

Evaluation of Fine Sediment Intrusion into Salmon Spawning Gravels as Related to Cougar Reservoir Sediment Releases

Prepared for Portland District Office, U.S. Army Corps of Engineers
October 4, 2002



Gregory Stewart¹, J. Reed Glasmann¹, Gordon E. Grant², Sarah Lewis², and Jeff Ninneman¹

¹Department of Geosciences
Oregon State University
Corvallis, OR, 97331-5506

²USDA Forest Service
Pacific Northwest Research Station
3200 Jefferson Way
Corvallis, OR 97331

Table of Contents

EXECUTIVE SUMMARY	1
INTRODUCTION	3
SITE DESCRIPTION	5
South Fork McKenzie Above Cougar Reservoir	6
South Fork McKenzie Below Cougar Reservoir	7
Mainstem McKenzie River	7
Cougar Reservoir	7
METHODS	7
Field Methods	7
Lab Methods	10
Clay (XRD) Methods	10
RESULTS	10
Grain-size Analysis	10
Coarse Sediment Fraction	12
Fine Sediment Fraction	13
Clay (XRD) Analysis	16
South Fork McKenzie Above Cougar Reservoir	16
Cougar Reservoir	16
South Fork McKenzie Below Cougar Reservoir	18
Mainstem McKenzie River	23
DISCUSSION	25
Additional research	27
REFERENCES CITED	29
APPENDIX A - METHODS	
APPENDIX B - GRAIN-SIZE DATA	
APPENDIX C - PHOTOGRAPHS	

List of Figures

Figure 1: Sampling sites along the mainstem and South Fork McKenzie Rivers.	6
Figure 2: Approximate location of Cougar Reservoir grab samples.	8
Figure 3: Freeze core showing 14cm bins lined with plastic and marked by relative depth.	9
Figure 4: Additional silt and clay obtained from samples by washing.	11
Figure 5: Relative abundance for <2mm fraction of core.	13
Figure 6: Within core variability showing relative abundance of silt and clay for each bin.	14
Figure 7: Ternary plot showing relative abundances of sand, silt, and clay for each site.	15
Figure 8. Comparison of XRD patterns of the <15- μ m fraction of fine sediment from 2 gravel bars on the South Fork of the McKenzie River	19
Figure 9. Comparison of XRD patterns of the <2- μ m Mg-Glycol treatment of samples represent- ing a vertical sequence through a gravel bar.	20
Figure 10. Comparison of XRD patterns of the <15- μ m fraction of samples obtained from a vertical transect at site SFB2.	20
Figure 11. Comparison of XRD patterns of the fine silt fraction of gravel bars from the lower South Fork of the McKenzie River illustrating the rapid reduction in quartz content in sedi- ments below Cougar Reservoir.	21
Figure 12. Simulated XRD patterns representing the crystalline clay components of the <2- μ m fraction of sample MS1-C and a hypothetical clay assemblage representing material from a hydrothermally altered watershed ("Blue River").	22
Figure 13. Comparison of the XRD patterns of the fine silt fraction of gravel bar sediments from the Main Fork of the McKenzie River at 3 locations.	24

List of Tables

Table 1: Site descriptions.	9
Table 2: Average grain-size by core.	12
Table 3: Surface and subsurface grain-size data.	12
Table 4: Mineralogy of the clay fraction of McKenzie River sediment samples as determined by X-ray powder diffraction analysis.	17

EXECUTIVE SUMMARY

Retrofitting Cougar Dam on the South Fork McKenzie River, Oregon, with a temperature control structure required drawdown of Cougar Reservoir over several months during spring 2002. The drawdown initiated incision of the reservoir delta that had developed in the 40 years since Cougar Dam was constructed. Remobilization of deltaic sediments resulted in a sustained release of turbid water from Cougar Reservoir from April to June 2002, prompting concern that sediment contained within the turbidity plume might intrude into river gravels, with potentially negative effects for fish and other aquatic biota.

To evaluate whether spawning gravels retained sediment related to this turbidity event, we sampled gravels at nine locations. Sampling sites included both upstream and downstream of Cougar Dam and on the mainstem McKenzie River both above and below the confluence with the South Fork. Because no pre-drawdown spawning gravels samples were available for comparison against the post-drawdown samples, we attempted to use a space-for-time replacement where sites above the dam and upstream of the confluence (e.g. not impacted by the release) were used as proxies for pre-drawdown samples and compared with sites downstream of the dam and in the mainstem McKenzie River. Sites were chosen to represent salmonid spawning areas and were located in areas of hydraulic downwelling on riffle crests downstream of pools. Two sites had replicate samples of 3 cores to evaluate within-site variance.

At each site, at least one freeze core was taken to a depth of approximately 30-50cm and then melted into a series of 11.5cm wide bins. Each bin was analyzed separately to identify changes in grain-size with depth. In the lab, sediment samples were sorted using standard sieves and a grain-size analysis using hydrometer methods was performed on those sediments smaller than 2mm. The grain-size distribution of the surface layer at each core site was characterized by Wolman pebble count. In addition, clay mineralogy using X-ray diffraction techniques were used to identify the fine-grained constituents present in each sample. Six additional grab samples were collected for mineralogical examination of Cougar Reservoir sediments.

Grain-size analysis of the South Fork and mainstem McKenzie river sediments suggests a relative enrichment in fines in the alluvial reaches below Cougar Reservoir as compared with the reaches above the reservoir. Upstream reaches and mainstem McKenzie sites have clay fractions representing 2.5% of the <2mm sample by weight as opposed to 9.5% in the South Fork below the dam. This increase in fines is not detectable below the confluence of the South Fork and the mainstem McKenzie River. Because no in-situ sampling of gravels was conducted prior to the reservoir release in the spring of 2002, we were unable to discern whether this fines enrichment pre-dated the release, although high levels of fine sediment stored in channels downstream of dams is relatively uncommon.

Although clay mineralogy varied substantially between sites, variation was explainable in light of dominant sources of sediment and delivery processes active within the watershed and reservoir. Enrichment of gravels with reservoir-derived fines is supported by the presence of distinct mineral assemblages, notably pedogenic quartz and mixed-layer clays that are found in the reservoir and immediately downstream in the South Fork but in no other sampled locations.

These two constituents are the only “confident” effect of Cougar Reservoir on the mineralogical properties of fine sediment entrained in downstream gravel bars. These components are most concentrated immediately below the dam, and then show a downstream pattern of rapidly decreasing abundance. There is no observable effect of hypothesized “Cougar” suspended sediments upon the mineralogy of fines identified in gravels from the lower reaches of the mainstem of the McKenzie River. In fact, the mineralogical character of gravel bars of the McKenzie River varies dramatically with location along the river. Tributary watersheds with unusual geologic character exert greater influence on fine sediment composition within gravel bars than sustained turbidity released from Cougar Reservoir.

These results suggest that intrusion of very fine clays into gravel substrate can occur even when the clay is carried as wash load. The length of time over which these clays persist in the gravel and the degree to which they are remobilized and scoured during high flow events have not been determined and would require additional studies examining depth of scour. Another unknown is whether other rivers below large dams in the Willamette system have gravel beds enriched in fines. Presence or absence of such fines would help resolve the likely source and timing of emplacement of elevated clays found in the South Fork below Cougar Dam.

INTRODUCTION

As part of the Willamette Valley Temperature Control Project, the U.S. Army Corps of Engineers (COE) is modifying the intake tower of Cougar Dam on the South Fork McKenzie River, Oregon. These modifications will allow operators to release colder water during the winter, and warmer water during the summer, to improve habitat conditions for bull trout and spring Chinook salmon. In order to carry out work on the intake tower, the COE lowered Cougar Reservoir below minimum pool elevation in April 2002, thereby exposing deltaic and lake bottom sediments to reworking by the South Fork McKenzie and other reservoir tributaries. The reworking of these sediments resulted in a prolonged discharge of turbid water from Cougar Reservoir that was highly visible for miles downstream and even affected the turbidity of the Willamette River below the confluence of the McKenzie. Although the COE had predicted in its Environmental Impact Statement (EIS) that turbidity would increase during the drawdown (predicted levels of 30 NTUs and spikes of 100 NTUs), they underestimated the magnitude, timing, and duration of the problem. Between April 1st and May 25th turbidity levels at the South Fork gauging station below the dam averaged 68 NTUs with spikes of up to 379 NTUs.

The release of highly turbid water from Cougar Reservoir captured public attention and raised concerns over possible downstream impacts to fish and wildlife. Responding to this concern, the National Marine Fisheries Service (NMFS) asked the COE to evaluate the potential impacts of the sediment release including possible impacts to spawning gravels by fine sediment intrusion. In August 2002, the COE contracted with Oregon State University and the USDA Pacific Northwest Research Station to conduct an investigation to determine: 1) to what extent and depth have fine sediments associated with the reservoir drawdown intruded into gravels in the South Fork McKenzie below the dam; and 2) to a first approximation, how much of the sediment released from the reservoir has traveled in suspension through the McKenzie River system and how much was still stored in the basin. In this report, we address only the first objective; the latter will be addressed in a separate report.

Sediment in rivers can be carried either as bedload, which is that portion of the total load whose immersed weight is carried by the solid bed, or as suspended load, which is that portion of the total whose immersed weight is carried by the fluid. Gravel bars are sedimentological features resulting from accumulation of coarse bedload under high velocity flow conditions. Discrete clay or silt particles are generally too small to settle from suspension in a gravel-dominated depositional environment because their fall velocities are too low to offset the hydraulic lift caused by turbulence. Fine sediments, including fine silts and clays that are typically transported as suspended load can, however, be carried into the bed by hydraulic forces or be deposited as bedload clay clasts. The accumulation of fine sediment via infiltration depends upon many factors including fine sediment concentration, bed particle grain-size, and the hydraulic gradient (Beschta and Jackson, 1979; Carling, 1984; Schmalchli, 1995). Fine sediment intrusion is of interest because it may decrease bed permeability and intergravel flow rates (Koltermann and Gorelick, 1995; Wu, 2000), and can result in fish egg mortality (Einstein, 1968) and/or decreased habitat for macroinvertebrates (Richards and Bacon, 1994). Depending on the depth of penetration, fine sediment can remain trapped in the bed until discharge exceeds the shear stress needed to mobilize the surrounding larger grains (Schmalchli, 1995).

In this study we focused on the potential intrusion of fine sediment into salmon spawning gravel beds in the South Fork and mainstem McKenzie rivers. Spring Chinook salmon spawn in both the mainstem and South Fork McKenzie Rivers and are listed as threatened by NMFS. To determine the quantity and the depth of penetration of fine sediment in the McKenzie River, we freeze-cored riverbed sediments and measured the relative abundance of different sediment sizes. Freeze coring involves pumping cold CO₂ into metal rods that have been driven into the bed of the river, and then removing the rods and the associated block of frozen river substrate. The advantage of freeze cores over other methods of sampling river bed sediments is that bed sediment stratigraphy is maintained, and fine sediment is not lost as the sample is extracted from the riverbed. Because no pre-drawdown spawning gravels samples were available for comparison against the post-drawdown samples, we attempted to use a space-for-time replacement where sites above the dam and upstream of the confluence (e.g. not impacted by the release) were used as proxies for pre-drawdown samples and compared with sites downstream of the dam and in the mainstem McKenzie River. While there are inherent problems with this approach, the most notable being the potential difference in geomorphic setting, hence depositional environment between upstream and downstream reaches, the technique is commonly used and can provide useful insight when carefully applied.

In addition to measuring the quantity of the different-sized fractions of sediment in the bed, we also used clay mineralogy as a means of fingerprinting potential sources for the clay found in each core. The inorganic component of turbidity consists of crystalline and non-crystalline substances eroded from bedrock, soils, and landforms within the watershed. The extremely small particle sizes of the suspended component of stream sediments preclude visual identification and characterization of individual particles; however, such materials may be effectively characterized by using X-ray powder diffraction (XRD) techniques, which identify crystalline components on the basis of unique structural properties. Through XRD analysis, the identity and relative abundance of crystalline phases in a fine sediment sample can be evaluated, and compositional trends within fine sediments of a watershed identified. This technique is ideally suited to answering the question related to the impact of prolonged discharge of sediment from Cougar Reservoir on downstream fish habitat. If the mineralogical character of released turbidity from Cougar Reservoir were identified, one need merely look for this same assemblage in modern gravel bars downstream of the reservoir as first order evidence of bar contamination. In addition, substantial downstream variability in the mineralogical character of fine sediment fraction of active gravel bars would provide strong evidence that sustained turbidity from Cougar Reservoir had very little effect on bar habitat. If Cougar mud invaded downstream gravel bars to a substantial degree, then the mineralogical fingerprint of reservoir-sourced sediments should be clearly discernable in these deposits and tend to mask local mineralogical variations.

In the following sections we first introduce the sites studied along the South Fork and mainstem McKenzie Rivers and their broad geologic setting, and describe field methods used for freeze coring and other data collection and lab methods used for analysis of the resulting sediment samples. We then present the results of our grain-size analysis, followed by a discussion of the clay mineralogy of the samples. We conclude with the implications of these findings for intrusion of fine sediments from the draw down of Cougar Reservoir into the gravels of the South Fork and mainstem McKenzie Rivers.

SITE DESCRIPTION

The South Fork of the McKenzie River drains two geologically distinct provinces. Its headwaters are in the High Cascades, with elevations >1200 m underlain by glacial deposits and <2 million year (MY) old, porous, volcanic rocks. Precipitation falls primarily as snow. Most of the basin, however, is located in the Western Cascades, with elevations of 400-1200 m underlain by 3.5 to 25 MY old, deeply weathered but relatively impervious, volcanic rocks, where precipitation falls as rain and snow (Sherrod and Smith, 1989). Within the Western Cascades, landforms have been sculpted by fluvial, glacial, and mass movement processes; the latter include shallow, rapid movements of soil on hillslopes (debris slides), rapid movements of alluvium, colluvium, and organic matter down stream channels (debris flows), and large, slow-moving landslides (earthflows) (Swanson and James, 1975 a,b). Streamflow regimes are characterized by high winter flows from November through April, with peak flows occurring primarily during rain-on-snow events (Harr, 1981). Timber harvest and road construction have affected little of the high-elevation zone which includes extensive Federal wilderness areas, but up to 25% of mid-elevation public forest lands have been harvested.

A total of nine field sites were chosen for freeze core sampling of bed sediments (Figure 1): two sites *above* Cougar Reservoir on the South Fork McKenzie (SFA1 & SFA2); four sites *below* Cougar on the South Fork McKenzie (SFB1, SFB2, SFB3, and SFB4); one site on the mainstem McKenzie above the confluence with the South Fork (MS1); and two sites on the mainstem McKenzie below the South Fork confluence (MS2 and MS3). Within this sampling strategy, SFA1, SFA2 and MS1 are assumed to represent baseline conditions against which other sites can be compared.

Sites were chosen based on the following criteria: 1) location just upstream of a riffle crest where downwelling could be expected; 2) no identifiable geomorphic or anthropomorphic disturbances (other than the drawdown) immediately upstream of the site that could be reasonably be expected to contribute fine sediment to the site (e.g. recent bank erosion or tree fall); and, 3) spawning gravels were present as identified by Mark Wade of the Oregon Department of Fish and Wildlife. Sampling sites were picked using these geomorphic and ecological criteria in order to minimize natural variation between sites. To evaluate within-site variability replicate samples were taken at SFA1 and SFB2.

South Fork McKenzie Above Cougar Reservoir

SFA1 and SFA2 are located above Cougar Reservoir in a relatively confined bedrock-controlled reach of the South Fork McKenzie. Channel morphology in this area is step-pool and pool-riffle, with a dominant substrate of cobble, boulder, and bedrock. Gavel patches are not common within this section of the river, though isolated patches do occur behind boulders and in eddies. SFA1 is located just downstream of the USGS gaging station in the tail-out of a large bedrock controlled eddy pool. This is the only site where downwelling was not expected, as hydraulic gradients are directed horizontally rather than vertically. At this site, three samples were collected within a 9m² area on the west side of the stream opposite the road (SFA1-1, SFA1-2, SFA1-3). SFB2 is located approximately 400 meters downstream of SFA1 at the head of a small transverse riffle on the west side of the South Fork; at this site one sample was collected.

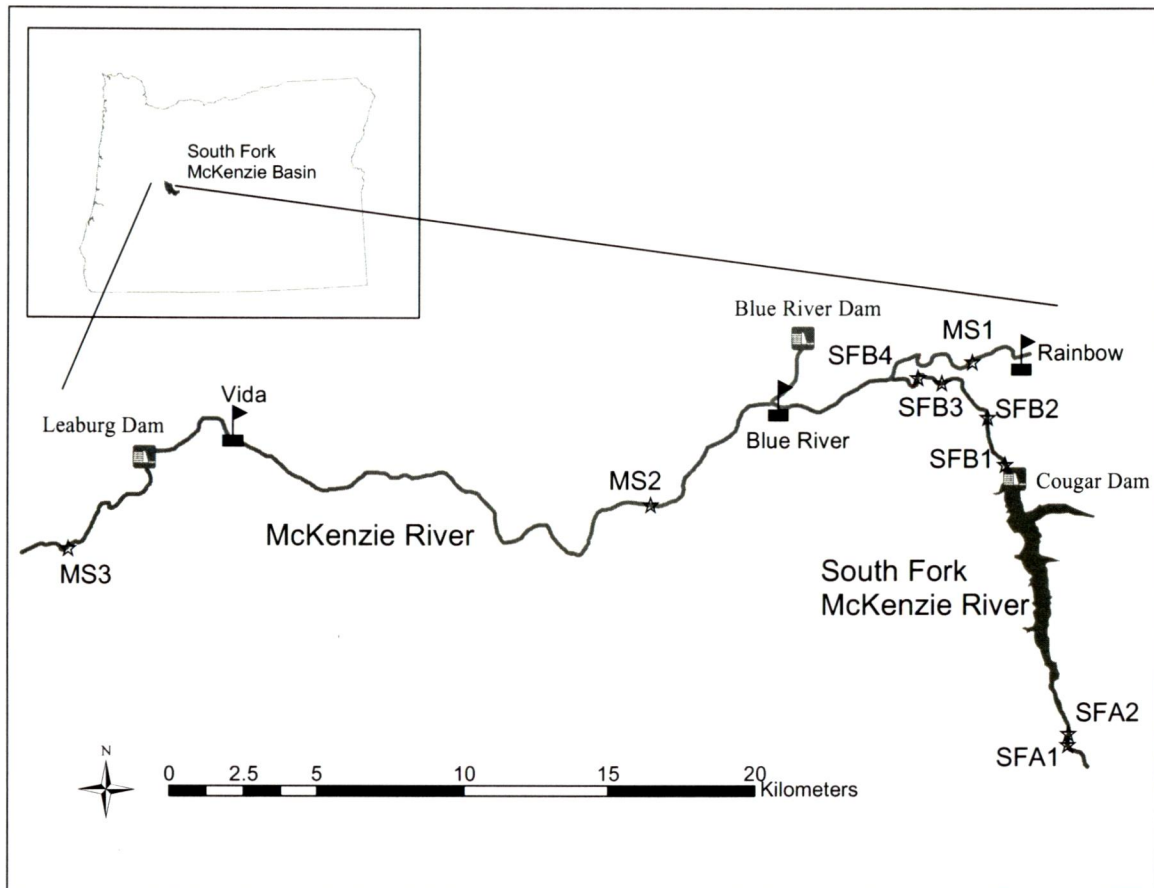


Figure 1: Sampling sites along the mainstem and South Fork McKenzie Rivers.

South Fork McKenzie Below Cougar Reservoir

The South Fork McKenzie below Cougar Reservoir transitions from a confined bedrock-controlled river to an anastomosing channel where secondary channels are largely controlled by large woody debris. Channel morphology is pool-riffle and forced pool-riffle. The dominant substrate is cobble and gravel patches are not common, except in side channels and small patches on margins of the main channel. Because Cougar Reservoir is operated for flood control, high winter discharges are reduced compared with above the dam and in the mainstem McKenzie. SFB1 is located on the west side of the South Fork approximately 400 meters downstream of the Cougar Dam powerhouse. This site has clearly been modified by the presence of the dam with armored banks regularly spaced gravel bars that look like revetments; but is heavily used by spawning salmon (Mark Wade pers. com). SFB2 is located approximately 2km downstream of the Cougar powerhouse in a side channel commonly used by salmon for spawning. This site marks the beginning of the anastomosing alluvial section of the South Fork and may be incised into glacial outwash deposits related to damming of the canyon by a terminal moraine located just upstream of the South Fork's confluence with the mainstem. Three cores were taken at this site on the west side of the east channel very close to the bank within a 12m² area (SFB1-1, SFB2-2, SFB2-3). SFB3 is located approximately 4.5km downstream of the Cougar powerhouse on the

north side of the main channel in a small patch of gravel on the channel margins. SFB4 is located 5.5km downstream of the Cougar powerhouse, approximately 1.5km upstream of the confluence with the South Fork McKenzie. This site was located just upstream of a large logjam that produces a forced pool and riffle. The core was taken in a small pocket of gravel in an area surrounded by sand.

Mainstem McKenzie River

The mainstem McKenzie is a moderately confined meandering channel with pool-riffle morphology and a dominant substrate of cobble and boulder. Gravel patches are not common except near side-channels and in small pockets along the margins of the main channel. MS1 is located approximately 200 meters upstream of Bunkard Bridge approximately 4km upstream of the South Fork confluence. The core was taken at the upstream end of a medial bar near the bank on the south side of the river (away from the road). MS2 is approximately 11km downstream of the confluence with the South Fork McKenzie at a site used annually by spawning salmon for at least the last 10 years (Barry Lopez pers. com). The core at this site was located approximately 50 meters upstream of the riffle crest very close to the bank. MS3 is near the beginning of a side channel 5.5km below Leaburg dam and 40km below the South Fork confluence. The site was located on the South side of the McKenzie just downstream from a large bedrock controlled pool. The core was taken between lateral bars approximately 2 meters upstream from the riffle crest. Salmon were observed spawning near the site at the time of sampling.

Cougar Reservoir

Six samples of lake sediment exposed by drawdown of Cougar Reservoir were obtained to characterize the mineralogy of materials actively being reworked by the South Fork and its tributary streams (Figure 2). Three of the samples represent delta-related deposits (RES-1, RES-3 and RES-4), one represents an eroded tributary delta (RES-5, Walker Creek delta), another represents an earth flow deposit that impinges on the exposed channel of the South Fork (RES-2), and, lastly, a sample of highly weathered andesitic gravel was obtained from an unstable hillslope (RES-6). Fine-grained sediments were preferentially sampled to provide appropriate material for clay mineralogical analysis.

METHODS

Detailed methodologies for field, lab, and clay analyses are included in Appendix A.

Field Methods

Sediment sampling was conducted using freeze cores. This method preserves the fine sediments within river gravels by the removal of a frozen block of river substrate. In order to create a pool of quiescent water, a trashcan with the bottom removed was placed over a section of spawning gravels at each coring location. Within the trashcan, three 2.5cm diameter hollow metal rods (triangular configuration with 5cm spacing between rods) were driven into the substrate to a depth of approximately 45cm. Approximately forty pounds of liquid CO₂ was then simultaneously sprayed into the three rods over a period of 5 – 10 minutes to freeze the pore water in the gravel. Each core was extracted using a portable tripod crane and then melted using propane torches into bins of approximately equal lengths (11.5cm). The bins marked A, B, C, and D represented

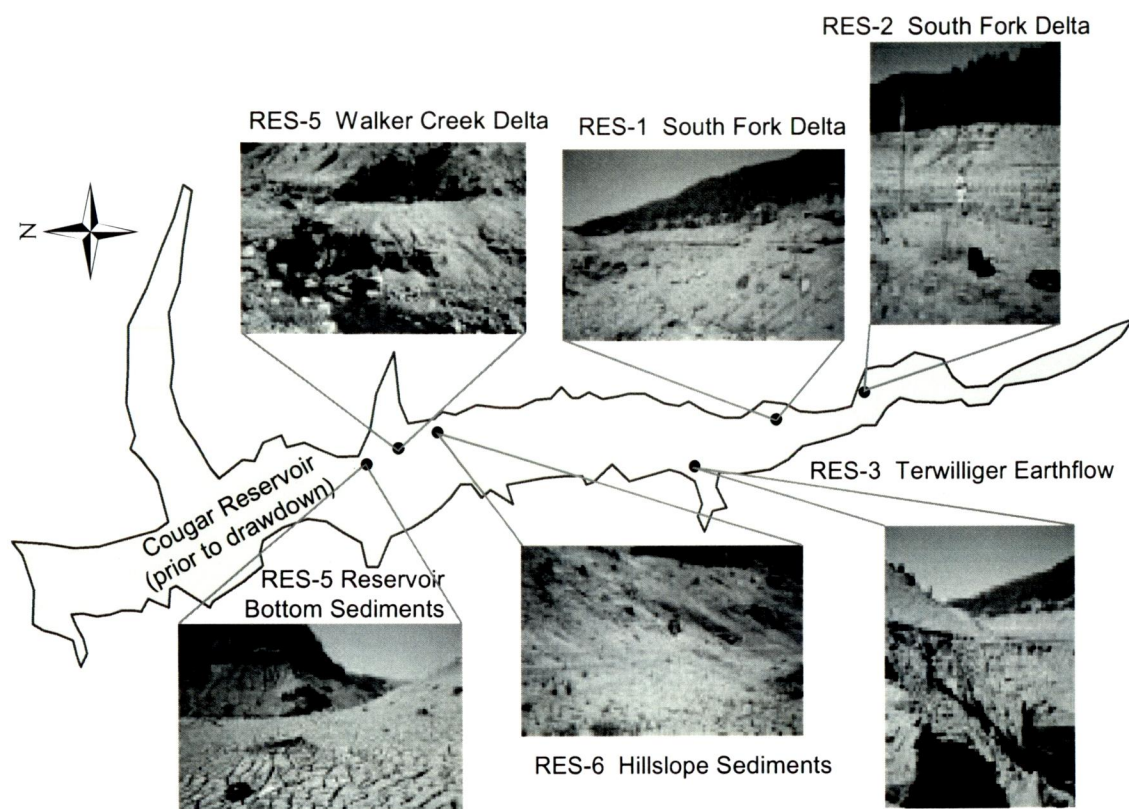


Figure 2: Approximate location of Cougar Reservoir grab samples.

relative depths at which sediment was collected with A representing the topmost layer and D representing the deepest layer (Figure 3). Because of variations in the freeze-coring process, not all bins were equally represented and individual bins cannot be correlated with absolute depth. Each bin was lined with a thick ziplock bag so that samples contained all sediments and associated pore water.

In addition to freeze coring, each site was described and characterized through a variety of measurements. These included a site description, photographs, GPS coordinates, stream velocity, vertical hydraulic gradient, stream width, distance from riffle or rapid, site sketch, and stream cross-section (Table 1). Surface grain-size at each site was determined by Wolman pebble count, in which 100 surface clasts were picked at random and measured across their medial axis. Vertical hydraulic gradients were determined by emplacing a piezometer (1.5m long metal pipe screened the bottom) into gravel bed at each site. After waiting for the internal water level to reach equilibrium, the depth to water was measured both inside and outside the pipe using a depth-o-meter. To verify that the internal water level represented actual equilibrium conditions, water was added to the pipe and the internal water level again allowed to reach equilibrium. This second set of measurements was compared against the first for consistency.

Eight grab samples were also collected for mineralogical examination: six from within Cougar Reservoir (not cored) and one at each of the replicate freeze core sites (SFA1 and SFB2).

Table 1: Site descriptions.

	North*	East*	Distance From Riffle (m)	Velocity (m/s)	Depth (m)	Vertical Head Gradient
SFA1	4877238	562742	10	0.19	0.48	0.00
SFA2	4877620	562774	1	0.25	0.21	-0.23
SFB1	4886803	560576	1	0.33	0.15	-0.13
SFB2	4888402	559972	2	0.15	0.15	0.00
SFB3	4889576	558378	33	0.10	0.21	-0.13
SFB4	4889757	557569	10	0.20	0.15	-0.10
MS1	4890293	559438	3	0.09	0.24	-0.05
MS2	4885445	548498	100	0.56	0.15	NA
MS3	4883929	528520	1	0.52	0.15	-0.25

*UTM Zone 10, NAD 27



Figure 3: Freeze core showing 11.5 cm bins lined with plastic and marked by relative depth (A-D).

Lab Methods

In the lab, grain-size analysis was performed on each of the freeze core bins to determine the quantity of fine sediment in the riverbed at different depths. Sediment from each bin was oven dried at 40° C and then weighed to the nearest 0.1 gram. Following weighing, gravels were separated from the sands and silts by dry sieving. We sieved the coarse fraction (>2mm) by phi class, and the fine sediment was analyzed using a hydrometer tube. By this method, a known mass of fines (40g) was placed in a known volume of water (1L) and allowed to settle; grain-size was then determined based on setting rates and the measured density of the water over time.

Because some clay and silt remained absorbed on the larger grains following dry sieving, a limited number of cores were sonically treated and washed to remove all fine sediments. The washed gravels were then re-weighed to determine how much additional clay and silt was removed during washing.

Clay (XRD) Methods

Samples for mineralogical analysis included a minimum of one sample from each core (usually bin C) and consisted of bottled residues from the hydrometer analysis, bagged composite gravels, and bulk gravel samples in field moist condition (without oven drying). Suspended fines were obtained from each sample, and the <64- μ m fines were separated into fine silt (2-15- μ m) and clay (<2- μ m) fractions. Following preparation of slides of the Mg-saturated clay for XRD analysis by a smear technique (Theissen and Harward, 1962), the clay fraction was then K-saturated and additional slides of the K-saturated clay were then prepared for XRD analysis.

XRD analysis of the fine silt and clay fractions was accomplished using a computer automated Philips XRG 3100 diffractometer equipped with a ceramic Cu tube and a focusing monochromator. The Mg-saturated samples were step scanned from 2-14° 2-theta under ambient humidity, and then after being solvated with ethylene glycol from 2-40° 2-theta. The K-saturated clay slides were scanned from 2-14° 2-theta, first at ambient humidity, and subsequently after heating for 2 hours at 110°C. Slides of the 2-15- μ m fractions were also analyzed under ambient humidity by step scanning from 2-40° 2-theta. The mineralogical components of the samples were identified using the International Powder Diffraction File database and simulated diffraction patterns generated using NEWMOD (Reynolds & Reynolds, 1996).

RESULTS

Grain-size Analysis

To best summarize our grain-size analysis we first explain how we composited our data. We then report our findings by coarse and fine fractions. Raw data and supporting tables can be found in Appendix B.

Due to time constraints, only one bin in each core was sonified and washed, with the exception of SFB2-3, in which the top three horizons were washed to see if there was any change in the abundance of absorbed clay and silt with depth. Analysis of the washed gravels revealed that an average of 6.2 g (+/- 4.6 g) of additional silt and clay remained sorbed to the gravels after sieving (Figure 4). This quantity of silt and clay represented between a 0.1 to 58.4 percent increase in the

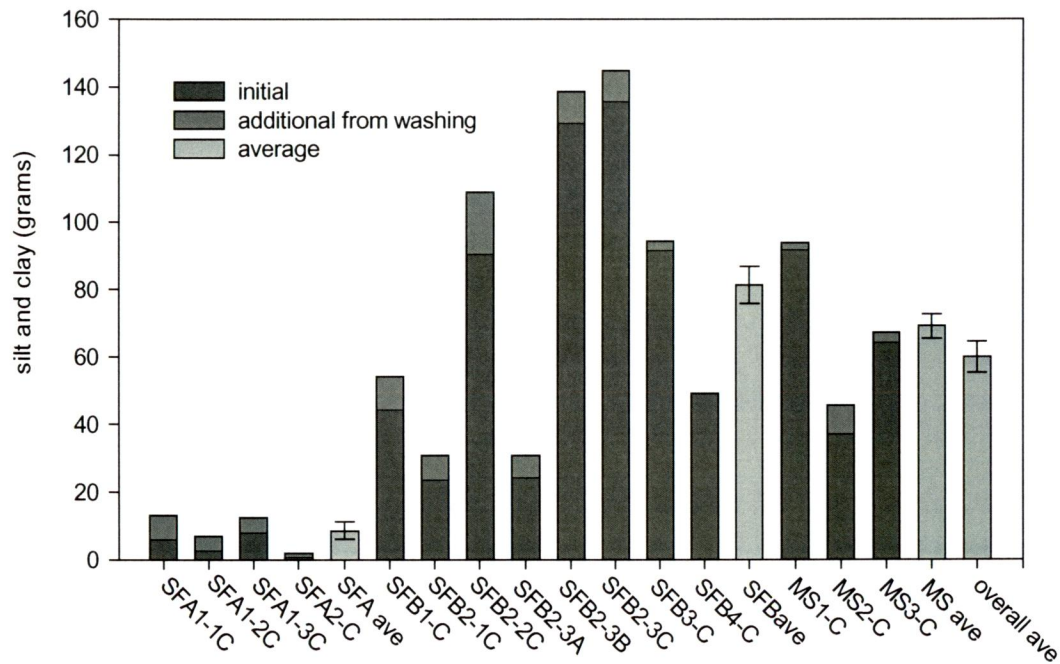


Figure 4: Additional silt and clay obtained from samples by washing.

amount of fine sediment in each sample, with the greatest percent increase involving those samples with very little initial silt and clay (SFA1, SFA2). In this paper, we report silt and clay volumes obtained by dry sieving with the caveat that these numbers underestimate the total volume of silt and clay in each sample.

In addition, examination of the variability in silt and clay content in those cores with all four bins present (SFA1-1,2,3; SFB1; SFB2-3; SFB3; MS1; MS3) reveals that the relative abundance of fine sediment in each core increases with depth (Appendix B). While all cores had large enough samples in B and C for hydrometer analysis, bins A and D were sometimes absent or contained a sample that was too small for analysis. This was because the top and/or bottom of the core were less likely to be frozen and more likely to be lost during core extraction. Thus, when reporting relative grain-size volumes for a core, we average sediment from bins B and C (Table 2). We believe that this compositing represents a reasonable average for the sediment contained at each site.

Freeze coring is an appropriate method for examining the fine fraction of sediment stored in the bed, but is constrained by the size of sample that can be collected and, thus, the ability to adequately represent the largest size fraction. Because each core was binned by depth, the number of clasts in the coarsest fraction tended to be small with only a few clasts in the dominant size class by weight. To compensate for the small sample size, coarse sediment data was composited by site. Subsurface grain-size for the >2mm fraction is therefore reported as an average for the entire core.

Table 2: Average grain-size by core.

	all data (coarse and fine fractions)					fine (<2mm) fraction only		
	% Gravel	% Sand	% Silt	% Clay		% Sand	%Silt	%Clay
SFA1-1	95.97	3.88	0.02	0.13		96.43	0.45	3.13
SFA1-2	96.86	3.01	0.05	0.08		95.80	1.70	2.50
SFA1-3	95.72	4.07	0.07	0.14		95.18	1.70	3.13
<i>SFA1 ave</i>	<i>96.18</i>	<i>3.65</i>	<i>0.05</i>	<i>0.12</i>		<i>95.80</i>	<i>1.28</i>	<i>2.92</i>
SFA2	96.20	3.78	0.00	0.02		99.55	0.00	0.45
SFB1	88.78	9.79	0.54	0.89		87.23	4.83	7.95
SFB2-1	91.36	7.64	0.22	0.78		88.66	2.40	8.93
SFB2-2	91.69	6.45	0.93	0.93		76.95	11.53	11.53
SFB2-3	73.82	21.72	1.61	2.85		82.58	6.53	10.90
<i>SFB2 ave</i>	<i>85.62</i>	<i>11.94</i>	<i>0.92</i>	<i>1.52</i>		<i>82.73</i>	<i>6.82</i>	<i>10.45</i>
SFB3	84.73	12.69	1.18	1.40		83.83	7.15	9.03
SFB4	46.67	46.35	2.50	4.48		86.95	4.65	8.40
MS1	81.66	16.63	1.31	0.39		90.70	7.15	2.15
MS2	83.63	14.64	1.17	0.56		89.45	7.15	3.40
MS3	40.84	53.66	3.73	1.77		90.70	6.53	2.78

Coarse Sediment Fraction

Pebble counts and freeze core analyses reveal that all the sites are composed of moderately to poorly sorted, coarse to very coarse gravel. Median surface grain-size (d_{50} , or grain-size for which 50% of the sample is finer) ranges from 19 to 49mm with an average of 28mm (Table 3). The subsurface grain-size generally mimics the surface grain-size with an average surface d_{50} /subsurface d_{50} ratio of 1.0.

Sites SFA2 and SFB1 have the coarsest gravel and the closest relation between surface and subsurface grain-size (d_{50} surface / d_{50} subsurface of 0.95). SFB2, SFB3, MS1 and MS2 are also composed of very coarse gravel, yet the ratio between surface and subsurface grain-size is either significantly greater, or less than, unity (d_{50} surface / d_{50} subsurface ranges from 0.5-1.3). SFA1, SFB4, and MS3 have the smallest gravels (still considered coarse gravel) and a surface grain-size

Table 3: Surface and subsurface grain-size data.

	Description	Mode	Sorting	Surface* (mm)			Subsurface# (mm)	
				d_{10}	d_{50}	d_{90}	d_{10}	d_{50}
SFA1	Coarse Gravel	Unimodal	Moderate	10	22	51	6	19
SFA2	Very Coarse Gravel	Unimodal	Poor	17	49	104	11	47
SFB1	Very Coarse Gravel	Unimodal	Poor	10	38	91	5	43
SFB2	Very Coarse Gravel	Unimodal	Poor	7	31	88	4	22
SFB-3	Coarse Gravel	Bimodal	Poor	4	20	56	4	37
SFB-4	Coarse Gravel	Unimodal	Poor	8	20	40	4	19
MS1	Very Coarse Gravel	Bimodal	Poor	4	24	84	6	38
MS2	Very Coarse Gravel	Unimodal	Poor	10	31	63	6	24
MS3	Coarse Gravel	Unimodal	Poor	6	19	49	3	15

* calculated from pebble count data

calculated from freeze core >2mm fraction

d_{90} not reported for subsurface because grainsize was truncated at approximately 128mm.

that is slightly larger than the subsurface (d_{50} surface / d_{50} subsurface ranges of 1.2). The close relationship between surface and sub-surface grain-size for all the sites suggests that little or no armoring has occurred in locations where salmon spawn.

Fine Sediment Fraction

Grain-size above Cougar Reservoir (SFA1 and SFA2) is relatively uniform, both between and within sites (Table 2). SFA1 and SFA2 are gravel dominated with minor amounts of sand and very little clay or silt. Of the small amounts of clay present in the sample, more than half appears to have been tightly absorbed onto the surface of the gravel (Figure 4) and is unlikely to play any role in reducing pore space.

Samples sites on the South Fork McKenzie below Cougar Reservoir (SFB1, SFB2, SFB3 and SFB4) are dominated by gravel with moderate amounts of sand and silt and relatively high clay abundance. All South Fork below dam samples are significantly enriched in all fractions of sediment less than 2mm compared with upstream samples though silt and sand abundances are similar to the mainstem McKenzie sites, including the site above the South Fork confluence (MS1) (Figure 5). Replicate cores at sites SFA1 and SFB2 show that downstream sites have much higher spatial variability in fine sediment when compared with upstream samples, but not enough variability to account for the differences in clay abundance (Figure 6). Clay abundance

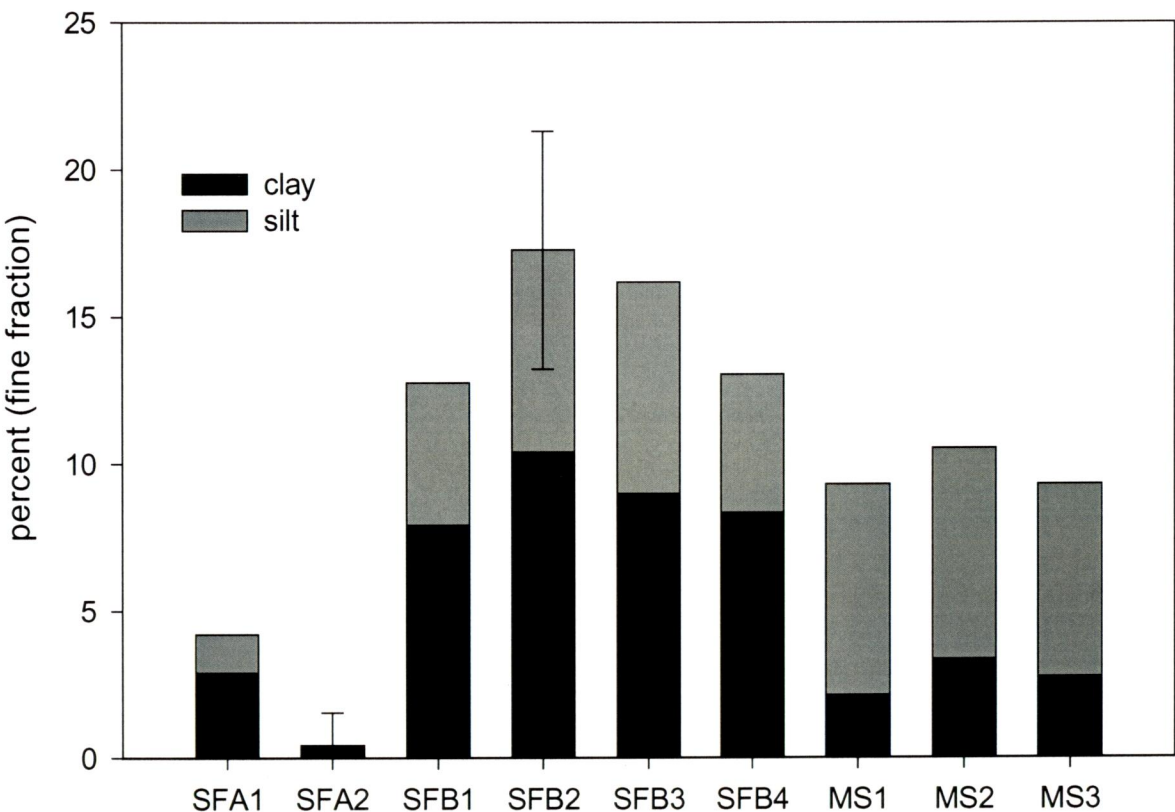


Figure 5: Relative abundance for <2mm fraction of core.

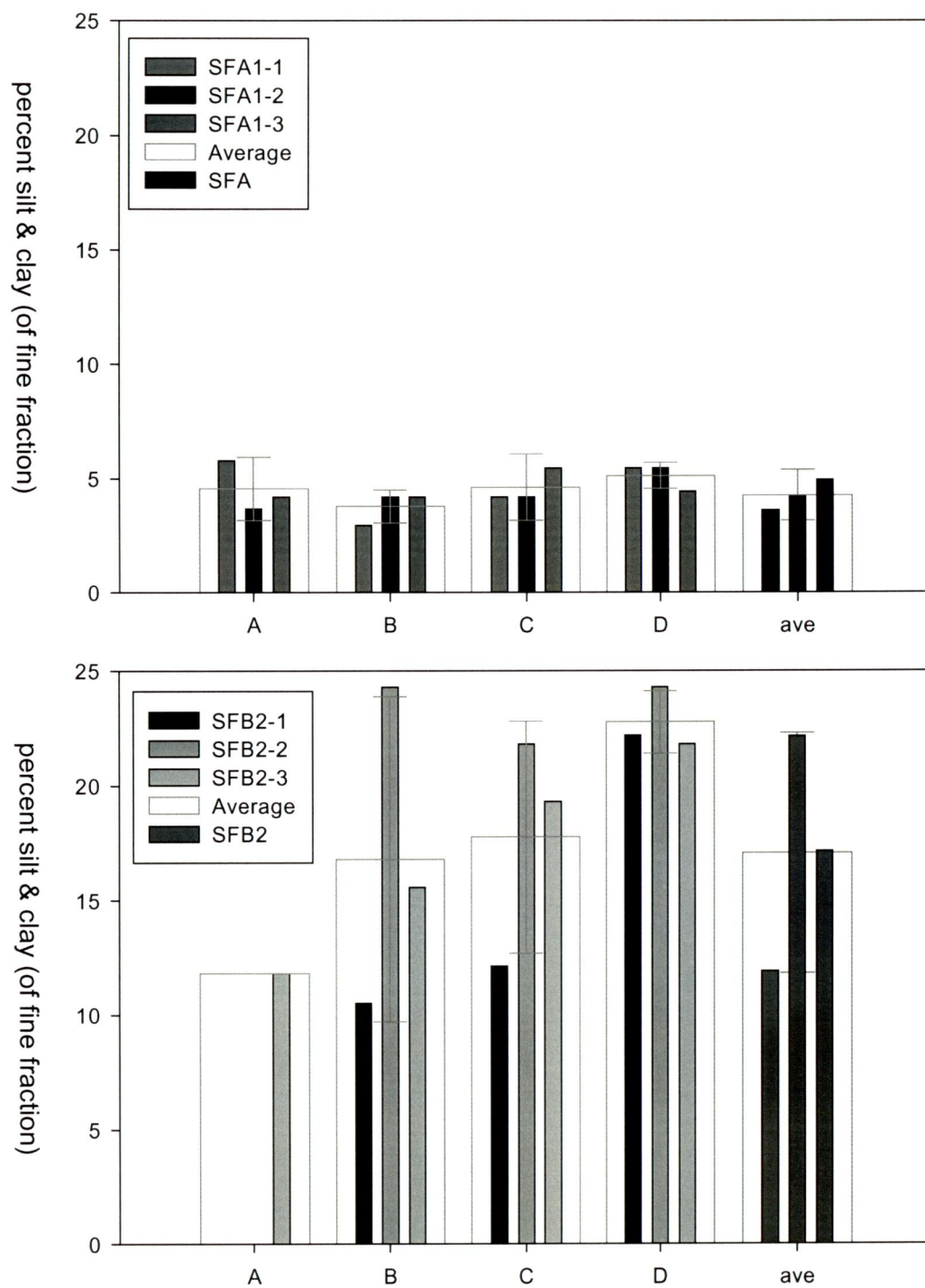


Figure 6: Within core variability showing relative abundance of silt and clay for each bin.

on the South Fork appears to peak at the upstream end of the South Fork alluvial reaches (SFB2) and decreases downstream.

The mainstem McKenzie sites are all dominated by gravel with moderate amounts of sand, silt and clay. While silt abundance on the mainstem McKenzie (~7% of less than 2mm fraction) is higher than above the dam, they are similar to the South Fork sites (~6%) and show no difference between sites located above or below the South Fork confluence. Mainstem samples below the confluence with the South Fork have significantly less clay than do the South Fork samples, approaching the low levels found above the dam and above the South Fork confluence.

When fine sediment data are plotted on a ternary diagram, the sites break out into three general groups: South Fork above the dam, South Fork below the dam, and mainstem McKenzie (Figure 7). Taken with the other data, this plot suggests that only the South Fork samples were significantly affected by the sediment release and only in terms of their clay content.

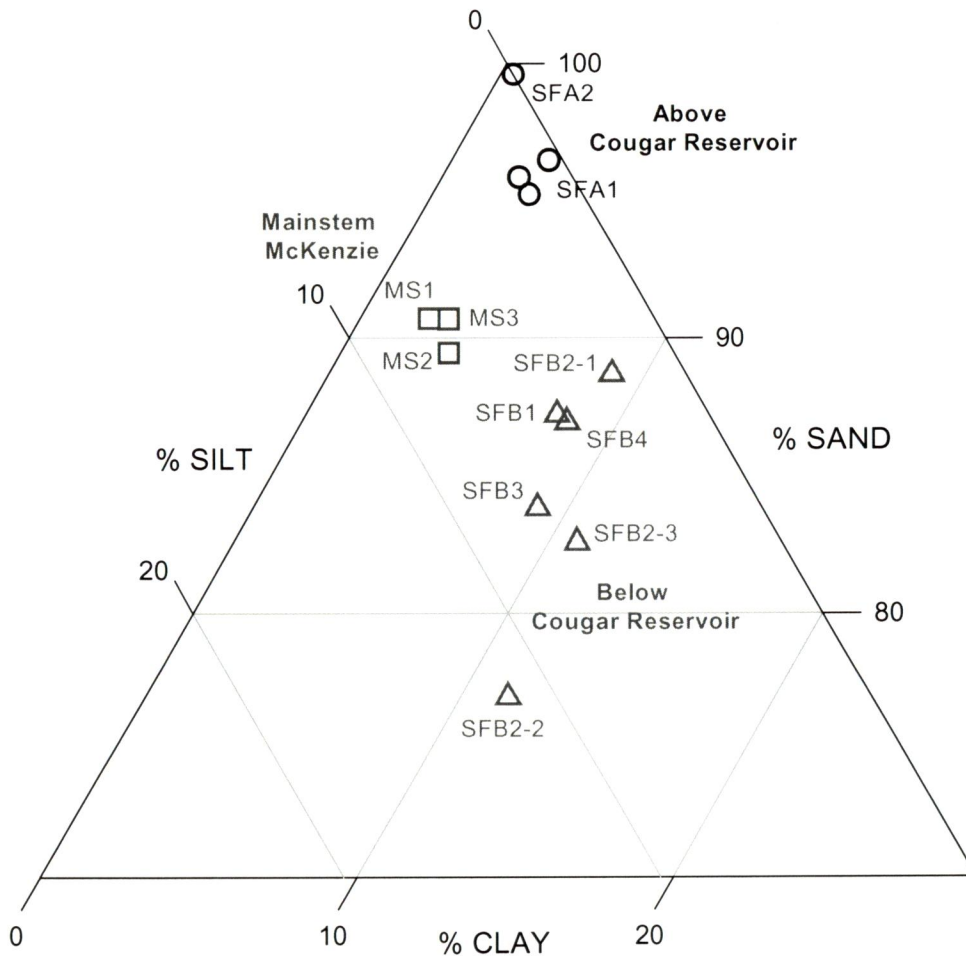


Figure 7: Ternary plot showing relative abundances of sand, silt, and clay for each site.

Clay (XRD) Analysis

We report results separately from each of the 4 reaches: South Fork above Cougar Reservoir, within Cougar Reservoir, South Fork below Cougar Reservoir, and mainstem McKenzie River.

South Fork McKenzie Above Cougar Reservoir

The clay mineral assemblage of the <2- μm fraction taken from gravel bars above Cougar Reservoir (SFA1 and SFA2) contains smectite and halloysite, with minor to trace amounts of other minerals (zeolite, plagioclase, hematite, pyroxene; Table 4). Smectite is the dominant component of the clay assemblage, comprising about 75-80% of the <2- μm fraction (Figure 2). Replicate cores taken at location SFA1 exhibit similar mineralogy, indicating considerable uniformity of the clay assemblage within this gravel bar. In addition, bar-to-bar mineralogical variations are insignificant, as the clay assemblage of the SFA2-C sample is nearly identical to that observed in sample SFA1-C (Table 4). Clays analyzed from the bulk sample were not oven dried prior to XRD characterization and show the presence of hydrated halloysite (1.0-nm spacing) in addition to the 0.73-nm halloysite (dehydrated form). The smectite-dominated mineralogy of the clay fraction is typical of suspended sediments derived from zeolitically altered volcanics of the Western Cascades (Pearch, 2000) that have experienced regional low temperature alteration in response to deep circulation of meteoric water. These deeply altered volcanics are often highly susceptible to plastic deformation and large-scale slumping, giving rise to earth flows and large slope failures. In contrast, active glacial scour of Pleistocene volcanics of the High Cascades generally yields eroded sediments enriched in amorphous clays and halloysite (e.g., Breitenbush River clays, Glasmann, 1997). Thus, the smectite-enriched nature of the clay assemblage of the South Fork samples indicates that older altered Western Cascade volcanics are probably the dominant source of clays entrained in gravel bars located 2-3-km upstream of Cougar Reservoir.

Cougar Reservoir

Samples RES-1, -3, and -4 are sedimentologically related to active deltaic processes of the South Fork, with RES-1 and -3 being coarser-grained, lower delta front turbidites, and RES-4 representing distal pro-delta muds. The clay mineral assemblages of these 3 samples show similar qualitative and quantitative features (Table 4). The primary difference in the mineralogy of the samples reflects decreasing halloysite content with distance from the head of the delta (from 18% to 14%), suggesting that halloysite may not persist in suspension as long as finer smectite particles. (It should be noted that none of the reservoir samples was oven dried prior to XRD analysis. Therefore, the halloysite component listed in Table 4 includes a mixture of hydrated and dehydrated halloysite. The clay assemblage of these reservoir sediments differs from that of the upstream bars in several ways: 1) smectite is much less abundant in the reservoir sediments (80% in river gravels vs. 50% in reservoir sediments); 2) reservoir samples are enriched in zeolite, halloysite, and quartz relative to the upstream gravels; and 3) the reservoir clays include components of mixed-layer clays that were not identified in the upstream gravels, specifically interstratified kaolinite/smectite and hydroxy interlayered smectite. These interlayered clays originate through pedogenic processes and are probably added to the reservoir by erosion of lake-margin soils by wave action. Similarly, halloysite and quartz are concentrated in soils by pedogenic weathering and their concentration in modern lake sediments probably indicates inter-reservoir sediment sources.

Table 4: Mineralogy of the clay fraction of McKenzie River sediment samples as determined by X-ray powder diffraction analysis.

SITE ID	SIZE (µm)	SM %	VM %	CH %	CINT %	ILL %	H %	KAO %	R0 K/S %	GIB %	OPAL %	OP-CT %	ZEO %	QTZ %	KSP %	PL %	HEM %	AMOR %	OTHER %
SFA1C1	<2	78.1	0	0.9	0	0	11.8	0	0	0	0	0.5	0.5	0.2	0	3	2	2	1
SFA1C2	<2	80.3	0	0.5	0	0	12.3	0.9	0.5	0	0	0	0.5	0	0	1.5	1.5	1	1
SFA1C3	<2	82.1	0	0	0	0	11.2	0	0	0	0	0.5	0.5	0.2	0	2	1.5	1	1
SFA1Bulk	<2	76.8	0	0.4	0	0	11.6	0	0.4	0	1	1	0.5	0.2	0	3	2	2	1
SFA2C	<2	80.7	0	0	0	0	12.2	0.9	0	0	0	0	0.5	0.2	0	1.5	2	1	1
RES1	<2	50.2	0	0.8	4.2	0	17.0	2.5	8.3	2	1	3	2	1	0	3	2	2	1
RES2	<2	4.1	1.6	0.8	20.4	0	42.4	4.1	8.2	3	2	3	0	2	0	0.5	3	4	1
RES3	<2	45.1	0	0.8	8.3	0	18.0	2.5	8.3	1	2	3	1	1	0	3	2	3	1
RES4	<2	50.4	0	0.8	8.4	0	14.3	1.7	8.4	0	1	3	1	2	0	3	2	2	2
RES5	<2	59.0	0	0.9	4.4	0	14.1	0.9	8.8	0	1	2	1	1	0	2	2	2	1
RES6	<2	65.9	0	0	0	3.9	3.9	0	3.9	0	1	1	10	0.5	0	5	1	2	2
SFB1C	<2	74.2	0	0.9	1.8	0	6.3	2.7	4.5	0	0	1	2	0.5	0	2	1	2	1
SFB2A3	<2	69.7	0	0	1.7	0	8.5	0.9	4.3	0	1	1	6	1	0	2	2	1	1
SFB2B3	<2	68.9	0	0	1.7	0	8.4	0.8	4.2	0	1	1	6	1	0	3	2	1	1
SFB2C1	<2	71.6	0	0	1.8	0	11.6	0.9	3.6	0	1	1	2	0.5	0	2	2	1	1
SFB2C2	<2	71.6	0	0	1.8	0	10.7	0.9	4.5	0	1	1	2	0.5	0	2	2	1	1
SFB2C3	<2	69.9	0	0	2.7	0	10.6	0.9	4.4	0	1	1	3	0.5	0	2	2	1	1
SFB2Bulk	<2	59.1	0	0.8	4.1	0	12.2	0.8	4.1	0	2	3	2	2	0	4	2	2	2
SFB3C	<2	68.8	0	0.9	2.6	0	7.7	1.7	4.3	0	1	2	2	1	0	3	2	2	1
SFB4C	<2	76.1	0	0	1.8	0	6.3	0.9	4.5	0	1	1	2	0.5	0	2	2	1	1
MS1C	<2	74.5	0	0	1.7	0	4.1	2.2	2.6	0	1	2	0.5	0.5	0	4	2	3	2
MS2C	<2	28.9	1.7	8.3	2.5	10.7	1.7	28.9	0	0	1	1	0.5	4	0	4	2	3	2
MS3C	<2	67.9	0.9	1.8	1.8	4.5	4.5	6.3	2.7	0	1	0	0.5	2	0	2	2	1	1

Mineral Key: SM = smectite, VM = vermiculite, CH = chlorite, CINT = chloritic intergrade (includes both hydroxy-interlayered smectite and vermiculite), ILL = illite includes detrital mica, muscovite and biotite), H = halloysite (sum of hydrated and dehydrated halloysite), KAO = kaolinite, R0K/S = randomly interstratified kaolinite/smectite, GIB = gibbsite; OPAL = amorphous silica (opal-A), O-CT = opal-cristobalite, ZEO = heulandite/clinoptilolite, QTZ = quartz, KSP = K-feldspar, PL = plagioclase feldspar, HEM = hematite, AMOR = undifferentiated amorphous material, OTHER = other minerals (includes augite, ilmenite).

The clay assemblage of the Walker Creek delta (RES-5) is very similar to that of the South Fork reservoir sediments, except that the assemblage contains less halloysite (Table 4). This slight mineralogical variation may reflect local differences in the mineralogy of sediments washed down Walker canyon and suggests that the Walker Creek deltaics are not strongly influenced by pedogenic enrichment in highly weathered clays. The highly smectitic nature of the fine component of the Walker Creek deltaic material is consistent with the Western Cascade provenance of the watershed and sediments derived from deep-seated erosional processes.

Sample RES-2 represents surficial material from the toe of an earthflow deposit. The clay assemblage of this soil is strongly halloysitic and exhibits well-developed hydroxy interlayered smectite (chloritic intergrade clays). The strong Al-Fe interlayering of smectite requires a prolonged history of wetting and drying and is a common feature of older, highly weathered soil profiles. Additional evidence of prolonged weathering is provided by the presence of gibbsite (Table 4), which is one of the end products of chemical weathering in a strongly leaching environment. The fine silt fraction of this sample is extremely enriched in quartz relative to other reservoir samples, reflecting the concentration of chemically stable minerals in this highly weathered soil. If similar soils occur on the lake margin, it is easy to understand how shoreline erosional processes could enrich modern lake sediments in pedogenically stable phases (quartz, halloysite, chloritic intergrade and interstratified kaolinite/smectite) relative to the smectitic mineralogy of upstream gravel bars.

Sample RES-6 was obtained from talus material at the base of an outcrop of weathered andesite. The smectite–zeolite mineral assemblage is characteristic of the regional occurrence of low temperature hydrothermal alteration of Western Cascade volcanics. Stream scour of such bedrock material is a principal source of the smectite–zeolite assemblage of the clay fraction of many Western Cascade streams (Pearch, 2000; Glasmann, 1997).

South Fork McKenzie Below Cougar Reservoir

The clay mineral assemblage of the SFB1-C sample is dominated by smectite with lesser amounts of kaolinite, chlorite, halloysite, and mixed layer clay (Table 4). The presence of minor amounts of mixed layer kaolinite/smectite and chloritic intergrade clays distinguishes the fine fraction of this gravel deposit from the smectite-halloysite assemblage of upstream gravel bars. In addition, the fine silt fraction of this sample is strongly enriched in quartz relative to the above reservoir samples (Figure 8). Precluding a local source of these minerals in eroded stream channel deposits immediately below the dam, the occurrence of elevated amounts of mixed layer clays and quartz suggests that site SFB1-C is contaminated by fine sediment released from the reservoir. This assumes that the pre-dam mineralogy of the gravel bars was similar to that of upstream gravel deposits. All that can be confidently said is that the clay assemblage of sample SFB1-C differs from that of upstream gravel bars and includes minerals that are also found in sediments that are actively eroded during low pool reservoir conditions.

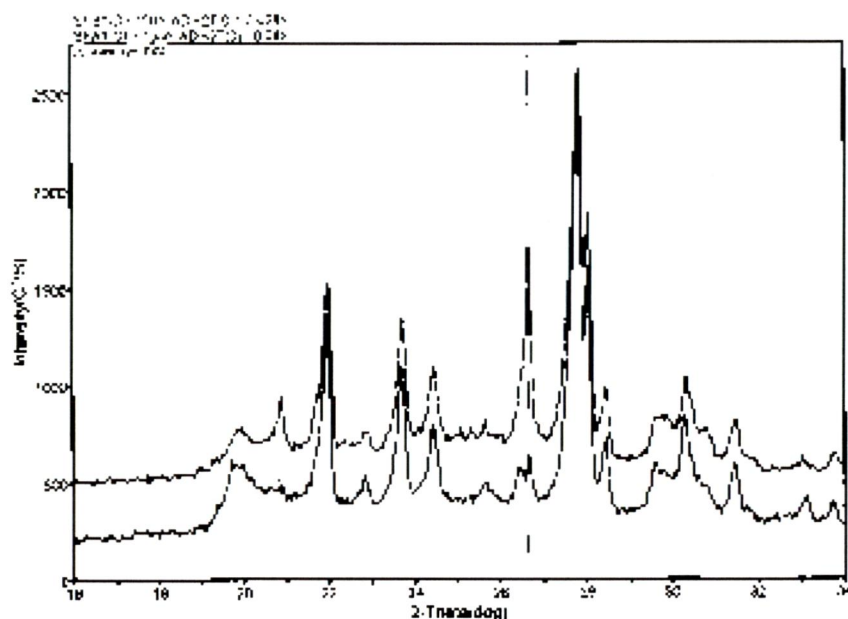


Figure 8. Comparison of XRD patterns of the <15- μ m fraction of fine sediment from 2 gravel bars on the South Fork of the McKenzie River. Sample SFA1-C1 (lower pattern) represents material sampled above Cougar Reservoir. Sample SFB1-C (upper pattern) was obtained from a gravel bar about 0.5-km below the reservoir. Two primary quartz peaks are labeled, illustrating the much greater intensity (and therefore greater abundance) of the quartz component in the SFB1-C sample. Other minerals in the specimens include plagioclase, pyroxene, cristobalite, smectite, and iron oxide (peaks not labeled).

The clay mineral assemblages of all 6 samples from SFB2 are remarkably similar, varying primarily in the amount of zeolite in the shallower samples (Table 4; Figure 9). The absence of significant variability in the clay assemblage within the bar suggests that the source of fine sediment entering the bar is homogeneous through time. Seasonal reworking of the bar by high discharge events should periodically cleanse the upstream end of the bar, suggesting that deeper (potentially older) bar sediments should have a more prolonged history of fine sediment accumulation. The similarity of the mineralogy of the fine fraction of bar sediments within slightly different zones of bar accretion (and therefore age) is evidence of long-term stability in the nature of infiltrated sediments. Although the slight difference in zeolite abundance through the vertical transect of the bar could be evidence of more recent addition of zeolitically-enriched clay, this pattern of surface enrichment is not repeated in other potentially reservoir-sourced minerals (e.g., quartz, Figure 10). In comparison to sample SFB1-C, the SFB2 samples show an important absence of kaolinite, yet maintain a minor component of mixed-layered clays; however, quartz abundance is significantly reduced in the <15- μ m fraction. The kaolinite-quartz association is frequently observed near local zones of hydrothermal alteration associated with intrusions and the downstream drop off of these phases between sites SFB1 and SFB2 could be related to local geology rather than reservoir discharge.

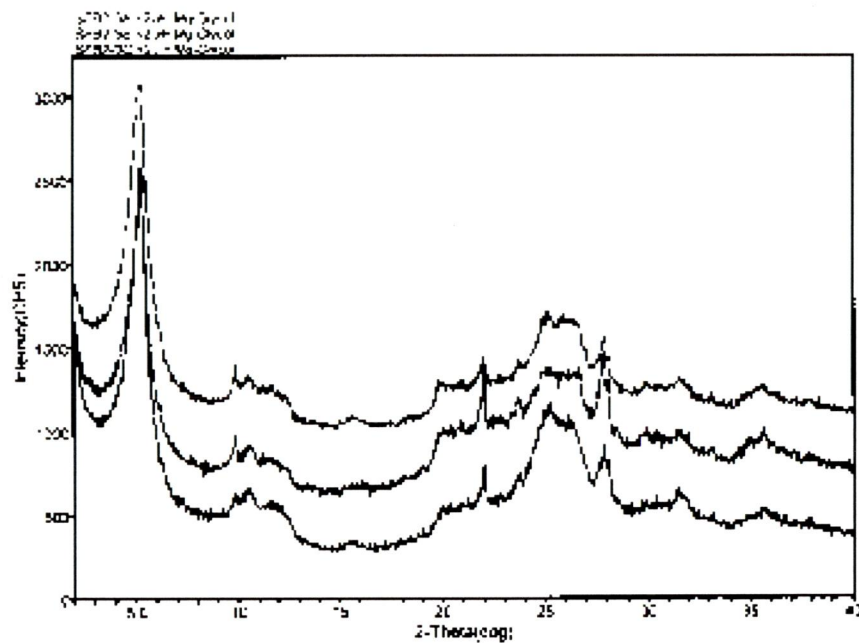


Figure 9. Comparison of XRD patterns of the <2- μ m Mg-Glycol treatment of samples representing a vertical sequence through a gravel bar. Sample 3A (top pattern) represents the bar surface (0-15-cm); 3B (middle pattern) represents approximately the 15-30-cm interval; 3C (bottom pattern)

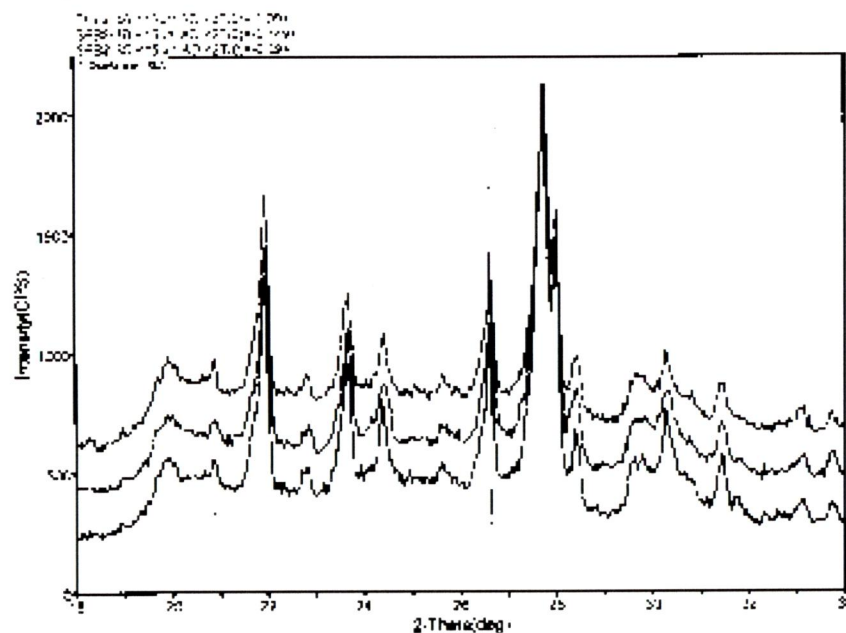


Figure 10. Comparison of XRD patterns of the <15- μ m fraction of samples obtained from a vertical transect at site SFB2 (depths as described in Figure 9). The locations of 2 principle quartz peaks are indicated, illustrating the similarity of quartz intensity (or abundance) between samples. Note that the quartz intensities in the silt fraction at site SFB1 (Figure 10) are greater by a factor of 2 compared to these samples, indicating that quartz is much more abundant in the fine fraction of the upstream gravel bar.

Samples SFB3-C and SFB4-C are mineralogically similar, exhibiting a <2- μ m fraction that is dominated by smectite and includes minor amounts of halloysite and mixed layer clays (Table 4). The fine silt fraction of these 2 samples contains even less quartz than either SFB1 or SFB2, documenting a downstream drop off in the quartz content of fine sediments below Cougar Dam (Figure 11). Sample SFB3-C also contains a minor component of chlorite that was absent in the SFB2 samples, but this phase is again absent in the SFB4-C sample, suggesting a local source influence. Compared to the gravel bar samples located above Cougar Reservoir, all of the lower South Fork samples contain minor amounts of mixed layer clay (generally about 5% hydroxy interlayered smectite and 5-10% randomly interstratified kaolinite/smectite). These materials have a “messy”, low intensity XRD pattern and are not easily identified in minor concentrations in mixtures with other clays possessing better structural regularity. Although potentially a characteristic fingerprint of muddy water released from Cougar Reservoir in response to low pool erosion, the low concentration and weak XRD signature of these phases in the clay fraction of lake sediments lessens their utility as downstream indicators of bar contamination (see Figure 12).

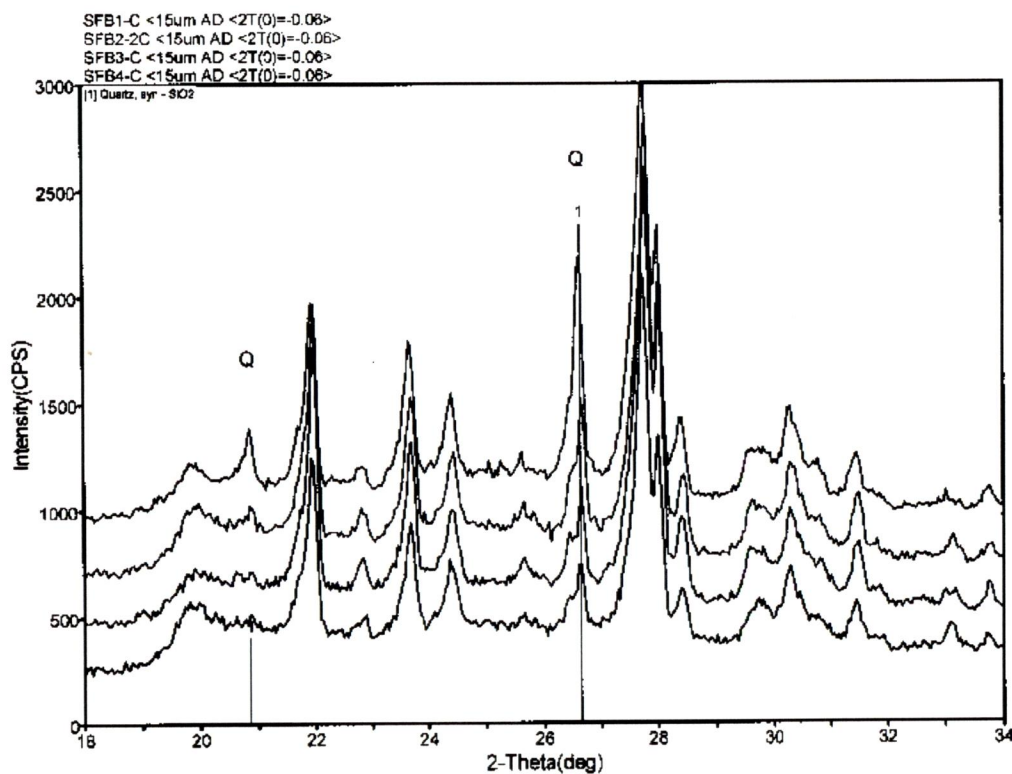


Figure 11. Comparison of XRD patterns of the fine silt fraction of gravel bars from the lower South Fork of the McKenzie River illustrating the rapid reduction in quartz content in sediments below Cougar Reservoir. Quartz is most abundant in the SFB1 sample (top pattern) obtained close to the dam. The intensity of the quartz component (and therefore its abundance) shows continual decrease with increasing distance from the dam. This pattern of quartz distribution suggests a point source of quartz-rich sediment affected by downstream dilution and sediment dispersal.

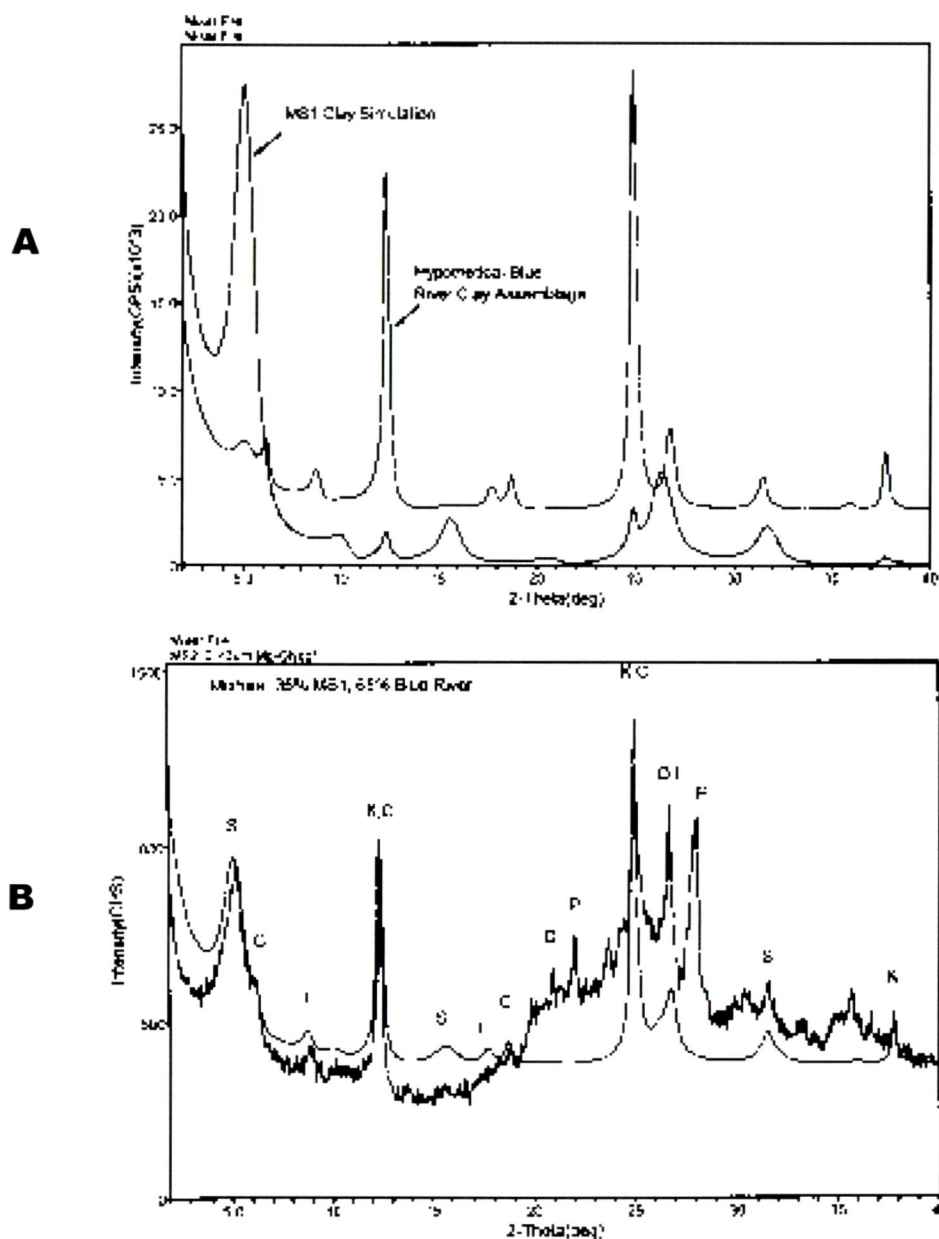


Figure 12. **A.** Simulated XRD patterns representing the crystalline clay components of the <2-µm fraction of sample MS1-C and a hypothetical clay assemblage representing material from a hydrothermally altered watershed ("Blue River"). The MS1-C model consists of a mixture of 90% smectite, 3% kaolinite, and 7% halloysite (modeled as highly disordered, thin kaolin). The "Blue River" assemblage is a mixture of 38% kaolinite, 30% illite, 15% chlorite, 3% vermiculite, 7% smectite, and 7% halloysite. **B.** Mixing these 2 end member models in a ratio of 35% MS1 to 65% Blue River yields a simulated XRD pattern that closely approximates the clay mineralogy of the MS2-C clay fraction. Note that non-crystalline and non-clay mineral phases are not modeled. The MS2-C sample contains minor amounts of quartz, plagioclase, amorphous silicate, and iron oxide. The amorphous component of the sample suggests shallow-seated erosional processes (debris avalanche, debris flow) are important sediment delivery mechanisms in the source area of these gravels.

Mainstem McKenzie River

The clay fraction of fine sediment from the upstream gravel bar (MS1-C) is composed primarily of smectite with a weak kaolinite component (Table 4). While traces of mixed layer clay are listed in Table 4, the amounts are so low that phase identification is uncertain. The mixed layer clay and halloysite components of this sample are much less abundant than those identified in South Fork gravel samples, particularly from below Cougar Dam. The quartz content of the fine silt fraction of the MS1-C sample is similar to that of South Fork gravels from above Cougar Reservoir. Again, the smectite-dominated character of the fine clays is indicative of Western Cascades provenance linked to deep-seated erosional processes (slumping, deep stream incision into zeolitically altered volcanics).

The fine fraction obtained from the gravel at site MS2-C has a unique mineralogical composition compared to all of the gravel bars thus far considered. MS2-C clays consist of a mixture of kaolinite, smectite, chlorite, illite, halloysite, and quartz (Table 4). The kaolinite component exhibits a narrow, sharp peak character that is indicative of thick, internally well-ordered clay particles. In the Western Cascades, the presence of this type of kaolinite in association with illite, chlorite, and quartz in fluvial sediments is evidence of upstream argillic alteration due to local hydrothermal mineralization. Similar clays were identified in sediments of the Santiam Watershed in association with local mineralized zones (Pearch, 2000; Bates et al., 1998; Glasman, 1997). In the McKenzie drainage, areas of local hydrothermal alteration occur in the Quartz Creek and Blue River watersheds (Figure 1). Site MS2 is located below the confluence of Blue River with the mainstem. The occurrence of the kaolinite-illite-chlorite-quartz mineral assemblage is probably a result of local geology and provides important clues for understanding the process of clay entrapment and sediment mixing in high energy gravel bars.

The modeled clay composition of the clay fraction of sample MS2-C includes about 35% smectite, 30% kaolinite, 8% chlorite, 15% illite, 10% halloysite, and traces of vermiculite and chloritic intergrade (Figure 12). If it is assumed that fine sediments in the mainstem upstream of the Blue River confluence are represented by the mineralogy of the MS1 sample, how much of the kaolin-illite-chlorite-quartz assemblage would need to be added to the clay fraction of the gravel bar to account for character of the MS2-C XRD patterns? The answer to this question assumes simple mixing of a two component system (Figure 12A), where one end member is represented by the MS1 clay assemblage and the other pattern represents a kaolin-illite-chlorite rich clay assemblage (hypothetical “Blue River” clays). A mixture based upon 35% MS1 clay with 65% “Blue River” clay provides a close match of the clay mineral assemblage of the MS2 sample (Figure 12B). This “feel good” exercise would only be meaningful if it could be demonstrated that the “Blue River” clay assemblage in fact occurs somewhere along Quartz Creek or another upstream tributary. It is, however, illustrative of the process used to infer or quantify sediment mixing, once end member components are identified. If we could be certain of the clay mineralogy of suspended sediments released from Cougar Reservoir during the spring 2002 turbidity event, it should theoretically be possible to quantify the mixing of this clay assemblage with other downstream phases. However, as mentioned previously, the poor crystallinity and low XRD intensity of the “unique” phases in potential reservoir effluent greatly increase the difficulty of simulating downstream sediment mixing.

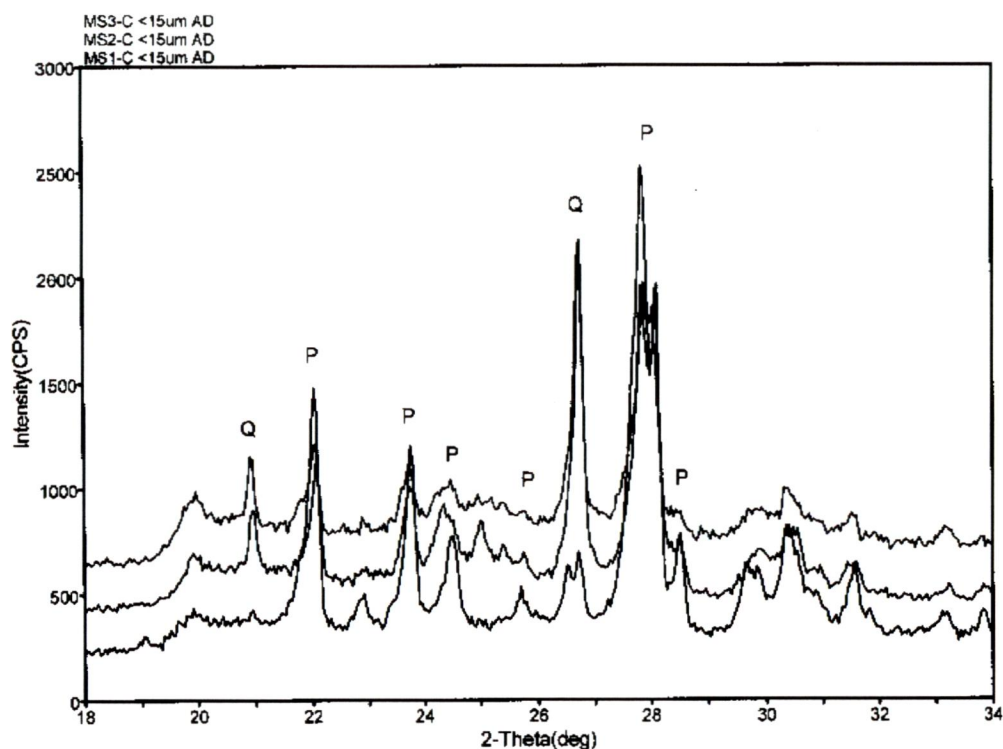


Figure 13. Comparison of the XRD patterns of the fine silt fraction of gravel bar sediments from the Main Fork of the McKenzie River at 3 locations (see Figure 1). The silt fraction of the upstream sample (MS1) is primarily feldspathic, with only trace amounts of quartz (bottom pattern). The intensity of the quartz component exceeds that of plagioclase feldspar in both the MS2 and MS3 samples (middle and top patterns). The appearance of quartz in the fine sediment fraction of sample MS2 reflects the input of sediment from watersheds affected by hydrothermal mineralization. The downstream persistence of quartz is favored by chemical stability and inter-channel mechanical supply as coarser quartz-bearing gravels are reworked by fluvial transport.

Sample MS3-C represents the most distal gravel bar sample below Cougar Reservoir. The clay assemblage of this sample is strongly smectitic, with minor amounts of kaolinite, illite, and chlorite (Table 4). The strongly kaolinitic-illitic character of included mud that was observed upstream at site MS2 has been significantly diluted by mixing with an extremely smectite-rich clay assemblage. Except for the occurrence of a minor illite phase, the XRD pattern for MS3-C looks very much like that of MS1-C. This similarity vanishes when the XRD patterns of the fine silt fraction are compared (Figure 13), as the downstream sample is significantly more quartzose than gravels from the upper portion of the watershed. This suggests that the fine clays associated with hydrothermal mineralization are winnowed from the system or diluted by mixing with more persistently supplied smectitic clays during normal sediment transport processes, while dispersion of silt-sized quartz is more difficult. Quartz may be continually added to the silt fraction by mechanical breakdown of quartz-bearing gravels, whereas clays are less likely to have a persistent inter-channel source.

Note that the pattern of quartz abundance in the lower reaches of the South Fork differs substantially from that observed in the lower mainstem (Figure 11). The rapid loss of quartz below Cougar Dam suggests that quartz does not have a major inter-channel source (i.e., quartz-rich gravels), but may be supplied by intermittent release from Cougar Reservoir. Such release would result in decreasing concentration of quartz downstream of the dam as a finite supply of sediment was diluted and dispersed by fluvial mixing and sedimentation. While hydrothermal quartz does not appear to have a major source in the Cougar Reservoir provenance, concentration of pedogenic quartz in lake sediments by shoreline sediment reworking processes increases the quartz content of lake bottom sediments relative to incoming fluvial sediment sources. Still untested is whether or not a local hydrothermal source of quartz occurs immediately below the dam, but the absence of quartz-rich gravels and associated chlorite-illite-kaolinite clays in the infiltrated sediment fraction of the lower South Fork (Table 4) argues against local hydrothermal alteration.

DISCUSSION

No samples of the actual suspended sediment released from Cougar Reservoir during the spring 2002 high turbidity event were obtained for mineralogical characterization. If one assumes that erosion of modern lake floor deposits was a primary turbidity source, the suspended clay assemblage released from the reservoir would reflect the mixing of multiple sediment sources modified by sediment settling in the low pool lake. Since suspended material was continually being generated and rapidly discharged by active erosion of exposed lake bottom sediments (as opposed to sporadic storm-related turbidity events), the effects of prolonged sediment suspension time in the reservoir should be minimal. In other words, the “soup” accumulated behind the low-pool reservoir was continuously “stirred” by the prolonged addition of fresh fine material. In contrast, normal storage/release reservoir operation facilitates episodic sediment supply with prolonged fluid residence time, during which fine sediments settle from suspension and the mineralogy of reservoir discharge evolves toward finer and finer colloidal materials (chiefly smectite). This process was clearly observed during the February 1996 storm event in Detroit Reservoir (Glasmann, 1997), where reservoir discharge was enriched in smectite relative to reservoir sediment input. Assuming Cougar Reservoir discharge was relatively unmodified by storage-related sediment settling processes, the effluent from the reservoir was probably enriched in halloysite, mixed-layer clays, quartz, and zeolite relative to upstream sediment sources or “normal” high pool discharge events. Therefore, downstream identification of contamination of fluvial environments by released reservoir turbidity should be possible, based upon recognition of elevated amounts of these reservoir-derived clays.

Grain-size analysis of the South Fork and mainstem McKenzie river sediments suggests a relative enrichment in fines in the alluvial reaches below Cougar Reservoir as compared with the reaches above the reservoir. Upstream reaches and mainstem McKenzie sites have clay fractions representing 2.5% of the <2mm sample by weight as opposed to 9.5% in the South Fork below the dam. An increase in fines is not detectable below the confluence of the South Fork on the mainstem McKenzie River. Because no in-situ sampling of gravels was conducted prior to the reservoir release in the spring of 2002, we are unable to discern whether this fines enrichment pre-dated the release. In general, however, it is unusual to see significant quantities of fine

sediment stored in channel beds below dams, as reservoirs typically act as large-scale sedimentation tanks where fine sediment deposition occurs. But it would require additional sampling of bed gravels below other dams located in similar geographic positions (i.e., Blue River) to determine whether presence of reservoir-derived sediments is more common than previously thought.

Enrichment of the gravels with reservoir-derived fines is supported by the presence of distinct mineral assemblages, notably pedogenic quartz and mixed-layer clays. In particular, the presence of elevated quartz in the below dam South Fork samples argues for pool erosion during drawdown as the source of the elevated clays. This is because under “normal pool” conditions, the higher settling velocity of quartz would result in its settling out and fractionation from the water column. In other words, water released under normal operating procedures would not tend to be enriched in quartz. The most likely source for the quartz that was observed below the dam is reentrainment of previously deposited reservoir sediments, as occurred during the drawdown.

But pedogenic quartz and mixed-layer clays are the only “confident” effect of Cougar Reservoir on the mineralogical properties of fine sediment entrained in downstream gravel bars. These components are most concentrated immediately below the dam, and then show a downstream pattern of rapidly decreasing abundance. There is no observable effect of hypothesized “Cougar” suspended sediments upon the mineralogy of fines identified in gravels from the lower reaches of the mainstem of the McKenzie River. In fact, the mineralogical character of the gravel bars of the McKenzie River varies dramatically with location along the river. Tributary watersheds with unusual geologic character exert greater influence on fine sediment composition within gravel bars than sustained turbidity released from Cougar Reservoir.

Although an interpretation of enrichment of gravels below Cougar Dam due to reservoir drawdown is supported by increased clay abundance in the gravels and the mineralogic signature of the clays, we are constrained from interpreting the higher clay levels found below the dam as *exclusively* due to the drawdown. A critical issue is the difference in depositional environments between sampled reaches upstream and below the dam on the South Fork. Upstream reaches tend to be steeper (average gradient = 1.2% vs. 0.7% below the dam), and although median grain sizes are similar for the two reaches (Table 3), the upstream reaches are a higher energy environment in contrast to the below dam reaches. The upstream channel is generally bedrock-floored, narrow, and boulder-filled, in contrast to the wider, alluvium and outwash-dominated fan environment with multiple channel threads. These geomorphic differences will inevitably result in greater deposition of finer-grained facies below the dam, and could result in some of the upstream/downstream differences observed. Furthermore, there is no systematic trend of decreasing clay abundance with distance downstream from the dam; in fact, the site closest to the dam (SFB1) has the lowest clay percentages. The replicate analyses at site SFB2 also show wide scatter in proportion of sand, silt and clay (Fig. 7). So although the evidence points in the direction of a dam- and drawdown-driven effect, these results are not unequivocal.

Cougar-related contamination would be difficult to recognize in small amounts (<20% in mixtures with pre-existing sediment) because of the poor crystallinity and weak diffraction character of “unique” mineralogical fingerprints (mixed layer kaolinite/smectite, pedogenic

quartz, and hydroxy interlayered smectite). However, these phases do not, in fact, have a unique reservoir source, but may be supplied to the McKenzie drainage by a variety of mechanisms (bank scour, debris flow, debris avalanche). Thus, the occurrence of these poorly crystalline phases in downstream bars may reflect local sediment supply and not accumulation by a prolonged sediment-flushing event. Since the prolonged release of sediment concentrated water occurred just prior to summer low flow conditions, optimal conditions existed for preservation and recognition of potential clay contaminants. The absence of significant mineralogical homogeneity in the fine sediment fraction below the confluence of the South Fork with the mainstem of the McKenzie suggests that the impact of sustained release of highly turbid water was minimal on the lower reaches of the river; however, flow-related contamination of gravel bars from the lower South Fork is suggested by below-dam trends in silt-sized quartz and clay content.

Although measurable, we did not consider whether the increased volumes of fines stored in the gravel below Cougar Dam are “big” or “little” numbers from the standpoint of river function or ecological impacts. Additional biological sampling would be required to evaluate whether riverine benthos or aquatic organisms are responding to the increased sediment levels. Other measurements would be required to determine whether hyporheic flow rates had been affected.

Additional research

To our knowledge, this is the first semi-quantitative analysis of the composition of river gravels in relation to dam operation in western Oregon. Accordingly, many interesting questions cannot be definitively answered. As noted above, although the fine sediments below Cougar Dam appear to be related mineralogically to those found in the reservoir, we cannot resolve whether they were present in the bed prior to the spring 2002 releases. A more systematic sampling of bed sediments above and below other reservoirs, such as Blue River, Detroit, and Hills Creek, would provide a useful reference point for interpreting whether reservoir operations tend to result in increased accumulations of fines in the bed. If other reservoirs also show fines enrichment, then it would be more difficult to argue that the observed increased levels of fines were uniquely due to the drawdown. On the other hand, if additional sampling shows the below Cougar levels to be anomalously high, then a stronger case for a drawdown-induced effect can be made.

Some additional clay mineralogy samples from the mainstem McKenzie below the confluence of the South Fork but above Blue River would also help resolve whether higher quartz concentrations found in the clays from MS2 were derived from Blue River and tributaries or the South Fork. Confounding this, however, is the fact that during the Pleistocene, the confluence between Blue River and the mainstem McKenzie was located approximately 4km upstream of its present location and upstream of the modern South Fork confluence (Swanson and James, 1975b).

A second key question is the persistence of these elevated fines through time. Will the first high flow events capable of breaking the surface armor and mobilizing bar sediment result in scour of fines, or is the depth of scour less than the depth of fines enrichment? Although absolute depths of fines cannot be firmly established, the observed increases come from depths of between 25-40

cm. These depths are approximately 10 times the median surface grain-size of 2cm. Depth of scour during high flows events is poorly constrained for gravel-bed rivers like the South Fork, but it would be possible to deploy scour chains to determine how deeply the bed is scoured during winter flows. Coupled with repeat freeze-core measurements of percent fines, such measurements would help predict how likely these elevated levels are to persist over time.

REFERENCES CITED

- Bates, D., Willis, K., Swanson, F., Glasmann, J.R., Halameier, D., and Wujcik, H, 1998. North Santiam River turbidity study, in *Watershed Management Council Networker*, Fall 1998, pp 1-17.
- Beschta, R. L. and Jackson, W. L. 1979. The intrusion of fine sediments into a stable gravel bed. *J. Fisheries Research Board of Canada*. 36(2), 204-210.
- Carling, P. A. 1984. Deposition of fine and coarse sand in an open-work gravel bed. *Canadian Journal of Fisheries and Aquatic Sciences*. 41(3), 263-270.
- Einstein, H. A. 1968. Journal of the Hydraulics Division, ASCE . 94(5), 1197-1205.
- Glasmann, J.R., and Simonson, J.G., 1985. Alteration of basalt in soils of western Oregon. *Soil Sci. Soc. Amer. Jour.*, 49, 262-272
- Glasmann, J.R., 1997. Clay mineralogy of soils and suspended sediments within the North Santiam River drainage. WGS Report 049704, April 28, 1997.
- Harr, R.D. 1981. Some characteristics and consequences of snowmelt during rainfall in western Oregon. *J. Hydrol.* 53(277)
- Koltermann, C. E., and S. M. Gorelick. 1995. Fractional packing model for hydraulic conductivity derived from sediment mixtures. *Water Resour. Res.* 31(12), 3283-3297.
- Pearch, J.M., 2000. Relationships between landscape stability, clay mineralogy, and stream turbidity in the South Santiam Watershed, Western Cascades, Oregon. Unpubl. M.S. Thesis, Geoscience Department, Oregon State University, Corvallis, Oregon.
- Reynolds, R.C. Jr., and Reynolds, R.C.III, 1996. NEWMOD-for-Windows. *The calculation of one-dimensional X-ray diffraction patterns of mixed-layer clay minerals*. Computer program available from the authors, 8 Brook Road, Hanover, New Hampshire 03755.
- Richards, C. and Bacon, K. L. 1994. Influence of fine sediment on macroinvertebrate colonization of surface and hyporheic stream substrates. *Great Basin Naturalist*. 54(2), 106-113.
- Schalchli, U. 1995. Basic equations for siltation of riverbeds. *Journal of Hydraulic Engineering*. 121(3), 274-287.
- Sherrod, D.R. and Smith, J.G. 1989. Preliminary map of upper Eocene and Holocene volcanic and related rocks of the Cascade Range, Oregon. U.S. Geological Survey Open-File Report 89-14.

- Swanson, Frederick J.; James, Michael E. 1975a. Geology and geomorphology of the H.J. Andrews Experimental Forest, western Cascades, Oregon. Res. Pap. PNW-188. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 14 p
- Swanson, Frederick J.; James, Michael E. 1975b. Geomorphic history of the lower Blue River-Lookout Creek area, western Cascades, Oregon. *Northwest Science*. 49(1): 1-11
- Theissen, A.A., and Harward, M.E., 1962. A Paste Method for preparation of slides for clay mineral identification by X-ray diffraction. *Soil Sci. Soc. Amer. Proc.* 26, 90-91.
- Wu, F. C. 2000. Modeling Embryo Survival Affected by Sediment Deposition Into Salmonid Spawning Gravels: Application to Flushing Flow Prescriptions. *Water Resources Research*. 36(6), 1595-1603.

Stewart, G., Glasmann, J.R., Grant, G.E., Lewis, S.L. and Ninneman, J., 2002. Evaluation of Fine Sediment Intrusion into Salmon Spawning Gravels as Related to Cougar Reservoir Sediment Releases. Unpublished report prepared for U.S. Army Corps of Engineers, Portland District Office, dated October 4, 2002.

APPENDIX A: METHODS

Field Methods.....	A1
Lab Methods.....	A3
Clay (XRD) Methods.....	A5

FIELD METHODS

Freeze Coring:

1. The sites were approached from down stream as to not cause upstream disturbances that may have contaminated the sampling site.
2. A staging area was established for equipment and sample thawing near the site.
3. The CO₂ jets and canisters were inspected. Checking to make sure that all jets and plugs were in working² order. If necessary the jets and plugs were tightened. (Slot screw driver)
4. The tri-jet adjustment fitting were screwed on to the CO₂ canisters. (Wrench)
5. The hoses were attached to the tri-jet fitting. (being careful not to allow fitting or top of canisters to get wet because they will freeze and cause problems)
6. Hoses were then screwed on to injection rods. (Wrench)
7. Once the injection system was ready, three hollow metal rods (4 ft long with pointed tips to penetrate subsurface and a gripping lip around the top) were placed in a bracket system.
8. The bracket system consisted of two discs that had three holes large enough for the rods fit through but the lip could not. The discs screwed onto a long metal eye bolt that attached through the middle of the discs. The discs were further secured by two nuts on either side of the disc on the bolt. The discs were then located 71.5 cm apart from each other. This arrangement allowed the bottom disc to sit on the substrate and the rods could sit on the top disc and still be able to penetrate the substrate to a depth of 45 cm.
9. Next an aluminum garbage can with the bottom cut out was placed around the core site.
10. The bracket system with rods in place was set in the center of the can and the rods were pounded into the substrate. (a bolt that fit into the rods and with a large head was used to pound on so as not to distort the rods)
11. Injection rods were then placed in the hollow rods.
12. Two 20lb siphon canisters of CO₂ were used for each core.
13. The CO₂ canister was then slowly² turned on until a small cloud of CO₂ and chunks of CO₂ ice was shooting² out of the rods.
14. As the CO₂ is being injected a second person was holding the rod and raising them up and down about 6 inches and turning them left and right. (The proper protective clothing for this job was long sleeve shirt or coat, eye protection, thick leather gloves, and protective shoes)
15. Approximately half way through the first canister the injection rods were rotated clock-wise, and this was repeated during each canister run.
16. After emptying the canisters, a eight foot tall tripod was placed around the garbage can and a come-along was attached to the tripod and the eye bolt connected to the bracket system.
17. The bracket system along with the frozen core was then pulled out of the stream bed.
18. The core was then carried over to a previously prepared cooler.
19. The cooler was subdivided into four plastic bins, each bin had a 2 gallon zip-lock bag covering it. The bins were connected by plastic report spines.
20. The portion of the rods that didn't have sediment on them was then braced on an additional cooler, in such a way as to allow the frozen core to be positioned over the bins. The top of the core was placed at the beginning of the first bin with the core extending down the bin cooler.
21. The core was then thawed with a propane torch. The torch was moved slowly up and down the core, being careful not to over heat one spot or melt the zip-lock bags. (one person was needed to hold the core still and another to thaw the core)
22. As the core thawed the pieces were allowed to fall into the bins below. If sediment fell outside of the bin, it was discarded.
23. The bags were then labeled, double bagged and placed in a cooler for transport back to the lab.

Site Characterization:

1. The site was described in fluvial geomorphic and hydrological terms. Noting any difference or unusual features of the area, stream bed, gravel, silt/clay layer on bed, etc.
2. Site measurements were conducted including; GPS coordinates, stream width, deepest point, average depth of stream, distance from riffle or rapid, site sketch and stream cross-section.
3. Green flagging, marked with the site number, was placed near the core with the it's location relative to the core noted on the site sketch.
4. The velocity at the site of the core was recorded using a flow meter at .6 the depth of the location.
5. The hydraulic gradient was recorded.
6. A piezometer was used. (a metal pipe 5ft long with one end pinched off and a screen drilled into the side ~5cm from the bottom)
7. The piezometer was placed into the subsurface at approximately .2 m whenever possible. The depth of the rod was recorded. The piezometer was place within 2m of the original core at each site, or approximately the middle of the three cores at the triple site locations.
8. The internal water level was then measured using a depth-o-meter. The measurement was recorded as depth from the casing of the pipe.
9. Water was then added to the internal water column and the time for the water column to return to the initial measurement was recorded.
10. Once the water returned to the original measurement the column was allowed to reach equilibrium by waiting a total of five times the amount of time that it took for the column to reach it's initial level.
11. After reaching equilibrium the internal column was measured again and the stream level was measured from the casing.
12. The depth of the stream from substrate to surface was also recorded.
13. A pebble count was conducted by one-step random walking around the site and blindly picking up 100 pebbles and measuring their median axis.

LAB METHODS

Dry Sieving:

1. The samples gathered in the field were arranged in sequential order.
2. Drying trays were cleaned of contamination, by washing and whipping clean with a paper towel and stacked two deep for strength
3. Sample bags were labeled with corresponding lab number and field identification number.
4. Sample bags were placed between the two drying trays.
5. The sediment was carefully removed from plastic field bags and placed in the clean trays.
6. The plastic bag was then folded open on its own tray, to dry.
7. Both trays were then placed in drying closet, until dry. (72-48 hrs)
8. The drying closet was keep at a constant 40° C.
9. The dried sediment was then shaken out of plastic bags into the sediment tray.
10. The sediment and tray was then weighed.
11. The sieve pan was pre-weighed.
12. If the core was to large for the scale then more clean trays were pre-weighed and the sample was split into two or three parts.
13. The extra trays generally contained large gravels and cobbles.
14. The larger grains were clean with a brass wire brush to remove silts and clays. Being careful to clean into the 2mm sieve. Butcher paper was place under the work area in order to catch and spills. The sediment was then returned to it's original pre-weighed tray.
15. The smaller dried sediment was then sieved through a 2mm (No. 10) sieve.
16. One additional tray was pre-weighed to contain the sieved material during the sieving process.
17. After each tray was sieved the sediment was re-weighed.
18. After all sieving was completed for one sample the sieve pan was then weighed.
19. The sands, silts and clays in the sieve pan were then placed in a pre-labeled lab sample bag.
20. The coarse grains were then sieved at 1 phi intervals and the weight for each interval was recorded.

Hydrometer Analysis:

1. The sand, silt, and clay sample bag was mixed by tipping up and down several time and mixing with a spoon.
2. Several spoonfuls were removed from the bag by pulling from the bottom.
3. 40 grams of sediment was removed from each bag and place on scale in weighting pan. With an accuracy of 40.01 to 39.99.
4. In case of small sample size less then 40 grams, the amount in the bag was recorded.
5. The 40 gram sample was placed in a milk shake shaker container.
6. 100 ml of soap was placed in the shaker and water was added up to the bottom of second lip in shaker.
7. The slurry was then mixed with a blender for 4 minutes.
8. A squirt bottle was used to rinse the blender as the slurry was removed from the mixer.
9. The mixture was placed in a settling tube with enough DI water to fill the tube to the 1 liter mark, being careful not to spill mixture, and to get all of the sediment off the walls of the shaker.
10. 12 to 18 samples were gathered in settling tubes as described above.
11. A control sample was also prepared using known sand, silt, and clay concentrations.
12. A blank sample was prepared using only DI water and a thermometer was placed in the tube.
13. After preparing the desired samples, the temperature in the blank was recorded.
14. The first sample was re-mixed with a mixing rod for 30 seconds and the time was recorded.
15. After mixing a hydrometer reading was taken after 40 seconds of settling.
16. The time between mixing and measuring of each tube was carefully space 2 minutes apart.

17. All samples were measured including the control and the trip blank. At the end of the measurement the temperature of the trip blank was recorded again.
18. 2 hrs after the first reading, another reading of the hydrometer from each tube and the thermometer from the trip blank was conducted. The measurements for each tube were again spaced by 2 minutes.
19. After an additional 5 hrs or a total settling time of 7 hrs, another reading of the hydrometer from each tube and the thermometer from the trip blank was conducted. The measurements for each tube were again spaced by 2 minutes.
20. After each use of the hydrometer it was cleaned in DI water.
21. The data was then converted into percent sand, silt and clay using Central Analytical's standard data procedures

Sonicating and Washing Gravel Fraction:

1. Two to three sample trays were washed and dried to remove contaminates per core section that was being washed.
2. The sample trays were then weighed.
3. Next the C-section of each core and sections A,B,C, and D for site SFB2-3 were selected.
4. One at a time each sample was remove from it's bag and placed on a pre-weighed tray. If necessary the sample was distributed between several trays.
5. Each tray with sediment on it was then weighed.
6. Each tray was then washed separately.
7. The sample was remove from the tray and washed through a ($<.0064\text{mm}$) wet sieve. The tray was then washed out through the wet sieve.
8. The remaining ($>.0064\text{mm}$) fraction was then placed in sonic bath and wash.
9. The bath water was poured off through the a ($<.0064\text{mm}$) wet sieve until the water was clear.
10. The sample was then returned to its original tray and placed in a drying closet for 24-48 hrs.
11. After drying the trays were re-weighed.
12. The difference in the before washing weights and the after washing weights was taken to be the remaining silts and clays that were not separated in the dry sieving process.

Clay (XRD) Methods

Samples for mineralogical analysis consisted of bottled residues from the hydrometer analysis, bagged composite gravels, and bulk gravel samples in field moist condition, without oven drying. Bottled residues were concentrated by centrifugation into 250-ml centrifuge bottles and washed several times to remove traces of salt used to flocculate the suspension. Suspended fines were obtained from the bulk gravels by dispersing the sediment in distilled water in an ultrasonic tank. The sediment was then sonified for 10 minutes with occasional stirring, and suspended fines were decanted into 250-ml centrifuge bottles using a 64- μm sieve to strain floating organic and sand-sized particles. The >64- μm fraction collected on the sieve was discarded. Suspended <64- μm fines were further separated into fine silt (2-15- μm) and clay (<2- μm) fractions using a slow speed centrifuge equipped with a 250-ml swinging bucket rotor. The clay fraction was flocculated by adding 2-3 ml 0.5 M MgCl_2 to the solution in the 250-ml bottles, then concentrated by high-speed centrifugation. Each clay concentrate was treated 3 times with 0.5 M MgCl_2 to facilitate cation saturation of the clay complex (Glasmann and Simonson, 1985). Excess salt was removed by rinsing the clay 3 times with distilled water. Following preparation of slides of the Mg-saturated clay for XRD analysis by a smear technique (Theissen and Harward, 1962), the clay fraction was then K-saturated by repeated washing with 1.0 KCl and subsequent rinsing with distilled water. Additional slides of the K-saturated clay were then prepared for XRD analysis.

XRD analysis of the fine silt and clay fractions was accomplished using a computer automated Philips XRG 3100 diffractometer equipped with a ceramic Cu tube and a focusing monochromator (tube operated at 40KV, 36 ma, quartz reference intensity = 37,000 counts per second). The Mg-saturated samples were stored under controlled humidity (54% relative humidity) and step scanned from 2-14° 2-theta under ambient humidity (ranged between 40-50% relative humidity; scan step = 0.04°, count time = 2 sec). Following the initial XRD scan, the samples were solvated with ethylene glycol by exposing the clay to glycol vapor for 3 hours at 65°C, followed by a minimum 12 hour equilibration period. Mg-glycol slides were step scanned from 2-40° 2-theta. K-saturated clay slides were scanned from 2-14° 2-theta, first at ambient humidity, and subsequently after heating for 2 hours at 110°C. The slides were taken directly from the oven and analyzed while hot to minimize re-expansion of smectitic clays. Additionally, the count time of heated K-treated slides was reduced to 1 sec/step to further reduce opportunities for re-expansion of swelling clay components. Slides of the 2-15- μm fractions were stored at 54% relative humidity and analyzed under ambient humidity by step scanning from 2-40° 2-theta. The mineralogical components of the samples were identified using the International Powder Diffraction File database and simulated diffraction patterns generated using NEWMOD (Reynolds & Reynolds, 1996).

Stewart, G., Glasmann, J.R., Grant, G.E., Lewis, S.L. and Ninneman, J., 2002. Evaluation of Fine Sediment Intrusion into Salmon Spawning Gravels as Related to Cougar Reservoir Sediment Releases. Unpublished report prepared for U.S. Army Corps of Engineers, Portland District Office, dated October 4, 2002.

APPENDIX B: GRAIN SIZE DATA

Hydrometer Analysis.....	B1
Sieving and Hydrometer Data.....	B2
Gravel Sieving Data.....	B3
Pebble Count Data by Site.....	B4
Piezometer Data.....	B4
Coarse Fraction Within Core Variability	B5
Fine Fraction Within Core Variability.....	B7

Hydrometer Analysis

	%				#g in 40g used		
	sand	silt	clay	silt & clay	sand	silt	clay
SFA1-1A	94.21	2.34	3.44	5.79	27.36	0.68	1.00
SFA1-1B	97.05	0.45	2.50	2.95	38.82	0.18	1.00
SFA1-1C	95.80	0.45	3.75	4.20	38.32	0.18	1.50
SFA1-1D	94.55	1.70	3.75	5.45	37.82	0.68	1.50
SFA1-2A	96.32	0.56	3.12	3.68	30.86	0.18	1.00
SFA1-2B	95.80	1.70	2.50	4.20	38.32	0.68	1.00
SFA1-2C	95.80	1.70	2.50	4.20	38.32	0.68	1.00
SFA1-2D	94.55	1.70	3.75	5.45	37.82	0.68	1.50
SFA1-3A	95.80	1.70	2.50	4.20	38.32	0.68	1.00
SFA1-3B	95.80	1.70	2.50	4.20	38.32	0.68	1.00
SFA1-3C	94.55	1.70	3.75	5.45	37.82	0.68	1.50
SFA1-3D	94.55	1.70	3.75	5.45	37.82	0.68	1.50
SFA2-A~							
SFA2-B*							
SFA2-C	99.55	0.00	0.45	0.45	39.82	0.00	0.18
SFA2-D*							
SFB1-A	89.10	4.20	6.70	10.90	35.64	1.68	2.68
SFB1-B	89.10	4.20	6.70	10.90	35.64	1.68	2.68
SFB1-C	85.35	5.45	9.20	14.65	34.14	2.18	3.68
SFB1-D	81.60	9.20	9.20		32.64	3.68	3.68
SFB2-1A*							
SFB2-1B	89.48	1.85	8.67	10.52	32.82	0.68	3.18
SFB2-1C	87.85	2.95	9.20	12.15	35.14	1.18	3.68
SFB2-1D	77.82	9.65	12.53	22.18	27.09	3.36	4.36
SFB2-2A*							
SFB2-2B	75.70	12.15	12.15	24.30	30.28	4.86	4.86
SFB2-2C	78.20	10.90	10.90	21.80	31.28	4.36	4.36
SFB2-2D	75.70	10.90	13.40	24.30	30.28	4.36	5.36
SFB2-3A	88.20	3.40	8.40	11.80	35.28	1.36	3.36
SFB2-3B	84.45	4.65	10.90	15.55	33.78	1.86	4.36
SFB2-3C	80.70	8.40	10.90	19.30	32.28	3.36	4.36
SFB2-3D	78.20	9.65	12.15	21.80	31.28	3.86	4.86
SFB3-A	88.20	3.40	8.40	11.80	35.28	1.36	3.36
SFB3-B	86.95	4.65	8.40	13.05	34.78	1.86	3.36
SFB3-C	80.70	9.65	9.65	19.30	32.28	3.86	3.86
SFB3-D	81.95	8.40	9.65	18.05	32.78	3.36	3.86
SFB4-A	88.20	3.40	8.40	11.80	35.28	1.36	3.36
SFB4-B	88.20	3.40	8.40	11.80	35.28	1.36	3.36
SFB4-C	85.70	5.90	8.40	14.30	34.28	2.36	3.36
SFB4-D*							
MS1-A	91.95	7.15	0.90	8.05	36.78	2.86	0.36
MS1-B	90.70	7.15	2.15	9.30	36.28	2.86	0.86
MS1-C	90.70	7.15	2.15	9.30	36.28	2.86	0.86
MS1-D	88.20	8.40	3.40	11.80	35.28	3.36	1.36
MS2-A*							
MS2-B	90.70	5.90	3.40	9.30	36.28	2.36	1.36
MS2-C	88.20	8.40	3.40	11.80	35.28	3.36	1.36
MS2-D	85.70	10.90	3.40	14.30	34.28	4.36	1.36
MS3-A	90.70	5.90	3.40	9.30	36.28	2.36	1.36
MS3-B	90.70	5.90	3.40	9.30	36.28	2.36	1.36
MS3-C	90.70	7.15	2.15	9.30	36.28	2.86	0.86
MS3-D	90.70	5.90	3.40	9.30	36.28	2.36	1.36

notes:

~ too small to sieve or hydrometer

*too small for meaningful result (<40g)

all cobbles >128mm removed from original samples in field

Sieving and hydrometer

	grams in bulk					percent in bulk sample				
	gravel	finer	sand	silt	clay	gravel	finer	sand	silt	clay
SFA1-1A	3115.9	29.6	27.8	0.7	1.0	99.06	0.94	0.89	0.02	0.03
SFA1-1B	2623.4	78.0	75.7	0.4	1.9	97.11	2.89	2.80	0.01	0.07
SFA1-1C	2651.3	144.8	138.7	0.7	5.4	94.82	5.18	4.96	0.02	0.19
SFA1-1D	1075.0	161.3	152.5	2.7	6.0	86.95	13.05	12.34	0.22	0.49
SFA1-2A	2134.1	32.7	31.5	0.2	1.0	98.49	1.51	1.45	0.01	0.05
SFA1-2B	2071.0	64.5	61.8	1.1	1.6	96.98	3.02	2.89	0.05	0.08
SFA1-2C	2011.3	68.0	65.1	1.2	1.7	96.73	3.27	3.13	0.06	0.08
SFA1-2D	1290.5	69.6	65.8	1.2	2.6	94.88	5.12	4.84	0.09	0.19
SFA1-3A	2212.6	153.6	147.1	2.6	3.8	93.51	6.49	6.22	0.11	0.16
SFA1-3B	2183.4	80.8	77.4	1.4	2.0	96.43	3.57	3.42	0.06	0.09
SFA1-3C	2827.8	148.4	140.3	2.5	5.6	95.02	4.98	4.71	0.08	0.19
SFA1-3D	1939.0	195.5	184.9	3.3	7.3	90.84	9.16	8.66	0.16	0.34
SFA2-A~	1146.5	0.2				99.98	0.02			
SFA2-B*	1424.8	4.8				99.66	0.34			
SFA2-C	1758.6	69.5	69.2	0.0	0.3	96.20	3.80	3.78	0.00	0.02
SFA2-D*	261.9	13.1				95.22	4.78			
SFB1-A	2511.9	140.8	125.5	5.9	9.4	94.69	5.31	4.73	0.22	0.36
SFB1-B	3239.1	427.0	380.4	17.9	28.6	88.35	11.65	10.38	0.49	0.78
SFB1-C	2507.3	303.4	258.9	16.5	27.9	89.21	10.79	9.21	0.59	0.99
SFB1-D	1513.0	175.1	142.9	16.1	16.1	89.63	10.37	8.46	0.95	0.95
SFB2-1A*		21.2				0.00	100.00			
SFB2-1B	524.0	36.9	33.0	0.7	3.2	93.43	6.57	5.88	0.12	0.57
SFB2-1C	1623.3	194.7	171.0	5.7	17.9	89.29	10.71	9.41	0.32	0.99
SFB2-1D	235.8	35.3	27.4	3.4	4.4	86.99	13.01	10.13	1.26	1.63
SFB2-2A*	3526.6	5.7				99.84	0.16			
SFB2-2B	2836.9	108.0	81.7	13.1	13.1	96.33	3.67	2.77	0.45	0.45
SFB2-2C	2792.2	415.2	324.7	45.3	45.3	87.05	12.95	10.12	1.41	1.41
SFB2-2D	654.6	205.2	155.4	22.4	27.5	76.13	23.87	18.07	2.60	3.20
SFB2-3A	632.8	207.2	182.7	7.0	17.4	75.34	24.66	21.75	0.84	2.07
SFB2-3B	1818.3	831.8	702.4	38.7	90.7	68.61	31.39	26.51	1.46	3.42
SFB2-3C	2652.5	704.0	568.1	59.1	76.7	79.03	20.97	16.93	1.76	2.29
SFB2-3D	2028.0	355.6	278.1	34.3	43.2	85.08	14.92	11.67	1.44	1.81
SFB3-A	1695.7	256.2	226.0	8.7	21.5	86.87	13.13	11.58	0.45	1.10
SFB3-B	4179.9	565.6	491.8	26.3	47.5	88.08	11.92	10.36	0.55	1.00
SFB3-C	2078.6	475.5	383.8	45.9	45.9	81.38	18.62	15.02	1.80	1.80
SFB3-D	197.5	68.5	56.1	5.8	6.6	74.25	25.75	21.11	2.16	2.49
SFB4-A	1090.4	332.9	293.7	11.3	28.0	76.61	23.39	20.63	0.80	1.96
SFB4-B	392.6	417.7	368.4	14.2	35.1	48.45	51.55	45.47	1.75	4.33
SFB4-C	279.8	343.5	294.4	20.3	28.9	44.89	55.11	47.23	3.25	4.63
SFB4-D*	68.2	25.2				73.05	26.95			
MS1-A	4650.8	491.6	452.0	35.1	4.4	90.44	9.56	8.79	0.68	0.09
MS1-B	5315.6	922.1	836.3	65.9	19.8	85.22	14.78	13.41	1.06	0.32
MS1-C	3526.4	988.7	896.7	70.7	21.3	78.10	21.90	19.86	1.57	0.47
MS1-D	3154.0	564.2	497.6	47.4	19.2	84.83	15.17	13.38	1.27	0.52
MS2-A*	465.4	10.6				97.78	2.22			
MS2-B	1471.2	285.0	258.5	16.8	9.7	83.77	16.23	14.72	0.96	0.55
MS2-C	1594.0	315.1	277.9	26.5	10.7	83.50	16.50	14.56	1.39	0.56
MS2-D	748.7	142.5	122.1	15.5	4.8	84.01	15.99	13.70	1.74	0.54
MS3-A	1477.6	834.8	757.2	49.3	28.4	63.90	36.10	32.74	2.13	1.23
MS3-B	306.7	1220.2	1106.7	72.0	41.5	20.09	79.91	72.48	4.71	2.72
MS3-C	1108.1	690.9	626.7	49.4	14.9	61.59	38.41	34.83	2.75	0.83
MS3-D	2225.5	210.0	190.4	12.4	7.1	91.38	8.62	7.82	0.51	0.29

notes:

~ too small to sieve or hydrometer

*too small for meaningful result (<40g)

all cobbles >128mm removed from original samples in field

Gravel Sieving

	total	grams						percent					
		64mm	32mm	16mm	8mm	4mm	2mm	64mm	32mm	16mm	8mm	4mm	2mm
SFA1-1A	3117.4	0.0	851.5	1255.3	709.4	232.1	69.1	0.00	27.31	40.27	22.76	7.45	2.22
SFA1-1B	2624.9	0.0	761.1	939.4	582.5	244.2	97.7	0.00	29.00	35.79	22.19	9.30	3.72
SFA1-1C	2645.6	910.6	710.3	309.8	377.2	209.5	128.2	34.42	26.85	11.71	14.26	7.92	4.85
SFA1-1D	1075.2	0.0	620.4	210.1	140.6	56.3	47.8	0.00	57.70	19.54	13.08	5.24	4.45
SFA1-2A	2136.1	0.0	111.0	867.0	797.5	300.9	59.7	0.00	5.20	40.59	37.33	14.09	2.79
SFA1-2B	2072.4	0.0	0.0	848.0	845.8	287.3	91.3	0.00	0.00	40.92	40.81	13.86	4.41
SFA1-2C	2007.4	0.0	340.5	842.4	503.8	197.6	123.1	0.00	16.96	41.96	25.10	9.84	6.13
SFA1-2D	1290.9	0.0	735.3	264.9	169.4	64.3	57.0	0.00	56.96	20.52	13.12	4.98	4.42
SFA1-3A	2213.3	0.0	68.4	684.9	883.8	382.2	194.0	0.00	3.09	30.94	39.93	17.27	8.77
SFA1-3B	2183.1	0.0	0.0	570.6	878.7	512.7	221.1	0.00	0.00	26.14	40.25	23.48	10.13
SFA1-3C	2825.0	0.0	509.8	1096.0	836.3	269.1	113.8	0.00	18.05	38.80	29.60	9.53	4.03
SFA1-3D	1939.6	621.2	128.4	631.3	388.5	111.9	58.3	32.03	6.62	32.55	20.03	5.77	3.01
SFA2-A~	1147.6	433.1	678.7	21.5	10.1	2.6	1.6	37.74	59.14	1.87	0.88	0.23	0.14
SFA2-B*	1426.0	1010.1	71.8	200.4	73.5	44.4	25.8	70.83	5.04	14.05	5.15	3.11	1.81
SFA2-C	1757.8	389.7	700.5	320.1	117.2	129.3	101.0	22.17	39.85	18.21	6.67	7.36	5.75
SFA2-D*	262.1	0.0	131.1	74.9	22.2	21.2	12.7	0.00	50.02	28.58	8.47	8.09	4.85
SFB1-A	2513.6	279.7	1181.9	524.0	264.0	148.5	115.5	11.13	47.02	20.85	10.50	5.91	4.60
SFB1-B	3240.0	1089.5	696.8	474.8	325.7	319.6	333.6	33.63	21.51	14.65	10.05	9.86	10.30
SFB1-C	2500.8	1328.6	108.7	468.1	225.6	173.7	196.1	53.13	4.35	18.72	9.02	6.95	7.84
SFB1-D	1513.2	682.3	417.9	107.5	144.9	77.0	83.6	45.09	27.62	7.10	9.58	5.09	5.52
SFB2-1A*													
SFB2-1B	523.3	0.0	164.4	149.9	104.2	66.7	38.1	0.00	31.42	28.65	19.91	12.75	7.28
SFB2-1C	1614.4	454.8	351.3	295.6	219.8	153.7	139.2	28.17	21.76	18.31	13.61	9.52	8.62
SFB2-1D	235.7	0.0	72.6	93.4	34.8	19.1	15.8	0.00	30.80	39.63	14.76	8.10	6.70
SFB2-2A*	3527.6	2164.4	911.8	347.2	79.5	19.3	5.4	61.36	25.85	9.84	2.25	0.55	0.15
SFB2-2B	2838.2	1066.5	247.3	715.9	440.7	235.2	132.6	37.58	8.71	25.22	15.53	8.29	4.67
SFB2-2C	2775.9	860.0	457.8	470.4	384.6	324.1	279.0	30.98	16.49	16.95	13.85	11.68	10.05
SFB2-2D	657.6	0.0	153.6	189.0	149.7	80.9	84.4	0.00	23.36	28.74	22.76	12.30	12.83
SFB2-3A	631.2	0.0	0.0	123.4	301.2	108.4	98.2	0.00	0.00	19.55	47.72	17.17	15.56
SFB2-3B	1818.5	0.0	257.5	208.3	429.3	511.5	411.9	0.00	14.16	11.45	23.61	28.13	22.65
SFB2-3C	2647.3	0.0	1141.3	531.8	305.1	310.2	358.9	0.00	43.11	20.09	11.52	11.72	13.56
SFB2-3D	1700.7	0.0	586.4	594.2	212.5	154.8	152.8	0.00	34.48	34.94	12.49	9.10	8.98
SFB3-A	2028.0	915.6	538.1	219.6	124.4	101.7	128.6	45.15	26.53	10.83	6.13	5.01	6.34
SFB3-B	4181.0	1244.2	1428.5	707.8	291.6	252.2	256.7	29.76	34.17	16.93	6.97	6.03	6.14
SFB3-C	2076.3	0.0	1321.7	118.9	225.6	189.6	220.5	0.00	63.66	5.73	10.87	9.13	10.62
SFB3-D	197.3	0.0	74.0	21.1	42.5	28.9	30.8	0.00	37.51	10.69	21.54	14.65	15.61
SFB4-A	1090.9	0.0	0.0	414.2	337.3	173.6	165.8	0.00	0.00	37.97	30.92	15.91	15.20
SFB4-B	392.8	0.0	0.0	138.2	114.0	73.6	67.0	0.00	0.00	35.18	29.02	18.74	17.06
SFB4-C	280.1	0.0	178.1	48.5	21.0	17.0	15.5	0.00	63.59	17.32	7.50	6.07	5.52
SFB4-D*	68.1	0.0	0.0	59.9	2.6	2.1	3.5	0.00	0.00	87.96	3.82	3.08	5.14
MS1-A	4652.9	1351.8	1076.9	1053.5	630.5	326.0	214.2	29.05	23.14	22.64	13.55	7.01	4.60
MS1-B	5319.1	2148.7	1422.7	575.7	487.0	347.2	337.8	40.40	26.75	10.82	9.16	6.53	6.35
MS1-C	2689.0	754.0	903.8	608.1	222.6	111.5	89.0	28.04	33.61	22.61	8.28	4.15	3.31
MS1-D	3981.2	953.3	884.1	1011.1	479.3	334.2	319.2	23.95	22.21	25.40	12.04	8.39	8.02
MS2-A*	465.6	0.0	195.9	177.2	64.8	21.1	6.6	0.00	42.07	38.06	13.92	4.53	1.42
MS2-B	1471.6	0.0	217.9	523.7	362.9	234.5	132.6	0.00	14.81	35.59	24.66	15.94	9.01
MS2-C	1585.8	0.0	572.3	512.4	242.5	153.1	105.5	0.00	36.09	32.31	15.29	9.65	6.65
MS2-D	749.0	0.0	410.9	146.2	91.2	54.1	46.6	0.00	54.86	19.52	12.18	7.23	6.22
MS3-A	1478.0	0.0	78.6	648.7	312.0	237.4	201.3	0.00	5.32	43.89	21.11	16.06	13.62
MS3-B	306.4	0.0	0.0	42.4	84.5	74.0	105.5	0.00	0.00	13.84	27.58	24.15	34.43
MS3-C	1103.1	0.0	127.3	406.3	300.1	166.0	103.4	0.00	11.54	36.83	27.21	15.05	9.37
MS3-D	2225.8	1451.2	88.6	273.9	197.1	125.7	89.3	65.20	3.98	12.31	8.86	5.65	4.01

notes:

~ too small to sieve or hydrometer

*too small for meaningful result (<40g)

all cobbles >128mm removed from original samples in field

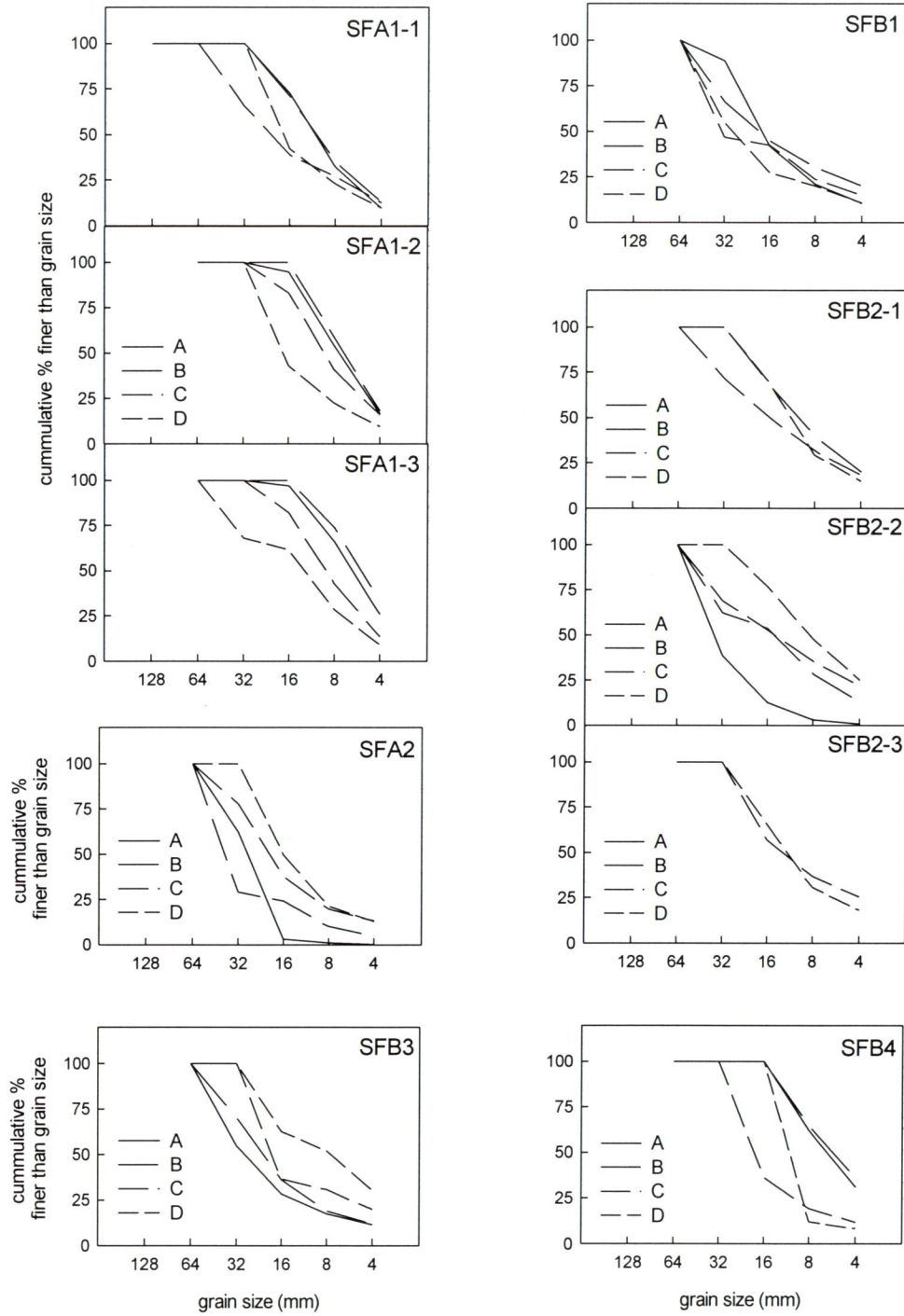
Pebble count data by site

phi	(mm)	SFA1	SFA2	SFB1	SFB2	SFB-3	SFB-4	MS1	MS2	MS3
0	<1	0	0	0	0	0	0	0	0	0
-1	1	0	0	3	3	4	3	7	1	2
-2	2	0	0	0	0	6	1	0	2	0
-3	4	4	2	4	5	5	4	3	2	12
-4	8	19	5	9	12	23	19	20	10	26
-5	16	52	13	23	29	32	60	31	34	35
-6	32	21	47	41	36	24	7	22	41	24
-7	64	3	33	20	11	5	1	15	10	1
-8	128	0	0	0	2	1	4	2	0	0
-9	256	1	0	0	2	0	1	0	0	0

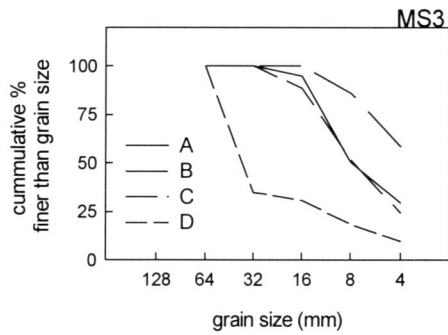
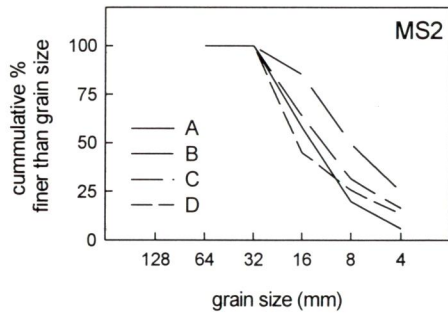
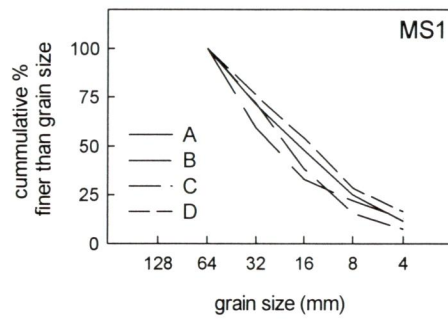
Piezometer Data (vertical head gradient)

	SFA1	SFA2	SFB1	SFB2	SFB3	SFB4	MS1	MS2	MS3
Depth of Rod (m)	0.2	0.2	0.2	0.2	0.2	0.1	0.22	NA	0.16
Stream Depth (m)	0.37	0.19	0.25	0.16	0.12	0.14	0.125	NA	0.18
Internal water column from casing (m)	0.84	1.045	0.965	1.045	1.105	1.215	1.07	NA	1.15
Stream Depth from casing (m)	0.84	1	0.94	1.045	1.08	1.205	1.06	NA	1.11
Difference in Head (m)	0	-0.045	-0.025	0	-0.025	-0.01	-0.01	NA	-0.04
Vertical Head Gradient	0	-0.225	-0.125	0	-0.125	-0.1	-0.045455	NA	-0.25

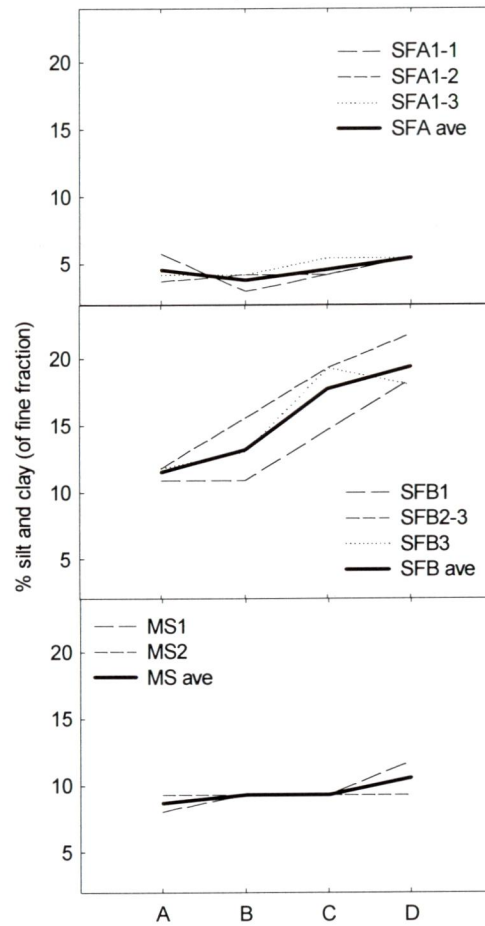
Within core variability - COARSE
no trend in data ($A+B+C+D = \text{ave}$)



Within core variability - COARSE



Within core variability - FINES
 %silt and clay generally increases with depth
 (B+C = ave)



Stewart, G., Glasmann, J.R., Grant, G.E., Lewis, S.L. and Ninneman, J., 2002. Evaluation of Fine Sediment Intrusion into Salmon Spawning Gravels as Related to Cougar Reservoir Sediment Releases. Unpublished report prepared for U.S. Army Corps of Engineers, Portland District Office, dated October 4, 2002.

APPENDIX C: PHOTOGRAPHS



SFA1 - Core #1



SFA1 - Core #2



SFA1 - Core #3



SFA2



SFB1

PHOTO NOT AVAILABLE

SFB2 - Core #1



SFB2 - Core #2



SFB2 - Core #3



SFB3



SFB4



MS1



MS2



MS3



Site SFB1 - Core just below Cougar Dam



Site SFA1 - Injecting CO₂



Melting SFA1 - Core #1 (note clear ice)



SFB2 - Core #2 (note dirty ice)



Hydrometer Setup