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CHANGES IN GRAIN-SIZE DISTRIBUTION IN A GRAVEL-BED STREAM DUE TO A POINT-SOURCE INFLUX OF FINE SEDIMENT

John A. Maloy

July, 1988

1899

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CHANGES IN GRAIN-SIZE DISTRIBUTION IN A GRAVEL-BED STREAM DUE TO A POINT-SOURCE INFLUX OF FINE SEDIMENT

A Thesis Presented to

The Faculty of

Western Washington University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science

by

John A. Maloy

July, 1988

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of the Requirements for the Degree
Master of Science

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ACKNOWLEDGMENTS

This study was greatly enhanced by the input of many people, but would not have been possible without the assistance and guidance of several people: Bob Thomas (Redwood Sciences Laboratory, Arcata, CA), John Wolcott (University of British Columbia), and Harvey Kelsey. Bob Thomas was responsible for much of the sampling design in this study, many of the statistical analysis procedures, and put lots of time and energy into trying to teach me the rudiments of statistics. John Wolcott was invaluable for his assistance with sampling and laboratory techniques. Harvey ended up being more a collaborator than an advisor, and it sometimes seems that this thesis is as much his as mine.

For financial assistance I would like to thank: The Forestry Sciences Lab in Corvallis, OR and the Geology Department. Both Kim Richey and my parents provided very generous financial and emotional support. I would also like to thank Mark Sandal, my field assistant, for his patience and ability to carry 50 kg of gravel after a long day of hefting large boulders. Additional field assistance was provided by John Sherriff, Kim Richey, and Paul Grabau. The remainder of my committee, Chris Suczek and Tom Lacher, provided many helpful reviews and comments, and were always quick to respond when I needed something. Tom Lisle and Leslie Reid, both at the Redwood Sciences Laboratory, also provided valuable and insightful comments. I would also like to thank anyone else I may have overlooked who helped make these two years a refreshing break from the realities of the working world.

ABSTRACT

The bedload of a gravel-bed stream was sampled from two reaches, one upstream and one downstream of a large ($1.0x10^6$ m^3 of material removed) landslide, in order to assess the change in particle-size distribution caused by the influx of the finer-grained landslide material. For sampling purposes, the bedload was initially stratified on the basis of apparent grain size variability into 11 strata, or channel map units. Surface and subsurface materials were sampled independently. Subsurface sample sites were selected using stratified random sampling, with 30 sites upstream and 36 downstream of the landslide. Sampling techniques were modified from Church et al. (1987) for the subsurface material and were based on weight proportion. Surface material was sampled using Wolman's (1954) pebble-count method. Thus subsurface statistics were based on weight proportion, while surface analysis was based on number of particles. The two reaches were compared using the same pairwise comparison for both the surface and subsurface material. Subsurface material differs significantly between upstream and downstream reaches (finer downstream) in all but the finest and largest grain-size classes. Surface distributions also differ significantly between upstream and downstream (also finer downstream). Surface material was compared to subsurface material by calculating the ratio of surface graphic mean (Folk, 1980) to subsurface graphic mean for the identical range of grain sizes. This technique assumes statistical equivalence between sieve-by-weight (subsurface) and grid-by-number (surface) techniques of data collection. Ratios of surface graphic mean to subsurface graphic mean for the channel map units ranged from 1.0 to 6.0, with only one channel unit having a ratio of less than 2. Surface to subsurface graphic mean ratios greater than 2 indicate different grain-size populations. Because of

different grain-size populations, the dominant mechanism of surface coarsening in the Deer Creek channel is probably equal mobility of all grain sizes during transport rather than winnowing of finer grain sizes.

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INTRODUCTION

This study documents the effects of a large point source of fine sediment introduced into a gravel-bed stream. Slight modifications of the techniques for sampling gravel-bed streams of Church et al. (1987) were used to assess the distribution of particle sizes immediately upstream and downstream of a large landslide. Two reaches, one upstream (611 m long) and one downstream (411 m long) of the landslide, were sampled in order to: assess whether the sampling technique could distinguish clearly between the two reaches (qualitatively it was clear that the landslide had enriched the bed surface of the lower reach with fines from the landslide); determine if the apparent finer-grained population in the lower reach is the result of intrusion of fines into the subsurface or mixing of fines into both the surface and subsurface layers during bedload transport of both layers; and investigate the relationship between subsurface and surface material.

River gravels are highly variable, both spatially and temporally, and sampling them is problematical. Statistically valid sampling techniques are a requisite for field measurements of grain-size distribution. Kellerhals and Bray (1971) provide an overview of available sampling methods and a set of conversions between particle-size data sets when data collected by more than one method is compared. In field measurements, surface and subsurface material should be sampled independently (Gomez, 1983a). Samples representative of the population can be attained only if samples of sufficient size are obtained (Mosley and Tindale, 1985). The most comprehensive analyses of the methods and problems associated with sampling river gravels are those of Church et al. (1987) and Wolcott and Church (1987); and many of the techniques used in this study are drawn from those investigations.

I used particle-size data to address the question of whether the fine sediment from the landslide intruded into the gravelly subsurface below the landslide, and to quantify the relationship between surface and subsurface material. Since the surface material was substantially coarser than the subsurface material, I attempted to clarify whether the surface material is an armour or a pavement. Armour is a truncated (winnowed), immobile surface layer (Bray and Church, 1980), while pavement is a mobile bed surface, resulting from equal mobility of grains of various sizes (Parker and Klingeman, 1982), rather than from selective transport of smaller grains.

These field results are pertinent to two concerns related to transport of heterogeneous grain sizes in a stream. The first is the measurement of the intrusion of fine sediment into the gravel bed of streams that support anadromous fish and other aquatic biota (Meehan and Swanston, 1977; Cederholm and Salo, 1979); the other addresses whether rates of bedload transport increase due to an introduction of fine sediment into a coarse bedload stream (Iseya and Ikeda, 1987; Dietrich et al., 1988).

STUDY AREA

Deer Creek is a steep (average gradient=0.014) gravel-bed stream that drains a 171 km^2 basin in the western foothills of the Cascade Mountains, Washington. It is tributary to the North Fork Stilliguamish River at Oso, Skagit County, Washington (Figure 1). Deer Creek is an important nursery stream for summer-run steelhead and as such has been closed to fishing since 1937. Seasonal variations in flow are high, due to the short, dry summers and long, wet winters. Annual precipitation is 2300 mm per year, 85 percent of which falls between September and April (John Thompson, oral comm., 1988).

In the study area (Figure 2), Deer Creek flows through a thick accumulation (~350 m) of upper Pleistocene glacial sediments deposited in a broad (average of 500 m wide) glacial valley. The glacial sediments overlie bedrock and form two distinct terraces that were probably cut just before and during deglaciation. The risers of both terraces are deeply dissected by slumping and landsliding. Landslides have occurred historically, and ancient landslides predate old-growth forests (Ryan et al., 1984), indicating that landsliding in the glacial sediment has been a persistent, major source of sediment to Deer Creek. Although many slides exist in the basin, the DeForest Creek landslide is presently the major point source of sediment to the Deer Creek channel. This sediment source prompted a comparative field study of channel reaches above and below the landslide.

Bedrock in the Deer Creek basin consists of Paleozoic and Mesozoic metamorphic rocks of the North Cascades (Reller, 1986; Brown et al., 1986) and the Eocene Chuckanut Formation (fluvial sandstone with minor shale), which is in both depositional and fault contact with the North Cascades rocks (Reller, 1986). Very few outcrops of bedrock occur in the channel

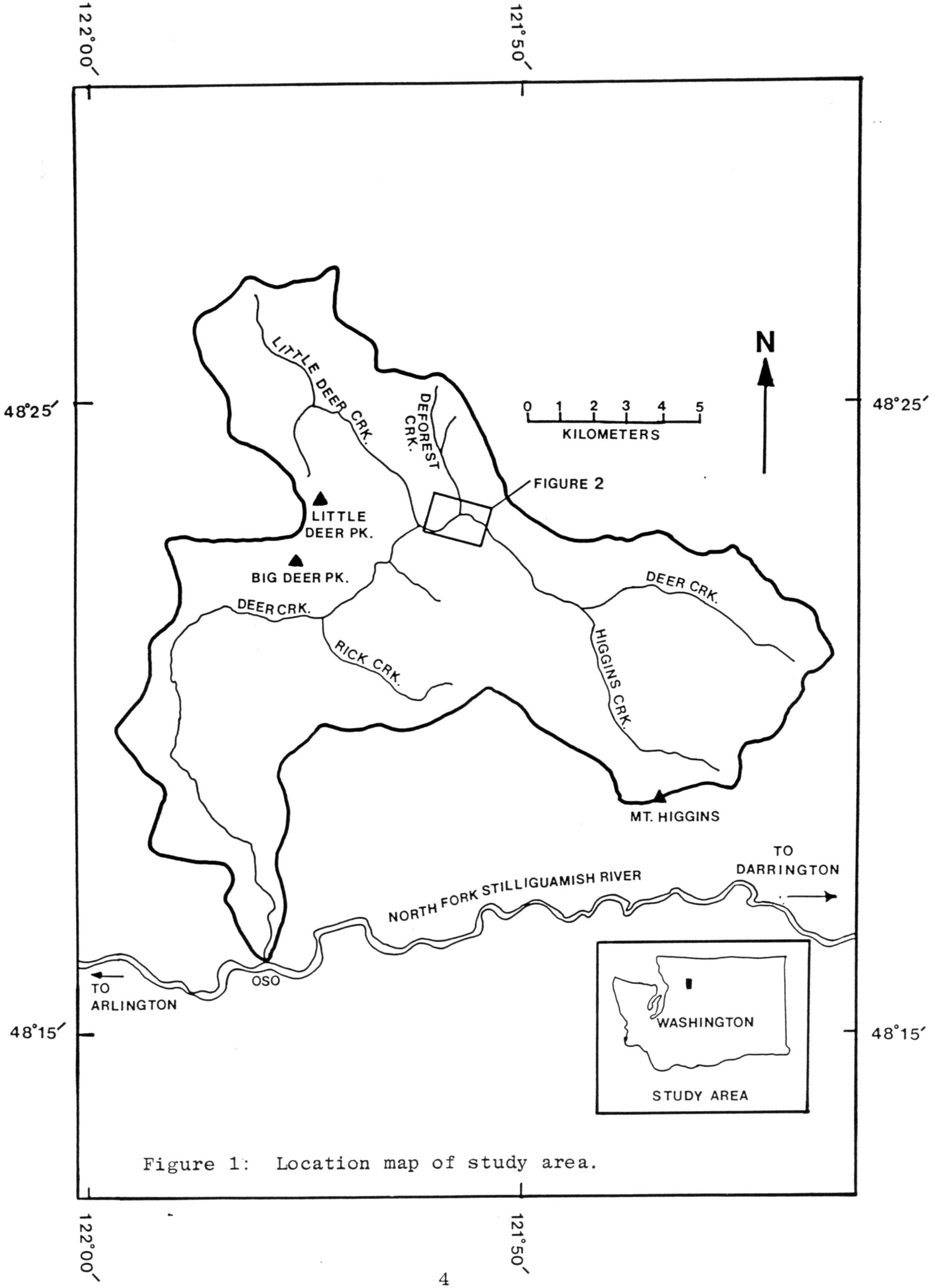

Figure 1: Location map of study area.

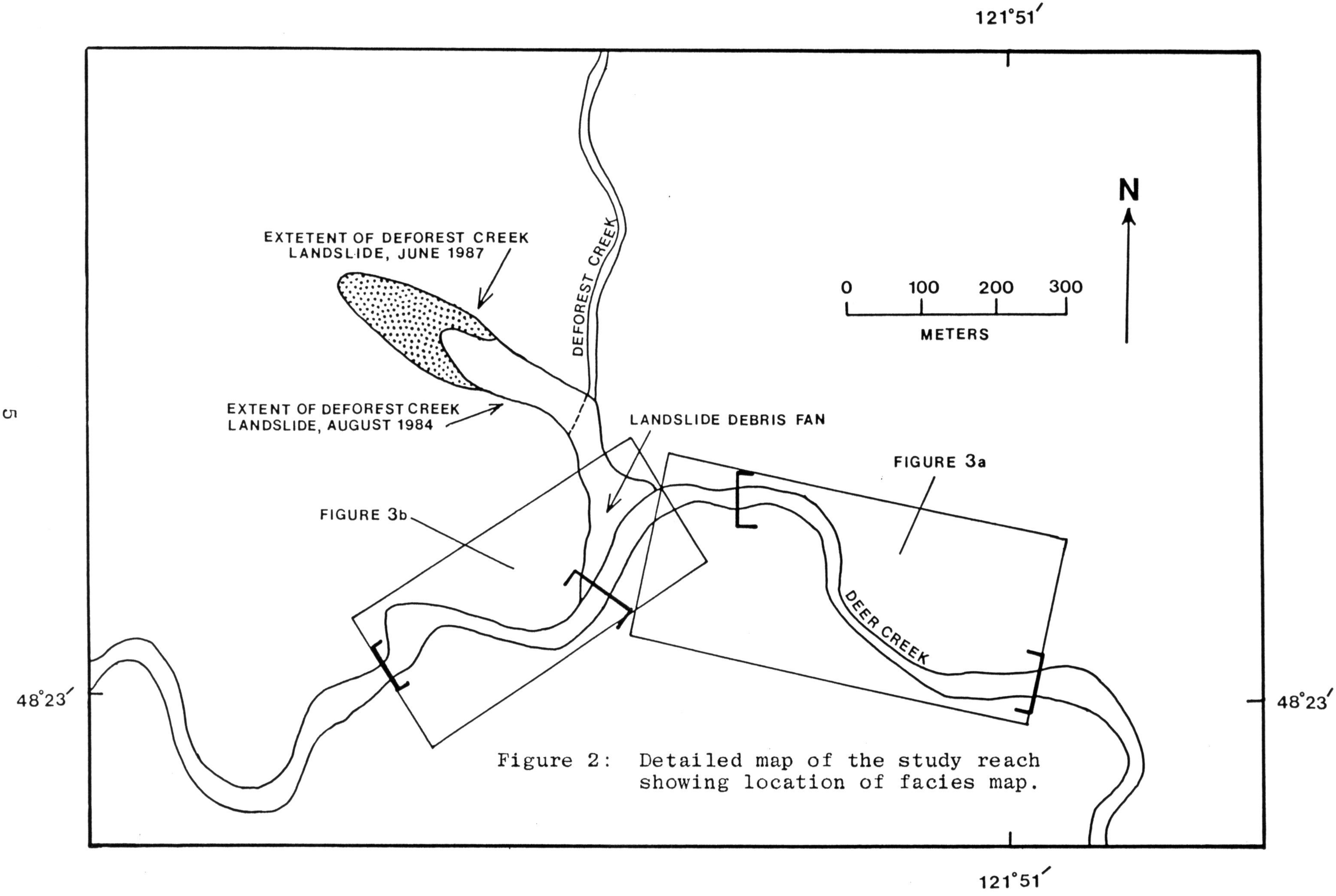

Figure 2: Detailed map of the study reach showing location of facies map.

reach, however; and most exposed bank material is unconsolidated glacial sediment. The largest transportable clasts in the channel (up to 2 m) are a mixture of Chuckanut sandstone boulders and North Cascades rocks from the drainage basin, and exotic, glacially-transported metamorphic and igneous boulders.

In winter, 1983, a large landslide occurred in the DeForest Creek basin (Figure 2). Exact cause of the failure is not known, though both the Washington State Department of Natural Resources (Ryan et al., 1984), and Thompson (1988) attribute the failure to unusually high seasonal groundwater levels. Over a two-year period (1983-1984), due to at least two debris-flow events from the DeForest Creek landslide (Thompson, 1988), the landslide introduced a large quantity of fine glacial sediment into the gravel-bed channel of Deer Creek, drastically increasing turbidity and noticeably changing channel-bed texture immediately downstream of the landslide. Total volume of the landslide as of 1987 exceeds 1.0×10^6 m^3, of which 93 percent has been introduced to the channel and the other 7 percent is stored in the debris fan (Thompson, 1988). As of spring, 1987, the headwall of the slide was receding at a rate of 0.3 m/day, providing a continuous source of fine sediment to the main channel of Deer Creek. For the period 1984 to 1987, turbidity in Deer Creek was high all year except for the lowest flow period in August.

Total length of the study reach is 1408 m, 611 m upstream of DeForest Creek and 411 m downstream of DeForest Creek, with an unsampled intermediate reach bordering the debris fan that is 386 m long (Figure 2). Geomorphology of the two reaches is quite similar (Figure 3), but bars downstream are substantially larger than those upstream. Although the downstream reach is 200 m shorter than the upstream reach, total area of the downstream bars is 1.5 times that of the bars in the upstream reach

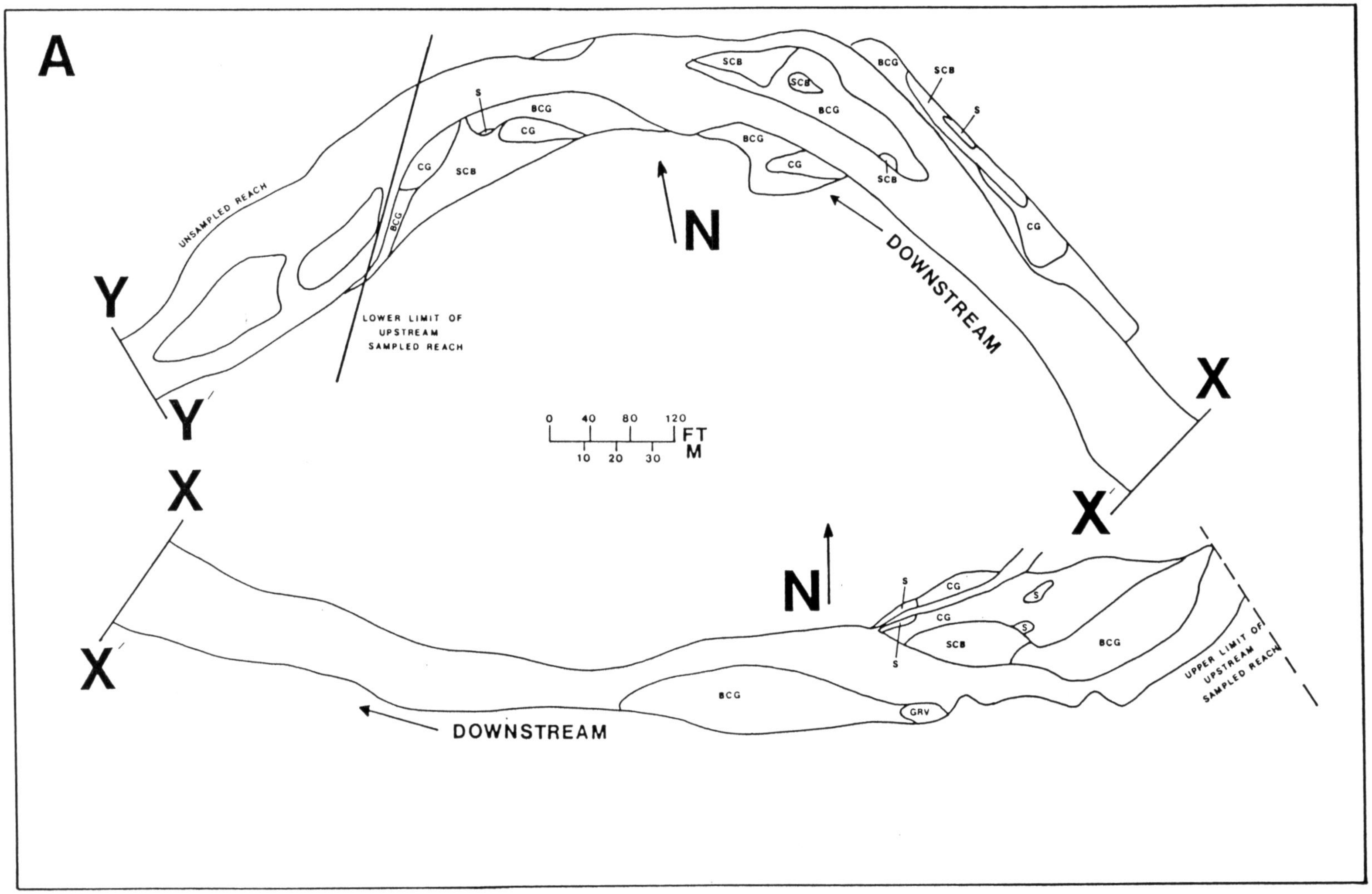

Figure 3a: Plane-table map of the upstream study reach. See Figure 2 for location of reaches in relation to the DeForest Creek landslide. Blank area within the sample reaches indicate area of wetted channel at time of sampling.

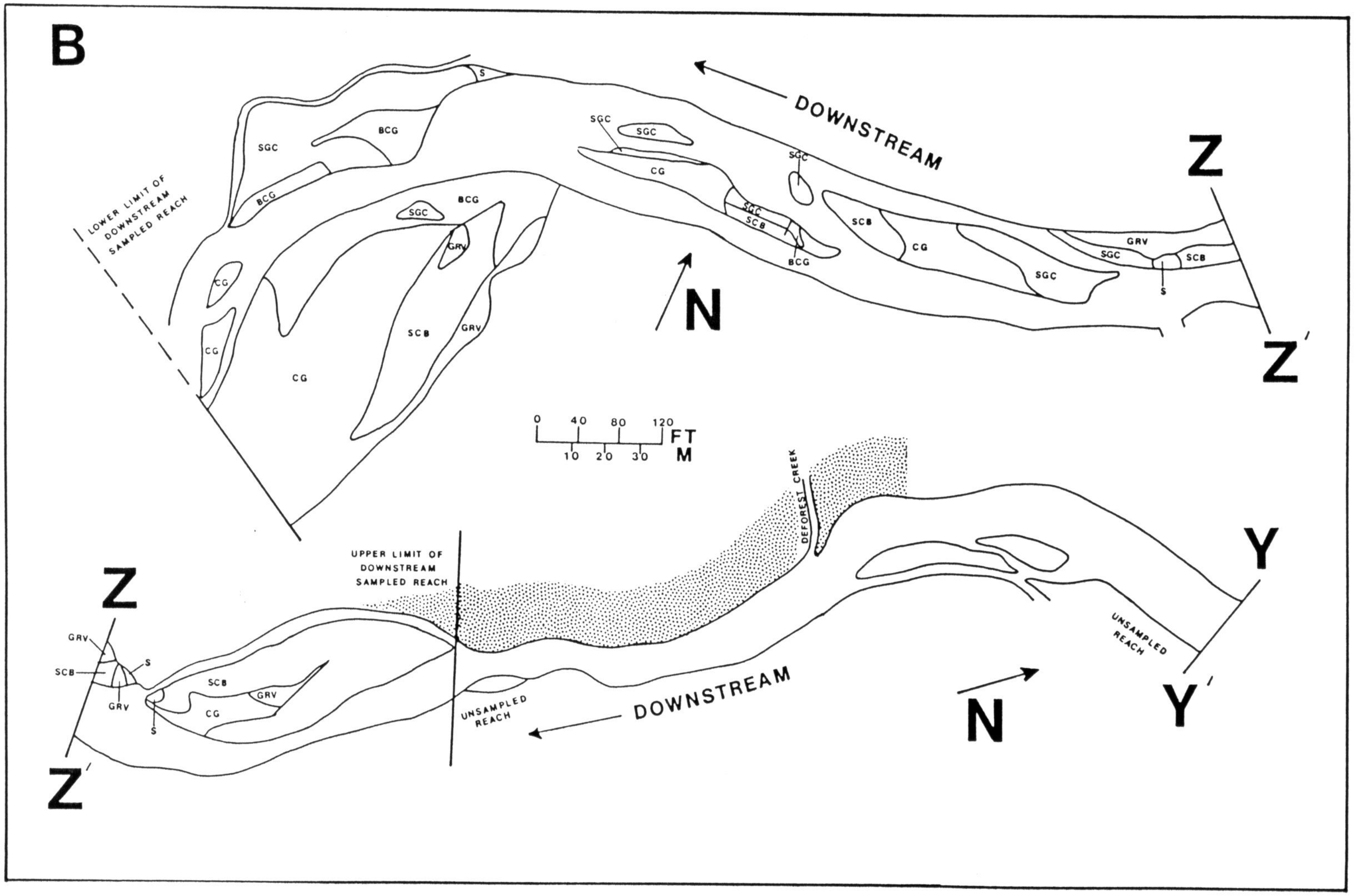

Figure 3b: Plane-table map of the downstream study reach. See Figure 2 for location in relation to the DeForest Creek landslide. Stipple pattern indicates portions of the right bank where the debris fan abuts the edge of the active channel. Blank areas within the sample reaches indicate area of wetted channel at time of sampling.

($9775\ m^2$ vs. $6344\ m^2$).

Qualitatively, gravel bars upstream of the landslide appear more coarse than those downstream. Channel-facies mapping, described in detail below, supports this impression. The coarsest facies comprises 57 percent of the total upstream area and only 15 percent of total downstream area, while one of the medium grain-size facies comprises 23 percent of the upstream area and 39 percent of the downstream area (Table 1). While these facies are not necessarily identical between upstream and downstream reaches, they are indicative of the relative coarseness between facies and illustrate the apparent greater abundance of finer grain sizes downstream of the landslide.

While the overall appearance of the surface material was different downstream from upstream, the downstream surface material was visually similar to the surface of the eroding debris fan at the base of the landslide. However, the debris fan has a greater slope than the downstream reach (.022 versus .015) and a much lower mean annual discharge. I was concerned about locating the downstream reach in close proximity to the debris fan (Figure 2), but the confluence of Little Deer Creek with Deer Creek is just downstream of the lower study reach (Figure 2). Because of the proximity of Little Deer Creek, I could not place the lower study reach any farther downstream without sampling a downstream reach with considerably larger flows than the upstream reach.

METHODS

Sampling Technique

Particle sizes were sampled from two reaches, one upstream and one downstream of the DeForest Creek landslide (Figures 2 and 3). The two selected reaches have similar gradients (0.0160 upstream and 0.0145 downstream) and similar geomorphic character (Figure 3). Subsurface particle-size classes ranged from 4 phi (.0625 mm) to -2 phi (4 mm) in 0.25 phi intervals and from -2 phi to -7.5 phi in 0.5 phi intervals. A size class consisting of all material finer than 4 phi was also measured, for a total of 37 size-classes. Surface samples were tallied into 13 size classes, -2 phi to -7.5 phi in 0.5 phi intervals. All material finer than -2 phi was measured as one size class. The classification of grain sizes used throughout this study is from Dunne and Leopold (1978).

For sampling grain sizes in the Deer Creek study reaches, I chose a random sampling procedure, rather than a systematic sampling design. Systematic sampling is easy to design and apply and generally lowers the variance (Cochran, 1963). However, there is no reliable technique for estimating variance in systematic-sampling schemes (Cochran, 1963), because variance calculations are based on random variables. In this study, I compare data sets, so estimating the variance is necessary. Random sampling is generally more difficult to apply, and more samples are needed to lower the variance to a level comparable with systematic sampling. However, variance can be estimated in random sampling schemes, and the number of samples needed to obtain lower variance can be reduced by using stratified random-sampling techniques (Cochran, 1963). Because of the great spatial variability in river gravels, I used stratified random sampling to determine subsurface sample locations.

Heterogenous bar material in the study reach was stratified

TABLE 1. CLASSIFICATION OF FACIES USED TO STRATIFY THE POPULATION OF GRAINS IN THE DEER CREEK CHANNEL FOR SAMPLING PURPOSES. FACIES ARE LISTED FROM SORTED AT THE TOP OF THE COLUMN TO INCREASINGLY MORE POORLY SORTED AT THE BASE OF THE COLUMN. THE CLASSIFICATION OF GRAIN SIZES USED FOR THIS STUDY IS FROM DUNNE AND LEOPOLD (1978).

FACIES (STRATUM)	TYPICAL CHARACTERISTICS	AREA(m^2)* UPSTREAM REACH	AREA(m^2)* DOWNSTREAM REACH	NUMBER OF SAMPLES
Sand	Typically all sand and finer material. Occasional scattered gravel.	80.0 (1.25)	227.0 (2.33)	3
CG	A mixture of cobbles and gravel, either can predominate. Interstitial sand is present.	1457.4 (22.74)	3833.0 (39.30)	6
GRAVEL	Mostly gravel with interstitial sand. Cobbles rare. Strongly bimodal.	73.1 (1.14)	732.1 (7.51)	3
BCG	Very coarse and pooly sorted. Interstitial sand only. Boulders sometimes predominate.	3605.8 (56.25)	1484.8 (15.23)	8
SCG	Same grain sizes present as CG, but much higher fraction of sand.	N.A.	1454.3 (14.91)	6
SCB	Very pooly sorted and coarse. Similar to BCG, but sand can predominate.	1193.8 (18.62)	2020.1 (20.72)	10

*Number in parentheses percent of total surface area for each facies.

(classified) into relatively homogenous facies in order to lower the sample variance and reduce the total number of samples needed to obtain a representative sample of the population. The criteria for the classification were grain-size and degree of sorting. The classification (Table 1) is subjective, and probably would not be strictly reproducible by other workers, but the intent of the classification (stratification) was to facilitate between reach comparisons by lowering overall variance, while at the same time selecting fewer samples. The intent was not to produce identical and reproducible facies maps for both reaches. Five facies were identified in the upstream reach, and an additional sixth facies was identified downstream. These facies are the stratum in the stratified random-sampling (Cochran, 1963); from here on, the field-mapped facies will be called strata.

The strata were mapped on a plane table (Fig. 3), and subsurface sample sites were then chosen randomly (see Appendix 1 for a more detailed explanation of sampling procedures). The number of sites per stratum was determined by the apparent variability of each stratum, the visually more variable strata being assigned a larger number of sample sites. Total number of sample sites was chosen based on a realistic estimate of available time for sampling.

Field Data Collection

Subsurface samples were weighed. The samples were obtained at the predetermined sites after clearing the surface to the depth of the largest exposed clast. Holes covered a one square-meter area and were excavated to a depth of 200 mm. If more material was needed, the holes were expanded in area rather than depth, so all holes were of equal depth.

Sample size was determined by the weight of the largest particle present at the cleared sample site (Church et al., 1987), a procedure designed to ensure the presence of a number of particles in that largest size-class sufficient for statistical analysis.

For subsurface samples, upper and lower truncation limits were necessary. Particle sizes less than 4 phi (.0625 mm) were sampled as one size class instead of in 0.25 phi intervals because material finer than 4 phi cannot be sieved by conventional methods. An upper truncation limit of -8 phi (256 mm) was imposed because particles greater than 256 mm necessitate unreasonably large (>500 kg) field samples. The upper limit is reasonable for this study, as I observed only 8 particles larger than 256 mm during the sampling of 66 sites.

After the correct weight for a particular sample was determined, bulk samples were collected; and material greater than -4 phi(16 mm) was sieved in 0.5 phi intervals in the field. A split of 10-12 kg, an amount of material finer than -4 phi sufficient for analysis, was taken from the remaining material less than -4 phi and carried back to the lab. Collection techniques for field data are described in detail in Appendix 1. Approximate field time for the collection of 66 samples was 400 man-hours.

Surface samples were collected within each stratum using Wolman's (1954) pebble-count method (pebble counts were taken within strata so comparisons between surface and subsurface material could be facilitated). Two hundred particles were measured along the b-axis from each stratum for each of the upstream and downstream reaches. The counts were obtained from each stratum, not each sample site. The number of individual exposures of a stratum sampled depended on the areal extent and distribution of that stratum (Figure 3). For example, in strata with small areas, counts were obtained from every occurence of that stratum while in strata of greater area, counts were obtained from only one large exposure of the stratum. A lower truncation limit of -2 phi (4 mm) was necessary, because I could not consistently differentiate -2 phi from -1.5 phi (2.83 mm) in the field.

Laboratory Analysis

Laboratory analysis was performed on subsurface splits (10-12 kg split fractions of the field-collected sample) of the less than -4 phi fraction. Surface samples did not require further laboratory analysis because these samples were tallied by number in the field. Splits of the subsurface material were completely dried in a greenhouse. They were then soaked in a deffloculent, wet-sieved to remove the material finer than 4 phi (.0625 mm), and then sieved down to 4 phi in a Ro-Tap machine. Several splits were necessary during the sieving process, necessitating that all measured weights were equilibrated back to the original field weight. The equilibration was accomplished by multiplying the measured weight by the appropriate split ratio. See Appendix 2 for further explanation of split ratio calculation and laboratory procedures. Ultimately, each sample was sieved into 37 size-classes (including field sieving), 4 phi (.0625 mm) to -2 phi (4 mm) in 0.25 phi intervals (25 classes), -2 phi to -7.5 phi (181 mm) in 0.5 phi intervals (11 classes), and all material finer than 4 phi grouped as one size class.

Data Analysis

The mean weight proportion of each size-class from the upstream and downstream reaches were compared using a Games and Howell modified Tukey

Wholly Significant Difference test (WSD) (Games and Howell, 1976). Significance level was .05, predetermined before data analysis. Because weight proportion data are not normally distributed, the weight-proportion data from the subsurface samples were transformed by taking the arcsine square-root of each porportion before statistical analysis (Sokal and Rohlf, 1981). Surface data were not transformed because the actual number of particles was obtained. See Appendix 3 for a more detailed explanation of statistical tests.

Subsurface samples were tallied by weight and surface samples were tallied by count. I compared subsurface and surface samples assuming statistical equivalence of the two sampling techniques (Kellerhals and Bray, 1971). Disagreement about the true equivalence between these two methods exsists (Gomez, 1983b), but experiments by Church et al. (1987) support the formal conversion of Kellerhals and Bray (1971), and I have accepted the statistical equivalence of these two sampling techniques in the subsequent analysis.

RESULTS

Comparison of Subsurface Grain Size Between Reaches

Cumulative percent distributions for upstream and downstream subsurface material (Figure 4) show that, with the exception of the very fine sand and silt and finer size-classes, the subsurface of the downstream reach is relatively enriched with fine sediment (pebble size and smaller).

A Games and Howell (1976) modified Tukey Wholly Significant Difference (WSD) test was used to determine if the means of the arcsin square-root transformed proportion of each particle-size class differed significantly between upstream and downstream reaches. This test accounts for multiple pairwise comparisons and allows for hederoscedastic variances in each pairwise test (R.B. Thomas, written communication, 1988). The variance, weighted number of degrees of freedom, and critical value were not identical for each pairwise test for each particle size-class (Table 2). The variances, however, were not tested for statistical differences.

At a signifcance level of .05, material finer than -5 phi (32 mm) and coarser than 4.0 phi (.0625 mm) differed between upstream and downstream reaches, with the exception of 2.5<phi<2, where there was no significant difference (Figure 4).

Comparison of Surface Grain Size Between Reaches

Cumulative percent distributions for the upstream and downstream surface data (Figure 5) qualitatively show that the downstream reach is clearly finer than the upstream reach. Finer overall sediment size downstream indicates additional storage of fine sediment in the surface layer below the landslide. Since the surface distribution was truncated at -2 phi, it was impossible to determine if there was a significant

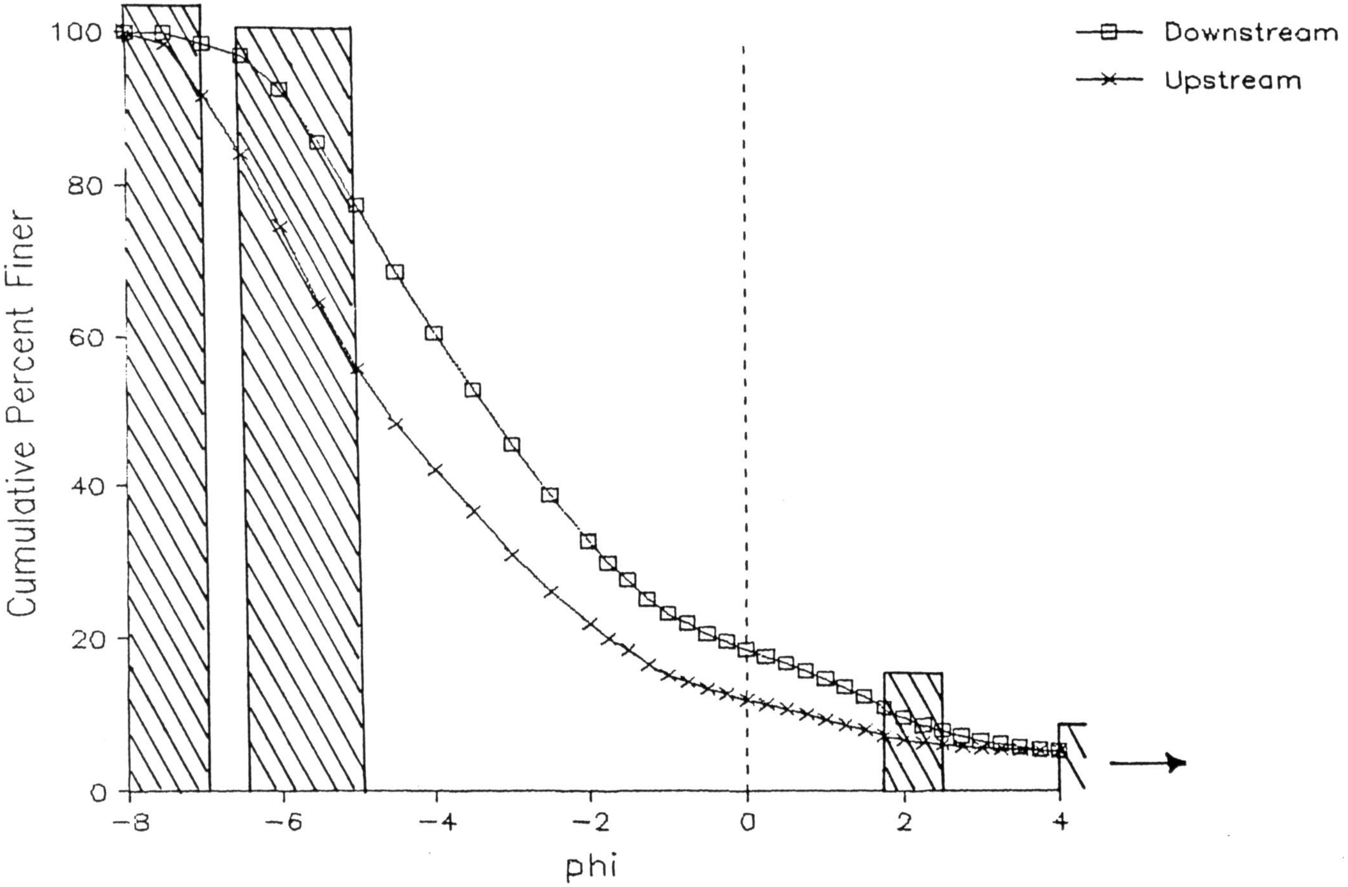

Figure 4: Cumulative plots for subsurface material: upstream versus downstream. Downstream appears much finer than upstream, indicating storage of fines. Shaded regions span the size-ranges of grains that are not significantly different (alpha=.05) between upstream and downstream reaches (see text).

TABLE 2. DATA FROM PAIRWISE COMPARISONS OF UPSTREAM REACH VERSUS DOWNSTREAM REACH FOR SUBSURFACE PARTICLES IN EACH OF THE 37 PARTICLE-SIZE CATAGORIES.

SIZE* (mm)	YBAR* UP	YBAR* DOWN	S^2+ UP	S^2+ DOWN	T STATISTIC*	CRITICAL VALUE*	ACCEPT Ho?*
181	.0406	.0060	.0000604769	.0000028771	1.2284	5.6851	YES
128	.1812	.0590	.0002507349	.0000218711	2.5599	4.3747	YES
90.5	.2320	.0741	.0000287638	.0000162382	7.7502	3.7395	NO
64	.2539	.1750	.0000643817	.0000525847	2.8204	4.0452	YES
45.3	.2637	.2499	.0000242476	.0000442303	.7495	3.6139	YES
32	.2516	.2837	.0000152149	.0000325812	2.1645	3.5954	YES
22.6	.2293	.2911	.0000118184	.0000177343	4.8678	3.5785	NO
16	.2071	.2843	.0000116691	.0000117432	7.0258	3.7742	NO
11.3	.1955	.2734	.0000388644	.0000138015	4.3375	4.0452	NO
8	.1985	.2701	.0000179720	.0000112396	5.6756	4.1327	NO
5.66	.1807	.2540	.0000139402	.0000172042	5.5232	4.0452	NO
4	.1687	.2413	.0000078156	.0000124192	6.4665	3.7742	NO
3.36	.1115	.1614	.0000020910	.0000020863	6.6043	3.9113	NO
2.83	.1018	.1454	.0000015488	.0000014557	5.9986	3.7395	NO
2.38	.1114	.1578	.0000027883	.0000020394	5.5858	3.9725	NO
2	.0964	.1337	.0000014255	.0000013649	4.9341	3.6812	NO
1.68	.0717	.1098	.0000005475	.0000012809	5.1143	3.6812	NO
1.41	.0751	.1137	.0000005178	.0000014463	4.9297	3.7395	NO
1.19	.0629	.0944	.0000002108	.0000007060	4.7685	3.7395	NO
1	.0671	.0994	.0000002237	.0000010019	4.6789	3.6812	NO
.841	.0619	.0930	.0000001514	.0000007820	5.1714	3.6812	NO
.707	.0635	.0943	.0000001499	.0000007728	5.6412	3.6341	NO
.595	.0643	.0972	.0000001335	.0000009578	6.1871	3.7087	NO
.5	.0649	.0989	.0000001594	.0000012141	5.8871	3.7395	NO
.42	.0650	.0986	.0000001961	.0000017280	5.5437	3.6812	NO
.354	.0662	.1053	.0000002779	.0000056818	4.9030	3.9725	NO
.297	.0664	.1081	.0000003637	.0000111581	4.3438	4.1327	NO
.25	.0549	.0937	.0000001723	.0000112451	4.1888	4.6649	YES
.21	.0500	.0877	.0000001633	.0000104514	4.0253	4.6648	YES
.177	.0402	.0720	.0000000611	.0000039334	4.4171	4.5485	YES
.149	.0394	.0706	.0000000658	.0000033220	4.4289	4.2400	NO
.125	.0354	.0681	.0000000394	.0000011118	5.9164	4.2400	NO
.105	.0271	.0501	.0000000102	.0000002604	6.3728	4.0452	NO
.0884	.0277	.0509	.0000000156	.0000002840	6.5266	3.8137	NO
.0743	.0261	.0465	.0000000080	.0000002446	6.5659	3.6812	NO
.0625	.0156	.0287	.0000000022	.0000000433	5.5463	3.6341	NO
Pan	.1867	.2189	.0000183375	.0000131930	2.4277	3.8589	YES

*Lower limit of class interval; pan=all particles <.0623 mm

*Ybar=mean weight proportion, arcsin square-root transformed.
Up=ustream, down=downstream

+S^2=variance

*$T=\frac{(ybark_1-ybark_2)}{(s^{2a}+s^{2b})^{.5}}$

*Critical vlaue for alpha=0.05, table from Bailey, (1977)

*Ho=hypothesis that the particles in the upstream and downstream reach are from the same population.

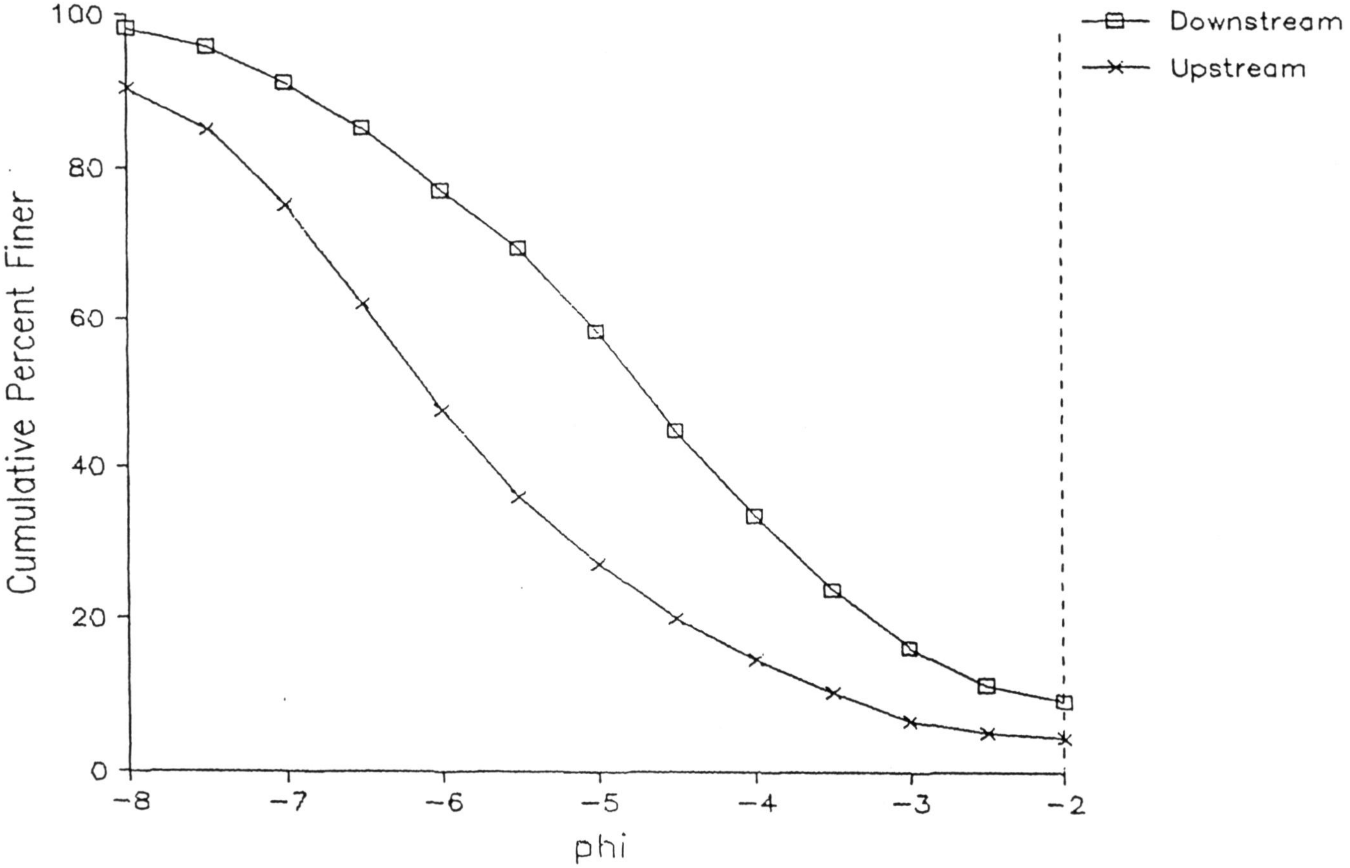

Figure 5: Cumulative plots for surface material: upstream versus downstream. Downstream appears much finer than upstream.

difference in proportion of sediment in the -2 phi to 4 phi size-range (granule to very fine sand) in the upstream versus downstream reach, as appears to be the case for the subsurface distributions.

A Games and Howell (1976) modified Tukey Wholly Significant Difference test was also used to assess significant differences for the surface data. The test was altered slightly for surface comparison between reaches because number of grains in each size-class was known, rather than the weight proportion present in each size class. Since particle measurement in the field is an independent observation, a mean particle size for each stratum was calculated, and then a mean particle size for each reach was calculated. These are true means and not medians because larger particles were assigned a greater weight (based on size) than smaller particles in order to calculate the means. The comparison was then identical to subsurface data analysis, but with only the one pairwise comparison between mean grain size of the two reaches (Table 3). At a significance level .05, the means of the upstream and downstream reaches differed significantly (Table 3).

Comparison of Surface versus Subsurface Grain Size within Reaches

Comparison of the surface and subsurface data assumes that the seive-by-weight and grid-by-number techniques are statistically equivalent (Kellerhals and Bray, 1971). Some researchers have questioned the validity of the Kellerhals and Bray (1971) general conversion. Gomez (1983b) proposed that when converting from area-by-weight to sieve-by-weight, the interstitial packing is non-uniform enough to reduce the conversion factor from $1/D$ to $1/D^{.5}$ (where D=diameter of grain). While this recommendation does not specifically apply for grid-by-number to sieve-by-weight conversions, it is in disagreement with the general

TABLE 3. DATA FROM PAIRWISE COMPARISON USING THE TUKEY WHOLLY SIGNIFICANT DIFFERENCE TEST FOR MEAN GRAIN SIZE OF SURFACE PARTICLES IN UPSTREAM REACH VERSUS MEAN GRAIN SIZE OF SURFACE PARTICLES IN DOWNSTREAM REACH.

YBAR* UP	YBAR* DOWN	S^2+ UP	S^2+ DOWN	t** STATISTIC	CRITICAL& VALUE	ACCEPT** Ho?
79.2627	37.4957	0.9284	0.5614	34.22	9.731	NO

*YBAR=mean grain size in reach, in mm; up=upstream reach; down=downstream reach.

+S^2=variance

**$t = \frac{(ybar_{k1} - ybar_{k2})}{(s^2_1 + s^2_2)^{.5}}$

&Critical vlaue for alpha=0.05, table from Bailey (1977)

**Ho=the hypothesis that the particles in the upstream and downstream reaches are from the same population.

conversion of Kellerhals and Bray (1971). However, no researchers have conclusively demonstrated that sieve-by-weight and grid-by-number sampling techniques are statistically .pa incompatable or produced an suitable alternative conversion model. To my knowledge, the only experimental test of the statistical equivalency of sieve-by-weight and grid-by-number techniques is that of Church et al. (1987), and their study seems to support a 1:1 conversion factor. The question of statistical equivalency is an intriguing problem worthy of future research.

A comparison was made between the surface and the subsurface for each upstream stratum and each downstream stratum. Because the strata were subjectively mapped, a stratum upstream is not necessarily similar to an identically-named stratum downstream. Therefore, all strata excluding sand (four upstream and five downstream) are renamed channel map units A through I (Table 4) to avoid any tendency to compare upstream and downstream surface versus subsurface data on the basis of strata. The channel map units are ordered A through I on the basis of increasing mean grain size of the surface grains.

Graphic means (Folk, 1980) of both the surface and subsurface were graphically determined from cumulative plots for each channel map unit within each reach. A graphic mean ($\overline{X}_g$) is the average of d_{16}, d_{50}, and d_{84} grain sizes (d_{50} is the diameter of the median grain) (Folk, 1980). Calculation of graphic means allows both tails of the distribution to affect the value of $\overline{X}_g$. Within the channel map units, there is a trend of increasing $\overline{X}_g$ in the subsurface as $\overline{X}_g$ at the surface increases (Figure 6), though subsurface $\overline{X}_g$ does not increase markedly. The surface to subsurface ratio of $\overline{X}_g$ for each channel map unit shows no systematic increase with increasing $\overline{X}_g$ of the surface grains (Figure 7). Degree of sorting was determined using the technique of Folk (1980). The sorting

TABLE 4. CHANNEL MAP UNITS, DEER CREEK, USED FOR SURFACE/SUBSURFACE COMPARISON

CHANNEL MAP UNIT*	EQUIVALENT STRATUM+	SORTING§
A	DOWNSTREAM SGC	8
B	UPSTREAM GRAVEL	2
C	DOWNSTREAM GRAVEL	4
D	DOWNSTREAM CG	5
E	UPSTREAM CG	1
F	DOWNSTREAM SCB	9
G	UPSTREAM SCB	7
H	DOWNSTREAM BCG	6
I	UPSTREAM BCG	3

*Map units are ordered in increasing graphic mean of surface grains.

+See Table 1 for facies symbols.

§Map units are ranked on basis of sorting criteria of Folk (1980): 1, best sorted; 9, least sorted.

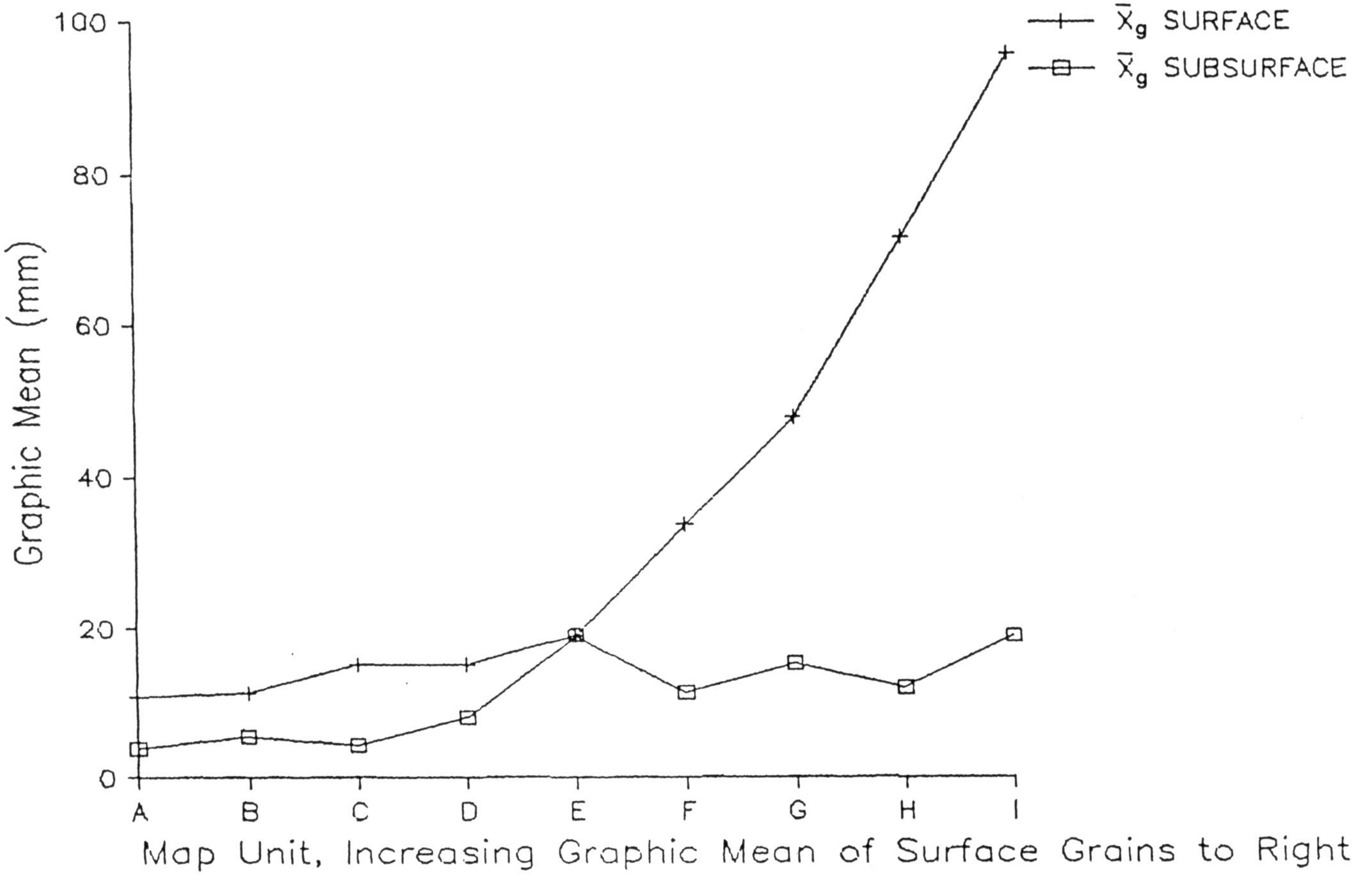

Figure 6: Graphic means of surface and subsurface versus surface mean grain size of different channel map units. Coarseness of surface grains increases to right.

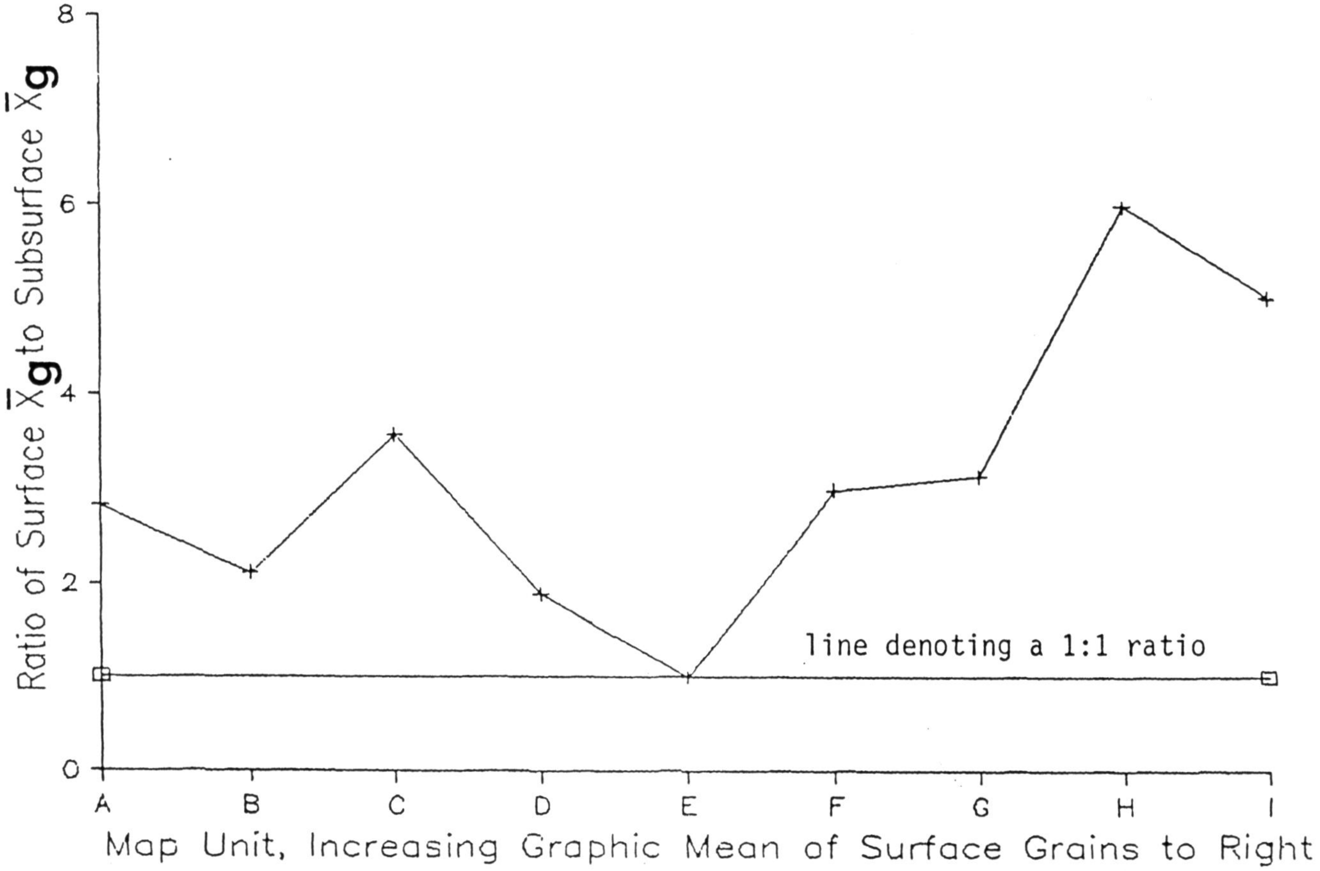

Figure 7: Surface/subsurface graphic mean ratio versus channel map units (see Table 4). Coarseness of surface grains increases to right.

was not systematically related to the ranking of map units by increasing grain size of the surface layer (Table 4).

DISCUSSION

Subsurface Comparison Between Reaches: Interpretation

Four size ranges of subsurface grains did not differ significantly between upstream and downstream reaches (shaded reaches in Figure 4, page 17). For the $-5<\mathrm{phi}<-6.5$ size class, the slopes of the two cumulative curves are the same and therefore the proportion of clasts of this size in the two reaches is about the same. Clasts larger than about -5 phi are more abundant (on a weight percent basis) in the upstream reach. In the region of the switchover in relative abundance, the abundance of clasts on a weight percent basis should be approximately the same, and the comparison test confirms this (Figure 4, Table 2). The lack of significant difference in the coarser than -7 phi size classes is unexplained because these clasts must be more abundant in the upstream reach. Due to Beta (Type II) error, there will be a failure to reject the null hypothesis even when the hypothesis is false.

The lack of significant difference in the interval $2.5<\mathrm{phi}<2.0$ (the three size classes represented by the to-right-of-middle shaded region in Figure 4) is probably not due to any transport phenomenon, but is instead a result of the sensitivity of the statistical analysis. These three size classes each have lower adjusted degrees of freedom (V_w) than adjacent size classes, resulting in a larger critical value (Table 2). No discernible pattern in variances is obvious, and I feel that an interpretation of the underlying cause for a lack of significant difference is unwarranted.

The lack of a significant difference for the <4 phi size-class (grain-sizes smaller than very fine sand) between upstream and downstream reaches (Figure 4) may have two reasons. First, grains finer than very fine sand are likely to be transported as suspended load and would not be selectively deposited in the lower reach despite the increased contribution of silt and clay between the two reaches. Secondly, material finer than 4 phi may be transported along the bed at flows subcritical for entrainment of material 4 phi and coarser.

Mechanism of Enrichment in the Subsurface

Enrichment of the subsurface sediment downstream of the landslide is generally supported both qualitatively and statistically. Two possible processes of enrichment of the downstream reach are: intrusion of gravel and finer material into a non-mobile subsurface, and mixing of the fines into the coarser substrate during mobilization of the entire bed. Beschta and Jackson (1979) have investigated, in a flume, the intrusion of coarse and medium sand into a stable gravel bed. Intrusion of both size fractions occurred to a depth of 10 cm in every flume run, with greater intrusion rates correlating with greater Froude numbers during high rates of sediment input. The coarse-sand fraction sometimes formed a sand seal about 1 cm deep that prevented further intrusion of sand. The fine-sand fraction, however, never formed a sand seal, but instead filled voids in the gravels from the bottom up. In addition, intrusion rates were greater for the fine-sand fraction, indicating that intrusion of sands is dependent upon grain size. In Deer Creek, therefore, it is possible that intrusion of medium sand and finer material into a stable bed could have occurred. However, the particle-size data (Figure 4) demonstrate enrichment of the subsurface with material as large as pebbles. For this reason, I feel it is most likely that enrichment of relatively fine material in the subsurface occurred during episodes of mobilization of the surface and subsurface grain populations (scour and fill) rather than by sediment intrusion.

Surface Comparison Between Reaches

Surface sampling was truncated at -2 phi (4mm). Because of this truncation, the distribution of grain sizes between upstream and downstream reaches does not resolve the question of whether there is more granule and finer material downstream. Thus the presence of a sand seal that would inhibit intrusion of sand and finer material (Beschta and Jackson 1979) cannot be assessed.

Mean diameter of the surface material is 79 mm for the upstream reach and 38 mm for the downstream reach (Table 3). During the field season, I observed a difference in appearance between the surface material in the downstream reach versus the upstream reach. The upstream reach was coarser and clearly imbricated. The downstream reach, on the other hand, was finer and not imbricated. In addition, in the downstream reach, there seemed to be a much greater abundance of sand and finer material in eddies and pools (which were not sampled) and behind large boulders and organic debris. Although the area of each of these sites was too small to map as a separate sand facies, the total area was probably significant. Thus, the mean grain size of the surface of the downstream reach is likely smaller than that reported.

Surface Versus Subsurface Populations and the Question of Armour versus Pavement

Comparing surface to subsurface material is one possible means of determining whether streams are armoured or paved. However, comparing surface to subsurface material is problematical. In addition to the question of statistical equivalency between different sampling methods (discussed above), there is disagreement about the definitions of pavement and armour, and how these dominantly theoretical definitions translate into usable field terms. Armour has been defined both as a static, winnowed, and immobile surface layer (Parker and Klingeman, 1982) or a winnowed, coarse surface layer which moves relatively frequently (Bray and Church, 1980). Pavement is the result of "vertical winnowing", a process that occurs through equal mobility of clasts such that a gravel-bed stream moves both its coarse and fine fractions at the same flows, maintaining both the coaser surface and finer subsurface layers during actual transport of the bedload (Parker and Klingeman, 1982). It must be kept in mind, furthermore, that the field definition of the surface layer is the volume occupied by the channel bed from the base of the largest exposed clast upward to the surface (Church et al., 1987).

While the armour definition of Bray and Church (1980) and the pavement definition of Parker and Klingeman (1982) may not be consistent, the following distinction is common to both definitions-armour is the result of winnowing, thus the surface material is simply a truncated distribution of the subsurface material whereas pavement is the result of equal mobility, with with both fine and coarse fractions of the bedload being transported individually and at roughly the same rate. In other words, the pavement observed during low flows is actually in place during flows capable of transporting the entire bedload. Therefore, if the transport of clasts occurs with equal mobility of all size fractions, then the surface and subsurface material should be two different populations.

To test whether the surface and subsurface material comprise two different populations, I first reanalyzed the distribution of the subsurface data (Figure 4) after truncating all samples at -2 phi, which is the smallest size counted at the surface. In this way, if the population of the surface is simply a truncated version of the subsurface, the graphic means ($\overline{X}_g$) of the two populations should be the same.

Comparing the $\overline{X}_g$ of the surface with the $\overline{X}_g$ of the subsurface for the nine channel map units (Figure 8) is a possible means of distinguishing pavement from armour. The diagonal line (Figure 8) represents a $\overline{X}_g$ ratio of 1, theoretically indicative of two grain size samples from the same popoulation. Therefore, a surface/subsurface ratio of 1 is indicative of armour. Only one surface versus subsurface ratio, that of map unit E, has a ratio near 1. All other surface/subsurface $\overline{X}_g$ ratios are 2 or greater suggesting that the transport process accounting for grain-size variation in and coarsening of the surface layer is one of equal mobility of clasts. Actually, both downstream winnowing and equal mobility are probably responsible for surface coarsening in most streams, but it appears that equal mobility may be the dominant surface coarsening mechanism in Deer Creek.

While the surface and subsurface appear to have different populations based on the ratio of surface $\overline{X}_g$ to subsurface $\overline{X}_g$, this criterion is at least a questionable one for distinguishing armour from pavement. Two major assumptions must be made: statistical equivalency between sampling methods, and theoretical similarity in distributions between the surface and subsurface material if the bed is armoured. The validity of these assumptions is uncertain. Until we have proper parametric statistics to test for a difference between the surface and subsurface, and we have a better understanding of the grain-size distributions that result from sediment transport, field differentiation between materials moved by different processes will remain a questionable endeavor.

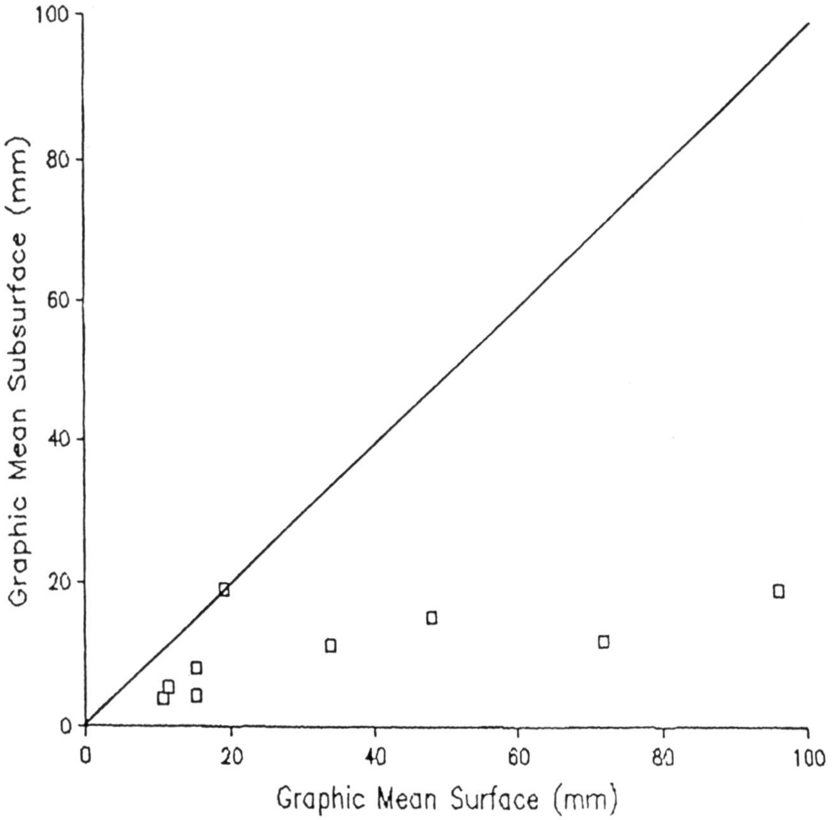

Figure 8: Surface graphic mean versus subsurface graphic mean. Diagonal line represents a surface graphic mean/subsurface graphic mean ratio of 1.

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APPENDIX 1

Field Sampling Procedures

Particle sizes upstream and downstream of the DeForest Creek landslide were sampled and compared. The comparison involved estimating the variance of 37 size-classes of particles from two reaches, one upstream and one downstream of the slide. Size-classes ranged from 4 phi (.0625 mm) to -2 phi (4mm) in 0.25 phi intervals and from -2 phi to -7.5 phi (181 mm) in 0.5 phi intervals. Material less than 4 phi was also measured, but as one large size-class. Two basic sampling techniques are recognized in sampling statistics, systematic and random. Systematic sampling is easy to design and apply and generally lowers the variance (Cochran, 1963). However, there is no reliable technique for estimating variance in systematic-sampling schemes (Cochran, 1963), because variance calculations are based on random variables. Estimating variance is necessary when comparison between groups is intended.

Random sampling is generally more difficult to apply, and more samples are needed to lower the variance to a level comparable with systematic sampling. However, variance can be estimated in random sampling schemes, and the number of samples needed to obtain lower variance can be reduced by using stratified random-sampling techniques. Stratified random-sampling involves stratifying a heterogenous population into two or more relatively homogenous populations. Since river gravels are spatially highly variable, stratifying them into populations will lower variance and reduce the number of samples needed to obtain a representative sample of the population. For example, a stratum consisting of boulders and sand will be statistically more variable than one of pebbles and sand, and more samples will be needed from that stratum to obtain a representative sample. A stratum containing mostly sand will have still lower variability, and even fewer samples will be necessary. Since variance had to be estimated in this study, and since one of the objectives of any sampling design is to obtain a representative sample, the technique used in this study was stratified random-sampling, resulting in both reduced sample variance and a reduction in the number of samples needed to obtain a good sample.

I located hydrologically similar reaches upstream and downstream of DeForest Creek. It was necessary for these reaches to have similar morphologic and hydrologic characteristics, such as mid-channel bars, point bars, and stream gradients. Figure 3 shows the similarity in geomorphological characteristics between the two reaches. Average gradient for the upstream reach is 0.0160 and for the downstream reach is 0.0145. Because similar stream discharges between the two reaches was necessary, the lower boundary of the downstream reach did not extend below the confluence of Deer Creek and Little Deer Creek (Fig. 2).

The strata were mapped using a plane table and alidade, with five strata upstream and an additional sixth stratum added for the downstream reach. The additional stratum downstream was indicative of a difference in particle-size distribution and did not affect either the sampling procedure or statistical analysis. Table 1 gives a brief description of each stratum. Stratifying the reaches into strata was subjective, especially when attempting to select identical strata in the finer downstream reach. However, the intent of the stratification was to lower overall variance while selecting fewer samples, not to produce identical stratification maps for both reaches. The shapes of the cumulative plots for each stratum (Appendix 4) are similar between upstream and downstream reaches, suggesting stratification was reasonable.

The stratafication map was digitized, obtaining total area for each stratum and total left-bank length for each reach (Table 1). All strata of identical character were then cut out and arranged in tight packing, and a grid was placed over these strata. Grid spacing was chosen to represent adequately the population present. The grid nodes were numbered, and sample sites were then determined by generating random numbers and identifying the sites for each random number generated. The number of sites for each stratum was determined by judgment and practicality. Table 1 shows how the 66 sample sites were distributed among the strata. There were 30 sites upstream and 36 downstream because of the additional stratum downstream. The sites were located with reasonable accuracy in the field with a tape and Brunton.

Subsurface samples were obtained at the predetermined sites after clearing the surface to the depth of the largest exposed grain. Sample size was determined by the weight of the largest particle present at that cleared sample site. If the largest grain present at the site was 150 mm or smaller, then this grain could not exceed 2 percent of the total sample weight. If the largest particle present exceeded 150 mm, a five percent instead of a two percent criterion was used. Only one sample included a grain that exceeded five percent of the total sample weight, and this was due to a miscalculation in the field. The largest grain present at most sample sites was under 2 percent of the total sample weight. These criteria guarantee the presence of a sufficient number of largest-size particles for statisical analysis. Holes covered a one square meter area, excavated to a depth of 0.2 m. If more material was needed, the holes were expanded with respect to area rather than to depth so all holes were of equal depth.

Truncation of the largest and smallest size-classes was necessary. Particle sizes less than 4 phi(.0625 mm) cannot be sieved by conventional methods. Larger particles had to be truncated to keep the sample sizes practical. An upper limit of -8 phi (256 mm) was established because at a 5 percent criterion, using the sampling guidlines of Church et al. (1987), the necessary sample weight is 500 kg, an upper limit for sample size due to time constraints during sampling. The largest sample collected in the field totaled 436 kg, taking approximately 16 man-hours to collect and analyze in the field. This demonstrates the necessity for truncation when 66 samples are to be collected in one summer. Only 8 grains greater than -8 phi were discarded during the entire study, verifying the validity of -8 phi as an upper truncation limit.

After the correct size for a particular sample was determined, samples were collected by shoveling material into a bucket and weighing the bucket on a 25 kg capacity spring scale. Each loaded bucket weighed as close to 25 kg as possible to minimize replications for each sample. Clasts greater than -5.5 phi (32 mm) were "sieved" by hand-fitting the stones through square-holed aluminum templates in 0.5 phi intervals. Material finer than -5.5 phi was sieved in the field with a rocker sieve down to -4 phi(16 mm). The material smaller than -4 phi was dumped on a tarp after each replication and mixed thoroughly by rolling the material vigorously from side to side on the tarp, sometimes difficult for two people to accomplish as the finer than -4 phi fraction often weighed in excess of 200 kg. A 10-12 kg split was obtained from the remaining size fraction by placing a shovel handle under the tarp and evenly dividing the material. Successive splits were performed until the split size looked about right. The material was then weighed, and, if the weight was not between 10 and 12 kg, the material was recombined and the split process repeated. The correct split was placed in plastic bags and taken to the lab for further analysis.

Surface samples were collected using Wolman's pebble-count method (Wolman, 1954). Sampling took place within each stratum by pacing each stratum area, stopping after each step, closing my eyes, placing my forefinger at the toe of my shoe, and measuring the median (b) axis of the stone touched, an attempt to obtain a random sample. Wolman (1954) suggests a sample of 100 stones is sufficient to define the distribution of the population being sampled. For this study, 100 stones were measured, and then the sampling was replicated using n=200 in order to define the gain in precision obtained by doubling the sample size. The larger sample (n=200) was used for final calculations, because the cummulative plots were smoother and larger sample size is a desirable statistical attribute.

For the Wolman count, stones were tallied by number into size-classes, the smallest including everything finer than -2 phi (4mm) because I did not feel I could consistently delineate -2 phi from -1.5 phi. Many problems are observed using Wolman counts. Since the method is not effective for particles less than about -2 phi, the smaller mode in a typical bimodal distribution will not be sampled with any precision, hindering comparison of surface particle sizes with the subsurface layer. The method also appears to be biased toward larger or more convenient size-classes, as very small particles next to larger ones tend to be ignored if the finger grazes both stones. Many other methods have been proposed (Leopold, 1970; Kellerhals and Bray, 1971; Adams, 1979), but these are either less effective or considerably more difficult to apply or both. In addition, some alternative sampling methods are not statistically equivalent to the sieve-by-weight technique used for subsurface sampling, presenting a conversion problem for comparison of subsurface to surface distributions (Kellerhals and Bray, 1971).

APPENDIX 2

Laboratory Procedures

Surface sample splits were carried back to the lab, placed in plastic tubs and allowed to dry in the sun in a greenhouse. Samples were weighed daily until they showed no further weight loss, then weighed with an Ohaus triple beam balance to obtain total weight of water lost. All further weight measurements were done on the triple beam. Samples were sieved through a -3.5 phi (11.3 mm) screen, and all material smaller than -3.5 phi was split using a large sample splitter. Target weight for the second split was 600-900 g. If the resulting split was too large or small, the material was recombined and resplit. Loss due to dust and measurement error was usually about 10 g for this split. Material less than -3.5 phi was soaked in a deflocculent of a 2.55 g/l solution of Calgon for about a half an hour. Soaking time was determined by examining the solution, after soaking for ten-minute time intervals, under a microscope for evidence of flocculation. Half an hour proved to be sufficient time, as clay content was generally low.

After soaking the sample in the deflocculent, the sample was dumped onto a -1 phi (2 mm) screen with a 4 phi (.0623 mm) screen directly beneath the larger screen. Both screens were first placed in a plastic tub. All material finer than -1 phi was washed onto the 4 phi screen using a squirt bottle of water. The larger screen was then removed, and all material finer than 4 phi was washed carefully into the plastic tub until the water running from the fine screen was completely clear. All material coarser than 4 phi but finer than -3.5 phi was recombined and washed into an aluminum pan. Material finer than 4 phi (material finer than the lower truncation limit) was washed into a separate pan, and both pans were dried for 14-16 hours at 100 degrees C. Oven-drying the finer fraction (<4 phi) renders it useless for further size analysis, but as no further analysis of these sizes was needed for this project, oven drying was used to save time.

After oven-drying the two size fractions, both were allowed to equilibrate to the ambient humidity for 12 hours. Both fractions were weighed, the finer material was bagged, and the coarser fraction (4<phi<-3.5) was sieved to -1 phi in appropriate intervals (see Appendix 1, page 36) in a standard Ro-Tap machine for 20 minutes. Material finer than -1 phi was split for a third time using a micro-splitter. Target weight was 50-75 g for the split, with typical losses of 0.1-0.2 g. This third split (4<phi<-1) was sieved down to 4 phi in the Ro-Tap; the resulting small quantity that was less than 4 phi possibly formed because of pulverizing of larger particles or incomplete washing during wet-sieving. The minor fraction of material finer than 4 phi was added to the greater amount of sediment this size obtained during wet sieving.

Equivalent weights were determined from net weights by assuming major losses in weight were due to loss of water and not loss of the sample material. Three split ratios were calculated and multiplied with the appropriate net weights to obtain the equivalent weight of each size-class. The total weight of all equivalent weights across all size-classes must equal the measured total field weight. To obtain the first split ratio, the total field weight greater than -4 phi (16 mm) was divided by the weight of split one, measured after drying the sample. The first split ratio was multiplied by only the net weight from the -3.5 phi size-class.

The second split ratio was calculated by subtracting the net weight of the -3.5 phi size from the lab weight of the first split. The difference between the net weight of the -3.5 phi size and the lab weight of the first split is the total split weight less than -3.5 phi. The number calculated was divided by the sum of the finer than -1 phi pan fraction, the measured weights greater than -1 phi and less than -3 phi, and the weight of the pan (<4 phi) fraction. The sum is the total weight less than -3 phi. After dividing, the dividend is multiplied by the first split ratio. All size-classes from -3 phi to -1 phi are multiplied by the second split ratio.

The third split ratio was obtained by subtracting the sum of the weights from -3 phi to -1 phi from the total weight less than -3 phi. This number was divided by the sum of the weights less than -1 phi, including the pan fraction, and then multiplied by the second split ratio. All size-classes finer than -1 phi was multiplied by the third split ratio.

Equivalent weights were totaled to guarantee that total equivalent weight equaled total field weight. Relative percentages for each size-class were totaled, and the sum for each sample totaled 100. Both of these calculations were to double-check the split ratios.

APPENDIX 3

Data Analysis

Statistical analysis of the subsurface samples was problematic because the statisics are necessarily based on weight proportion instead of number of particles. For statistical analysis, the number of particles present in a sample will yield better results than using average weight proportion of each size-class present in a sample (R.B. Thomas, U.S.F.S. Pacific SW Forest and Range Experiment Station, Arcata, CA., oral comunication, 1987). Using number of particles rather than weight proportion results in a complete change in the character of the distribution of the sample. Analysis by weight proportion yields a bimodal distribution (see distribution of the subsurface data in Figure 9). In contrast, analysis by number of particles will strongly skew the distribution to the fine end. No statistical solution for dealing with such a strongly skewed distribution has yet been formulated, so I have proceeded with weight proportion statistics in this study. An additional problem with using number of grains for river samples is the observed variation in number of particles per unit weight for each size class, caused by variations in size, shape, and density of particles within the 0.25 phi class intervals (J.F. Wolcott, oral comunication, 1987).

The means of each size-class of the subsurface samples were compared between upstream and downstream using a Games and Howell modified Tukey Wholly Significant Difference test (WSD) (Games and Howell, 1976). This procedure tests the hypothesis that the means of the upstream and downstream reaches represent the same population. Because proportions are not considered to be normally distributed, weight proportion data was first arcsin square-root transformed (Sokal and Rohlf, 1981). The purpose of the transformation is to compress the distribution curve from a .pa

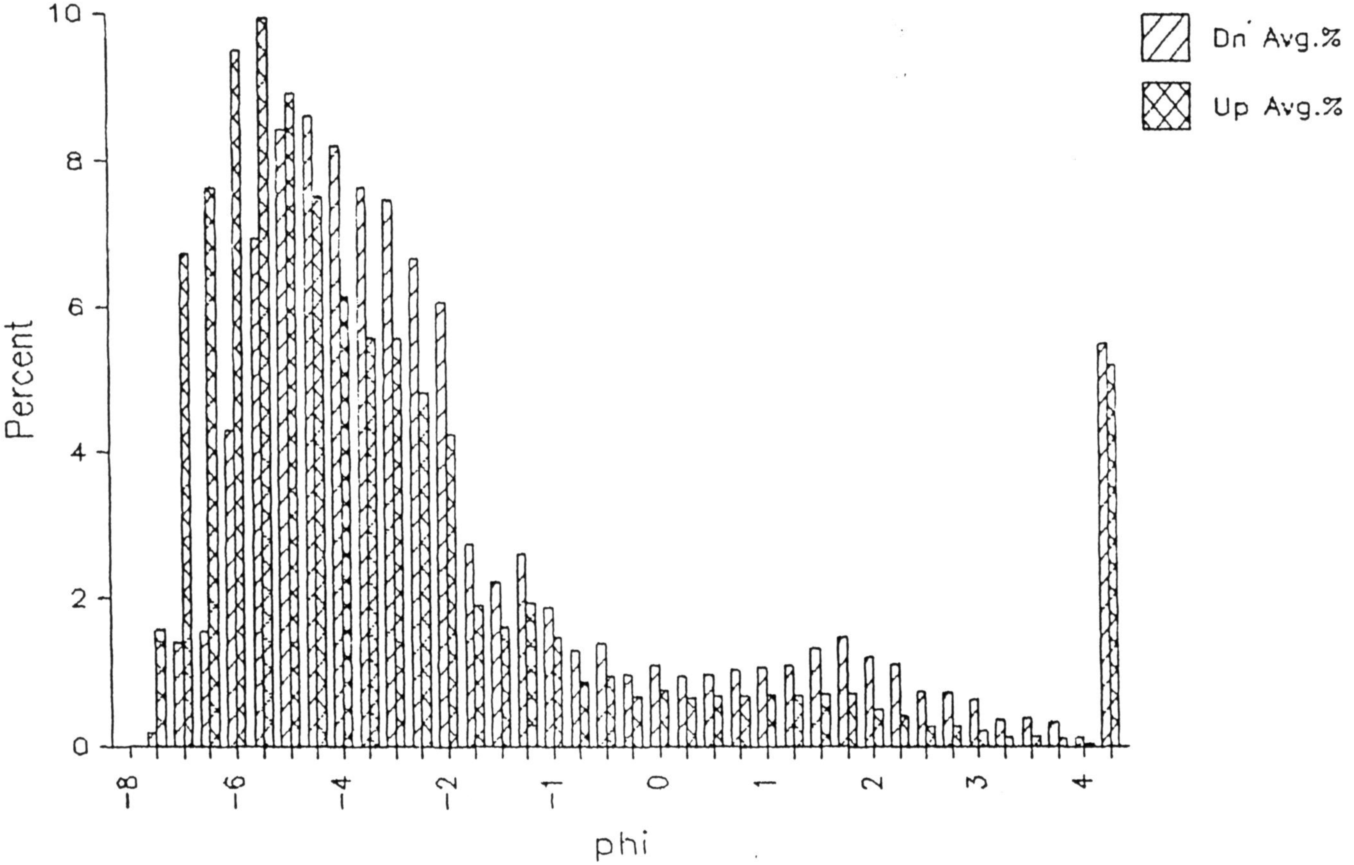

Figure 9: Histogram of upstream versus downstream for subsurface material showing strong bimodality.

flattened bell shape to a more normal bell-shaped curve.

Total area for all strata is denoted by A. Total area for each stratum j is denoted by A_j. Total number of samples is n, and number of samples for each stratum is n_j. The weight of the ith sample taken from the jth stratum falling in the kth size class is denoted by X_{ijk}. The sum of weights containing all size-classes from the ith sample is described by X_{ij}. Y_{ijk} describes the proportion of the ith sample from the jth stratum in the kth particle-size class and was calculated by X_{ijk}/X_{ij}. The average proportion of the kth size class in the jth stratum was calculated by:

$$\mathrm{ybar}_{jk} = \frac{1}{n_j} \sum_{i=1}^{n_j} Y_{ijk} \qquad (1)$$

The sample variance for ybar_{jk} was calculated by:

$$s^2_{jk} = \frac{1}{n_j(n_j-1)} \sum_{i=1}^{n_j} (Y_{ijk} - \mathrm{ybar}_{jk})^2 \qquad (2)$$

An estimate of the sample mean proportion ybar_k could then be estimated by weighting ybar_{jk} with respective areas of each stratum A_j:

$$\mathrm{ybar}_k = \frac{1}{A} \sum_{j=1}^{J} A_j \mathrm{ybar}_{jk} \qquad (3)$$

An estimate of the sample variance for ybar_k could finally be calculated by weighting s^2_{jk} by area:

$$s^2_k = \frac{1}{A^2} \sum_{j=1}^{J} A^2_j s^2_{jk} \qquad (4)$$

The means of the two reaches were compared using a Games and Howell modified Tukey Wholly Significant Difference test (WSD). The first step was to calcuate adjusted degrees of freedom (m_k) for the variance estimates in each particle size class:

$$m_k = \frac{(A^2_j s^2_{jk})^2}{[(A^4_j s^4_{jk})/(n_j - 1)]} \qquad (5)$$

The test statistic is given by:

$$t = \frac{(ybar_{k1} - ybar_{k2})}{(s^2)^{.5}} \qquad (6)$$

$$\text{where } s^2 = s^2_{k1} + s^2_{k2} \qquad (7)$$

The critical point is given by $B(a;k,v_w)$, where a is the significance level, k is the number of pairwise comparisons (in this case 37), and v_w is the weighted degrees of freedom:

$$v_w = \frac{(s^2)^2}{\frac{(s^2_{k1})^2}{m_{k1}} + \frac{(s^2_{k2})^2}{m_{k2}}} \qquad (8)$$

The critical value comes from tables of the Bonferroni t-Statistic (Bailey, 1977).

Surface sample comparison was more straight-forward, since numbers of particles were obtained rather than weight proportions. Samples were tallied into 13 size classes (-2 phi to -7.5 phi in 1/2 phi intervals, and all material finer than -2 phi) and the cumulative percent finer than the lower limit of each size-class was calculated. As in the subsurface test, the null hypothesis is that the means of the upstream and downstream reaches are representative of the same population. I employed the identical pairwise statistical test as that used for the subsurface material, except number of particles was used rather than weight percent. A mean particle-size was obtained for each stratum by multiplying the number of particles in each size-class by the lower limit of that size-class, and then summing that number for all size-classes. The sum was then divided by the total number of particles present for all size-classes. Since the smallest size-class (§-2 phi) was open ended at the lower end, all particles in that size-class were assigned the value of -1.5 phi. After the mean particle size for each stratum was determined, the data analysis was identical to that of the subsurface analysis.

For the purpose of a comparison of the surface and subsurface grains, I first determined the graphic means ($\overline{X}_g$) of all strata in the surface and subsurface. Graphic means are the average of the d_{84}, d_{50}, and the d_{16} values, read from the cumulative plots (Figures 4 and 5). The resultant $\overline{X}_g$ values for surface and subsurface distributions were plotted against one another, resulting in a ratio of surface verus subsurface $\overline{X}_g$. The significance of this ratio is discussed in the text.