, and comparison with known rates of aggradation in the lower gravel-bed reach of the river. We take up the methods in detail before reporting those results.

Mined Sediment: results

Mined Volume

The volume of each mine was calculated by applying regression relations to mine area, which varies over almost 4 orders of magnitude. The mean area of mines mapped by Nelson and Kennedy (in press) is 26,000 m^2, the median area is 29,000 m^2, indicating a preponderance of small mines. The largest is 565,000 m^2, the smallest is 114 m^2, and the standard deviation of area is 48,500 m^2. Mean site depths of surveyed mines range from 0.6 m to 9.4 m. The mean depth is 3.8 m for surveyed sluice sites, 3.8 m for groundsluice sites, and 6.6 m for hydraulic sites. Figure 3 shows topographic maps of mine surfaces and mine excavation depths exemplary of survey results.

Mine-site excavated volume increases in a power-law relation with mine area for all types of mines. A forward stepwise regression predicting log(volume) by log(area) with mine type as a class variable shows that the trends for hydraulic and groundsluice sites are not distinguishable at $\alpha = 0.10$ ($t = -1.260$, $Pr>|t|) = 0.213$). (We adopt the $\alpha = 0.10$ criterion in order to minimize the probability of ignoring a significant difference). Therefore, two separate regressions were developed: one with the ground sluice and hydraulic sites grouped, and another for sluice sites. Results of these regressions are plotted in figure 6.

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For sluice sites the relation predicting excavated volume (V) from area (A), after applying the transformation bias reduction method of Miller (1984), is:

$$V = 0.51A^{1.21} \tag{3.1}$$

This regression is significant ($p = 3.69 \times 10^{-16}$). The residual standard error for this regression is 0.238 logarithmic units. Because the regression was performed in logarithmic space, the back-transformed standard error is asymmetric about the predicted value and is +73% or -42%. These values are larger than our estimated measurement errors and subsume a measure of real variance about the relation.

For ground sluice and hydraulic sites, the transformation bias-corrected relation predicting volume from area is:

$$V = 1.27A^{1.17} \tag{3.2}$$

($p = 1.77 \times 10^{-14}$). The residual standard error for this regression is 0.182 logarithmic units and the back-transformed standard error is +52% or -34% of the predicted value. For both the sluice, and groundsluice/hydraulic regressions, the assumptions of simple linear regression are met: there is no trend in the residuals and the residuals are homogeneous (Figure 6, insets). There is some possibility that the input values are spatially correlated, but there is no evidence that this is a problem. Confidence intervals around the predicted regressions range from $\pm$ 10% of the predicted volume at the mean value to $\pm$ 50% at extreme values.

Consideration of the regression exponents reveals that mine volume is only modestly nonlinear in relation to area, indicating that mine expansion was affected mainly by expansion of area and only to a limited degree by increase of depth. The coefficients show that a hydraulic or groundsluice site of any given area is typically deeper than a sluice site of the same area. Ground sluice mines are typically smaller than hydraulic mines in both area and volume (figures 4 and 6) so the similarity in the area-volume relation for groundsluice and hydraulic mines results from the fact that they both tend to consist of fairly deep cuts (figure 2). The shapes of these cuts are different, however: groundsluices tend to have U-shaped cross sections, with steep walls and flat bottoms while hydraulic mines tend to have V-shaped cross sections. Application of the regression relations to the set of mapped mine areas yields the distribution of individual excavation volumes along the Fraser River (Figure 7).

Summed together, the individual mine-excavation volumes estimate the total amount of sediment discharged to the Fraser by placer mining. The best estimate for the total volume of material excavated by mines along the main stem of the river between Hope and the Cottonwood Canyon (Figure 7) is $58x10^6$ m^3 (bulk volume). The 90% confidence interval for this prediction, calculated by applying the 90% confidence interval from the regression (which subsumes mine depth measurement error) ranges from $55x10^6$ to $62x10^6$ m^3. A key source of possible error in the calculation of the total volume of excavated material is possible errors in the mapping, which would introduce a bias error. The lower bound for the 90% confidence interval excluding all locations mapped as "possibly mined" is $47x10^6$ m^3. This value can be considered a nearly absolute lower bound for the total possible contribution of tailings from placer mining along the river. The upper bound is much less certain because unmapped mines probably exist. It should also be borne in mind that these figures do not include contributions of sediment to Fraser River tributaries. The total volume of sediment input estimated here amounts to an average annual input to the river of about 1 million m^3 during the 50-year history of mining along the river.

Sediment Texture

Not all sediment excavated by mining is of a size that is likely to impact the Fraser River's morphology over a decadal to centennial timescale. Therefore, it is important to consider the GSD of

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tailings. Four facies of excavated sediment are identified: loess, fluvial sand, fluvial gravel and mass wasting. These facies are fairly broad groupings. Figure 8 and Table 1 show grain-size distributions of samples from each of these facies and representative grain-size distributions for each facies. The fluvial gravel and mass wasting facies have a considerable range of possible upper limits in cobble/boulder size, but information about this limit is provided by Wolman counts of lag deposits at mines.

Loess is wind blown material composed of fine sand or finer particles. Along theFraser River, it typically has a reddish or brownish tint and is easily recognized. In some cases, in the extreme northern and southern parts of the study region, soils consisting of fine sediment (primarily loess though there may be components of colluvium or sand) and substantial amounts of organic material were grouped into the loess facies. Because of its fine grain size, a single sample of the loess facies was deemed sufficient to characterize it for the purposes of this study. The D_{50} of sediment in the facies is 0.06 mm and the D_{90} is 0.18 mm.

Fluvial sands are moderately well-graded deposits ranging in size from silt to granules. They are locally interbedded with fluvial gravel and fill paleochannels on the bank side of gravel deposits. As with the loess facies, a single bulk sample was used to characterize this facies. The D_{50} of sediment in the facies is 0.21 mm and the D_{90} is 2.0 mm.

Fluvial gravel consists of silt through cobbles, and in some instances, boulders. Clasts are rounded and deposits are clast supported. Locally, material is recognizably of glaciofluvial origin, distinguishable only by steeply sloping bedding. Six bulk samples were used to characterize this facies (Figure 8). A representative GSDwas determined by visually fitting a line that approximated the median distribution of the sampled sites. This representative GSD (Table 1) has a D_{50} of 8.5 mm and a D_{90} of 110 mm (Figure 8).

The mass wasting facies contains angular clasts ranging in maximum size from gravel to

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boulders, which are either supported in a fine-grained matrix of clay to sand sized material or clast supported within a very fine-grained matrix. It contains material interpreted to be of both debris flow and colluvial origin. Four bulk samples were used to characterize this facies, and a general GSD was determined in a manner similar to that for fluvial gravel. The GSD for this facies has a D_{50} of 21 mm and a D_{90} of 180 mm.

A sensitivity analysis shows that the percentage of sediment in each facies belonging to each size class is not very sensitive to the particulars of the averaged GSD estimation. Table 1 shows that the absolute difference between the estimated mean percentage of each grain size range and the measured percentage of that grain size in the coarsest and finest samples range from 2 to 12 % (both in the debris flow distributions).

Approximately half (53%) of all surveyed mines are mantled by loess. Sand, gravel, and mass wasting material may be interbedded. Fifteen percent of surveyed sites have fluvial sand, 34% of sites have mass wasting material, and 68% of sites have fluvial gravel. Figure 9 shows box plots of the observed thicknesses of each facies. Weighted averages of the proportion of material belonging to each facies at the mines that were surveyed were determined by multiplying the total volume of the mine by the proportion of that mine assigned to each facies and summing the results by facies. The resulting estimate (based on the assumption that each of the three less common facies is known to within ±50%) is that 16±8% of the excavated material at surveyed sites was loess, 7±3.5% fluvial sand, 9±4.5% mass wasting material, and 68±15% fluvial gravel.

Another factor affecting the GSD of tailings is sorting processes that occurred during the process of mining. Because placer gold is found in small nuggets and flakes cobbles and larger grains were not processed through sluice boxes and remained at the site of mines as lag deposits. Paired samples of bulk distributions of the unaltered deposit and Wolman counts of lag deposits show how sorting affects the bulk distribution. Mine lag deposits (Figure 10) are very well sorted and truncated relative to the unaltered deposits (Figure 8) below the size of large cobbles (128-181mm). There is little relation between the bulk grain-size distribution of the unaltered deposit and the point at which the lag deposit is truncated. Therefore, it seems reasonable to truncate the upper end of the grain-size distribution of the unsorted material at 128 mm to produce an estimate of the grain-size distribution of the potentially mobilized tailings. The resulting estimates of the grain-size distribution for tailings from the fluvial gravel and mass wasting facies are shown in Table 1.

The composite grain-size distribution for all tailings, obtained by multiplying the proportion of material of each grain size for each facies by the proportion of material removed that belonged to that facies (as determined from the surveyed sites) and summing these values for each grain size, is shown in Figure 8 and Table 1. On the basis of this distribution, we estimate that of the total 58×10^6 m^3 tailings produced by mining (bulk measure), 8×10^6 m^3 were small cobbles, 19×10^6 m^3 were gravel, 24×10^6 m^3 were granules and sand, and 7×10^6 m^3 were were silt and clay.

Impact of Mining Excavation on the Fraser River

Once excavated by mining, sediment was either rejected immediately because of large size and left near its original position on the mine site, or was passed through a sluice box. At the downstream end of the sluice box a slurry of sediment and water was discharged to the river. Along the Fraser River nearly all mines (three observed exceptions) discharged sediment directly into the river. In order to appraise the effect of these additions to the river sediment burden, it is necessary to consider the fate of this sediment.

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Methods

The capacity of the river to transport the load of sediment supplied by placer mining was evaluated by applying an uncalibrated version (because no calibration data are available) of the Wilcock and Crowe (2003) surface-based sediment transport function. The function explicitly treats sand transport and includes the nonlinear effect of sand on the gravel transport rate. It was used to estimate the capacity of the river at two locations: in the upper part of the study area at Marguerite, and at Hope, the head of the gravel-bed reach of the lower Fraser (Figure 1). These locations have the longest established gauges on the river and useful cross section information. Furthermore, they are located on reaches with low gradients relative to the overall reach of Fraser River under consideration, and so represent reaches of potentially low transport capacity. The average annual potential bedload transport at these stations can be calculated by using annualized partial duration series of flows (average number of days/year of a given flow) for the period of record 1912-2009 at Hope, and 1950-2009 at Marguerite, which were calculated based on Water Survey Canada (WSC) gauge records (Water Survey Canada 2009).

Average channel shear stress was calculated for the range of flows represented in the partial duration series by using the hydraulic geometry of the channels to define average depth for each flow condition at Marguerite (from Hickin 1995), and Hope (based on WSC data provided by D.G. McLean, personal communication 2010) and defining the slope. The channel at Marguerite is entirely alluvial whereas, at Hope, the right bank is rock-defended. The channel slope over 4 km centered at the gauging station at Marguerite is 0.0007 on the basis of high-precision GPS data from a raft transect (C. Rennie, personal communication 2010). The channel slope from Hope to Ruby Creek, 13 km downstream, is 0.0006 (McLean, personal communication 2010). Using average channel depth, hence an averaged measure of shear stress, should lead to underestimation of sediment transport capacity, because bedload sediment transport is nonlinear with respect to shear stress (Ferguson 2003).

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Sediment transport calculations assume channel widths of 175 m at Marguerite (based on cross sections presented in Hicken 1995) and 150 m at Hope (based on cross sections 30 m upstream of the bridge between 1983 and 2001 by the British Columbia Ministry of Transportation; McLean, personal communication, 2010).

The sediment transport function of Wilcock and Crowe (2003) is highly sensitive to the grain-size distribution on the bed of the river. Unfortunately, very little is known about the grain-size distribution on the bed of the Fraser River above Agassiz, which is located on the Lower Fraser (Figure 1). Figure 11 displays 14 bulk samples of bed material collected by Church and colleagues on the river and river terraces at Lillooet and in the uppermost part of the aggraded gravel bed reach of the lower river. The figure shows that the placer tailings are considerably finer than material in the river bed. Sediment transport was calculated using three different GSDs that are plausibly of interest: the estimated synthetic GSD for mine tailings, the GSD for the fluvial gravel facies, and the GSD observed by Ryder and Church (1986) on Orchard Bar just downstream of Lillooet, in the middle of the reach between the uppermost placer sites and the lower river (Figure 1).

Once sediment is shown to be transported in the river, the important question arises as to how long it takes to translate the material from the placer sources to the lower reach of the river. This amounts to estimating the virtual velocity of bed-material sediments in the Fraser River, which could be used to make a simple kinematic estimate of movement through the system of gravel and cobbles introduced by placer mining. Combined with estimates of the timing of mining for each site (see Nelson 2011), such an estimate will allow a retrospective forecast of gravel delivery volumes to the aggrading reach of the river.

Nicholas et al. (1995) report that the virtual velocity of riverine sediment slugs typically ranges from 0.1 to 0.5 km a^{-1} but that slugs generated by mine tailings may move up to 1-5 km a^{-1}. They do not specify the physical basis for the apparently distinctive behavior of “mine tailings”. Perhaps it is because mine waste tailings may typically be finer grained relative to natural channel sediment, as appears to be the case in the Fraser River. Beechie (2001) compiled observations of annual travel distance (L_b) of bed load sediment at sixteen locations, five of which were in gravel bed streams, and created regression relations predicting L_b from bankfull width. We apply his regression to the Fraser River in order to understand possible rates of downstream movement of placer waste sediment. The widest stream included in Beechie's (2011) study had a bankfull width of ~75m, and the largest drainage area was ~550 km^2. He found annual travel distance to be equivalent to approximately 20 bankfull channel widths ($r^2 = 0.86$, $p < 0.001$). The bases for this relation are established relations between bar spacing and channel width and between channel width and virtual velocity. Assuming a bar spacing of 5 to 7 channel widths (Leopold et al., 1964), he concluded that L_b in typical alluvial channels is equivalent to three or four bar spacings.

Because the relations amongst channel width, drainage area, and bed load transport distance are physically plausible, it may be reasonable to extrapolate the regression to the Fraser River, which is much larger than rivers included in Beechie's (2011) regression. There is no reason to expect that the trends observed by Beechie (2011) would reverse with increasing stream size, so 1 km, the upper end of annual travel distances observed by Beechie, can be considered the lowest reasonable L_b for the Fraser River. Bankfull widths in alluvial reaches of the Fraser River are typically between ~150 and 300 m. If Beechie's regression relation is extrapolated to the bankfull widths on the Fraser River, the predicted annual travel distance through its alluvial reaches is 3.1 to 6.3 km a^{-1}. Canyons, which occupy about 10% of the middle Fraser, can be considerably narrower. However, because of high gradients, deep water, and a lack of storage zones, it is probable that sediment is conveyed very rapidly through the canyons (Hooke 2003).

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We apply annual travel distances of 1 km a^{-1} $\leq L_b \leq$ 6.3 km a^{-1} to the Fraser River mine tailings according to the place and approximate time (estimated from archival records compiled by Nelson and Kennedy (in press)) of their introduction into the river in order to estimate sediment movement to the lower river. Our computations are supported by historic descriptions of the impact of placer mining on the Fraser River and direct observations of the current state of the river.

Results

Observations of the banks of the Fraser River below mines, and of mobilization of sediment from a recent large landslide into the river, indicate that mining sediment dumped into the river has indeed been transported away. There is virtually no sign of excavated sediment on the banks of the river below most mines although, at some sites, very small (10 to 200 m^3) relict fans still protrude into the river. The surface GSD of one such fan where a Wolman count was done (n = 197) is very coarse (D_{10} = 181 mm, D_{90} = 600 mm). The very large size of the surface sediment of this tailings fan indicates that selective transport has removed a large amount of smaller material from the fan. The fan below the Lillooet Hydraulic Mining Co's Excavation at the “Old Bridge” in Lillooet provides a vivid illustration of the construction and destruction of a tailings fan (Figure 12).

The channel of the middle Fraser River has been generally stable following placer mining. Modern observations show that several sites that were dredged still have distinct scars that are visible at low water (including the mouth of the Anderson River, 52 km north of Hope; Horsebeef Bar, at Lillooet; and perhaps High Bar, 41 km north of Lillooet (Kennedy 2009)) (Figure 1). Early placer-mining-era descriptions of the locations of bars match, for the most part, the locations of modern bars (see Nelson and Kennedy, in press). The only region of the middle Fraser where there are substantial, unstable bars indicating the presence of a large amount of episodically mobilized sediment (and

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possible aggradation), is the reach between Cottonwood River, 28 km north of Quesnel, and Soda Creek, 23 km south of Marguerite (Figure 1). This reach has been affected by major landslides, and may be impacted by placer waste discharging from the Cariboo mining district and Quesnel River.

Historical accounts also suggest that the middle Fraser River was stable in the late 19th and early 20th centuries. The mining commissioner at Lillooet, in 1891, stated:

> In view of probable extensive hydraulic mining on the various benches of the Fraser River in this district in the near future it is, perhaps, not out of place here to refer to a similar method of mining in [the Sacramento basin], where legislative action was invoked to put a final stop to it on account of filling up the rivers … with silt, and the practical destruction and flooding of unnumbered acres of, probably, the best alluvial lands in that state. From personal observation I am clear in saying the same conditions do not exist here. (British Columbia Dept. of Mines 1891 p. 573)

An account from 1923 maintains the same theme, indicating that major channel changes had not taken place over another thirty years: "[hydraulic mining] is not hampered by anti-debris laws, damage suits for injury to farm lands, or interference with navigation as in California" (Haggen, 1923 p. 65). We conclude that the river did not aggrade significantly during the mining era.

If sediment has been added to a channel that has not significantly aggraded, then that sediment (or an equivalent volume from the streambed) must, necessarily, have been transported downstream. We note that the volume of placer waste gravel in the river, if evenly distributed along 500 kilometers of the Fraser's 250 m wide channel, would produce only 17 cm of aggradation, which would not be detected by the coarse observations that have been presented. However, considering irregularity in the gradient of the channel, constraining canyons, and the normal bed-material transporting habits of alluvial rivers, evenly distributed aggradation is highly unlikely. Results of the capacity calculations (table 2) using different input GSDs span a wide range. The way in which mine tailings interacted with the existing bed of the river determines which capacity estimate should be used to approximate transport rate of the mine tailings. The transport calculation using the GSD of Orchard Bar (Figure 11) is probably reasonably representative of the capacity to transport the resident bed material in the river and represents a minimum rate for transport of placer tailings. To the degree that placer tailings have mixed into the natural riverbed sediment, which the Wilcock and Crowe (2003) transport function indicates is partially mobile in the range of examined flood flows, the transport rate for the tailings is well bounded by the gravel transport capacity calculated using the Orchard Bar GSD 0.2×10^6 to 0.4×10^6 m^3a^{-1}) (table 2). These estimates are similar to the influx estimated in the gravel reach of the lower Fraser (Church et al. 2001). It is also possible, however, that mine tailings could have moved over top of the coarse (and, in this scenario, largely immobile) natural channel sediment. In this case, the very high capacity estimated using the mine tailings GSD (2.1×10^6 to 4.6×10^6 m^3a^{-1}) (table 2) may appropriately indicate that the transport of tailings was almost entirely supply-limited, and the only constraint on downstream sediment movement of the slug would be the sediment's virtual velocity. It is probable that, with the admixture of placer tailings into the river bed over the years, actual bed material flux is intermediate between our two bounding estimates. At the least, the observation that Fraser River bed sediment is coarser than the run of mine tailings indicates that tailings sediment has been transported.

In summary, simple models of sediment transport in the Fraser support the hypothesis that the Fraser River is capable of transporting the introduced mine tailings. The Wilcock and Crowe (2003) transport function predicts that the Fraser River is capable of moving an amount of sediment comparable to the average annual input of approximately 1 million m^3 during and immediatly following the fifty-year period of mining.

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Figure 13 shows the results of applying our proposed virtual velocity calculations to the estimated time and place of sediment discharge from mining to the river (described in the methods section). With an annual travel distance (L_b) of 6.3 km a^{-1}, annual delivery to Hope (Figure 1) ranges up to 1,000,000 m^3. Peak delivery of gravel to Hope would have occurred around 1890 and all sediment that was dumped into the main stem of the Fraser would have been delivered before the turn of the millennium. With L_b = 3.1 km a^{-1} (the velocity we consider to be most likely) annual delivery values range up to 700,000 m^3, peak delivery of sediment to Hope would have occurred in the first decade of the 20th century, and sediment from the main stem of the Fraser will continue to be delivered to Hope through the 21st century. At L_b = 1 km a^{-1}, the lowest reasonable estimate for the Fraser, annual delivery is up to 300,000 m^3, peak delivery of gravel to Hope occurred in the late 20th century, and persistence of sediment in the middle Fraser will continue beyond the year 2350. The variability within the curves shown in figure 13 is a consequence of our method. Sediment from inputs from individual mines are dumped according to the time and place of the mining onto the conceptual virtual velocity "conveyor," which transports them downstream at a constant rate. Variability in the delivery of sediment to Hope, therefore, reflects variability in the addition of sediment to the river.

Discussion

Approximately 58,000,000 m^3 of sediment was excavated from 456 identified individual mines and dumped directly into the Fraser River between Hope and the Cottonwood Canyon, north of Quesnel (Figure 1). This sediment appears to have been transported rapidly away from mine sites.

Placer waste tailings along the Fraser River consisted of 14±7% small cobbles, 32±9% gravel, 41±4% granules and sand, and 13±4% silt and clay. Sediment fine enough to be carried as suspended

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load (clay, silt, and sand in the Fraser) would have mostly washed directly into Fraser delta and the Strait of Georgia. Hales (2000) found high concentrations of mercury in Fraser delta sediment at depths dating to the late19th and early 20th centuries. She speculated that this mercury was derived from gold mining.

Approximately 27,000,000 m^3 of gravel and cobbles discharged in placer tailings to the Fraser River must still be in the river because gravel does not travel in significant quantities beyond Mission (Figure 1), near which a gravel-to-sand bed transition occurs. This coarse bed material appears to have been washed though the steep middle reaches of the Fraser (where gradients up to 0.003 occur) without causing significant channel instability (British Columbia Department of Mines 1891, Haggen, 1923) until it reached the lower gravel-bed reach of the river, where the river's slope decreases (eventually to approximately 0.0002 at the downstream limit of gravel travel) as it approaches the sea.

Unlike the middle Fraser River reach, the lower gravel-bed reach of the Fraser River is aggrading. If placer waste sediment has been transported through the middle Fraser, it is likely an importantsource of the gravel accumulating in the lower reach. Church et al. (2001) estimated a sediment budget for the Fraser River between Laidlaw and Mission for the period 1952 to 1999. They compared bed elevation surveys from 1952, 1984, and 1999 to derive their sediment budget, and compared their estimated budget to measurements of gravel transport at Agassiz. Their best estimate for gravel recruitment to the river between Agassiz and the downstream limit of gravel lies in the range 171,000 to 229,000 m^3a^{-1} of gravel (bulk measure). In addition, both Church et al. (2001), and Church and Ham (2004) detect indications of downstream advancement of a sediment slug that would have entered the lower gravel-bed reach between the late 19th and early 20th centuries. Church et al. (2001) produced a map of net bed-level change that shows that the sub-reach between Agassiz and Laidlaw (Figure 1) has recently (later 20th century) degraded, while the sub-reach (downstream) between

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Agassiz and Mission is generally aggrading. Church and Ham (2004) identified a zone of instability that has propagated downstream through the 20th century. In the area between Agassiz and Laidlaw a significant volume of channel sediment appears to have been deposited early in the 20th century, causing island growth and channel instability, followed by channel simplification and degradation in the latter half of the century. This suggests that there was a high influx of bed material between the late 19th century and early 20th century, and a substantial reduction of incoming bed sediment in the latter part of the 20th century. The assumed sediment virtual velocities all yield sediment fluxes into the lower river in the late 20th century that compare reasonably with the observed rate of aggradation of 171,000 to 229,000 m^3a^{-1} of gravel for the period from 1952 to 1999 on the lower Fraser (Church et al. 2001). The estimate of 3.1 to 6.3 km a^{-1} gravel propagation rate (Figure 13) is consistent with Church and Ham's (2004) observation of morphological patterns, suggesting a large influx of sediment at the beginning of the 20th century followed by a reduction in the sediment feed.

The movement of placer waste sediment from mine sites to the aggrading reach of the Fraser River is also consistent with general models of the impact of sediment slugs on fluvial systems (e.g., Nicolas et al. 1995, Lisle et al. 2001, Cui et al. 2003a and b), and shows that that the paradigm of wave-like propagation of sediment through a river may reasonably apply to modest disturbances in very large streams. Though historical information about the Fraser River's morphology is not sufficient to constrain the mode of wave evolution, two conditions observed on the Fraser River are consistent with observations of translation of sediment slugs. First, in flume experiments, Cui et al. (2003a) found that when the caliber of grains in a sediment slug was finer than the bed material, slugs evolved rapidly through both translation and dispersion. However if the caliber of grains in a slug was coarser than the bed material the slug evolved almost exclusively through dispersion. Second, a Froude number (*Fr*) much less than 1 typically promotes translation (Lisle et al. 2001, Cui et al. 2003a and b). The

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possibility of downstream translation of placer waste sediment in the Fraser is supported by the fact that placer tailings are substantially finer than sediment on the bed of the Fraser and the fact that the Froude numbers along most of the middle Fraser is modest. At mean annual flood, $Fr = 0.45$ at Hope and 0.56 at Marguerite. These values are slightly higher than the threshold of $Fr < 0.4$ that Lisle (2008) found for translation in uniform sediment. On the other hand, the absence of any recorded history of aggradation in the middle Fraser River argues for relatively rapid dispersion of sediments introduced at the height of the mining era. It is likely that both translation and dispersion affected the fate of the introduced sediment.

Regardless of the mode of wave evolution, individual sediment inputs from mines along the Fraser River would have been of little consequence to the river. However, evidence of sediment delivery to the aggrading lower reach of Fraser River appears to demonstrate coalescence of a dispersed and non-detectable wave into a detectable wave of geomorphic significance where the slope of the river is reduced, behavior hypothesized by Lisle et al. (2001). Sediment delivery to lower Fraser River represents an example of the way modest and distributed anthropogenic impacts may be translated in space, concentrated by natural processes, and persist as an influence over a centennial timescale. Ironically, the river, which transported placer waste away from the mines, thereby "disposing of the sediment", has concentrated the impact of distributed activity into a relatively short reach.

The apparent persistence of legacy placer waste sediment in the lower Fraser River's channel has important consequences for interpretation of geomorphic process studies. For example, the accumulation of gravel associated with this sediment slug exacerbates the flood hazard for communities along the lower gravel-bed reach of the river. Church et al. (2001) have documented the rate of river bed aggradation over the past 50 years, and on this basis a program of gravel extraction has

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been initiated for flood hazard mitigation. These efforts must be carefully managed so as to not overly disturb the channel morphology (Church et al. 2001, Church 2010). Aggradation forecasts based on extrapolation of the recent rate, without understanding of the historical geomorphic context and the possibility of legacy sediment effects, could lead to substantial damage to the river ecosystem. If placer-waste sediment indeed controlled the historical aggradation, then caution should be used when applying the measured historical gravel budget in the aggrading reach as a forecast for the future and a basis for management decisions. The data presented here (figure 13) suggest that the influx of placer-derived waste sediment to the aggrading reach was likely dramatically reduced sometime during the 20th century. As the river adjusts to the reduced delivery of placer mining waste, there is a substantial probability of a change in channel form and behavior, which makes vigilant monitoring of the current movement of sediment into the lower Fraser and effects of ongoing sediment removal activities more critical.

It must be recognized, however, that placer waste from mines along the main stem of the Fraser River is but one of several sources of mining waste that might affect the lower Fraser. Significant quantities of placer waste sediment were also dumped into streams in the Cariboo district, the Bridge River, Cayoosh Creek at Lillooet, and the Thompson River. Although the volume of material discharged into streams draining the Cariboo district (Willow River, Lightning Creek, Cottonwood River, Quesnel River) was probably around $2x10^8$ m^3, the limited bedload capacity of these streams has likely limited gravel delivery to the Fraser River (Nelson 2011). The Quesnel River received the largest charge of sediment, but the contemporary state of the river, with abundant gravel deposits, and sediment transport capacity estimates made in a way similar to those described above for the Fraser River indicate that relatively little of this material has been transported into the Fraser at the mouth of the Quesnel. The quantity of sediment dumped into the Bridge River is not known, but certainly

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significant (a single mine produced around $12x10^6$ m^3), and the stream may have had substantial capacity prior to contemporary regulation. The impact of placer mining along the Thompson River is unknown but probably modest.

In addition, there is annual recruitment of gravel into the Fraser River from natural failures along the banks of the river, which consist of extensively high and abrupt terrace edges composed of mixed Quaternary sediments. We have no precise record of this sediment volume input from such sources but suppose, from contemporary sediment transport measurements, that it must be of order 10^5 m^3a^{-1} (McLean et al. 1999; Church et al., 2001). Our estimates of tailings dumped directly into the Fraser River clearly are low estimates of the total bed material load introduced into the river during the latter half of the 19th century. Nevetheless, they are substantially greater than a plausible estimate of 'natural ' sediment recruitment. Furthermore, the key evidence in our connection of placer sediment influx to 20th century aggradation is not the absolute quantity of sediment transported but the plausible range of time scales for delivery of the placer sediment into the lower river.

More generally, observation of the impact of placer mining along the Fraser River underscores the the argument that it is critical to historically contextualize geomorphic process studies and engineering monitoring programs (cf. Church 1980, Baker 1988, James 1999, James 2010). In particular, we observe that many relatively small excavations along the Fraser River have had a substantial cumulative impact on the river. The majority of sediment excavated by placer mining was moved from mines with sluice morphology and from mines smaller than 500,000 m^3. This challenges the assumption that the primary geomorphological consequences of placer mining result from large, heavily-capitalized hydraulic operations (cf. Rohe 1986), and should encourage further study of the geomorphic impact of placer mining in regions that were mined by smaller-scale "traditional" methods.

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Conclusions

Approximately 58×10^6 m^3 (bulk measure) of tailings sediment was discharged into the Fraser River from many small mines distributed along its length between Hope and the Cottonwood Canyon north of Quesnel (a distance of 515 km) at an annual rate of about 1 million m^3a^{-1}. The grain-size distribution of this discharged sediment consisted of 46% gravel and small cobbles, which persists in the river channel as legacy sediment.

The history of, and response to, placer mining disturbance along the Fraser River contributes to our understanding of the behavior of sediment slugs and episodic sediment transfer. Widespread, small- to medium-scale disturbances agglomerated into a sediment slug spanning some 500 km, perhaps the longest hitherto documented. This slug moved (or is moving) downstream at an estimated rate between 3 and 6 km a^{-1} over a period that may already be closing, but that might persist for as much as another 300 years and has concentrated much of the dispersed impact of mining into the currently aggrading lower gravel-bed reach of the river. That concentration of sediment in the lower river appears to have produced a zone of aggradation and instability that has propagated downstream through the 20th century to the present. If this is indeed the case, then historical and current geomorphic processes in the lower gravel-bed reach are influenced by historical placer mining along the river. Researchers who study ongoing processes should consider historical context and the possibility of legacy effects from historical activity in order to understand whether the processes they observe are occurring as quasi-equilibrium processes or are in fact transient adjustments to sediment-driven perturbation. Managers along the Fraser River and elsewhere who may use historical estimates and past observations of sediment transport rates should be wary of the assumption that historical rates represent normal conditions that will continue into the future.

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Acknowledgments

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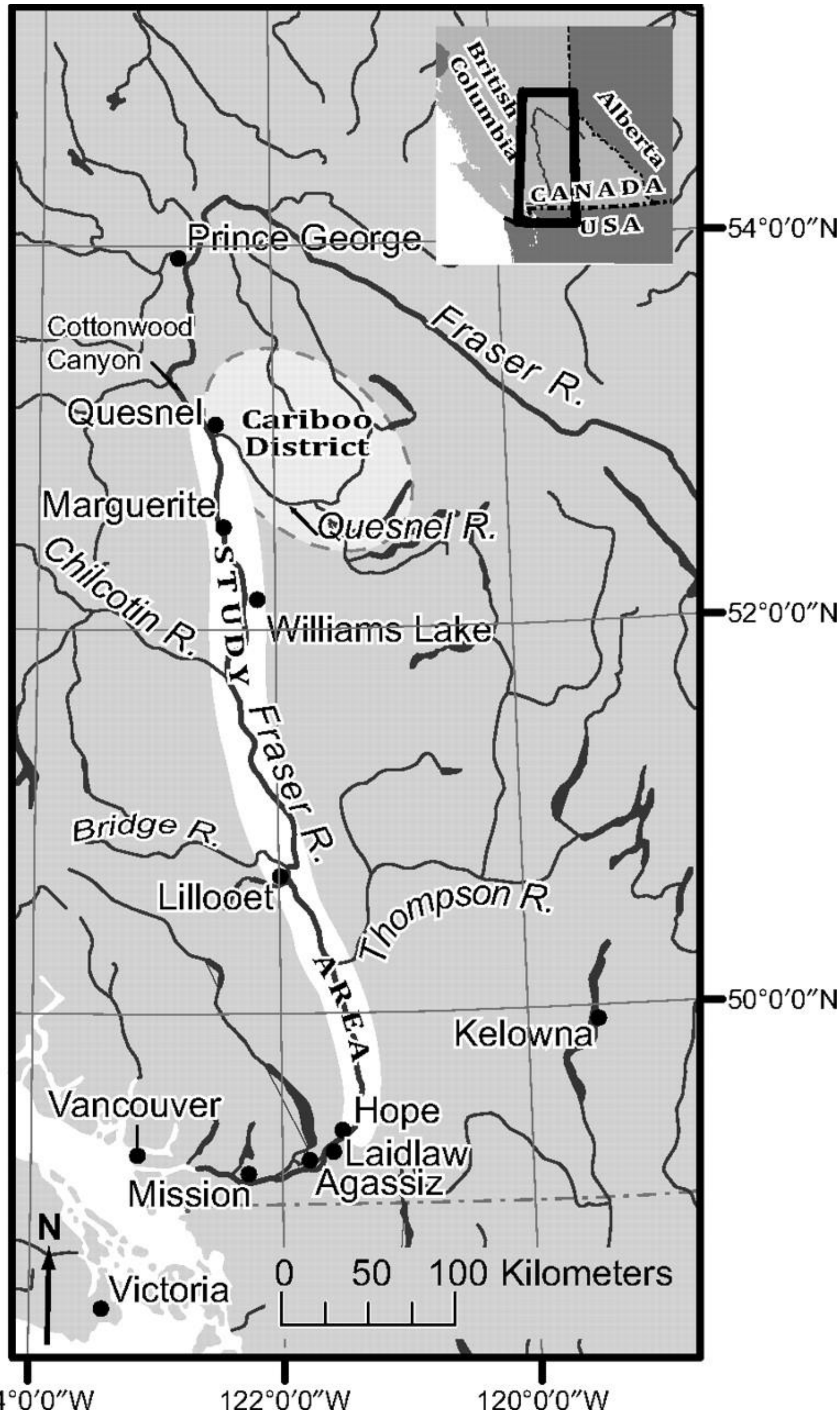

Figure 1: Location map showing study area, the Cariboo Mining district, and other rivers where significant mining occurred. The Middle Fraser is the area between Hope and Quesnel. Here the Fraser flows through a series of deep canyons. The Lower Fraser is the part of the river downstream of Hope. At Hope the River exits the mountain front and enters a broad alluvial plain. Initially, it flows over a gravel fan in a reach that extends downstream to near Mission. Below Mission the river has a sand bed.

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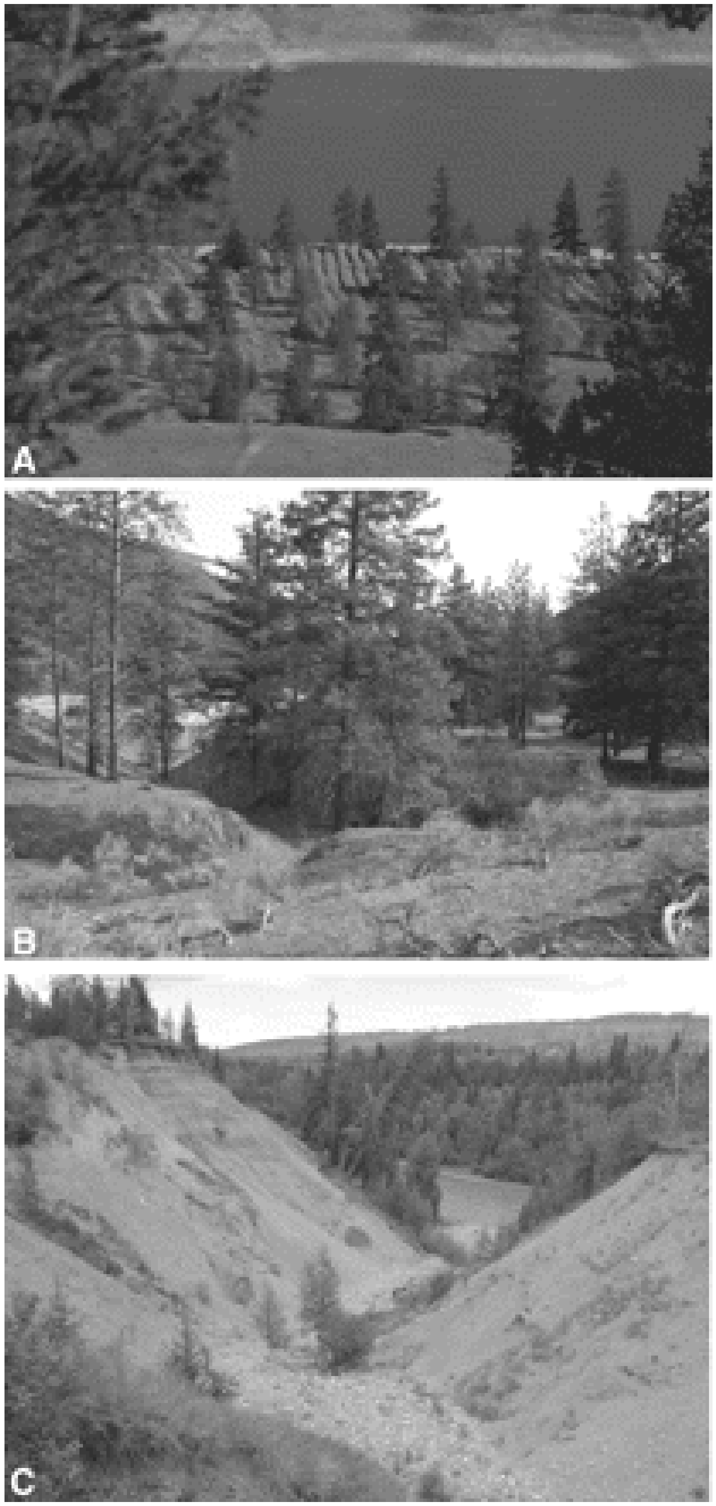

Figure 2. The landscape effects of different mining techniques. At sites associated with the use of sluice boxes (a), the ground surface is often lowered by 1-3 m, leaving lag gravels in neatly stacked rows. Ground sluicing (b) leaves eroded depressions with steep scarps and level floors, and large heaps of cobbles. Hydraulic mining (c) leaves high steep scarps above gently sloping wash pits containing large boulders and cobbles.

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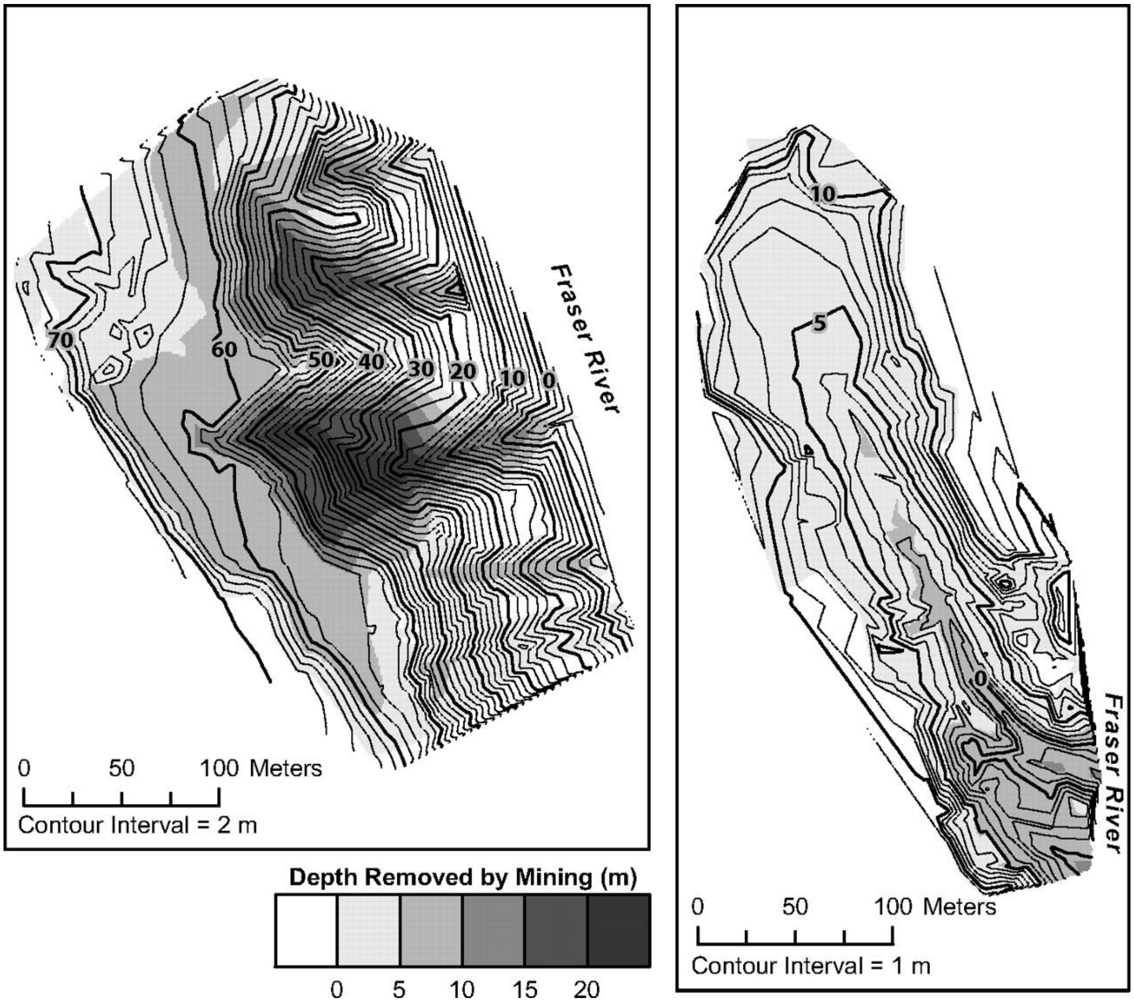

Figure 3. Examples of mine surveys and landscape interpretation. The mine site on the left is an example of a compound site with multi-layered history showing both classic sluice and hydraulic morphologies, where construction of the pre-mining surface was a straightforward exercise. The upper portion of the site has classic sluice site morphology: one to three meters of sediment are excavated from the surface of a terrace. Scarps around the mine and some "buttes" of unmoved sediment provide clear indications of the depth of sediment removal in this portion of the mine. Three large hydraulic pits were cut up to 20 meters into the terrace. This probably removed much of the part of the site that had been sluiced. Reconstruction of the original surface over the hydraulic part of the mine was facilitated by interpolation between clearly preserved facets of the pre-mining terrace scarp. To the south of the hydraulic pits, two gullies run down to the river below the mine. These gullies may have been incidental, resulting from erosion associated with outwash below the sluice site on the terrace above, or may have been intentional prospecting efforts associated with the hydraulic phase of mining at the site. Such gullies are not uncommon below mine sites.

The site on the right is an exceptional example of the landscape effects of groundsluicing. Steep scarps, level floors, and large heaps of cobbles behind walls of steeply stacked cobbles characterize the site. A single large drain (11 m deep) services the whole site and irregular elongate pits are excavated in a fan above that drain. These pits gradually get shallower with increasing distance from the drain. Reconstruction of the pre-mining surface is a relatively straightforward task of connecting a wall on the river side of the excavation to the top of the scarps on the upslope side.

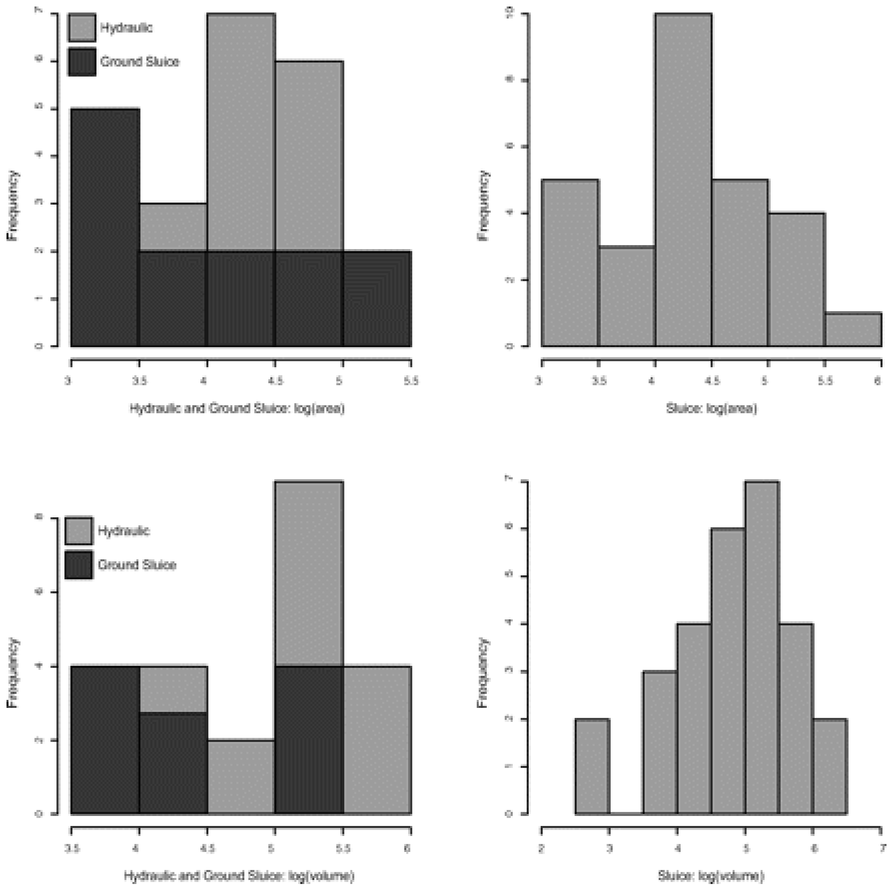

Figure 4. Histograms of the logarithmically transformed variables area and volume for surveyed mine sites. Sluice sites are displayed separately (right column), hydraulic and groundsluice sites are stacked (left column). Groundsluice sites are represented by the dark gray color.

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Figure 5. Photo showing a typical lag deposit at Rip Van Winkle Flat just upstream of the confluence of Fraser and Thompson rivers. These coarse (128-360 mm) stones were excluded from sluice boxes and manually stacked in rows.

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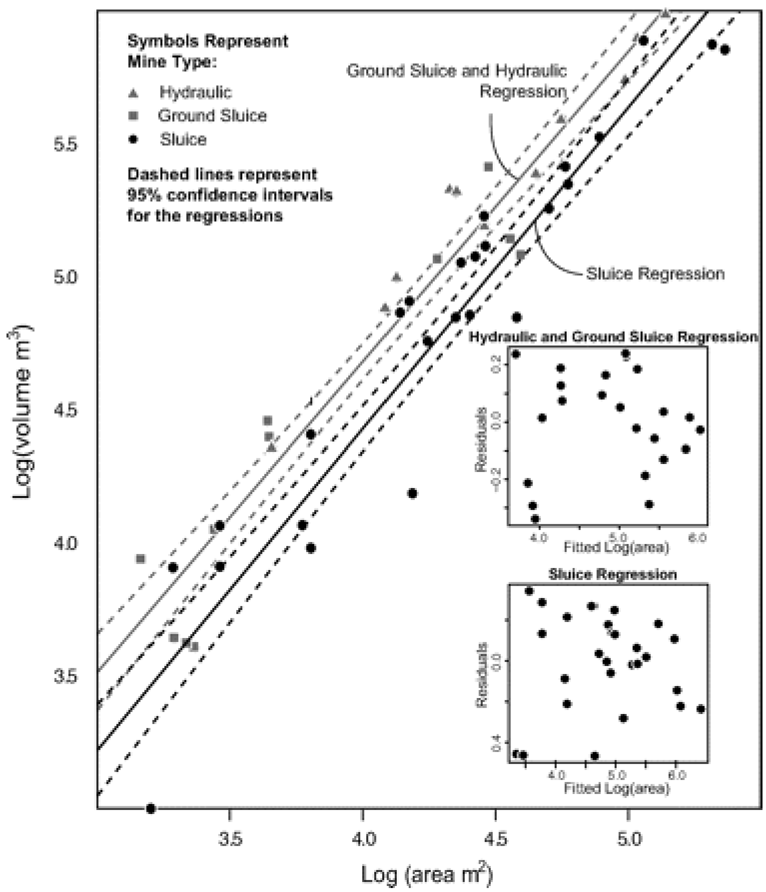

Figure 6. Plot of regression relations predicting mine site volume from area for sluice and combined groundsluice and hydraulic geometries: insets, residuals from regression. See text for details of the regression relations.

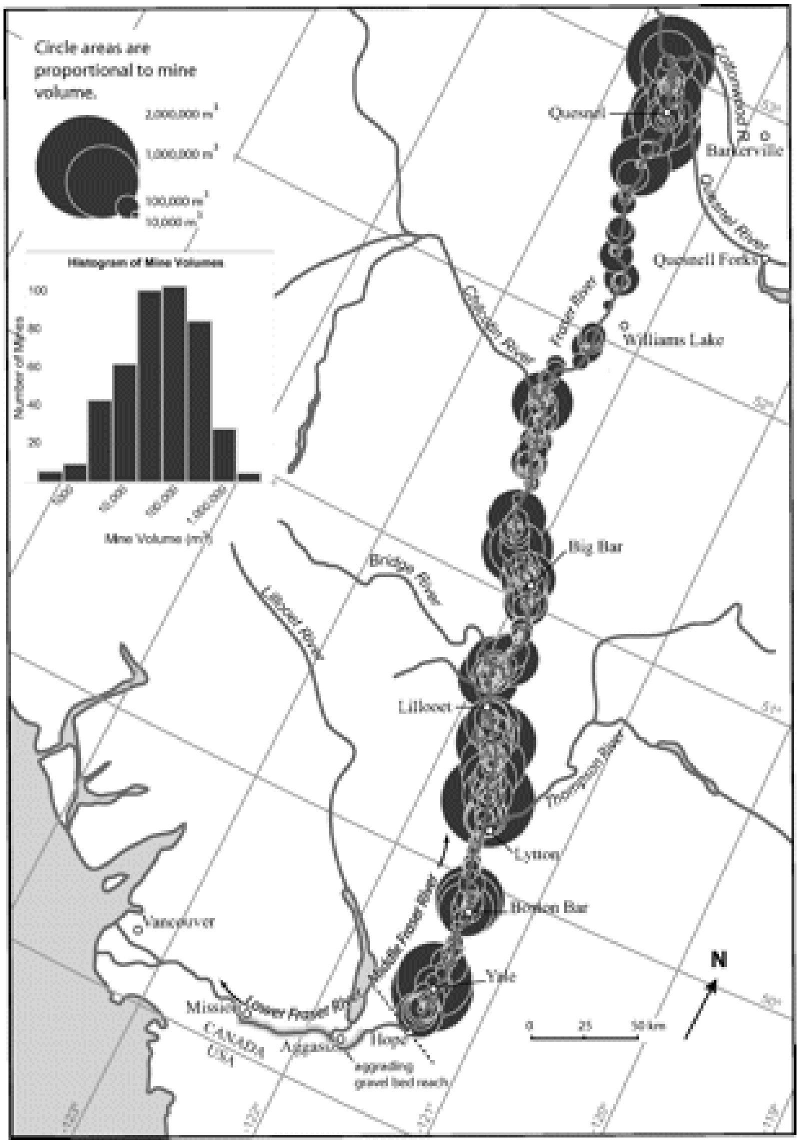

Figure 7. Proportional symbol map of estimated mine excavation volumes along the Fraser River between Hope and Cottonwood Canyon.

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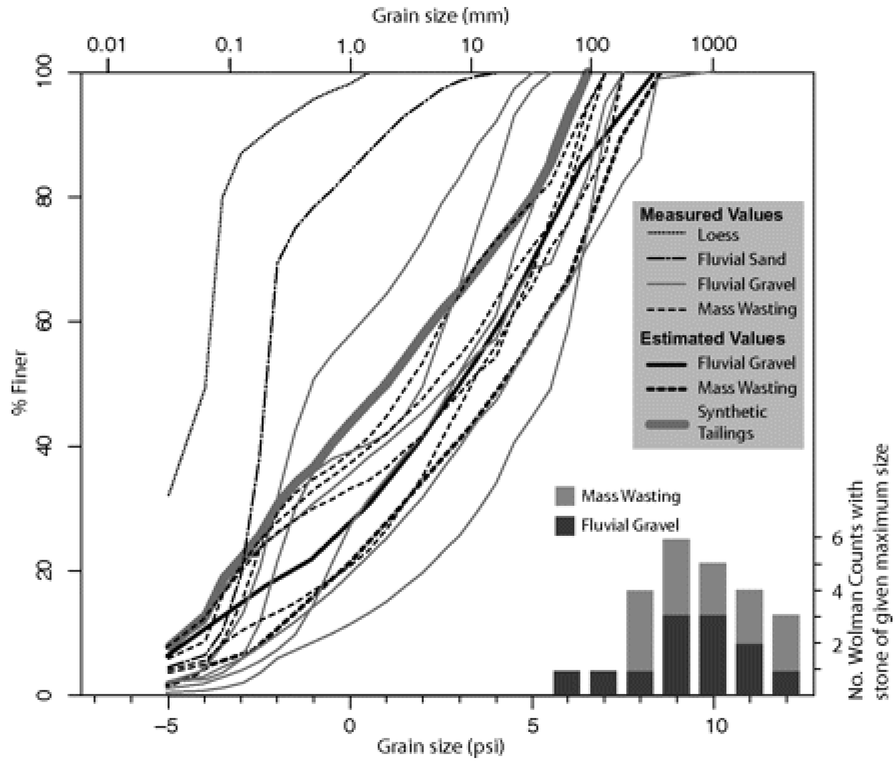

Figure 8. Grain-size distributions of bulk samples, estimated grain-size distribution for each facies, and histogram of the largest stone encountered in all Wolman counts. The "Synthetic Tailings" curve was obtained by multiplying each grain-size distribution by the proportion of excavated material belonging to that facies and summing the results. The coarse end of the Fluvial Gravel and Mass Wasting facies were determined by comparison of bulk and Wolman samples; see text for further discussion of the method. Grain sizes are shown in terms of psi units: psi = -phi = $\log_2(D)$ where D is grain diameter in mm.

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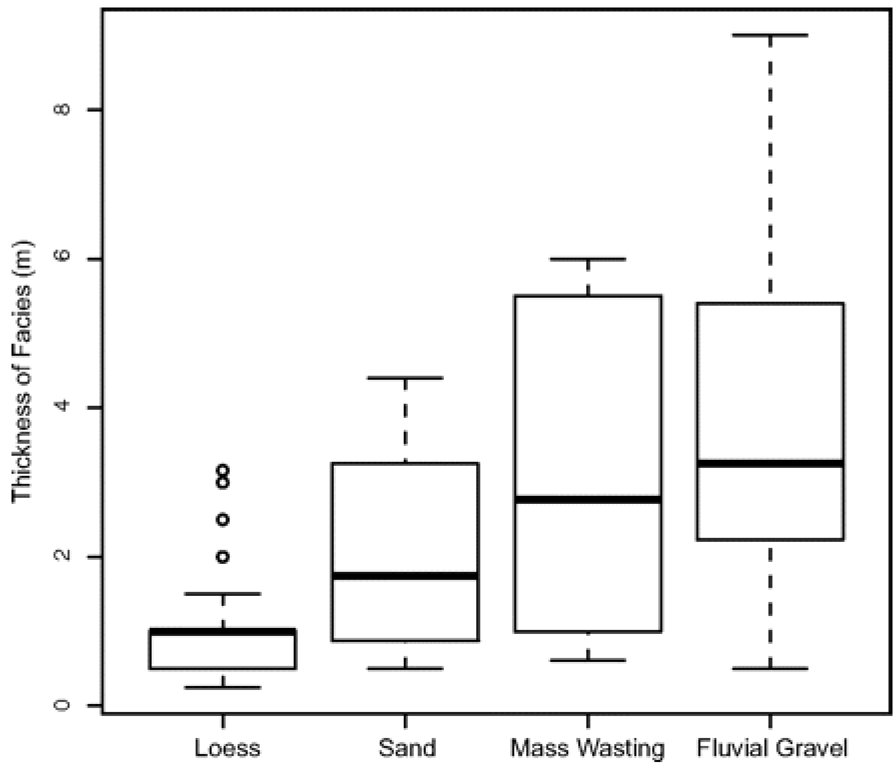

Figure 9. Box and whisker plot of the thickness of each facies where that facies was observed (i.e., values of zero excluded from calculation).

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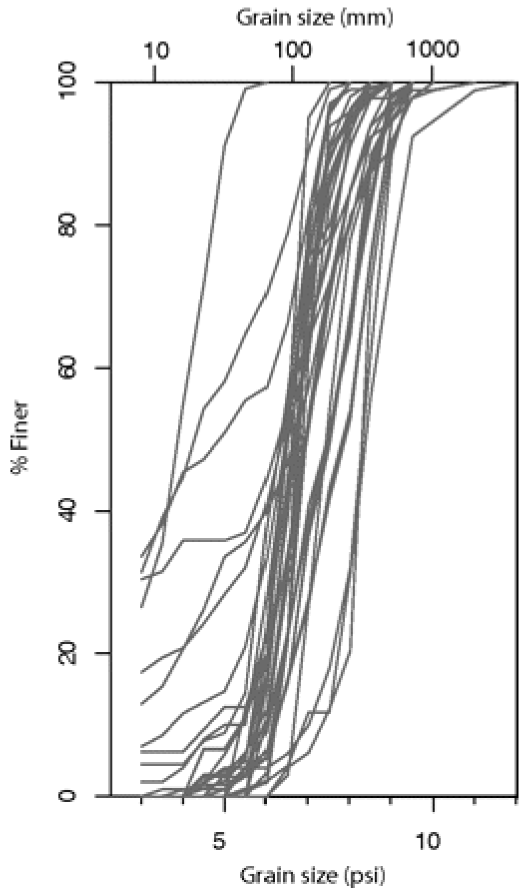

Figure 10. Cumulative distribution plot showing results of Wolman counts on mine lag deposits.

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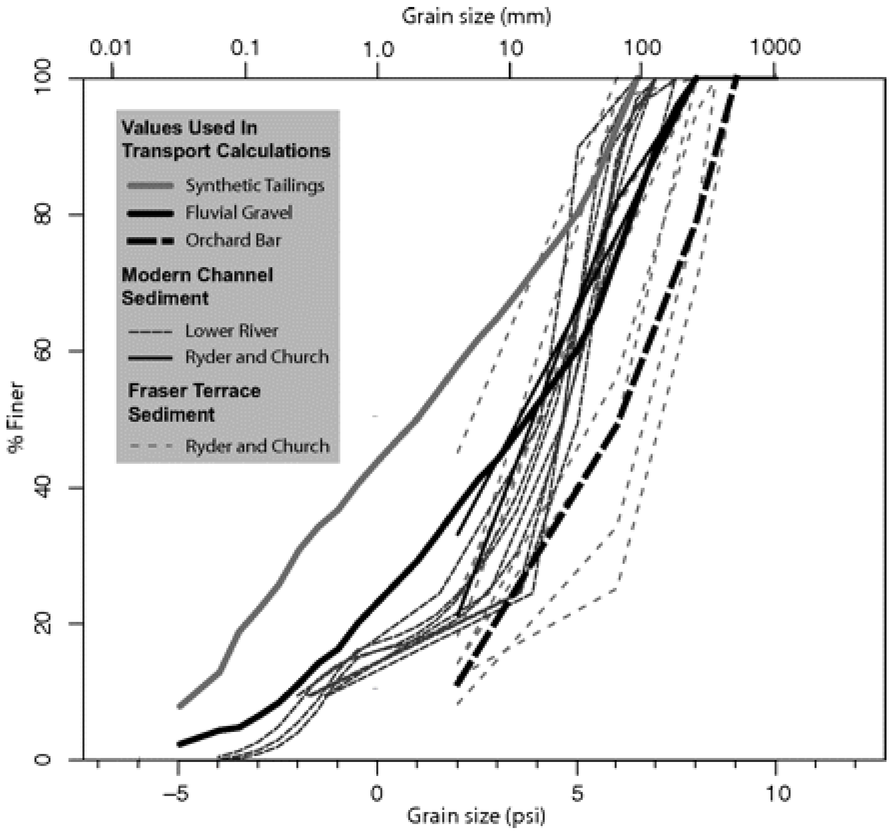

Figure 11. Grain-size distributions used in transport calculations, observed in the Fraser channel, and observed in terraces at Lillooet. Creation of the Synthetic Tailings and Fluvial Gravel estimates has been described in the text. Ryder and Church (1986) collected samples of Fraser River sediment both from the channel (including the Orchard Bar sample) and terraces above the river. Lower River samples were collected at the head of the gravel fan, from Peters Island to Upper Herrling Island. Part of these data are published in Mclean (1990), and part are unpublished data by Church.

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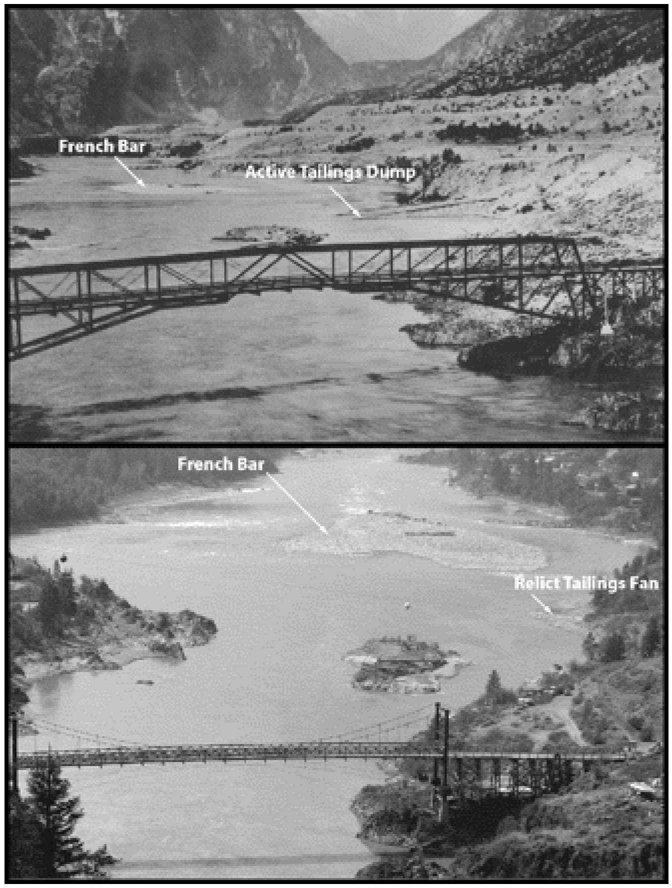

Figure 12. Paired historical (1886, top) and modern (2009, bottom) photos looking downstream from the left bank of the Fraser above Lillooet. The stage of the river in the historical photo appears to be about 2 m higher than it was at the time the modern photo was taken. In the historical photo, sluice box lines are visible on top of a growing tailings fan on the RB of the river just downstream of the bridge. The highly eroded relict fan is visible in the modern photo. Also of interest is stability in the location of French Bar, the large medial bar just downstream of the mine. The historical image is a detail of a photo housed in the collection of the Lillooet Museum that was made by A.W.A Phair.

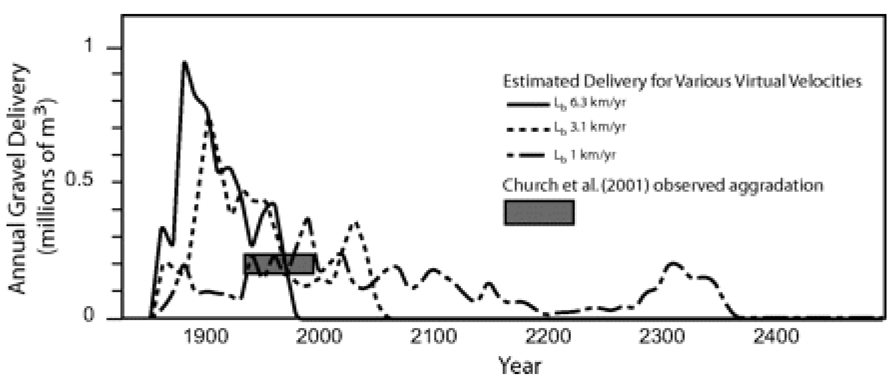

Figure 13. Estimated gravel delivery to Hope assuming unlimited capacity and various virtual velocities as specified in the figure. The range of modern estimates of sediment flux into the distal gravel reach is indicated (from Church et al. (2001). See methods description in the text.

TABLE 1. PERCENT BY WEIGHT OF GRAINS FOR EACH FACIES AND RESULTING TRUNCATED TAILINGS*

Facies	Silt and clay	Sand and granules	Gravel	Cobbles	Boulders
Loess	5	88	7		
Fluvial sand	48	52			
Fluvial gravel	4 ± 3	29 ± 10	33 ± 9	34 ± 12	
Fluvial gravel (truncated)	*5 ± 2*	*35 ± 7*	*40 ± 13*	*20 ± 12*	*0 ± 7*
Mass wasting	12 ± 7	27 ± 12	37 ± 7	22 ± 3	
Mass wasting (truncated)	*14 ± 6*	*30 ± 6*	*43 ± 9*	*13 ± 7*	*2 ± 2*
Average tailings	*13 ± 4*	*41 ± 4*	*32 ± 9*	*14 ± 7*	

*Error margins for the estimated values are the average absolute difference between the estimate and the coarsest and finest samples of each facies at a given grain size. Single values are shown for sand and loess because only one sample was taken to represent each of those facies. These error margins were carried directly into the "Average tailings" estimate without adding unknown errors in the estimate of the proportion of each facies that was mined.

TABLE 2. RESULTS OF SEDIMENT TRANSPORT CALCULATIONS TO ESTIMATE AVERAGE ANNUAL SEDIMENT TRANSPORT CAPACITY(m^3 yr^{-1}) AT HOPE AND MARGUERITE USING THREE BED GRAIN-SIZE DISTRIBUTIONS*

	All sediment		Gravel only	
Input grain-size distribution	Marguerite	Hope	Marguerite	Hope
Mine tailings	8,885,000	14,324,000	2,052,000	3,593,000
Fluvial gravel	3,368,000	6,061,000	1,218,943	2,330,000
Orchard bar	297,000	696,000	197,044	396,000

*Values shown are in bulk cubic meters of gravel assuming a bulk density of 1.75 metric tons per cubic meter. Bulk measure is used to allow direct comparison with the estimated excavated volumes.

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