THE GRAIN SIZE GAP IN RIVERBED GRAVELS

by

JOHN FREDRIC WOLCOTT

B.Sc., B.F.A., University of Washington, 1982

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

in

THE FACULTY OF GRADUATE STUDIES

Geography

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

September 25, 1984

86

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the The University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the Head of my Department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Geography

The University of British Columbia
2075 Wesbrook Place
Vancouver, Canada
V6T 1W5

Date: September 25, 1984

Abstract

Four hypotheses for the apparent paucity of grains within the size range between 1 and 10 mm of some fluvial gravel deposits are 1) that the material does not enter the channel, 2) that the material is present elsewhere in the system, 3) that the material is preferentially abraded, and 4) that the material is preferentially entrained. Data from material in the footslopes and bed sediments collected at Flynn Creek, Oregon, and from material over a large and complex bar in the Quesnel River, British Columbia, show that Hypothesis Two may be rejected, but Hypothesis One is tentatively plausible. Although lithology is not a process, it appears to exert a dominant control on the presence or absence of the gap. Hypotheses Three and Four remain as proposals for future work.

Table of Contents

List of Tables

List of Figures

Acknowledgements

The two years represented by this report were most enjoyable, largely due to the guidance of a small group of good friends. I thank Dr. Larry Hansen for reawakening in me my love of the earth, Dr. Tom Dunne for introducing me to the excitement of geomorphology, Dr. Arthur Nowell for the opportunity to conduct research in a laboratory environment of the highest standards and also for encouraging me to continue my education at the Masters level. I thank my committee, Dr. Douw Steyn for discussions on the physical and philosophical aspects of science, Dr. Olav Slaymaker, my second reader, for broadening my narrowly incised fluvial perspective, and Dr. Mike Church, my supervisor, for giving me the freedom to wander through the subject, yet with sufficient input to keep me on track with numerous discussions on matters academic and otherwise. Graduate students Dave McLean at the University of British Columbia and Claudia Owen at the University of Washington have provided many stimulating discussions and valuable field assistance during the inevitable low periods of any serious undertaking. I especially thank my parents; their continued support and faith in me has been very important. Funding for this project was provided in part by the Natural Sciences and Engineering Research Council of Canada, Operating Grant A7950 to Professor Church. Personal support was partially provided by a University Graduate Fellowship.

I. INTRODUCTION

A. THE PROBLEM

Several investigators have noted the typical absence of sediments in the 1 - 10 mm range in gravel bedded river deposits. Pettijohn (1949, pp. 41-45) summarized the early data and thoughts on the subject. He stated

> In conclusion it can be said that the possible causes of polymodal distributions are several and that present data are insufficient to show which are important and which are not. Undoubtedly, a little well-planned laboratory and field study could settle this question. The prevalence of the polymodal distribution in published analyses of stream gravels seems significant, whatever its explanation.

In the third edition, Pettijohn (1975) omitted this paragraph and instead said the following:

> In short, despite the voluminous literature and extended efforts made to define grain size, measure it, and calculate the parameters of grain size distribution, the net input toward the solution of geological questions has been disappointing and disproportionately small relative to the effort expended.

This polymodal distribution problem seems significant; its study may provide further understanding of fluvial hydraulics, sediment transport, and river morphology.

For the purposes of the present study, the grain size gap under investigation may be defined as a "valley" located somewhere within the range of 1 to 10 mm on a histogram of the size distribution of the sample. Others have defined the gap as existing between 2 and 4 mm (Sundborg, 1956) or 1 and 8 mm (Shea, 1974). Recent work on the Quesnel River, however, has shown that it may occur between 8 and 10 mm.

One of the first field studies to investigate the nature of sedimentary deposits was done by Udden (1914). He analyzed both wind and water deposits. The water deposits included sediments from rivers in Alaska and the continental United States, Pleistocene terraces, beach gravels, deep sea deposits, and silts from ships' anchors from various ports in the western hemisphere. The consistency of a gap in the 1 to 10 mm range in the individual coarse samples led Udden (1914) to formulate his Law of the Secondary Maximum:

> When a transporting medium is supplied with sufficiently heterogeneous material it will tend to carry and to deposit more of two certain sizes of material than of any other sizes. The principle deposit it makes will consist of materials it can momentarily lift. With this it will leave an excess of another considerably coarser ingredient which it can roll, smaller in quantity. This makes what we call a secondary maximum. For water deposits, the secondary maximum will consist of elements having a diameter about sixteen times the diameter of the elements in the chief ingredient.

Figure 1 represents material from a glacial outwash terrace deposit near Drummond, Illinois, and shows a typical bimodal distribution. This sample has the primary maximum in the coarser material, contrary to Udden's (1914) Law. The gap occurs in the 2 - 4 mm range.

Shea (1974) believed that the gap between 1 - 10 mm may not exist. In a review of 11,212 data sets, he offered evidence to prove his point. Most of his examples, however, consist of samples from different areas lumped together. For example, his histogram with all 11,212 data sets shows a remarkably normal distribution, but these data include eolian as well as fluvial, glacial and marine deposits. Figure 2, which is from Shea's Figure 3A (1974, p. 988) of Udden's (1914) data presents an average of 371 analyses of sediments from glacial tills, water deposits, and wind deposits. The gap present in Figure 1 simply disappears when combined with the predominantly finer samples from other fluvial and nonfluvial environments.

Recent data from Carling and Reader (1982), Shaw and Kellerhals (1982), and the present study confirm that a gap exists in some fluvial deposits when analyzed to contemporary standards. Figure 3 is a histogram of a bar head sample from Quesnel River, British Columbia, taken in 1982. It shows a distinctive gap in the 4 - 11 mm range. Although Shea has shown that at the global scale a gap does not exist, gravel deposits within individual streams and rivers have a depleted fraction somewhere in the 1 to 10 mm range. Why?

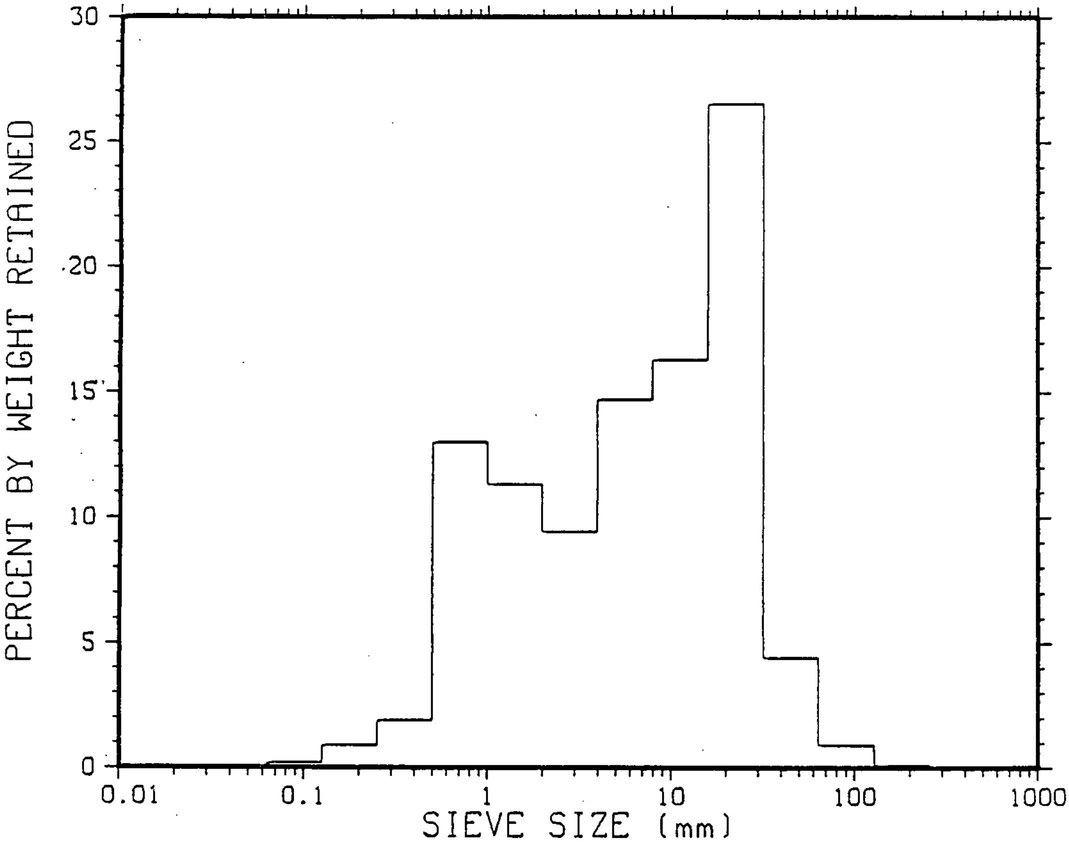

Figure 1. River deposit from Udden (1914)

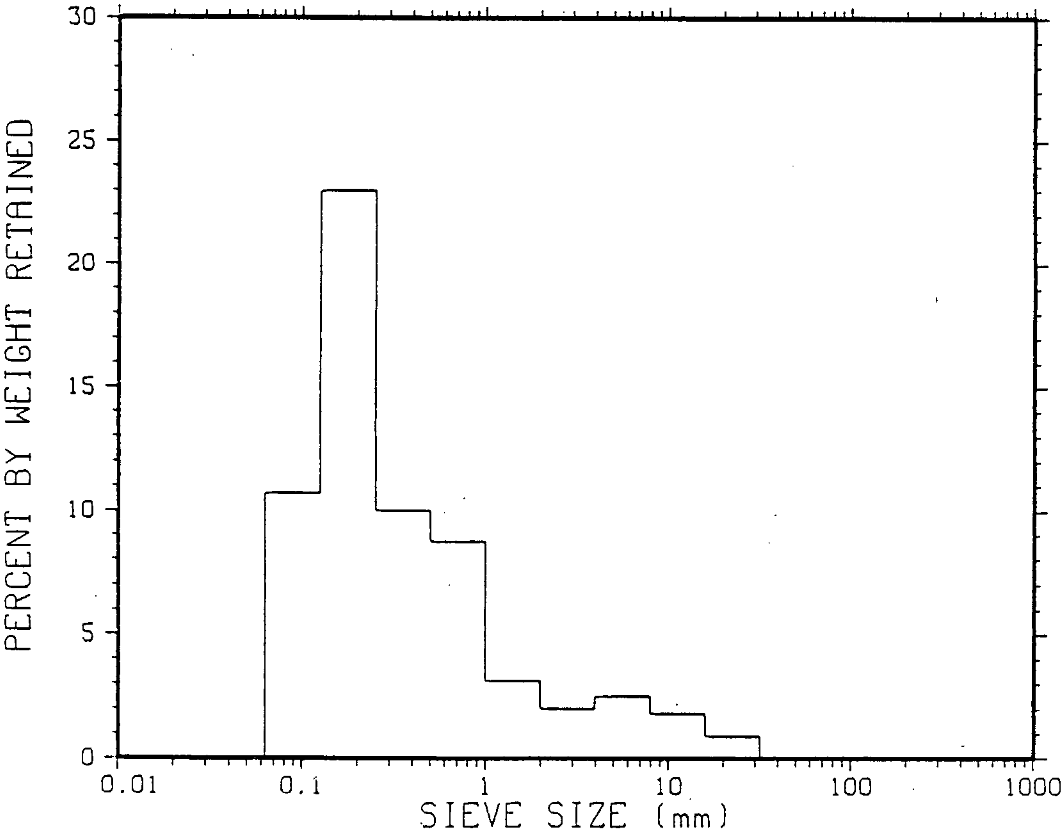

Figure 2. All of the Udden (1914) data

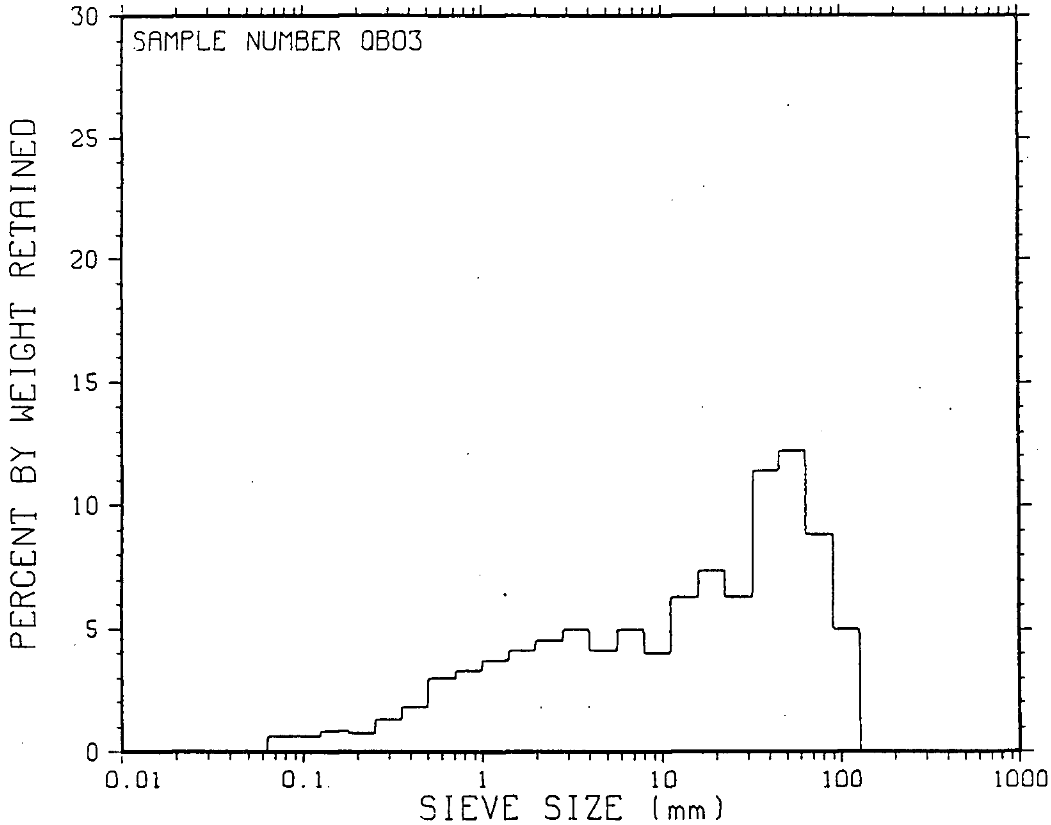

Figure 3. Quesnel River bar head sample

B. THE ANSWERS

Several people have offered explanations for the polymodal nature of some coarse grain size distributions. Udden (1914) offered his Law of the Secondary Maximum noted above. In the present terminology, Udden believed that the primary mode, or chief ingredient, and the secondary mode represented the principal methods of transport, namely saltation and traction.

Pettijohn (1949) noted Udden's explanation for the gap, and added several more. He suggested the following.

1. Bimodal distributions may result from faulty sampling; that is, several different sedimentary units or layers may be included in a single sample.
2. Incomplete mixing of two distinct populations, such as glacial ice containing gravel or larger fragments moving over a sandy outwash plain, would yield bimodal distribution.

3. Entrapment of fines in the interstices of a gravel may also explain the secondary mode.

4. Finally, there may be little material in the 2 – 4 mm size range because this size is mechanically unstable, or it is not produced by normal weathering since some rocks undergo granular disintegration and produce sand whereas others fracture into blocks and produce gravel.

Pettijohn concluded by saying that if the distributions were the result of hydraulic factors, as suggested by Udden, then the material should eventually be deposited somewhere. His preferred hypothesis was that the material was mechanically unstable since the constituent mineral grains were relatively large compared to the whole fragments in the 2 – 4 mm range. Pettijohn (1949, p. 45) suggested, "Such granules, therefore, are structurally weak and hence unable to survive vigorous abrasion. Such an hypothesis is susceptible to experimental study." Subsequent abrasion studies, such as that by Kuenen (1956), have failed to support this hypothesis.

Sundborg (1956, p. 192) ignored the second and third hypotheses mentioned above, and argued in favor of Udden's (1914) views. It is interesting to compare his reasoning with that of Pettijohn (1949) and Shea (1974).

> 1) The sample was taken in such a manner that material from two different strata with different grain size distributions was included. The overall distribution may then acquire two maxima, corresponding to the maxima of the two components. 2) The process of weathering of the source rock and the process of wear during transport produce sediment where certain grain sizes are more common than others, mainly because some grain sizes, among them the 2 – 4 mm, are mechanically unstable. 3) The selective transportation of material by flowing water for some unknown reason gives rise to bimodal frequency distributions with a minimum in the interval 2 – 4 mm.
>
> The first explanation may of course often be true. But it cannot explain why the frequency minimum so often lies in the range 2 – 4 mm, nor why there seems to be a definite deficiency of material in this range.
>
> The second explanation could account for the deficiency of 2 – 4 mm particles. But it is difficult to see why the selective transport process could not compensate for a natural deficiency in a particular interval of grain size, and relatively often produce fluvial sediment with a maximum in the interval concerned. Finally, it appears that a bimodal frequency distribution in a fluvial sediment may occur equally well if the source rock is coarse–crystalline intrusive rock as if it is fine–crystalline lava rock, or some sort of sedimentary rock (Arnborg). It would be expected that mechanical stability

> should be dependent on the size and character of the individual mineral grains in the source rock. Pettijohn (1949, p. 45) points out that "another factor to be considered is the nature of the material produced by the weathering. Some rocks yield *blocks* upon breakdown, whereas others undergo granular disintegration and yield *grains* of sand size." It may then be stressed that the mechanical instability of grains in the grain sizes 2 – 4 mm is not likely to be considered as a general explanation for the discontinuities in the grain size distribution.
>
> The third explanation seems plausible, since flowing water is certainly an effective sorting agent. But the details of the explanation have proven difficult, and no unobjectionable theory has been put forward. The assumed general deficiency of fine gravel has been difficult to explain, and moreover a satisfactory interpretation of the circumstance that the frequency minimum is in just the 2 – 4 mm range has been hard to obtain.

Although his point against the separate populations is well taken, the case against mechanical instability is based on an apparently unpublished report by Arnborg. No published abrasion mill study of gravel has produced a sand size mode. Furthermore, part of the difficulty with the hydraulic explanation is that curves of critical erosion velocity and grain size, such as Figure 13 in Sundborg (1956, p. 177), show that in a bed of uniform material the most easily entrained particles are between 0.1 and 0.3 mm. Therefore, if preferential entrainment were the cause, material between 0.1 – 0.3 mm should be missing, not larger particles. Sundborg (1956, pp. 185–188) cites several experimental results which show that in heterogeneous mixtures, under certain conditions, the coarse material moves before the finer material. He believes that in a mixed sediment, the following occurs. For very coarse material (larger than 6 mm), the fine fractions are most easily entrained and transported. For fine material (between 0.3 and 1.0 mm), the coarsest grains move most easily. For the intermediate sizes (between 1 and 6 mm), the medium size grains (2 – 4 mm) are most easily entrained. Grains less than 0.3 mm may be controlled by cohesion and move in larger clumps as suspended material; in any case, the coarsest grains will move first, again usually as suspended load. Thus, the grains between 1 and 6 mm are the least stable in a mixture. Two experiments by Meland and Norrman (1969) show that for a sediment mix between 0.85 – 7 mm with a log normal distribution in half phi intervals, the 4 mm size traversed the length of the flume most rapidly, implying that it was the most easily moved.

So what happens to the granular fraction, assuming that it is the most easily entrained in gravel mixtures? Sundborg (1956, p. 193) says

> Let us consider the situation where fine gravel has been deposited on a part of a river bed. Under what conditions may other material be deposited on top of this layer, thus preserving it? If coarser material is transported from upstream as bed load, the flow velocity will as a rule have to be so high that the previously deposited fine gravel is set in motion. The same often applies if finer material is brought down as bed load. The only sure possibility of further deposition and consequent preservation of the fine gravel layer is the deposition of suspended material. This possibility is certainly rather seldom realized.
>
> The conclusion to be drawn from this reasoning may be put thus: when gravel grains have been worn down to a size of about 5 - 6 mm, the transportation of them by the stream becomes more relentless, and they are often prevented from coming to permanent rest until they have been worn down to a size of 1 - 2 mm or less. This may well be an important cause of the general deficiency of particles in the interval 1 - 6 mm.

Shea (1974, p. 1000) summarizes the published "causes" of deficiencies, including both the gap in the 1 - 10 mm range and a further gap in the 0.063 - 0.125 mm range.

> The following mechanisms have been postulated as possible explanations for the alleged "gaps":
>
> A. Modal-region highs in polymodal grain size curves occur where the various transporting mechanisms (i.e. traction, saltation, suspension) were most effective. Histogram B (Fig. 3) {see Figure 4, this report}, for example, would indicate that grains larger than about 1 mm were moved by traction and those less than 1 mm by saltation. This mechanism was used by Wentworth (1933), Conkling and others (1934), Krumbein (1942a), Udden (1914) and Tanner (1958).
>
> B. Particles with diameters in the range 1 to 8 mm are moved more easily by currents and waves than particles of either greater or lesser diameters (Sundborg (1956), Russell (1968)).
>
> C. Particles with diameters greater than about 1 mm constitute stormwave or flood-current load and those with diameters smaller than about 1 mm are "normal" load (Trowbridge and Shepard(1932)).
>
> D. Particles in the range 1 to 8 mm are relatively easily broken into smaller particles, and particles near 0.062 mm are seldom produced either by abrasion or "chipping" of larger particles (Hough (1942), Yatsu (1955), Rogers and others (1963)).
>
> E. Gravels with modes coarser than about 16 mm consist of a framework of larger particles with later-deposited, smaller particles filling in the interstices (Plumley (1948)).
>
> There are several problems with these proposed mechanisms. The most obvious is that A and B are mutually exclusive. Using histogram B (Fig. 3) {see Figure 4}, hypothesis A holds that the grains lying on the coarser side of the histogram valley centering at about 2 mm were moved by traction but

> that smaller grains lying in the range 1 to 4 mm were not moved as effectively, and that grains to the right of 1 mm were moved by saltation. Thus there was a size range of grains that were not being moved much while both coarser and finer grains were carried effectively. This suggests that grains in the range 1 to 4 mm were the most difficult to move, exactly the opposite of hypothesis B. Hypothesis C is similar to A in that it postulates the moving of coarse grains by storm-waves or flood-currents, while finer particles were not carried. All three of three of {*sic*} the proposed patterns of transport seem to be explicitly refuted by published graphs of the critical velocity necessary to initiate movement. They show that a continuous increase in velocity is necessary with increase in grain size from about 0.500 mm. Such curves are included in practically every textbook of sedimentology and stratigraphy and they have been independently developed or confirmed by Allen (1965, p. 109), Bagnold (1941, p. 88-89), Committee on Sedimentation (1966, p. 299), Helley (1969, p. 13), Hjulstrom (1939, p. 10), Inman (1949, p. 56), Nevin (1946, Plate 1) and Rubey (1938, Fig. 23, p. 133).
>
> Hypothesis D has received some support from data gathered by Moss (1972) who showed that primary quartz grains in the size range 1 to 5 mm tend to be more easily broken by crushing between cobbles and boulders than smaller quartz grains. In general, insufficient data have been gathered to establish either D or E as correct.

Shea (1974, p. 1001) concludes by saying "In single analyses such distributions may be caused by the agent of deposition, but in the kind of overall average computed here, it seems more likely the distribution is controlled by the nature of parent material and the effects of sedimentary attrition."

His dismissal of hypotheses A, B, and C because they are mutually exclusive seems superficial. Likewise, his validation of the critical erosion velocity curves ignores Sundborg's (1956, pp. 185-188) examples of the effects of sediment mixtures on erosion velocities. All of the studies quoted refer to Hjulstrom's (1939) curve, except Bagnold (1941), and Hjulstrom and Bagnold used uniform sediment sizes. Subsequent work on overpassing by Raudkivi and Ettema (1982) has shown that particles between 0.9 and 2 mm will be preferentially entrained on either a bed of 0.1 to 2 mm particles or a bed of 1.5 to 9 mm particles.

The work by Moss (1972) used to support hypothesis D consisted of noting the force necessary to mechanically crush river stones between 0.5 and 4.76 mm gathered along 80 km of river in Australia. The results showed that stones larger than 1 mm became stronger downstream, implying that the weaker stones were destroyed.

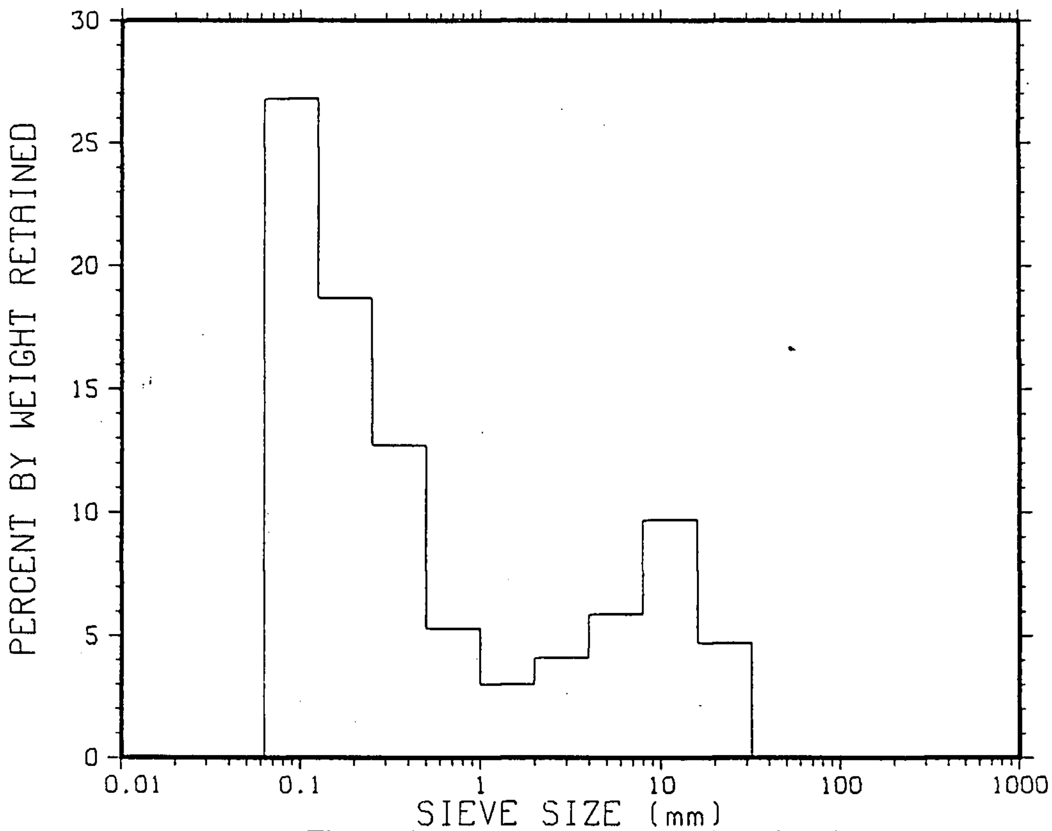

Figure 4. Histogram B from Shea (1974)

What exactly happened to the weaker stones was not observed, nor were stones larger than 4.76 mm studied.

Hypothesis E appears to have been covered by Sundborg (1956) in his discussion of hydraulic sorting. Although subsequent infiltration by fines into an open gravel framework has been demonstrated in flume studies by Jackson (1981), the results show that the extent of infiltration is highly dependent upon the size of the fines. With a bed of fresh gravel with a median particle size of 17 mm and a minimum size of 4 mm, coarse sand and coarse sand mixed with fine sand accounted for 10% or less by weight of the sample volume when averaged over 3 sample sites. Fine sand alone averaged 21.5% by weight of the three sample volumes. Subsequent experiments with gravel and sand mixtures dumped into the flume simultaneously had higher concentrations of sand in the resulting bed forms than any of the intrusion experiments. Here the sand was deposited simultaneously with the gravel. Flume work by Parker et al. (1982) has also demonstrated the entrapment of fines during deposition of gravels.

Finally, in many cases, the size of the mode finer than the gap precludes the finer material occupying only the voids in a coarser clast supported framework. For example, Dunne and Leopold (1978, p. 201) list the porosity of gravel as 25% - 40% and sand as 30% - 52%. This gives a maximum value of 28% sand in the voids. Many bimodal samples contain more than 28% sand. This simple calculation is supported by Jackson's (1981) maximum weight of intruded sand of 21.5% noted above.

Pettijohn (1975, pp. 40–41) subsequently modified his earlier (1949) views quoted above.

> In general the interpretation of grain size analyses has followed three paths. One path relates the characteristics of the grading curve to hydrodynamics (to the depositional process itself). This view was advanced by Udden (1914) to account for the bimodal distribution of many coarse river sediments, the coarser mode being a product of traction transport, the lesser and finer mode being the result of saltation transport. The interpretation of grading curves in hydrodynamic terms has been advanced by Inman (1949), Moss (1962, 1963), Friedman (1967), and Visher (1969) in particular. A second approach considers the grain size distribution largely a product of the sediment generative processes. In this case the distribution is attributed to the source materials and the size distributions generated by their disintegration. The breakage theories of Rosin and Rammler (1934), Tanner (1959), and Kolmogorov (1941) and the observations of Rogers, Krueger, and Krog (1963) and Smalley (1966) are illustrative of this approach. A third approach is to make an empirical study of grading characteristics of sediments from various natural geomorphic environments to see what relation, if any, exists between them. This approach was initiated by Udden (1914), expanded by Wentworth (1931a), and in more recent years promulgated by Sindowski (1957), Friedman (1961, 1962), Moiola and Weiser (1968) and many others.

Another important factor not mentioned directly is the gradient of the river. Yatsu (1959) found a break in slope associated with the transition from gravel to sand in alluvial fans in Japan. He believed that at the lower gradient the river is not capable of moving the coarser fraction so the size distribution is unimodal. At the higher gradient, the river moves both sand and gravel, hence the distribution is bimodal. Shaw and Kellerhals (1982), however, found no change in gradient at the sand–gravel interface of 12 rivers in Alberta, and these rivers showed a typical bimodal size distribution with a gap between 0.5 - 2 mm.

Milhous (1982) has suggested that fine grained rock, such as limestone or basalt, will abrade uniformly down to sand or silt, creating a distribution without a gap, whereas coarse grained rock, such as granite or sandstone, will break down into individual grains from larger fragments, thereby producing a bimodal distribution. Abrasion mill experiments support the first claim, but not the second (*cf.* Chapter II)

The grain size gap appears to be better developed in larger river systems (see Udden, 1914; Klingeman and Emmett, 1982; Shaw and Kellerhals, 1982). This may be due to the greater likelihood of varied lithologies in the sediments, or it may be due to the greater distance, and hence longer time, that the fluvial processes may act upon the sediment.

C. THIS STUDY

All of the previously mentioned explanations of the polymodal size distribution of some gravel river deposits may be grouped into four testable hypotheses.

The first hypothesis assumes that the missing fraction in river deposits is also missing in the source material. That is, the gap material never enters the fluvial system, and it is therefore independent of fluvial processes. This does not mean that gap material is not produced in the environment, but rather that it does not reach the rivers which have polymodal size distributions. Included here is the possibility that each mode represents a distinct lithology, perhaps from different source areas. The first hypothesis is more specific than the notion that parent material or lithology controls the distribution as suggested by Shea (1974) and Milhous (1982), among others.

The second hypothesis assumes that the missing material is present in the system, but it is not found at the usual sampling sites. In other words, if the entire system were sampled uniformly, the overall average would not show a gap. This is a modification of the faulty sampling technique mentioned by Pettijohn (1949) and

Sundborg (1956). It suggests that the location of the sample site may be to blame rather than the actual techniques used to extract the sample from a given site.

Hypothesis Three assumes that material in some size class within the 1 - 10 mm range will be preferentially eroded over all other sizes, given certain conditions such as rock type, degree of rock weathering, or flow velocity. Can a gap be made to occur by abrasion alone, and if so, under what conditions? Does this occur in natural streams, or is the energy requirement greater than what is available in most rivers? Krumbein (1941) and Pettijohn (1949) both noted that simple laboratory experiments could resolve the abrasion versus selective transport issue. Others, such as Sundborg (1956), suggested that perhaps the two are inter-related. As a first step, the effects of abrasion alone should be identified.

The fourth hypothesis assumes that the gap material is preferentially entrained and thereby removed from the system. This was proposed by Sundborg (1956) and has received some support from the experimental flume work of Everts (1973) and Raudkivi and Ettema (1982). Unfortunately, little flume work has been directed at studying selective transport in heterogeneous gravel sediments. Most early investigators were primarily concerned about the decrease in the mean size of sediments downstream. Krumbein (1941, p. 482) stated that the smaller particles may outrun the larger ones during transport. In a natural reach, however, sediment has probably been supplied to the river for a sufficiently long time that if differences in velocity were the sole criterion, the larger particles would have had time to reach the lower parts of the reach and thus uniformly cover the bed. Furthermore, the work by Meland and Norrman (1969) shows that for heterogeneous sediment betweeen 0.85 mm and 7 mm, the coarse fractions move most quickly through the length of the flume.

The idea that each mode represents a transport mode may be tested under Hypothesis Four. The concept that lithology controls the size distribution can be tested under Hypotheses One and Three, depending upon where the breakdown occurs.

Although the association between lithology and the gap appears throughout this study, by itself lithology is a control, an initial condition, rather than a process. In the context of the present study, lithology is an inadequate explanation for the presence or absence of the gap without amplification of how it controls the gap.

The first two hypotheses are mutually exclusive and sequentially related. They are field testable and form the main body of the present work. The third and fourth hypotheses may be independent; for example, material in the gap range may be inherently weaker, or the two hypotheses may be highly correlated as suggested by Sundborg (1956) when he said that the missing fraction may be preferentially entrained and therefore subject to more abrasion. As a result of this possible interaction, these last two hypotheses are better suited to flume studies, once the first two hypotheses have been rejected, and they are not considered further in this study.

To test the first hypothesis, source area control, two headwater reaches were explored directly, Flynn and Oak Creeks in Oregon, and the published data of a third, Bridge Creek (Nanson, 1972) in Alberta, were evaluated. The two Oregon creeks are in unglaciated, single lithology watersheds. The Flynn Creek basin contains only medium grained sandstone; the Oak Creek basin contains only aphanitic basalt. Bridge Creek basin is predominantly limestone covered in places with glacial till of mixed lithologies. These three streams are discussed in Chapter III. Distance was purposely excluded since it is not relevant to the first hypothesis.

To observe the effects of increasing the size of the system without increasing the distance, samples were collected from the Quesnel River in British Columbia, 12 km downstream from its source at Quesnel Lake. The lake is approximately 270 km^2 in area and is an effective sediment trap for bed load. The discharge at the mouth of the lake is several orders of magnitude larger than that at Flynn, Oak, and Bridge Creeks. The effects of increasing both size and distance were noted with samples from a bar on the Fraser River, 1,300 km from its source. Its discharge at this location is an order of magnitude larger than that of the Quesnel River, which is a tributary to the Fraser. The pattern in the gap characteristics of deposits from a single river system over a distance of 890 km may be seen in the first 29 samples from the North Saskatchewan data (Shaw and Kellerhals, 1982) from Alberta.

If the gap is related to distance downstream, then either abrasion and/or selective transport and/or source area input may create the gap. Hypotheses Three and Four cover the first two, and Hypothesis One includes the last. On the other hand, sampling strategies may be at fault. To test the effects of sample site location within a bar, Hypothesis Two, single bars were sampled thoroughly on Flynn Creek, Quesnel River, and Fraser River. These results are discussed in Chapter IV. A summary of morphometric and hydrologic information for the six rivers studied may be found in Table 1. Before exploring the first hypothesis, however, a brief review of previous work in the present context is helpful.

Table 1. Selected morphometric and hydrologic data for six rivers.

River	Drainage Area (km^2)	Stream Length above sample site (km)	Annual Mean Discharge (m^3/s)	Maximum Discharge (m^3/s)	Remarks
Flynn (Edwards, 1980)	2.02	2	0.13	3.94	single lithology, sandstone, unglaciated
Oak[1] (Milhous, 1973)	7.25	3.5	0.24	20.50	single lithology, basalt, unglaciated
Bridge (Nanson, 1972)	15.8	8.4	not available	2.60	dominant lithology, limestone, glaciated
Quesnel[2] (Water Survey of Canada, 1983)	5,930	12	128	606	multiple lithologies, glaciated
North Saskatchewan[3] (Shaw and Kellerhals, 1982)	54,528	890	231	3,396	multiple lithologies, glaciated
Fraser (Water Survey of Canada, 1983)	228,000	1,300	3,430	14,400	multiple lithologies, glaciated

[1]Area, distance, and discharge based at vortex sampler, 3.8 km upstream from last sample site.

[2]Area and discharge based at Likely gauge, at lake outlet, 12 km upstream from the bar. Lake traps bed load from higher tributaries.

[3]Area and discharge based at Lea Park gauge, 60 km upstream.

II. PREVIOUS WORK

A. INTRODUCTION

Shea (1974) noted that no studies he could find in the literature had set out specifically to investigate the grain size gap. Ten years later that statement is still valid, yet several studies have been reported which offer some background information for the four hypotheses.

Udden (1914) provides a comprehensive data set containing every type of sediment deposit he could sample. The paper is fascinating to read and displays a thoroughness rarely found in contemporary reports. Of the 371 samples analyzed, 14 contain material coarser than 16 mm and represent fluvial deposits from large and small streams, Pleistocene terrace deposits, and glacial outwash deposits. Since he used whole Phi intervals for his groupings, the 16 - 32 mm size is the first size larger than the gap range. Eleven of the 14 samples show modes on either side of a minimum in the 1 - 16 mm range. Although Udden (1914) states that the secondary maximum will be in the coarser range, with the primary mode in the finer range, seven of the 11 coarse fluvial deposits have the secondary maximum in the sand range (see Figure 1). Still, Udden's data show unequivocally the existence of polymodal size distributions.

The next series of reports consists of abrasion studies. These were undertaken to explore the nature of the general decrease in grain size downstream in fluvial sediments. Thus, few of these studies analyzed changes in size distribution beyond noting a change in mean diameter. Furthermore, most used a single lithology which abrades easily, such as limestone, so a gap may not necessarily develop, according to Milhous (1982). Nonetheless, they provide information on the process of abrasion under various conditions, and are relevant to the third hypothesis.

B. EXPERIMENTAL ABRASION STUDIES

Abrasion studies may be divided into two major groups based on the methods used to move the material under investigation. All experiments have used either gravity or water to propel one stone past another. Until 1943, almost all experiments were carried out in a variety of ball mills or tumbling drums which used gravity and friction to carry the particles up to a certain height and then drag them down past one another. According to Krumbein (1941), Schoklitsch (1914) initially used a jet of water to move stones around two concentric tubs although his subsequent work (1933) was done in a rotating drum. Lord Rayleigh (1943, 1944) used both tumbling drums and jets of water. Since then, studies have been made by investigators who have used Kuenen-type circular flumes driven by large paddle wheels (Kuenen, 1956; Bradley, 1970). The shift in method reflects a progression from the initial investigations which isolated individual variables to a more general integration of several variables and specific processes in a more natural simulation. This orderly approach has produced a wealth of information from relatively few studies, although the work has been spread over a century.

Rotating drum experiments began with Daubree (1879) and culminated with Krumbein (1941). The historical precedence of this technique stems from the simplicity of design and the minimal material requirement. Virtually any cylindrical container may be used, from plastic bottles (Schubert, 1964) to steel drums lined with wood (Wentworth, 1919; Krumbein, 1941). Commonly, the cylinder is laid horizontally between a rotating shaft and an idler shaft, the former turned by an electric motor. The recent availability of small tumbling drums for polishing gemstones has further simplified procuring the necessary experimental apparatus (Adams, 1978, 1979).

The volume of material has ranged from a single stone resting on sand to 4 – 5 kilograms of gravel for a cylinder 63.5 cm in diameter and 45.7 cm long. Wentworth (1919) found that the rate of abrasion increased with the amount of material in the cylinder until the material in motion moved over only other stones. Beyond this, additional material had no effect on the rate of abrasion. Water typically covers the material in the cylinder, although Alling (1944) thought that water introduced the possibility of chemical dissolution of the material and did all of his experiments in dry cylinders. In some cases (Wentworth, 1919; 1922) fresh water was circulated through the cylinders, and the old water was passed through a series of traps to remove the suspended material. Other workers (Daubree, 1879; Krumbein, 1941) also analyzed the suspended material in the water used in the cylinders.

Several disadvantages of tumbling mills have been noted by Kuenen (1956). He observed that: 1) water, instead of impelling the fragments, acts as a brake, 2) the movement of the fragments may be more or less rotary than in a river, 3) the fragments alternately drop down a steep slope and then lie still until dropping again instead of rolling continuously over a horizontal surface, and 4) consequently, the rolling velocity is not simply the distance divided by time. This last point shows the difficulty of assessing the effect of velocity on abrasion since increasing the revolutions per minute of the drum only shortens the time that the material is at rest.

To overcome these difficulties, Kuenen (1956) designed a circular flume approximately 1.2 meters O.D. with a channel width of 0.3 meters and a depth of about 0.3 meters below the water surface. Initially the flume had a concrete bed; later it contained 4 cm diameter pebbles set into the concrete. Bradley (1970) constructed a 4.3 meter O.D. Kuenen-type tank with a channel 18.3 cm wide and 18.3 cm deep. These flumes allowed comparison of abrasion rates between sand and cobble beds as well as abrasion rates at different velocities. In addition, other experiments showed the effects of various concentrations of sand and clay material mixed with the pebbles.

The circular flumes, however, are more complicated to construct and require much larger volumes of bed material than do the drums. More significantly, the paddles induce very large horizontal eddies which in turn cause large vertical displacements of the bed load. Kuenen (1956, p. 364) notes the striking of the paddles by pebbles "with a loud report."

Krumbein (1941, pp. 484–489) provides an excellent summary of the results of tumbling drum data from Daubree (1879), Wentworth (1919, 1922), Marshall (1927, 1929), and Schoklitsch (1933). A brief summary of the various principles discovered by these early workers includes the following, arranged in order of increasing relevance to the present study.

1. Rounding of angular particles occurs very rapidly.
2. Rate of wear is greater for angular particles than for well rounded particles.
3. Rate of wear is greater for larger particles than for smaller ones.
4. Both roundness and sphericity increase with distance traveled and approach asymptotes which may be a function of original shape and size.
5. For an angular particle, size changes most slowly, sphericity changes more rapidly, and roundness changes most quickly.
6. Sternberg's law is valid during abrasion and may be expressed not only in terms of weight but also in terms of volume or diameter for given pebbles.
7. Abrasion of a particle is controlled in part by the size distribution of the material with which it is associated. An increase in the mean size of the associated material causes a linear increase in the exponent in Sternberg's law.
8. During abrasion a mixture of various sized particles tends to approach equilibrium proportions among the sizes present, after which prolonged abrasion will not change mean size, kurtosis or skewness.
9. The product of abrasion is almost entirely mud rather than sand.
10. If a gravel mixture contains an appreciable amount of material less than 4 mm, the smaller particles are crushed to silt and finer material, and the mean size of the remaining gravel may actually increase with abrasion.

Additional insights have come from the circular flume work of Kuenen (1956) and Bradley (1970).

11. The rate of abrasion increases as the square of the velocity. Over the range of natural stream velocities it can double for fine gravel.
12. Coarse gravel can lose a percentage of weight that is up to 5 times as much as fine gravel at equal velocities.
13. The type of bed is extremely important: abrasion may be 5 times less for medium pebbles rolling over sand than over gravel. On a sandy bed, weight and velocity have only slight effect on the rate of abrasion.
14. On a pebble bed, a cube will move more easily than a sphere. On a sand bed, a sphere will move more easily.
15. The addition of sand reduces the rate of pebble abrasion 10–15%, but even large quantities of clay have no effect.
16. Abrasion occurs by splitting, chipping, disintegrating, cracking, crushing, and grinding. On sand beds only grinding occurs. Crushing pulverizes sand caught between impacting larger fragments. Cracking refers to small, conical concussion cracks which develop during impact. All of these mechanisms produce very fine suspended load material with little reduction in size of the original material. Splitting, chipping and disintegration occur within the first few kilometers of transport and then cease. These processes result in substantial changes in size and shape. The by-products range from sand to clay.
17. The effects of weathering of material stored in channel deposits may completely dominate the results and are largely controlled by lithology.

All of these studies were concerned with the effects of abrasion, and thus may be considered to be part of Hypothesis Three. Results 9 and 10, however, suggest that the sand mode must develop by some other means, perhaps controlled by source area input (Hypothesis One) or selective entrainment and deposition (Hypothesis Four).

Results 13 and 14 indicate that hydraulic effects (Hypothesis Four) may be important.

Result 3 is from Daubree (1879). Wentworth (1919) found the opposite result using Niagara limestone, ranging in size from 10 to 40 mm. As the Niagara limestone size decreased, the rate of wear increased. It appears that Wentworth (1919) studied complete mixtures of cobbles as well as the history of individual stones, and in both cases he found that the rate of wear increased as the size decreased. This discrepancy may be resolved by Marshall's (1927) work. Marshall found that, using seven groups of samples of well sorted gravels ranging in size from 3.4 to 50.8 mm, the largest fraction, the 38.1 - 50.8 mm group, abraded most rapidly, and each successively smaller group abraded less rapidly than its larger neighbor. If all seven groups were combined into a single heterogeneous sample, the smallest size, 3.4 - 6.3 mm, abraded most rapidly. Additional experiments with 25.4 - 38.1 mm gravel showed that it could turn an addition of 10% sand (0.07 - 0.4 mm) into silt in one and a half hours. The crushing of small amounts of sand by gravel may be the reason why Daubree (1879), Wentworth (1919), Marshall (1927), and Krumbein (1941) found no sand as an abrasion product in tumbling mill studies.

The only abrasion study which has reported sand as an abrasion product is from Bradley (1970). Result 16 is from his study using weathered granites from the Colorado River deposits in Texas. Unfortunately, he does not provide any data or size distribution curves to substantiate result 16. The purpose of Bradley's (1970) experiments, however, was primarily to compare abrasion rates for weathered and unweathered river sediments. He typically used paired samples of similar size and shape stones, one fresh and one weathered, ranging in size between 19 - 83 mm. Result 17 is based on approximately 50 pairs of fresh and weathered granitic gravels. Comparison of the rates of abrasion in the flume with size decreases observed in the field led Bradley to decide that where the agreement was good, downstream decrease in size of bed material was controlled by abrasion, and where it was not, selective transport must be the reason. This led him to conclude that downstream decrease in the size of bed material may be controlled by both abrasion and selective transport.

C. R. J. RUSSELL'S (1968) SOLUTION

Russell (1968) claims to have located the missing fraction which, he states, is selectively transported by rivers and deposited on beaches. The report, however, is far from conclusive. The beaches studied were in the Lesser Antilles on the islands of Antigua, St. Lucia, Martinique, and Grenada. None of the stream deposits were analyzed to see if a gap was present in the fluvial system. The lithology of the islands is limestone and volcanics which, according to Milhous (1982), would not produce a gap in the stream deposits. Of the 144 samples, only 7 contained material coarser than 4 mm. No histograms or cumulative plots of the data are presented. Instead, there is a table of maximum, minimum, and median percentages by weight within millimeter grades. In support of his argument that rock disintegration produces material in the 1 – 6 mm range, he cites three field studies in basalt terrane and one limited study of 7 samples of weathered crystalline rock disintegration in which the specimens were not subject to any abrasion more strenuous than rubbing between the fingers. The basalt studies showed a uniform rate of decrease through the 1 – 6 mm sizes, and the crystalline rock study showed an abundance of particles in the 2 – 4 mm range. Shea (1974) noted further shortcomings of the Russell (1968) paper.

D. FIELD STUDIES

A number of field studies have noted bimodal size distributions in gravel river deposits, and only four representative ones are mentioned here. A more complete, but by no means exhaustive, list may be found in Shea (1974) and Shaw and Kellerhals (1982).

Yatsu (1959) examined the size distribution of sediment along eight major rivers in Japan. He noted that the mean size decreased downstream in all cases in a manner predicted by Sternberg's law of exponential decrease with distance. In six cases, however, there were two distinct curves, with a size discontinuity between 2 - 4 mm. Of the two exceptions, Yatsu (1959, p.231) says, "The Abe River transports gross materials to the river mouth, and the course of the Yahagi River under consideration is replete only with the coarse sand on the other hand. This observation led Yatsu to conclude that material in the 2 - 4 mm range did not obey Sternberg's law but instead abraded very rapidly. An examination of the slopes of these rivers showed similar exponential decreases, with discontinuities for those rivers which displayed a sand-gravel transition, and continuous profiles for the all-sand and the all-gravel rivers. Since the discontinuities of size and slope occurred at the same location, Yatsu (1959) used the argument that a graded river adjusts its slope to move the load supplied to it (Mackin, 1948) to explain the break in slope. There are few particles in the 2 - 4 mm range; therefore, there are no slopes in the range which would just move these particles.

Shaw and Kellerhals (1982) presented the grain size distribution and lithologic composition for bed material in twelve major rivers in Alberta. They found no change in slope at the sand-gravel transition. They did observe (1982, p. 48) that:

> The rivers can be divided into three reaches: a mountain reach in which there is a tendency to increasing grain size with distance; a central, gravel reach in which decrease in grain size follows Sternberg's relationship; and a lower reach which is sand bedded {and shows little change}.

They also noted that of the 125 gravel samples, only three did not have a sand mode, and all three were from headwater reaches in the mountains or foothills.

A possible explanation, although not stated, is that those reaches drain single lithologies which do not produce a gap, such as limestone or basalt (Milhous, 1982). Since the lithologies are included for sizes larger than 2 mm, this is readily tested. The McLeod-1 sample consists of 49% limestone, 22% quartzite, and 25% sandstone.

Sandstone should produce a bimodal size distribution, using Milhous's (1982) criterion. The North Milk-2 sample contains 27% limestone, 44% quartzite, and 16% sandstone. Oldman-1 consists of 13% limestone, 8% volcanics, and 72% sandstone. Not only are these not single lithology basins, they also each contain rock types which should produce a bimodal size distribution. Seven other bimodal samples from five different rivers contain greater than 50% limestone. The Bow-Saskatchewan-3, for example, has 71% limestone, 10% chert, and 9% quartzite. Without the lithologies of the less than 2 mm fraction, it is not possible to observe the composition of the sand size mode; hence it is not possible to determine if Milhous's (1982) hypothesis is correct.

The Shaw and Kellerhals (1982) data also suggest a relationship between distance downstream and the difference in height of the gap and the secondary mode. All twelve rivers show gaps in the 1 - 10 mm range which are greater than 1% of the secondary mode after 350 km downstream, except the Peace River, which was not sampled closer than 816.4 km from its source. Seven of the rivers were sampled closer than 65 km from their sources. Two of these had gaps in the initial sample, at 44 km and at 29 km. The other five required 90 -190 km for the gap to exceed 1%. Thus, the Alberta rivers suggest that if the gap is not present in the headwaters, it develops on the order of 100 km downstream from the source. Concurrent changes in slope, velocity, discharge, or sediment input have not been investigated.

At least two studies have sampled both stream deposits and sediment source areas. McPherson (1971) sampled approximately every 330 meters (1000 feet) along Two O'Clock Creek, an 8 km long tributary to the North Saskatchewan River in Alberta. The lithology is predominantly limestone. At three locations slope samples were taken 330 meters from the stream sample site; at two of these sites additional samples were taken 660 meters from the stream; and at one of these sites a third sample was taken 990 meters from the channel. The cumulative curves for the slope samples appear to be very similar to the stream deposits, and neither suggests the presence of a gap. In the lower two–thirds of the basin some till exposures are being actively eroded, and cumulative plots of three till samples show gaps in the 0.01 to 1 mm range. The proportion of till to total sediment input was not assessed.

Nanson (1972) studied both Two O'Clock Creek and Bridge Creek, which is in the next watershed north of Two O'Clock Creek. Nanson's data are similar, but weirs were contructed to trap bed load rather than sample bed deposits. His results are considered in more detail in the next chapter.

E. SUMMARY

Two notable results from previous work are the following. Sand does not appear to be the result of abrasion; in fact, small amounts of sand in gravel mixtures are quickly crushed to silt. A few field studies in small streams have suggested that there may be a relationship between basin lithology, especially aphanitic rocks such as limestone or basalt, and the lack of a gap in the stream deposits. The effect of the size distribution of material entering the channel on the size distribution of material deposited in the channel deserves further study.

III. HYPOTHESIS ONE: SOURCE AREA CONTROL

A. INTRODUCTION

Hypothesis One assumes that the material missing from downstream river deposits is also missing from the source areas for those deposits. Here, source areas are considered to be any area providing sediment to the river deposit under study, and include upstream bars, bank deposits, and point source areas such as landslides, rock falls, debris torrents or other mass wasting processes which are presently supplying sediment to the stream upstream of the sample site.

The concept that the gap is the result of a mixture of two or more lithologies, each represented by one of the two or more modes, comes under this hypothesis, for the main point is that the gap is created outside of the fluvial system. The river deposits simply reflect what is supplied to the channel. Typical arguments against different populations, differing either in lithology or in hydrological characteristics, causing the modes have been that this fails to account for either the uniformity of the gap, usually in the 2 – 4 mm range (Sundborg, 1956), or the fact that there are usually only two modes regardless of the number of different lithologies present. The breakdown characteristics suggested by Milhous (1982) and summarized in Chapter I provide a possible explanation for these two common features of gravel river deposits. The effects of mixed lithologies on grain size distributions were not explored in the present study.

In order to test this hypothesis, a stream with a well developed gap in the 1 – 10 mm range in a downstream bar sample could be systematically sampled. Material from the bars, banks, and slopes upstream should either support or refute the hypothesis.

Initially two small streams, Deer Creek near Toledo, Oregon, and Oak Creek near Corvallis, Oregon, were chosen based on previously published reports by

Klingeman and Emmett (1982) and Milhous (1982). These streams had the following advantages:

- they were both fairly accessible,
- each was in a relatively undisturbed watershed,
- each watershed contained a single lithology; Oak Creek drained basalt, and Deer Creek drained sandstone,
- neither watershed had been glaciated, so foreign lithologies were not present,
- there appeared to be a data base for bedload measurements, at least in Oak Creek, and
- both streams appeared to have a gap in the 1 - 10 mm range, although the Oak Creek data were inconclusive.

During the initial investigation, discussions with Dr. Klingeman and Dr. Beschta at Oregon State University revealed that Flynn Creek, which was adjacent to Deer Creek, was better suited for this study. It was in an unlogged watershed which had been used as the control for the 10 year Alsea Forest Study reported by Brown and Krygier (1971). Furthermore, a vortex sampler had been installed, similar in design to the vortex sampler on Oak Creek (Klingeman and Emmett, 1982), and several research projects had been completed on Flynn Creek (Adams, 1980; Edwards, 1980, Jackson, 1981; O'Leary, 1980). Downstream samples taken on Oak Creek during the initial investigation failed to disclose any gap, confirming the observations of Milhous (1982). Thus, Flynn Creek became the principal river investigated to test Hypothesis One.

B. FLYNN CREEK

The Flynn Creek watershed is a south facing, undisturbed, forested basin located in the Alsea Forest, approximately 25 km southeast of the Pacific Coast town of Newport, Oregon, as shown in Figure 5. Selected morphometric and hydrologic data are contained in Table 1. The underlying geology consists of Tyee Sandstone and is

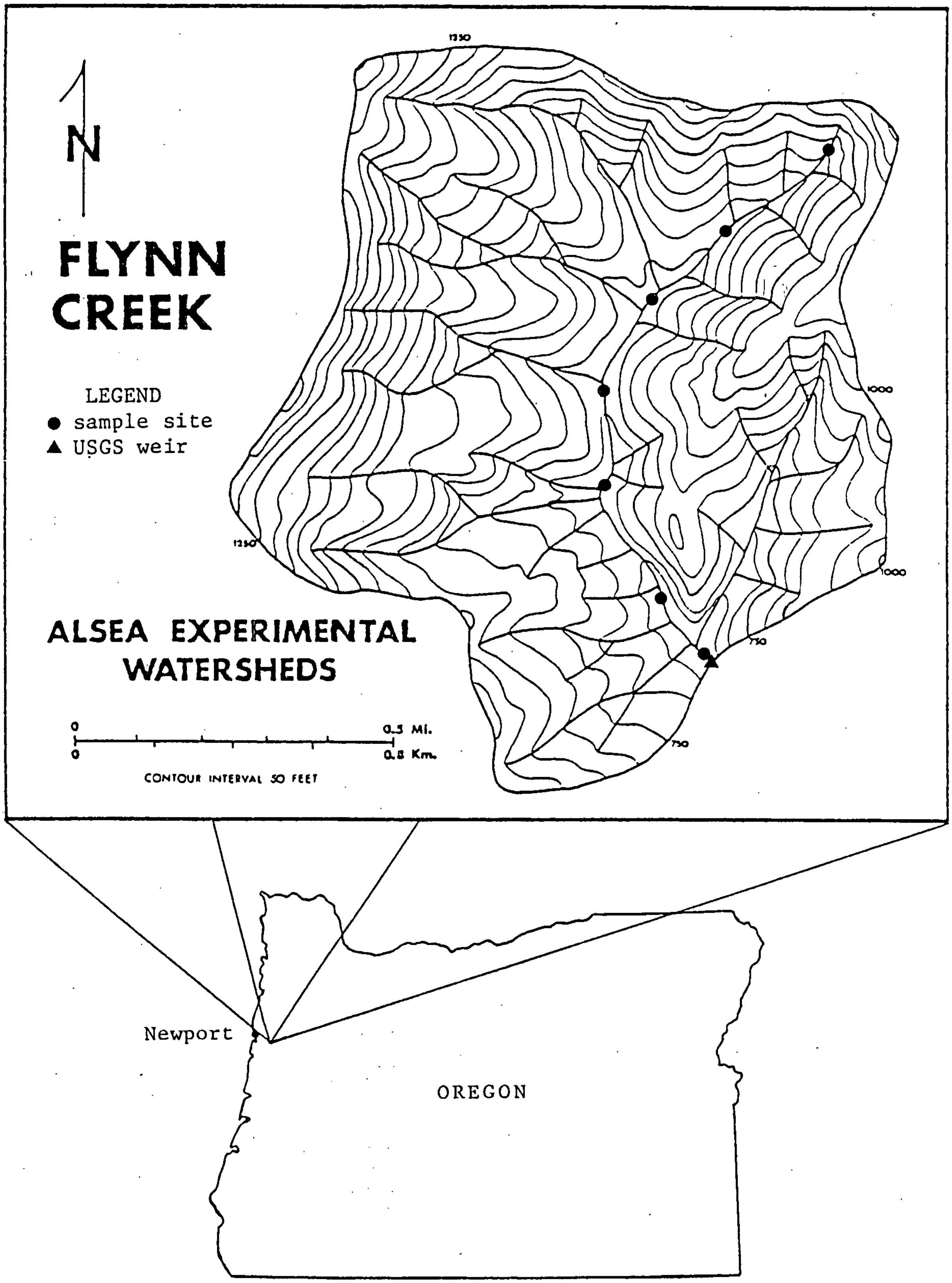

Figure 5. Flynn Creak study area (after Marston, 1978)

more fully described in Chan and Dott (1983). Bedrock is exposed along the channel at only two locations within the basin. Each bedrock reach is less than 100 meters long. No outcrops were observed on the hillsides, which are covered with Douglas fir (Pseudotsuga menziesii) between 95 and 110 years old, and red alder (Alnus rubra) in stands between 50 and 75 years old. Smaller vegetation is primarily salmonberry (Rubus spectabilis), sword fern (Polystichum munitum), bracken fern (Pteridium quilinum), and sedges are also present. A more complete description of the Flynn Creek watershed may be found in Edwards (1980) and O'Leary (1980).

The climate is temperate humid. According to VanSickle and Beschta (1983), most precipitation falls during the winter months, from October through March, in the form of long duration, low intensity frontal storms which move inland from the Pacific Ocean. They state that within these major frontal storms periods of moderate to high rainfall intensities generate runoff events in which most sediment is transported. Edwards (1980) states that a single large storm may move virtually the entire annual sediment yield.

Particularly noteworthy is the lack of any vegetative evidence of landslides or slumping, at least during the last 100 years. Morphological evidence for failures earlier than this is indistinct. During the summer, 1983, no slumping was found along the 1500 meters of stream channel. At Christmas, 1983, one recent slump was discovered covering less than one square meter of steep bank surface, less than 10 cm deep. This was located approximately 1050 meters upstream of a USGS weir which marked the downstream end of this study area.

Within the study area, the stream width varies from a maximum of 5 meters to a barely distinguishable intermittent sheetwash area in a shallow valley on a steep hillside near the ridge crest. The bed material consists predominantly of medium to coarse sand and fine gravel (0.25 - 8.0 mm) armored with fine to coarse gravel (4 - 32 mm). Figure 6 is a histogram of the size distribution of sediment on the most downstream bar in the study area, 30 meters upstream of the weir. The sample is a subsurface sample, containing more sand than the surface armored layer.

Sediment sources and storage zones were assessed by walking along the channel. The primary sources of sediment in the lower two–thirds of the basin were the small but ubiquitous flood plains, typically 1 - 3 meters wide and 0.5 - 1 meter deep, and the deposits trapped behind large organic debris within the channel. In the upper one–third of the basin the flood plain disappears, and the slopes feed directly into the channel. As a result of the smaller volume of water, small organic debris and large stones (90 - 180 mm) also trap sediment. The observation by Hack and Goodlett (1960) and by Kirkby (1980) that the most active source areas are along first and second order channels appears to hold in Flynn Creek. The principal mode of transport to the channel is assumed to be creep because no other form of mass wasting was readily discernible. Hortonian overland flow is not likely with the thick vegetation cover and forest litter, and low intensity rainfall. Zones of saturated overland flow and return flow are limited to the flood plains, which are heavily vegetated and quite flat.

Rates of creep were not measured in this study, but work by Swanston and Swanson (1976) suggests a value of 64 metric tonnes per lineal kilometer of stream channel per year for forested hillslopes in the Oregon Cascade Range, which includes Flynn Creek. Field checking the map in Figure 5 showed that most of the exterior links of the channel are very shallow and ephemeral, flowing only during extreme events. The third order sections in Figure 5 have well developed flood plains. Measuring the second order sections of Figure 5 gives 3.5 km of channel length, and using 64 tonnes/km length gives an annual yield of 224 tonnes per year. Larson and Sidle (1980) report an annual suspended load average from 1959 to 1973 of 984 kg/hectare for Flynn Creek, and an annual bedload average from 1978 to 1980 of 26 kg/hectare, or a total of 204 tonnes per year from Flynn Creek. The 10%

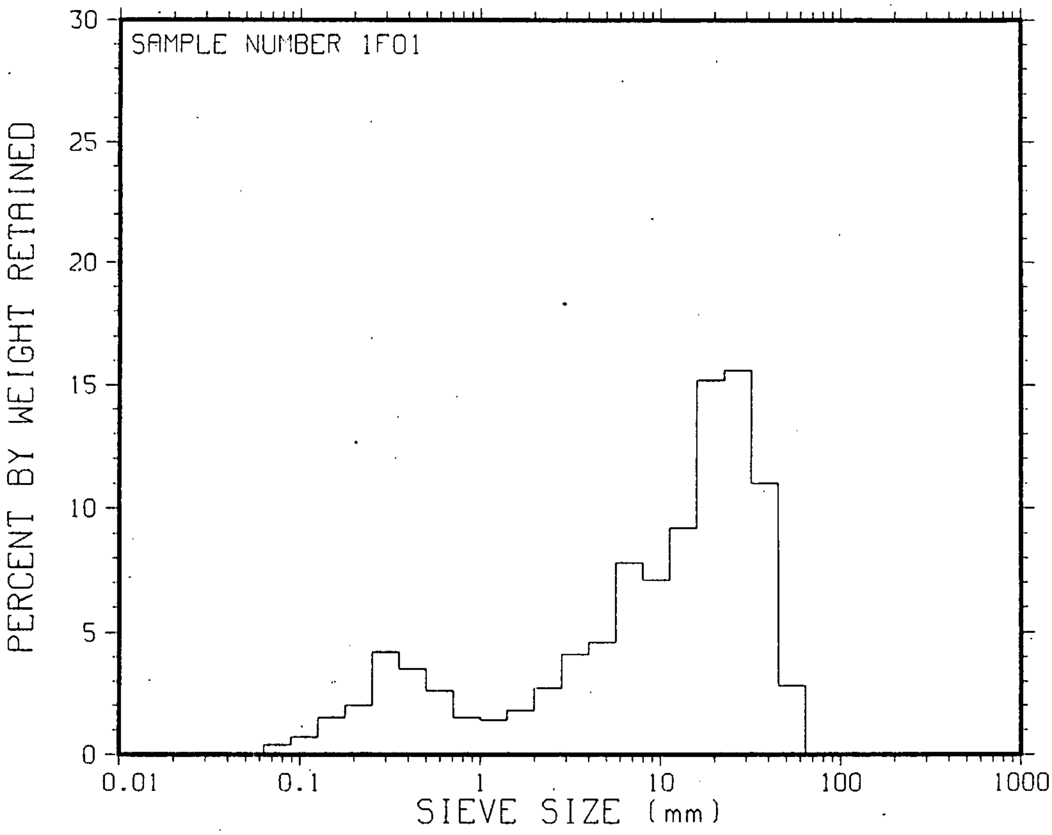

Figure 6. Downstream bar on Flynn Creek

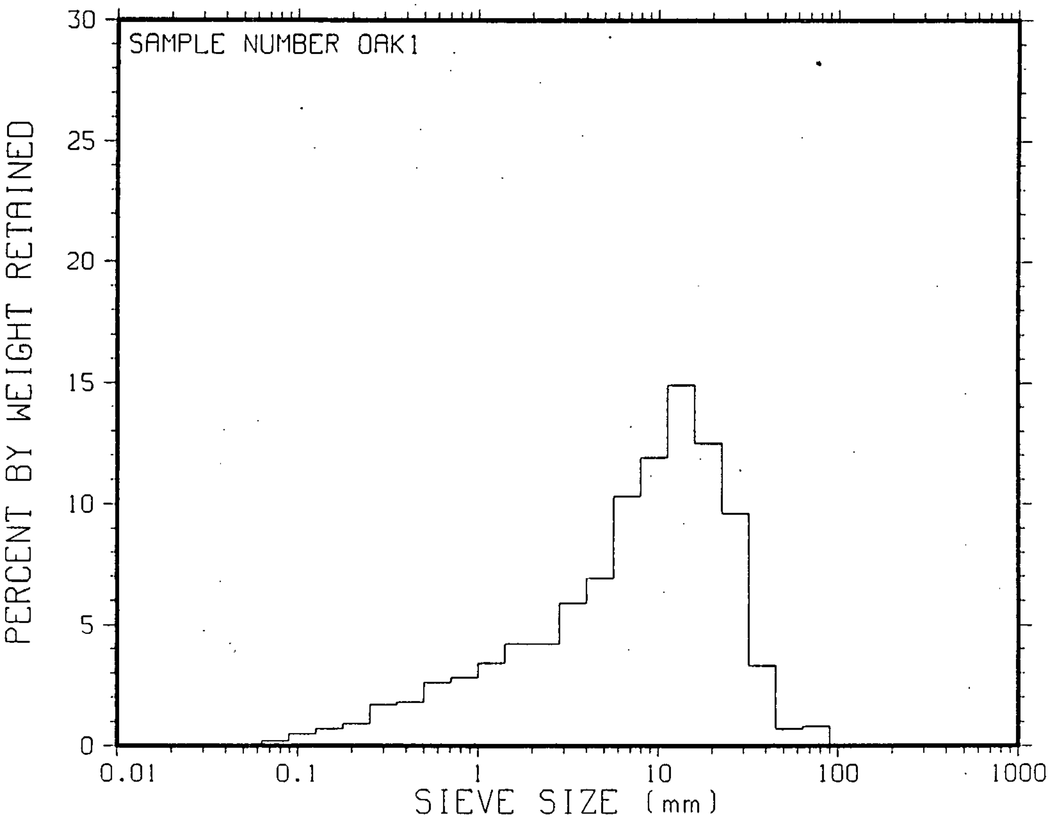

Figure 7. Downstream bar on Oak Creek

overestimation of the sediment load using a regional average creep rate suggests that creep is the dominant process delivering sediment to the stream.

C. METHODOLOGY

Samples were collected during three trips to Oregon. In late April and early May of 1983 all of the Oak Creek samples and two of the Flynn Creek samples, the most distal bar and the headwater slope samples, were collected. Analyses of these samples showed that only the Flynn Creek deposits were bimodal (see Figures 6 and 7) so no further sampling of Oak Creek was done. During late August five additional channel deposits and six bank deposits were sampled. Sampling disturbance on the original downstream bar site was still evident at this time, indicating that no bedload transport had occurred at this elevation on the bar since May. The results from the second set of samples suggested that slope samples adjacent to the flood plain samples would be informative, and an additional channel, bank, and slope site farther upstream would be useful. Consequently, at Christmas the last group of samples was collected. The stream channel had changed noticeably, with many of the previous channel sites underwater. The slope sites, however, should not be affected by the intervening changes in discharge. Although the uppermost channel deposit, which was collected at this time, may have undergone several cycles of scour and fill, the stream at this site was about 25 cm wide and any changes which may have occurred are thought to have been averaged out.

Based on McPherson's (1971) study the sample sites shown in Figure 5 were determined by measuring 305 meter (1000 foot) intervals along the middle of the channel beginning at the weir. At each location, the stream bar, the bank, and the adjacent footslope were sampled. All samples were subsurface samples, and a complete description of the field and laboratory methodology as well as a justification for the statistical confidence levels used may be found in Appendix A. Appendix A also contains a graph comparing 1/4, 1/2, and whole phi interval spacing of the size distribution data from a unimodal bank sample and a bimodal channal deposit from Flynn Creek. The actual data from the sample analyses are included in Appendix B.

D. CHANNEL DEPOSITS

Figure 8 shows that each bar sampled is remarkably similar with respect to the gap. Since only six sites were sampled, the mean of the 1 mm size class of 2.1% has a 95% confidence range from 0.1% to 4.1% which is not statistically different than the mean of the lower mode of 3.1%. Shea (1974) in his thorough review article claims that no gap can be shown to exist, statistically, unless an expected value is known. The variation from the expected value can then be measured. A theoretical basis or mathematical model for gravel bed grain size distributions is unlikely to be forthcoming, although Shirazi and Seim (1982) list five references for justifying a log normal distribution for river sediments. If a log normal distribution is assumed, the gap in Figure 9, which is the average of all channel deposits, is not significantly different from the expected values. Beschta (1982) points out several problems with the log normal assumptions for gravel streams, and the samples from Flynn Creek support his argument that gravel samples are not log normal but are negatively skewed, with a tail of fine sediments. Regardless of the shape of the distribution or the statistical significance of the persistent gap, Figure 8 shows that none of the bars has an abundance of 1 mm diameter material.

E. BANK DEPOSITS

The principal sources of sediment in the lower two-thirds of the basin are bar and bank erosion. To evaluate the grain size distribution of the bank material, six samples were taken along the stream bank, one adjacent to each bar site. Two of the sites, however, were in steep ravines, and these sites were considered to be slope sites

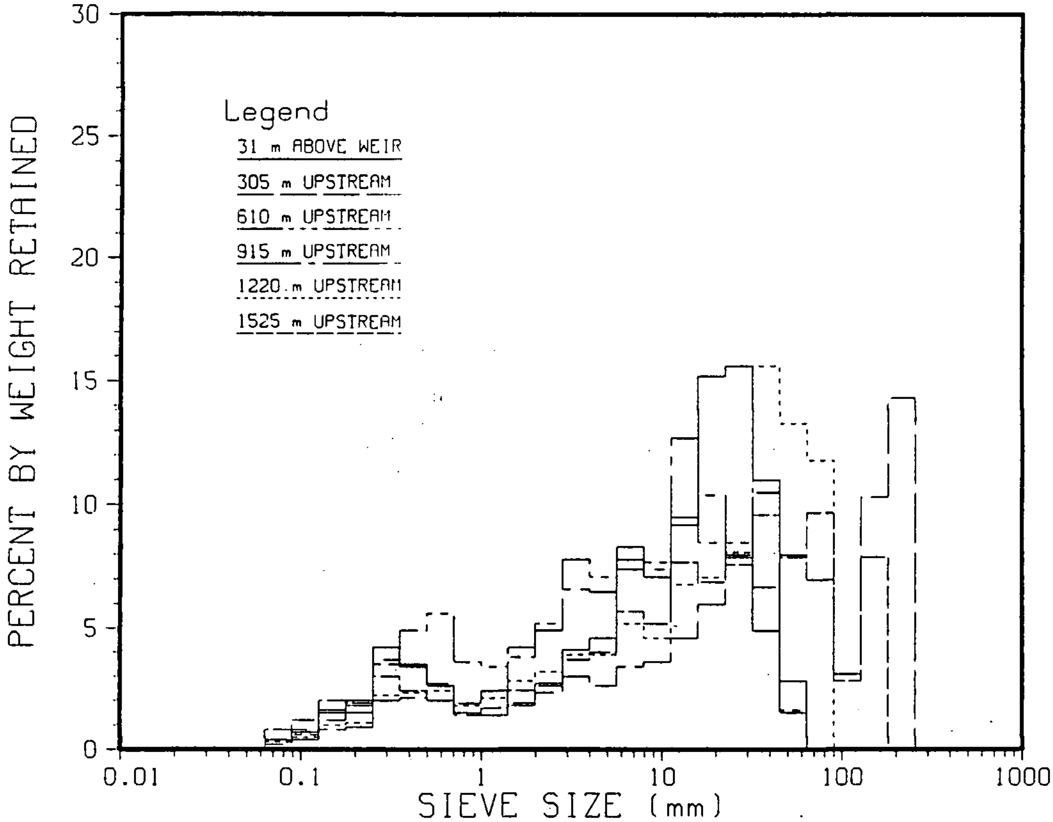

Figure 8. Six channel deposits on Flynn Creek showing similar gaps

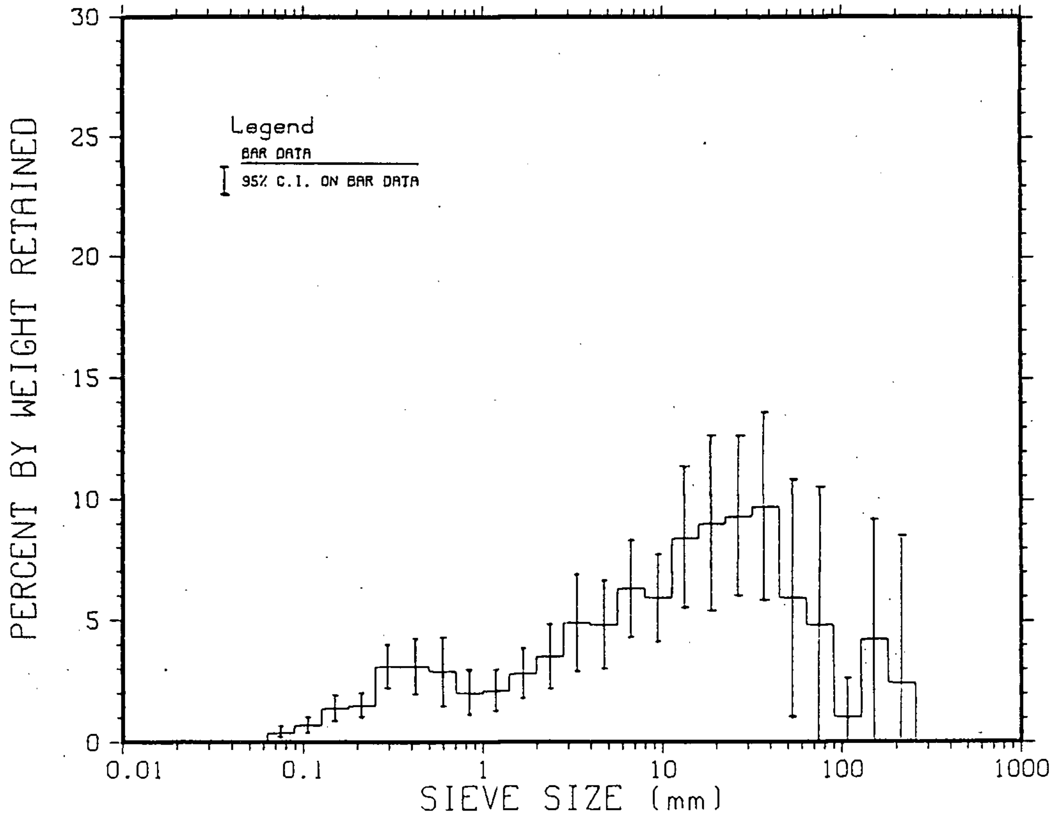

Figure 9. Average of 6 channel deposits on Flynn Creek

rather than flood plain sites. Figure 10 presents the average of the four bank samples and also the average of the six bar samples for comparison. Not only are the locations of the gaps visually similar, but the amounts of gap materials are not statistically different.

Initially this similarity may not appear noteworthy. After all, the flood plain is composed of material transported by the stream so it may seem reasonable that it should resemble the material stored in the bars. On the other hand, the flood plain represents a much different environment, hydraulically, than the main channel, as expressed in the modes in Figure 10. Each bank site contained a thick sand deposit overlying a thin lens of gravel just above the water table. This predominance of sand is shown in Figure 10, and suggests that the formation of the flood plain occurs primarily as overbank deposits, where the depth of flow is much less than in the main channel. That the gap occurs at almost the same size and within half a standard deviation of the amount is interesting. Further comparison between the bank and bar distributions in Figure 10 confirms the field observation that in the flood plain samples the fines are enhanced at the expense of the material larger than 1 mm. The modes are not, however, significantly different at the 95% confidence level.

F. SLOPE DEPOSITS

Although the flood plain deposits have been reworked by the fluvial system, the slope material represents fluvially undisturbed source areas. To reject the first hypothesis, the slope samples must be different than the bar deposits. At Flynn Creek a slope sample was taken adjacent to each bar site. The lowest portion of the slope that clearly had not been subject to direct stream contact was sampled in a manner similar to the bank samples. At 305 meters upstream of the weir the slope was approximately 60 degrees so the pit was excavated horizontally. At 1525 meters upstream of the weir the soil was less than 25 cm thick so a larger but more

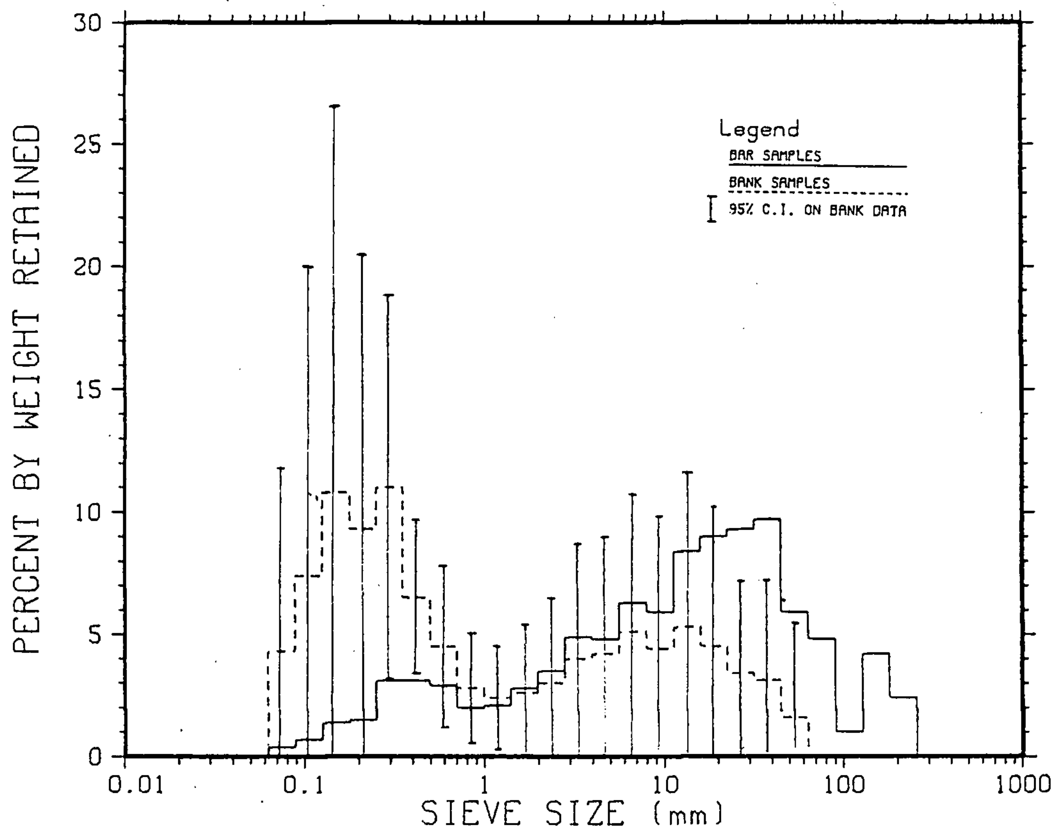

Figure 10. Average of 4 bank deposits on Flynn Creek

shallow area was sampled. The soil was thin enough in places that when the vegetation was scraped away, a few large clasts were broken off by the shovel blade. These have been included in the sample and explain some of the coarseness of this sample.

The large variation in the size distributions of the slope samples is shown in Figure 11. Still, there is remarkable consistency of little material at 1 mm, as shown in Figure 12, which contains the six distributions superimposed upon one another. Figure 13 is the average slope distribution plotted with the average bank distribution and the average bar distribution. Again the location and size of the gap is remarkable. The slope gap mean is within half a standard deviation of bar sample gap mean.

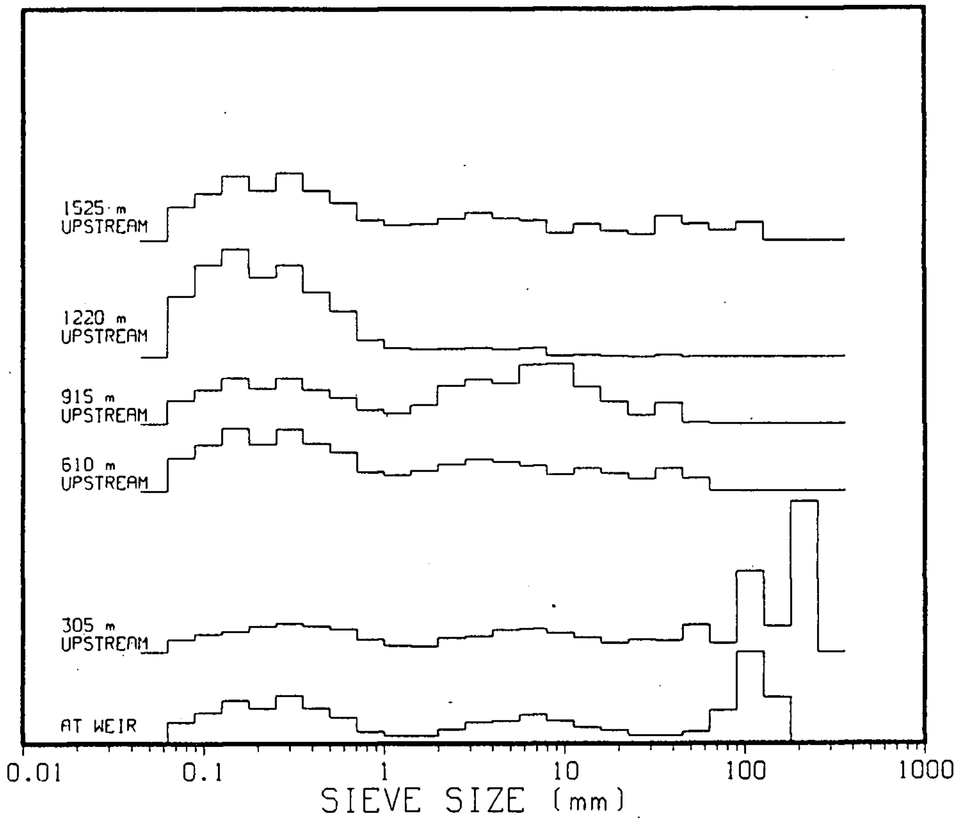

Figure 11. Six slope deposits on Flynn Creek

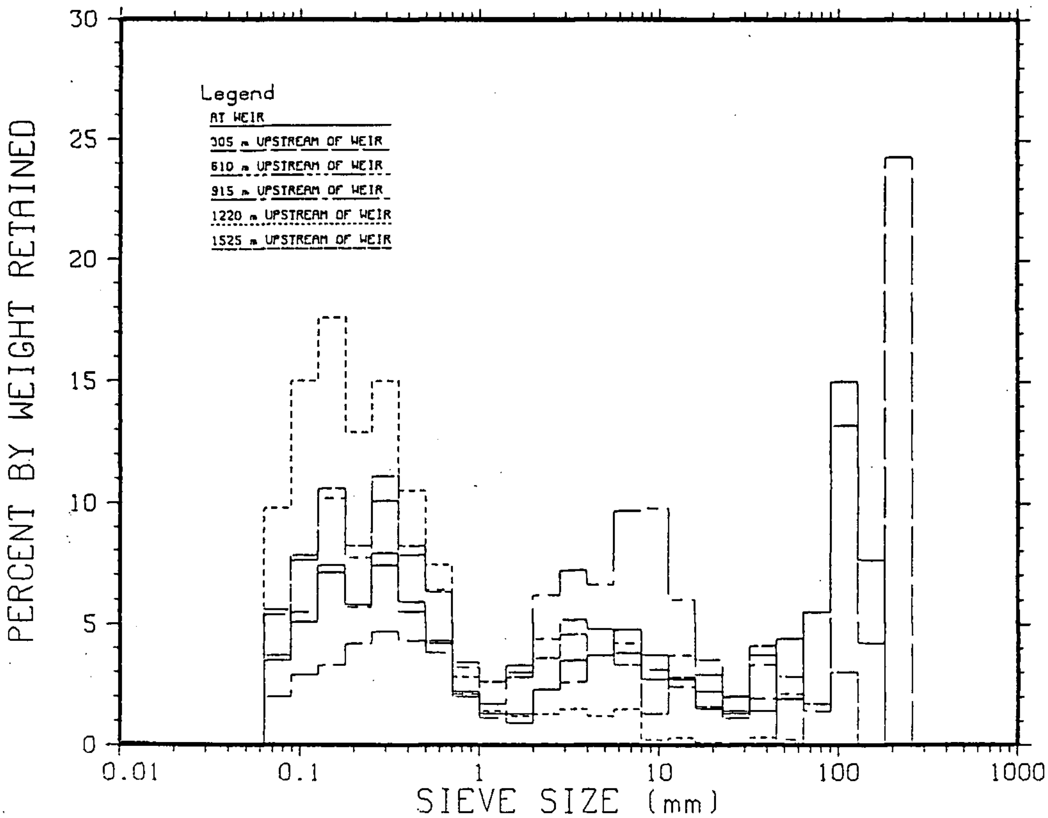

Figure 12. Superimposed slope samples showing consistency of gap.

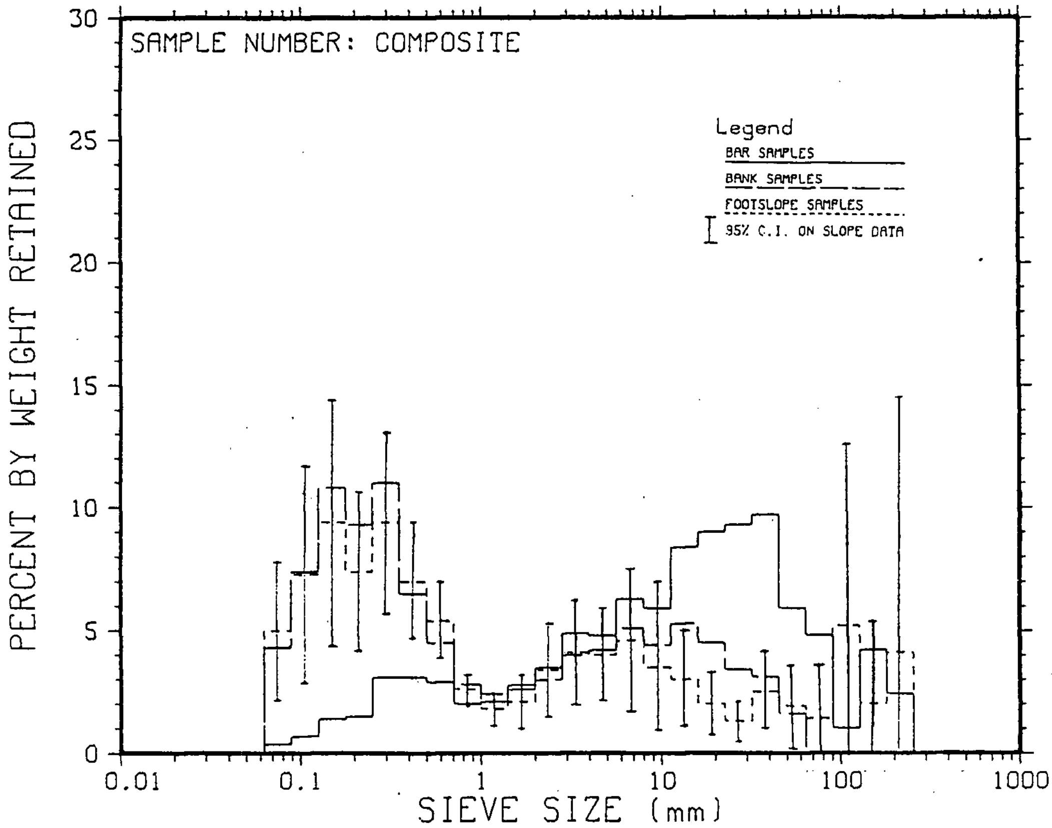

Figure 13. Average bar, bank and slope deposits

G. <u>CONCLUSIONS</u>

These results effectively support the first hypothesis, that the stream input controls the stream output size distribution. Although the individual size classes are not statistically different, certain qualitative speculations may be made concerning the processes which occur on the slope, flood plain, and stream bed. Figure 13 shows that the hillslope distribution is slightly more broad, or less well sorted, than the bar deposits. It has more material at each tail. It is also noticeably finer, with two identical modes at 0.25 mm and 0.125 mm, and a secondary mode at 5.6 mm which is half as large. The bar sample, by contrast, has its primary mode at 32 mm, which contains slightly more material than the two primary modes below 1 mm of the slope sample. The bar sample has a secondary mode between 0.25mm and 0.355 mm which has one-third of the material of the primary mode at 32 mm. It is also one-third of the primary slope modes at the same size class.

The bar distribution in Figure 13 has much less material below about 1 mm than either the bank or slope samples. This suggests a more energetic transport environment, and a winnowing of fine material. At the coarser end of the distribution, larger material has been concentrated by removal of the smaller particles. The very largest stones are probably lag deposits which are now weathering in place. Their source area clearly is the slope, as can be seen in Figure 12.

Some of the material below 1 mm which is removed from the bar deposits is stored on the flood plains. Figure 13 shows the better sorting of the flood plain deposits, suggesting a more uniform transport environment. The secondary mode in the flood plain samples is due entirely to the gravel lens just above the water table. A shallower sampling depth would probably yield a unimodal distribution: the bank sample located 30 meters above the weir did not contain the gravel lens, and Figure 14 shows a more normal distribution for this sample.

The channel and flood plain data support the concept that each mode corresponds to a particular transporting mechanism which is characterized by suspended load or bed load (Udden, 1914; Wentworth, 1933; Krumbein, 1942; Tanner, 1958; Middleton, 1976; Bridge, 1981). This explanation, however, is untenable for the slope material.

To test the possibility that the finer mode was the result of fragments breaking down into individual grains, 30 grams of each of the 18 size classes below 32 mm down to 0.063 mm from a slope sample located 305 meters upstream of the weir were broken down into individual grains. Concentrated potassium hydroxide dissolved the clastic cement after three days. Figure 15 compares the distribution of the grains from the clasts with the grains from the slope and flood plain samples. The shapes of the distributions are similar, but the modes from the clasts appear to be shifted one class size smaller. A comparison with the unimodal flood plain sample from Figure 14 is even more similar, as shown in Figure 16, suggesting that the fines in

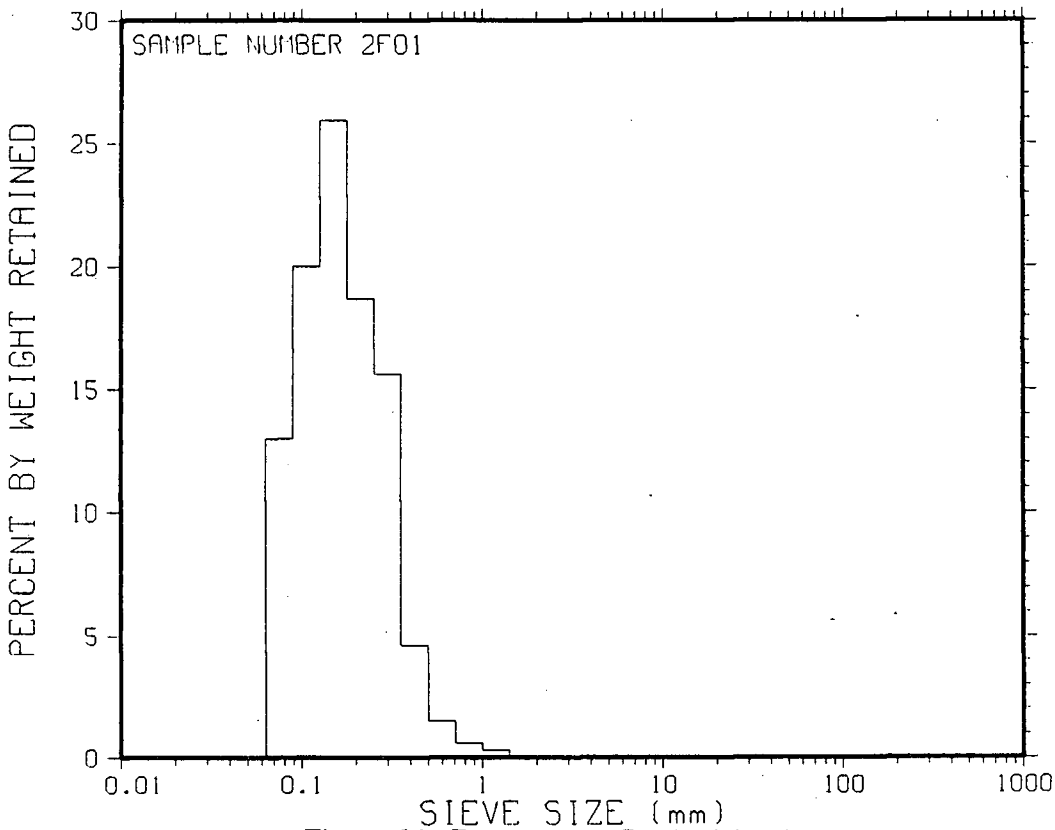

Figure 14. Downstream flood plain deposit

the flood plain material come from the breakdown of the slope material into individual grains.

If the slope samples are ignored for the moment, the remaining data suggest that the following occurs at Flynn Creek. First, material of a variety of sizes enters the stream. Once there, it is broken down into individual grains which are transported as suspended load and larger clasts that are being broken down which move as bed load. The suspended load is deposited on the flood plain as well as trapped in the bed material. The coarse material is stored in the channel deposits.

There are three problems with this explanation. First, abrasion experiments (Chapter II) do not support it. Second, it does not explain the presence of the gap. Third, the slope samples do not support it.

The slope data suggest a modification of this hypothesis: that the breakdown of the clasts into individual grains occurs primarily on the slopes rather than in the

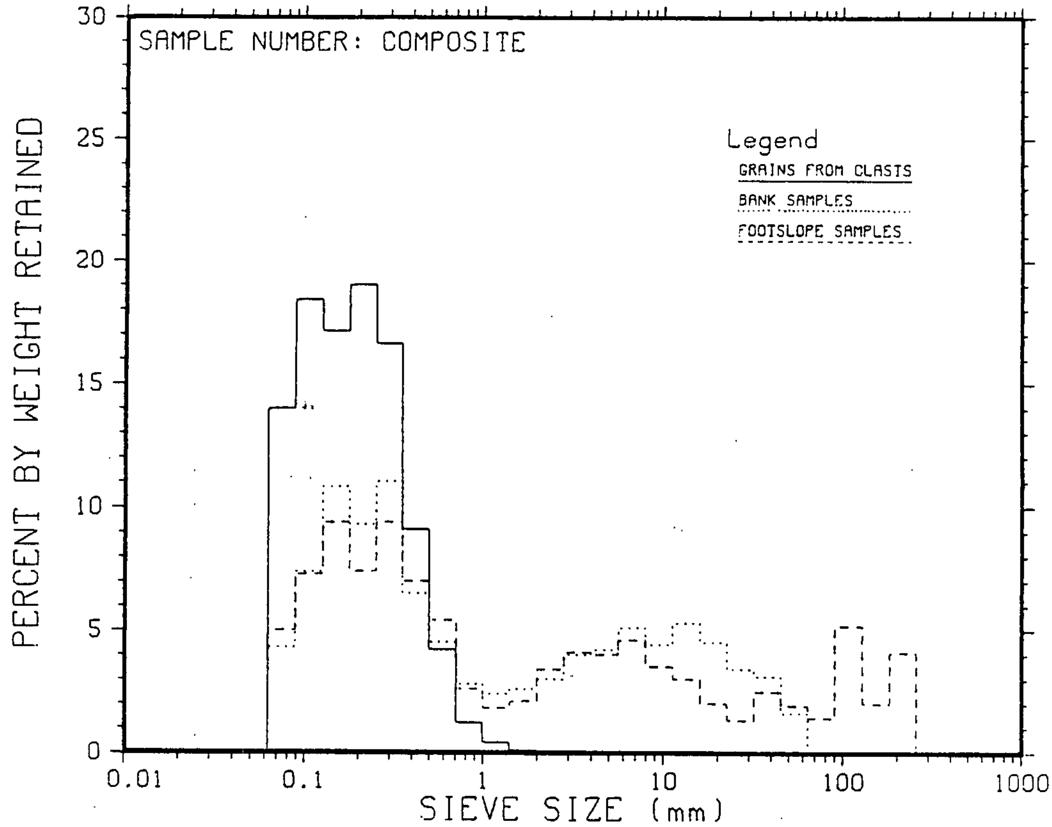

Figure 15. Clast, slope, and flood plain deposits

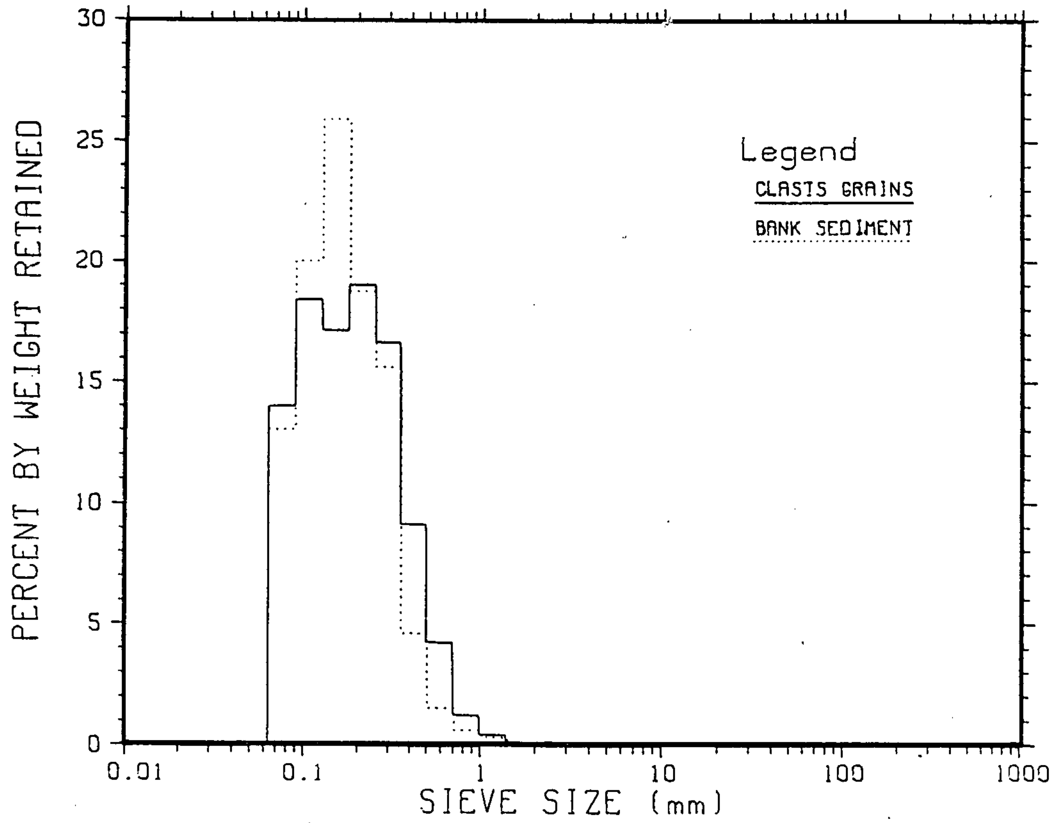

Figure 16. Clast and last flood plain deposit

stream. Sand is produced by slope weathering processes rather than by stream abrasion. Although this still does not explain how the gap is formed on the hillslope, it does suggest that the gap may not be the result of a fluvial process, and future work should explore hillslope weathering processes.

Lithology may nevertheless play a dominant role. The data from Oak Creek show that in a similar climatic environment in similar terrane, a gap is not produced in a single lithology basin composed of basalt. Figure 17 shows the size distributions of six channel deposit samples covering the first 10.5 km of the stream headwaters. Although the decrease in mean size might be attributed to abrasion, the stream gradient also decreases over this distance. As a result of the unimodal nature of the channel deposits, no bank or slope samples were taken from Oak Creek. The texture of the banks and soils was noted, however, to contain almost exclusively silt and clay, the expected weathering products of aphanitic rock (Milhous, 1982). Both were also much thicker, by a factor of approximately three, than the Flynn Creek deposits.

H. COMPARISON WITH OTHER AREAS

A comparison with other areas is difficult because so few studies have looked at both hillslope and stream deposits. Soil scientists and foresters concentrate their analyses on the less than 2 mm material. Most fluvial sediment studies do not measure hillslope material. Only two other studies could be found which looked at both hillslope and channel sediments, by McPherson (1971) and by Nanson (1972), and both of these were in limestone areas. Since these two studies were conducted in adjacent basins at approximately the same time, only the Nanson study (1972) on Bridge Creek is considered here.

Before comparing Nanson's data, several comments are in order. His data were presented as cumulative plots for the alluvial samples and as both cumulative plots and raw percentages for the weir trapped bed load. The data interpreted from the

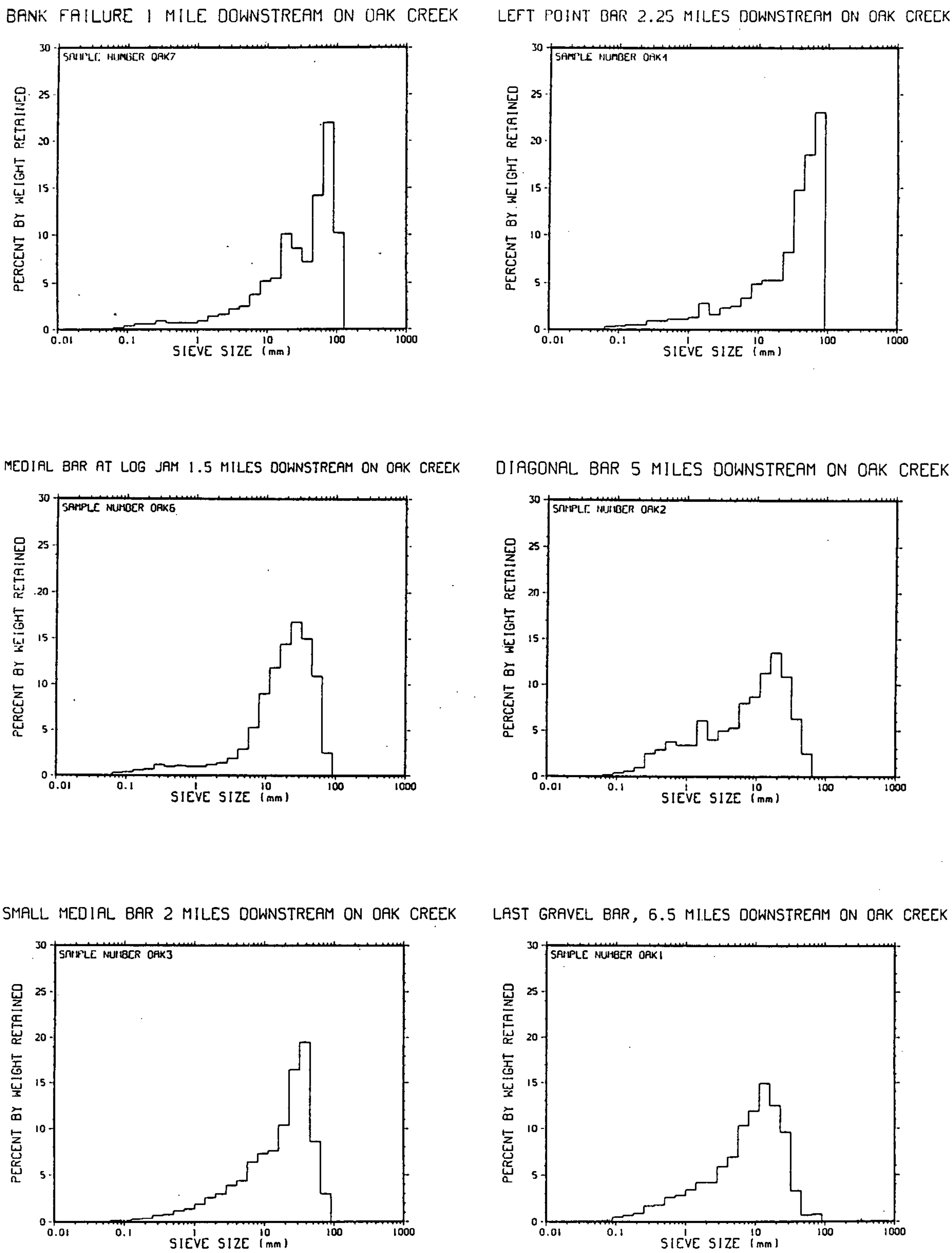

Figure 17. Six bar deposits on Oak Creek

cumulative plots are accurate to at most plus or minus 1%. For the weir and one additional bar data, Nanson used different size screens for analysis than were used in the Flynn Creek study. Below 4 mm the difference is insignificant, but the large increase in volume above 4 mm is due to the wider spacing of the screens in the Nanson analysis above 4 mm, as noted below. Also, the geology of the Bridge Creek basin is more highly varied, consisting mostly of limestone and dolomites, with some sandstone, quartzite, slate, shale, and a pebble conglomerate. More importantly, the region has undergone extensive glaciation. Bridge Creek basin is located approximately 90 km northwest of Banff, Alberta. The elevation extends from 1500 meters to 3000 meters above sea level at the head of the basin. It is eight times larger in area than Flynn Creek basin (Nanson, 1972).

Nanson identified three sediment source areas: till, colluvium-till, and glaciofluvial. Figure 18 shows the size distributions for his source samples. Since he did not state the relative amounts that each area contributed, it is not possible to combine these into an average. He did state that the glacio-fluvial area was small. Consequently, only the till and the colluvium-till data have been compared to the weir and bar sample in Figure 19. The large increase in proportional volume of the stream material above 4 mm is due to the double spacing in screen sizes. Each interval above 4 mm should be about half as high, but there was no basis for determining the correct proportions so the data were left in the original form. As with Flynn Creek, the stream distribution has a concentration of large material at the expense of material below 1 mm, relative to the source areas. The fit between the input and output distributions at Bridge Creek is similar to that at Flynn Creek, but there is no notable gap.

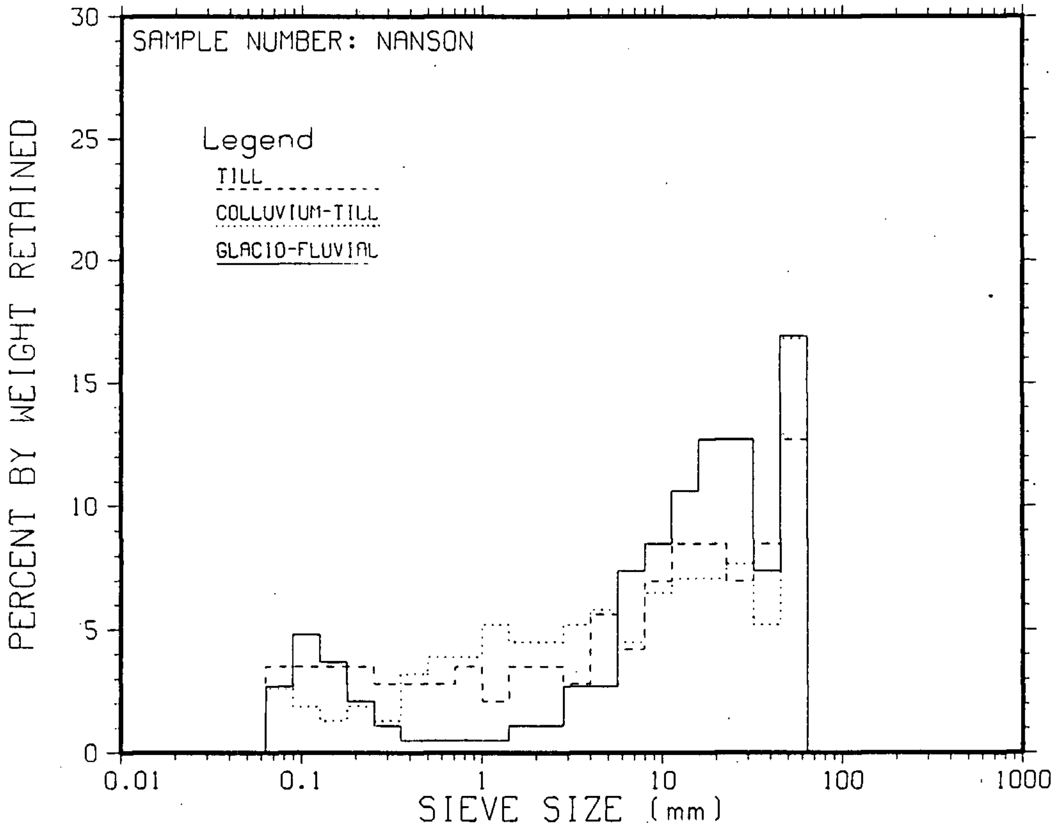

Figure 18. Alluvial source samples from Nanson (1972)

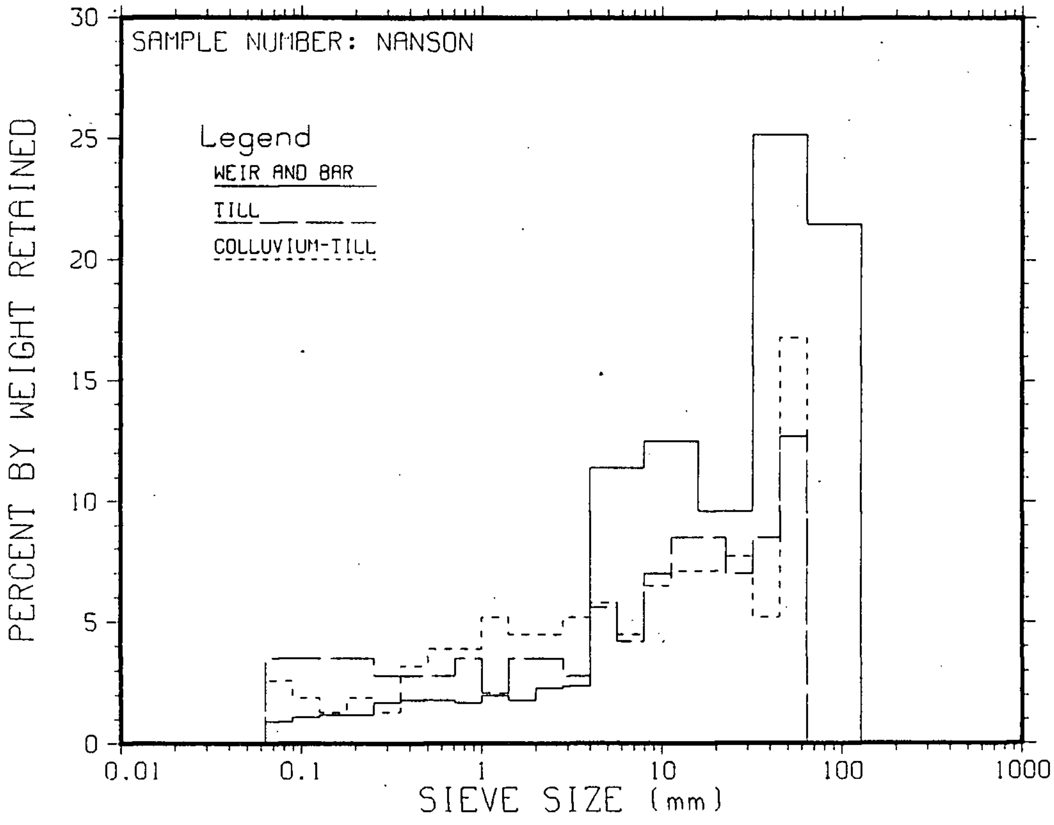

Figure 19. Stream, till and colluvium-till samples (Nanson, 1972)

I. SUMMARY

Two conclusions may be drawn from the Flynn Creek and Bridge Creek studies. First, in the stream deposits from Flynn Creek the shape of the size distribution curves appears to be controlled by the bedrock lithology which breaks down into larger clast and individual grains. This breakdown, however, occurs before the material reaches the stream channel. Second, in both of these small mountain streams the texture of the channel deposits is reflected in the slope deposits. At Flynn Creek a gap is present in both; at Bridge Creek there is no gap in the sediments in either the major source area or the stream deposits. Larger systems contain lithologically complex source areas and do not lend themselves to such simple sampling strategies. One approach to resolving the source area issue in a larger river system is to attempt to eliminate the other hypotheses.

IV. HYPOTHESIS TWO: SAMPLE SITE CONTROL

A. INTRODUCTION

Hypothesis Two claims that the sediments which seem to be missing from fluvial deposits are actually deposited in the system in an area which is not sampled. Flynn Creek provided one opportunity to test this hypothesis in two ways. First, six channel deposits and flood plain sites were sampled over 1.8 km of headwater reach, and none of these contained the gap material. Second, the bar located 915 meters upstream of the weir was sufficiently small that the entire exposed bar surface was sampled. Its size distribution, which is shown in Figure 20, has the persistent gap around 1 mm. At two other sites, 330 and 1650 meters upstream of the weir, the entire volume of material behind organic debris jams was analyzed. Figure 8 shows that both of these samples also have a deficit of material around 1 mm. Thus, the missing fraction is not in storage elsewhere on the bar or in log jams, nor is it found in the bank deposits. Although this refutes hypothesis two, the small size of Flynn Creek inhibits any sort of generalization about larger systems. Therefore, to explore more thoroughly the notion that the missing fraction is deposited somewhere on the bar, a larger system was investigated.

B. QUESNEL RIVER

The Quesnel River begins at Quesnel Lake, British Columbia, on the western slopes of the Cariboo Mountains, approximately 400 km north–northeast of Vancouver, British Columbia. About 9 km downstream from the lake the river joins the Cariboo River. It continues on as the Quesnel River for another 70 km to the town of Quesnel where it joins the Fraser River. A bar sampled for this study begins 3 km downstream from the confluence and is hereafter referred to as the Quesnel bar.

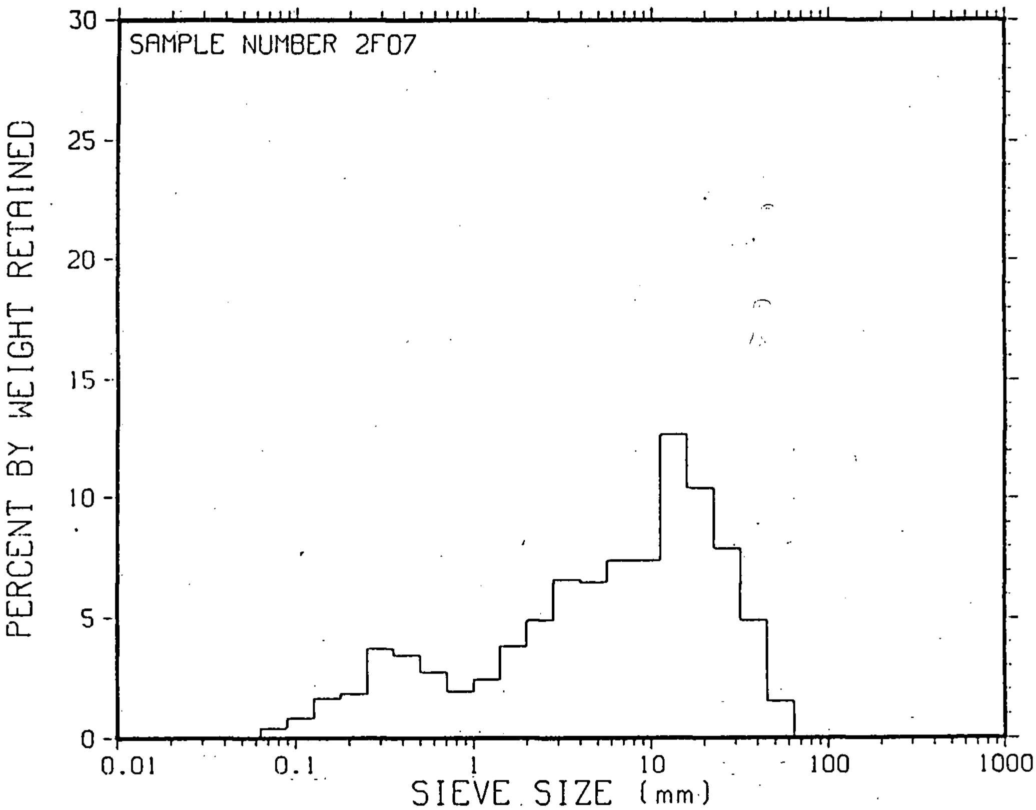

Figure 20. Entire bar on Flynn Creek

The following hydraulic data are from Water Survey of Canada (1983). The average annual maximum discharge for the Quesnel River from 1926 to 1982 is 394 cumecs (m^3/s). measured at the mouth of the lake, and has a return period of three years. The Cariboo River gauge 500 meters upstream of the confluence shows an almost identical record. Kellerhals (1962) states that the peak discharges taken from daily discharges of these two gauges show 864 cumecs on July 1, 1960, 790 cumecs on June 7, 1961, and 774 cumecs on June 27, 1962.

Air photos from flights made in 1930, 1949, 1955, 1967, and 1978 show major changes in the channel deposits. The Quesnel bar was just beginning to form in 1930. A placer gold mine operation, the Bullion Mine, was located approximately 8 km upstream. This placer operation is believed to have been the primary source of sediment for the bars downstream. Between the mine and the lake outlet the river flows through a bedrock canyon with no visible major supply of sediment. Below the mine there is one area which has been actively failing, but the material contributed between 1930 and 1978 appears to be less than one-third of the volume of the mine excavations. This zone had stable vegetation along the river by 1968.

It should be noted that the Bullion Mine was not a small operation. Work began in 1884 and continued intermittently until 1942. A report by Sharpe (1939), who was general manager at that time, states that an average of 571,500 cubic meters of material per year were dumped into the river during 1933 - 1938. This amounts to 5 -20 ppm during the summer months, the time the mine was active (Kellerhals, 1962). Kellerhals (1962) reported slightly over a meter drop in stream bed elevation between 1955 and 1961. Air photos show that the Quesnel bar had stable vegetation by 1968. Bars upstream of the Quesnel bar had vegetation established as early as 1949. Both the degradation and the establishment of vegetation on the bars are believed to be the result of the cessation of sediment input from the mine after 1942.

C. QUESNEL BAR

The Quesnel bar is a left point bar approximately 675 meters long and 400 meters wide. Figure 21 shows the shape of the bar as well as the sample sites, dominant backwater channels, and surface sediment texture. Sediments range from silt to boulders with intermediate axes between 128 - 180 mm. Large vegetation is Black Cottonwood (Populus balsamifera ssp. trichocarpa). The largest tree cored (1983) contained 22 rings at breast height, and was located near sample site 17, Figure 21. It may have been older, however, since during the first few years of growth young cottonwoods may be buried repeatedly by gravel flood deposits, only to emerge at the surface half a meter or so downstream the following season. The process may be repeated until the tree becomes strong enough to resist burial or the bar aggrades sufficiently to prevent thick gravel deposits from burying the shoots. By then, the small sapling seen at the surface may be the top of a 3 - 5 meter horizontal tree.

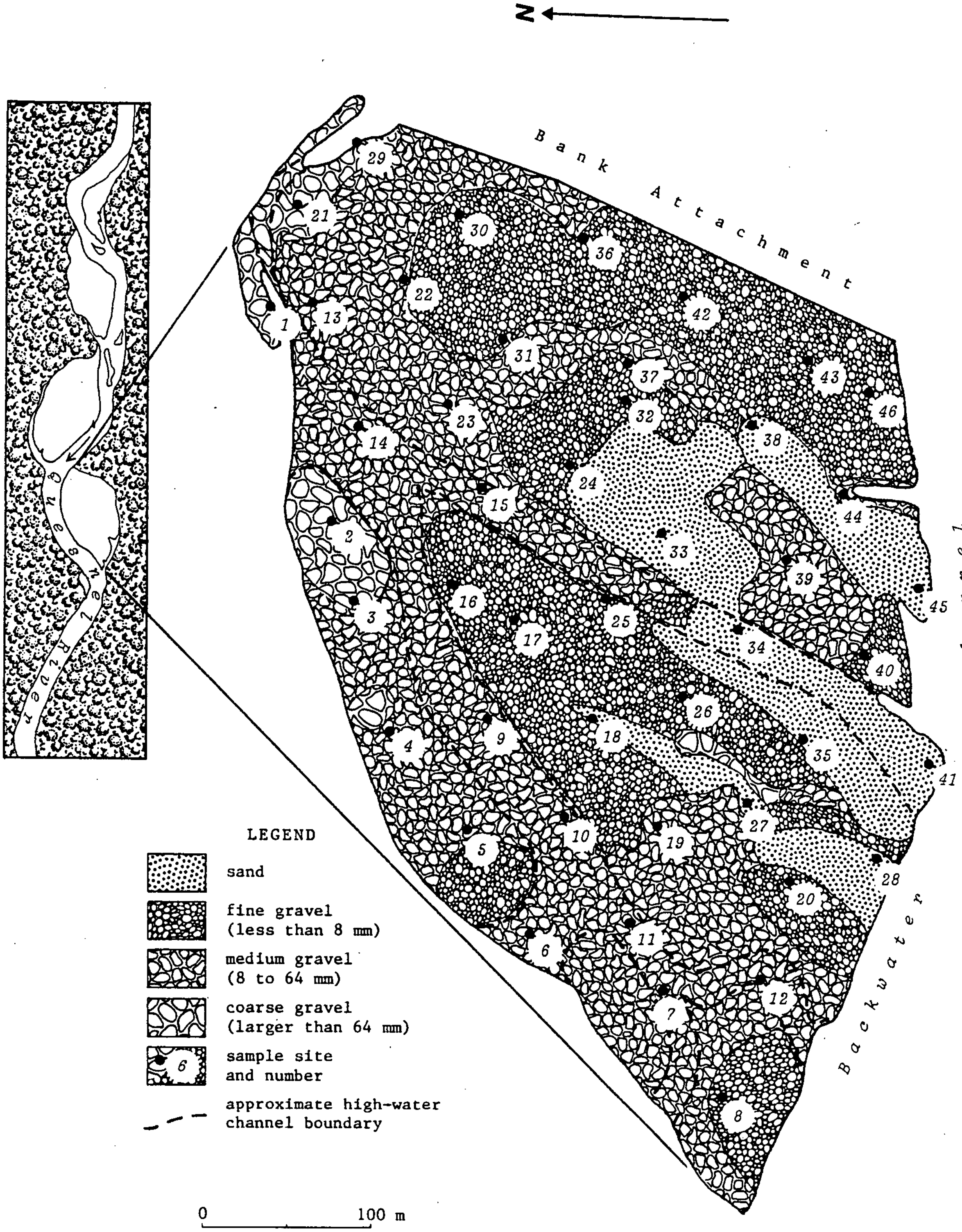

Figure 21. Quesnel bar study area

The age is thus a minimum.

During the first ten days of sampling, beginning on May 24, 1983, the river gauge at the mouth of Quesnel Lake indicated a 30 cm rise. The effect on the bar was noticeable as each day fewer of the perimeter survey stakes remained above water. After five days some of the backwater channels began flowing. Three sites, numbers 9, 10, and 29, were sampled underwater as a result of poor planning.

Forty-six sample sites were laid out on a map of the Quesnel bar and then located on the actual bar by pace and compass. Eight control points were established to minimize cumulative location errors; all sites were located by one of these eight reference points. A stratified, systematic, unaligned sampling system was used because Taylor (1977) has shown that it provides more accurate estimates in areal sampling than either stratified (grid) or completely random designs.

The map of the bar was divided into nine rows and eight columns which gave 46 usable rectangles. Each rectangle was 50 meters by 75 meters. A random number between 0 and 99 was taken from a random number table for each row and each column. These numbers were then scaled by either 75 meters or 50 meters to give distances on the bar. Individual sites were located by the intersection of the row and column numbers. All sites within a given row were the same distance from the left edge of each rectangle in that row. All sites within a given column were the same distance from the bottom edge of each rectangle in that column. A more complete description of the technique may be found in Taylor (1977).

The results from the Quesnel bar samples show that a small but persistent gap appears between 4 and 5.6 mm (Figure 22). The complete data set is included in appendix B. Although not all samples are bimodal, none contains a primary or secondary mode between 4 and 5.6 mm. Thus, the material is not found at any of the 46 sample sites.

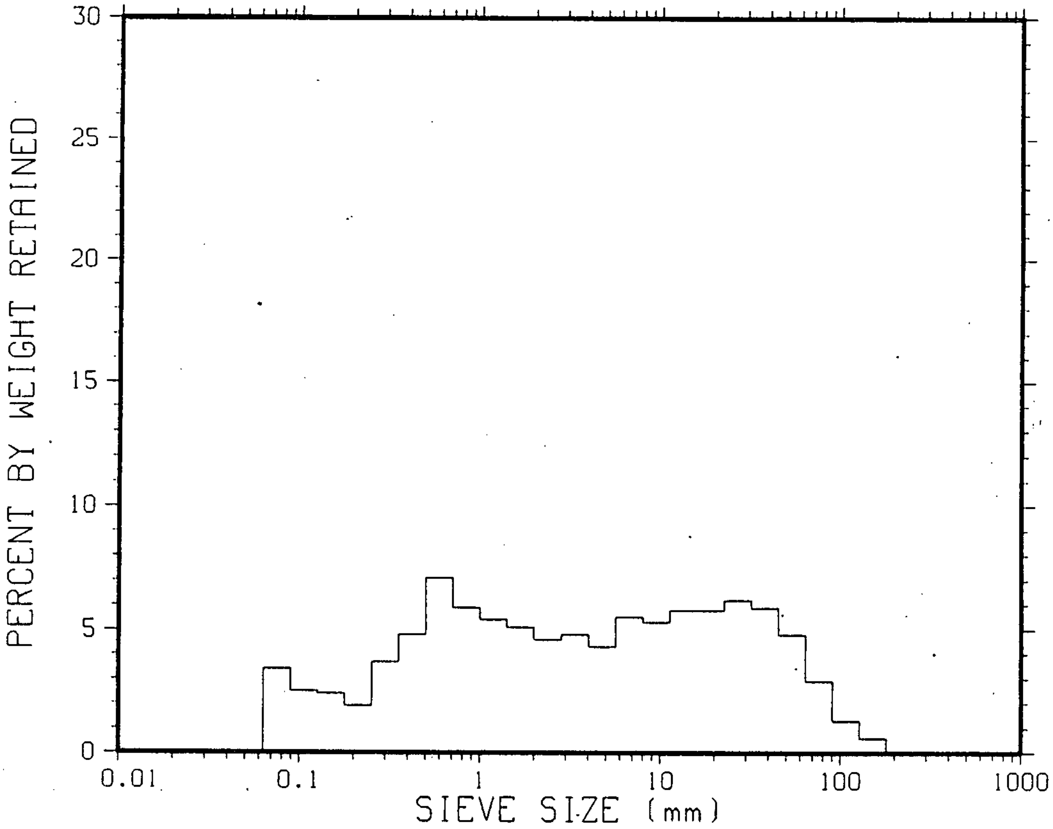

Figure 22. Average of 46 samples from a Quesnel bar

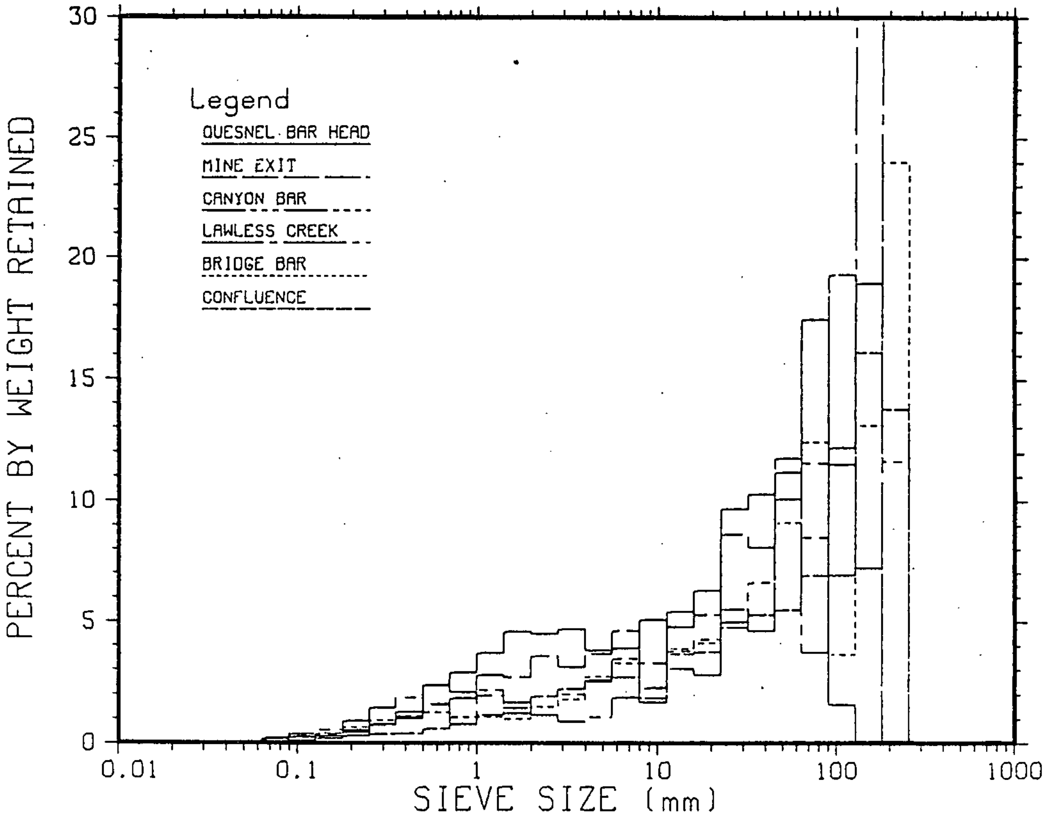

Figure 23. Several other Quesnel River sites

Bar head samples collected by R. Ferguson and M. Church in 1982 from several sites between the mine and the bar may be compared to a bar head site from the Quesnel bar (sample site 21) to ensure that the Quesnel bar is not an anomaly. Figure 23 shows that the bar head site is typical, although the material is slightly finer, and confirms the field impression that the bar is similar to all of the other sites along the river.

D. FRASER BAR

One drawback of the Quesnel bar is that almost half of the bar is no longer active. An additional bar that was known to be active was therefore sampled on the Fraser River, approximately 80 km from its mouth at Vancouver, British Columbia. It is the last gravel bar downstream on the Fraser. A grid of 16 sample points was laid out as shown in Figure 24, but points 7, 8, and 14 were not sampled due to the incoming tide. The results are shown in Figure 25.

This sampling was part of a comparison between two sampling techniques. Samples from the 13 sites were taken with a new and more expedient method so it is possible that this is not a true representation of the bar. Figure 25 also shows the results of the same technique that was used at the Quesnel bar, although only 5 of the 13 sites were sampled with this method as a result of the tide. The sites sampled were numbers 4, 5, 6, 11, and 12. The difference between the two histograms is less than 1% for any size class between 0.71 - 5.6 mm. Figure 25 shows that the gap material is not found at any of the sample sites on the Fraser bar either, and the second hypothesis is rejected.

The studies on the Quesnel and the Fraser Rivers sampled only a single bar. An ideal study would sample every possible site of deposition from the headwaters to the mouth of a large river. Neither this study nor work by others suggest such exhaustive sampling would provide much additional insight. Shaw and Kellerhals (1982)

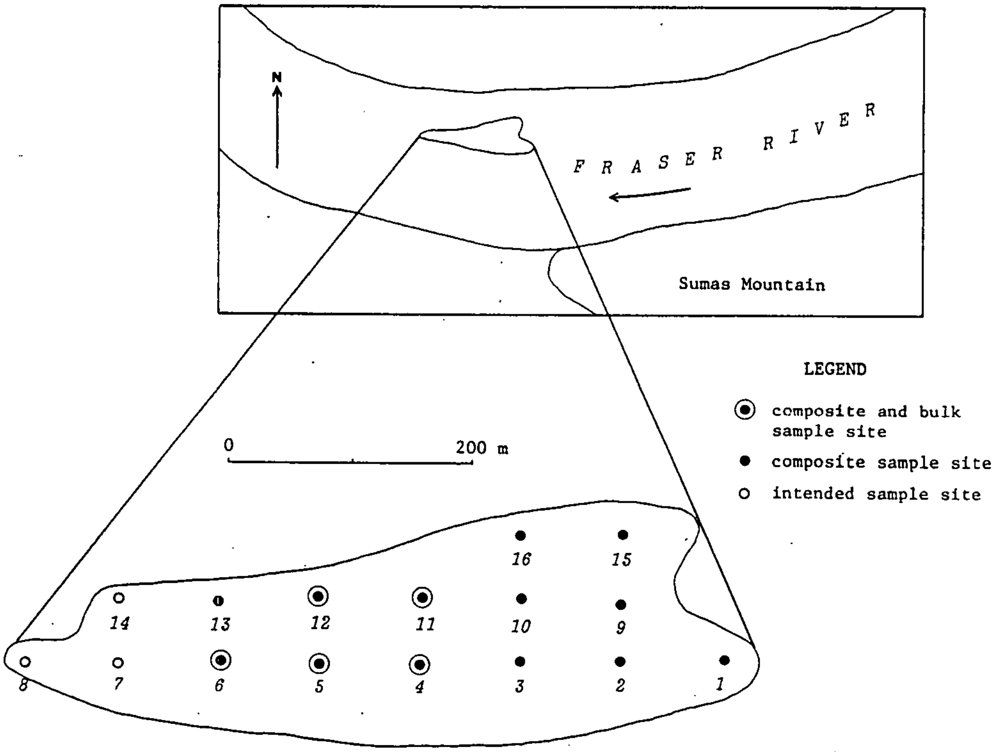

Figure 24. Fraser River study area

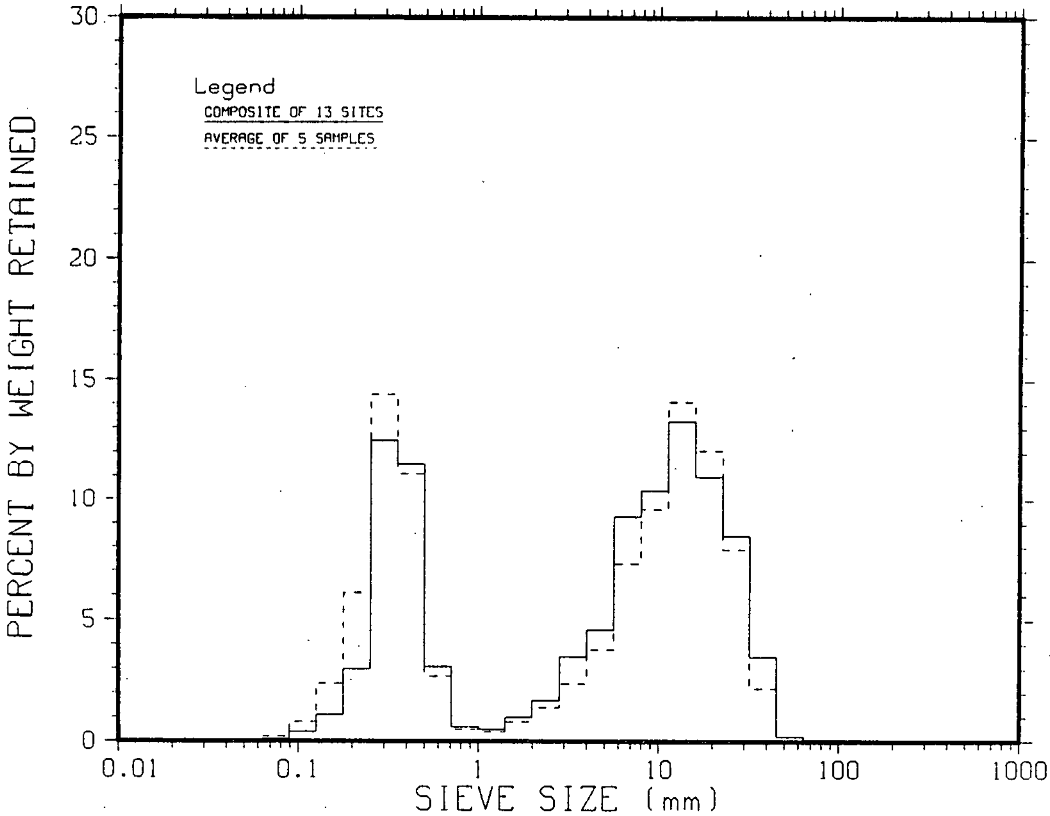

Figure 25. Fraser River bar samples

present data from single bar head sites at various distances downstream for twelve rivers. The North Saskatchewan River exhibits a bimodal distribution in the greatest number of samples. Samples were taken approximately every 50 km beginning 30 km from the source. The first 29 sites are bimodal, ending 888 km from the source. Only six sites do not have the gap located between 1 and 1.41 mm. The sites at 178 km, 262.3 km, 573.1 km, and 599.1 km have the minimum between 0.71 and 1.00 mm. The sites at 836.7 km and 855.5 km have a gap between 1.41 and 2.00 mm. Since the gap is consistently found between 1 and 2 mm in all 29 samples from similar environments, the bar head, for a distance of 890 km, it seems reasonable to assume that any single bar will be similar to the immediate upstream and downstream bars. If randomly chosen bars such as those from the Quesnel and the Fraser Rivers do not show a mode in the gap range from some site on the bar, then likely no bar in that system will.

V. STATE OF THE PROBLEM

A. A SUMMARY

If an initially unimodal grain size distribution of some sort is assumed, then there are two general explanations for multimodal grain size distributions. The valleys or gaps may indicate that material has been removed, or the peaks or modes may indicate that material has been added. Hypothesis One, for example, suggests that the modes represent material that is added to the fluvial system from the hillslope or other source area. This may occur as the breakdown of the coarse material into a coarse clast mode and a finer constituent grain mode (Milhous, 1982), or it may be the result of combining two lithologically and texturally distinct populations.

Hypothesis Three assumes that the gap material is present initially somewhere in the fluvial system and is then preferentially destroyed. Abrasion studies have yet to show the possibility of producing a multimodal distribution in the sand–gravel range by abrasion alone. Marshall's work (1927) needs to be carried further. Hypothesis Four assumes that hydraulic forces generate a polymodal distribution, either by selectively removing and possibly abrading the gap material (Sundborg, 1956) or by selectively depositing the modal materials. Other investigators (Udden, 1914; Wentworth, 1933; Inman, 1949; Friedman, 1967; Visher, 1969; Middleton, 1976; Bridge, 1981) assume that the modes represent different forms of transport, such as on the bed surface, by saltation, and in suspension.

Also possible is the concept that each mode represents a different event, or different times within an event. Unfortunately, satisfactory bedload sampling systems have yet to be devised for gravel rivers. The spatial and temporal variations make point sampling imprecise, and vortex tube sampling may underestimate the amount of fines (O'Leary and Beschta, 1981). The East Fork bedload sampler (Klingeman and Emmett, 1982) may have worked satisfactorily, but the river transported very little gravel.

Evidence presented in the preceding chapters may be summarized as follows.

1. Abrasion experiments rarely produce sand (Krumbein, 1941).
2. Small amounts of sand in gravel mixtures are quickly crushed to silt (Marshall, 1927).
3. Large amounts of sand decrease the rate of abrasion (Kuenen, 1956).
4. The sand size fraction in Flynn Creek fluvial deposits is also present in the slope samples in a similar shaped size distribution (this study).
5. Rivers that have gaps in the 1 – 10 mm range in bar head deposits do not appear to store these sediments elsewhere in the fluvial system (this study).

Based on these observations the following explanation for bimodal grain size distributions is offered.

1. The sand size mode represents an additional population of material superimposed upon the more or less normal, log normal, or skewed log normal distribution of the coarser material.
2. This sand population is produced on the hillslopes, before the material reaches the channel. The relatively passive nature of the slope environment may produce greater rates of diminution in terms of distance traveled than either stream beds or tumbling mill experiments. Soil particles have long residence times compared to channel deposits, and they are subjected to a variety of organic and inorganic acids, wetting and drying cycles, perhaps freeze–thaw cycles, and bioturbation.
3. The continued existence of the sand in the channel is dependent upon the rate of supply exceeding or balancing the rate of attrition through crushing by larger material. This rate of attrition is a function of the size of the larger material, the energy of the stream, and the percentage of fine material in motion and on the bed.
4. As distance downstream increases, the odds of sand surviving in the channel

increase as a result of

a. more varied lithologies in the watershed which provide greater chances for the formation of sand,.

b. less vigorous stream action as a decreasing energy gradient diminishes the effectiveness of crushing,

c. larger storage zones for sand increase the proportional rate of supply to and in the channel.

5. The increased sand fraction causes a decrease in the rate of abrasion of the larger material until finally abrasion virtually stops. At this point the coarsest material that can be entrained may become buried in the troughs of the sandy bed forms.

It should be noted that these statements are speculative. Also, many of these ideas have been expressed before, individually, by various authors. The primary contribution here is the unification of several distinct concepts into a more consistent story. No correlation between modes and transporting mechanisms is implied. A test of the last point would be to analyze the size distributions from several cores of the bed forms immediately downstream of the sand-gravel transition. A lack of coarse material, larger than 1 mm, would refute this explanation for the disappearance of the finest coarse fraction.

As noted in the first two chapters, most investigators have chosen either the abrasion or the preferential entrainment argument, or a combination of these two, to explain the gap. Yet little progress seems to have been made since Kuenen (1956) and Bradley (1970).

The results from the North Saskatchewan River (Shaw and Kellerhals, 1982) imply that either the source area lithologies change to include material that is capable of producing sand in sufficient quantities to form a secondary mode in conformity with the above speculation, which is difficult to assess in such large systems, or the processes of abrasion and/or preferential entrainment cause the gap. Hypotheses Three and Four explore these last two concepts in greater detail. Furthermore, the results from the present study suggest further experiments which should clarify the abrasion/selective transport issue.

B. FUTURE FLUME WORK

At least four different studies need to be conducted to understand the abrasion process better:

1. What are the abrasion products of various lithologies,
2. What are the abrasion products from different degrees of weathering on the previously tested lithologies,
3. How does the original size distribution affect the abrasion products, and
4. What is the effect of the size distribution of the bed material?

These elementary studies could be done in either an abrasion mill or a circular flume, although the latter more nearly approaches natural conditions.

The following studies would clarify hydraulic sorting processes:

1. What are the effects of size distribution of the bed material on the size of the first particles to move during increasing velocities,
2. What is the shear stress at initial motion with various heterogeneous bed mixtures,
3. What is the shape of the velocity gradient profile with different size distributions of bed material,
4. What controls the process of infiltration of fines, or reverse winnowing, and how deeply into the bed does it penetrate,
5. What is the nature of bed deposits after total bed mobilization,
6. What is the relationship between modes in the transported material and modes in the bed material.

These could be done either in a recirculating or non recirculating linear flume or in a circular flume.

A third set of studies would consist of a combination of the abrasion and selective transport studies. Although either process may produce a gap, the interaction of abrasion and hydraulic sorting may produce a distinct result not predicted by the separate studies. This would require a circular flume to accommodate the abrasion aspect.

The success of this approach depends upon the design of the flume. As noted in Chapter II, the Kuenen-type flumes introduce large horizontal eddies into the flow. An alternative driving mechanism is a surface shear plate - a continuous ring approximately the width of the channel. The underside of the ring drags the surface water along by the shearing force applied to the water as the ring turns. The surface shear is transmitted to the bed in a velocity profile similar to that in a normal stream channel. A more complete description of such a flume may be found in Tahgon, Nowell and Jumars (1984). Use of this type of flume promises to provide further insights into the mechanisms of abrasion and selective transport, the deficiency of granules in fluvial sediments, and possibly to answer in part the question of why sediment size decreases downstream.

C. FUTURE FIELD WORK

The results from Flynn Creek may be unique. Several additional studies would be useful to test the above concepts. For example, additional slope samples from Oak Creek should show whether the slope material is similar to the fluvial deposits in a single lithology basin without a gap in the stream sediment. The relationship between distance and the development of the gap suggested by the data of Shaw and Kellerhals (1982) may support or contradict the ideas presented here. What is needed is a river - or better would be several rivers - longer than 200 km which contains sediments from a single aphanitic lithology. If a gap develops, then perhaps it is the result of strictly fluvial processes. Such a situation may not exist in nature.

D. <u>POST SCRIPT</u>

It is much easier to reject a hypothesis than to prove that one is true. Indeed, Popper (1969) has noted that it is not possible to prove that something is true, only that it is false. The present study was designed in the belief that a single example would be sufficient to refute the first two hypotheses. In the case of the first hypothesis, the single exception has yet to be found.

REFERENCES

Adams, J., 1978. Data for New Zealand pebble abrasion studies. New Zealand Journal of Science, **21**, 607–610.

Adams, J., 1979. Wear of unsound pebbles in river headwaters. Science, **203**, 171–172.

Adams, J. N., 1980. Variations in gravel bed composition of small streams in the Oregon Coast Range. M.Sc. thesis, Oregon State University, Corvallis, Oregon, 160 pp.

Alling, H. L., 1944. Grain analysis of minerals of sand size in ball mills. Journal of Sedimentary Petrology, **14**, 103–114.

Beschta, R. L., 1982. Comment on 'Stream system evaluation with emphasis on spawning habitat for Salmonids' by Mostafa A. Shirazi and Wayne K. Seim. Water Resources Research, **18**, 1292–1295.

Beschta, R. L., and W. L. Jackson, 1979. The intrusion of fine sediment into a stable gravel bed. Journal of the Fisheries Research Board of Canada, **36**, 204–210.

Bradley, W. C., 1970. Effect of weathering on abrasion of granitic gravel, Colorado River (Texas). Geological Society of America Bulletin, **81**, 61–80.

Bridge, J. S., 1981. Hydraulic interpretation of grain-size distribution using a physical model for bedload transport. Journal of Sedimentary Petrology, **51**, 1109–1124.

Brown, G. W., and J. T. Krygier, 1971. Clear-cut logging and sediment production in the Oregon Coast Range. Water Resources Research, 7, 1189–1198.

Chan, M. A., and R. J. Dott, Jr., 1983. Shelf and deep-sea sedimentation in Eocene forearc basin, Western Oregon - fan or non-fan? American Association of Petroleum Geologists Bulletin, **67**, 2100–2116.

Carling, P. A., and N. A. Reader, 1982. Structure, composition and bulk properties of upland stream gravels. Earth Surface Processes and Landforms, 7, 349–365.

Daubrée, A., 1879. Etudes Synthétiques de Géologie Expérimentale. Two volumes, Dunod, Paris.

Dunne, T., and L. B. Leopold, 1978. Water in Environmental Planning. Freeman, San Francisco, 818 pp.

Edwards, R. E., 1980. Sediment transport and channel morphology in a small mountain stream in Western Oregon. M.Sc. thesis, Oregon State University, Corvallis, Oregon, 114 pp.

Everts, C. H., 1973. Particle overpassing on flat granular boundaries. Journal of the Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers, **99**, 425–438.

Graf, W. H., 1971. Hydraulics of sediment transport. McGraw-Hill, New York, 513 pp.

Hack, J. T., and J. C. Goodlett, 1960. Geomorphology and forest ecology in the Appalachians. U. S. Geological Survey Professional Paper 347 pp.

Jackson, W. L., 1981. Bed material routing and streambed composition in alluvial channels. Ph.D. dissertation, Oregon State University, Corvallis, Oregon, 160 pp.

Kirkby, M. J., 1980. The stream head as a significant geomorphic threshold. **In** Thresholds in Geomorphology, edited by D. R. Coates and J. D. Vitek; Allen and Unwin, London, 498 p, pp 55–73.

Klingeman, P. C., and W. W. Emmett, 1982. Gravel bedload transport processes. **In** Gravel-bed Rivers, edited by R. D. Hey, J. C. Bathurst and C. R. Thorne; Wiley, Chichester, New York, 875 p, pp 141–179.

Krumbein, W. C., 1941. The effects of abrasion on the size, shape and roundness of rock particles. Journal of Geology, **49**, 482–520.

Krumbein, W. C., 1942. Flood deposits of Arroyo Seco, Los Angeles County, California. Geological Society of America Bulletin, **53**, 355–1402.

Kuenen, P. H., 1956. Experimental abrasion of pebbles: 2. Rolling by current. Journal of Geology, **64**, 336–368.

Larson, K. R., and R. C. Sidle, 1980. Erosion and sedimentation data catalog of the Pacific Northwest. U. S. Forest Service, Pacific Northwest Region, 66 pp.

Mackin, J. H., 1948. The concept of the graded river. Geological Society of America Bulletin, **59**, 463–512.

Marshall, P., 1927. The wearing of beach gravels. New Zealand Institute, Transactions, **58**, 507–532.

Marshall, P., 1929. Beach gravels and sands. New Zealand Institute, Transactions, **60**, 324–365.

Marston, R. A., 1978. Morphometric indicies of streamflow and sediment yield from mountain watersheds in Western Oregon. U. S. Forest Service, Pacific Northwest Region, Siuslaw National Forest (internal report).

McPherson, H. J., 1971. Downstream changes in sediment characteristics in a high energy mountain stream channel. Arctic and Alpine Research, 3, 65–79.

Meland, N., and J. O. Norrman, 1969. Transport velocities of individual size fractions in heterogeneous bed load. Geografiska Annaler, Series A, **51**, 127–144.

Middleton, G. V., 1976. Hydraulic interpretation of sand size distributions. Journal of Geology, **84**, 405–426.

Milhous, R. T., 1973. Sediment transport in a gravel-bottomed stream. Ph.D. thesis, Department of Civil Engineering, Oregon State University, Corvallis, 232 p.

Milhous, R. T., 1982. Discussion **in** Gravel-bed Rivers, edited by R. D. Hey, J. C. Bathurst and C. R. Thorne; Wiley, Chichester, New York, 875 p, pp 169–172.

Moss, A. J., 1972. Initial fluviatile fragmentation of granitic quartz. Journal of Sedimentary Petrology, **42**, 905–915.

Nanson, G. C., 1972. Sediment transport in two Rocky Mountain streams. M.Sc. thesis, University of Alberta, Edmonton, Alberta, 127 pp.

O'Leary, S., 1980. Bedload transport in an Oregon Coast Range stream. M.Sc. thesis, Oregon State University, Corvallis, Oregon, 107 pp.

O'Leary, S., and R. L. Beschta, 1981. Bedload transport in an Oregon Coast Range stream. Water Resources Bulletin, **17**, 886–894.

Parker, G., S. Dhamotharan, and H. Stefan, 1982. Model experiments on mobile, paved gravel bed streams. Water Resources Research, **18**, 1395–1408.

Pettijohn, F. J., 1949. Sedimentary Rocks. Harper, New York, 526 pp.

Pettijohn, F. J., 1975. Sedimentary Rocks. Third edition, Harper and Row, New York, 628 pp.

Popper, K. R., 1969. Conjectures and Refutations. Routledge and Kegan Paul, London, 231 pp.

Raudkivi, A. J., and R. Ettema, 1982. Stability of armor layers in rivers. Journal of the Hydraulics Division, American Society of Civil Engineers, **108**, 1047–1057.

Rayleigh, Lord, 1943. The ultimate shape of pebbles, natural and artificial. Royal Society of London Proceedings, Series A, **181**, 107–118.

Rayleigh, Lord, 1944. Pebbles, natural and artificial. Their shape under various conditions of abrasion. Royal Society of London Proceedings, Series A, **182**, 321–335.

Schoklitsch, A., 1914. Über Schleppkraft und Geschiebebewegung (Leipzig, 1914) p 12.

Schoklitsch, A., 1933. Über die verkleinerung der geschiebe in flussläufen, Sitzungsbericht der Akadamie der Wissenschaft in Wien, **CXLII**, part IIa, 343–366.

Schubert, C., 1964. Size frequency distributions of sand-sized grains in an abrasion mill. Sedimentology, 3, 288–295.

Shaw, J., and R. Kellerhals, 1982. The composition of recent alluvial gravels in Alberta river beds. Alberta Research Council Bulletin **41**, 151 pp.

Shea, J. H., 1974. Deficiencies of clastic particles of certain sizes. Journal of Sedimentary Petrology, **44**, 985–1003.

Sundborg, A., 1956. The river Klaralven; a study of fluvial processes. Geografiska Annaler, **38**, 127–316.

Swanston, D. N., and F. J. Swanson, 1976. Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest. **In** Geomorphology and Engineering, edited by D. R. Coates. Dowden, Hutchinson, and Ross, Stroudsburg, Pa., pp 199–221.

Taghon, G.L., A. R. M. Nowell, and P. A. Jumars, 1984. Transport and breakdown of fecal pellets: biological and sedimentological consequences. Limnology and Oceanography, **29**, 64–72.

Tanner, W. F., 1958. The zig-zag nature of type I and type II curves. Journal of Sedimentary Petrology, **28**, 372–375.

Udden, J. A., 1914. Mechanical composition of clastic sediments. Geological Society of America Bulletin, **25**, 655–744.

VanSickle, J., and R. L. Beschta, 1983. Supply-based models of suspended sediment transport in streams. Water Resources Research, **19**, 768–778.

Water Survey of Canada, 1983. Historical Streamflow Summary: British Columbia. Water Resources Branch, Department of the Environment, Ottawa, 940 p.

Wentworth, C. K., 1919. A laboratory and field study of cobble abrasion. Journal of Geology, **27**, 507–521.

Wentworth, C. K., 1922. A field study of the shape of river pebbles. U. S. Geological Survey Bulletin, **730**, 103–114.

Wentworth, C. K., 1933. Fundamental limits to the size of clastic grains. Science, **77**, 633–634.

Yatsu, E., 1959. On the discontinuity of grain size frequency distribution of fluvial deposits and its geomorphological significance. Proceedings of the International Geographical Union Regional Conference in Japan, 1957, pp 224–237.

APPENDIX A

A. STATISTICS

Although little use is made of inferential statistics in this thesis, other than to show that no statistical difference exists amongst certain sediment texture distributions, the confidence level used should still be justified. Two purposes of inferential statistics are exploratory and confirmatory. In the initial stages of an hypothesis, at the hunch level or before, any occurence of a phenomenon with greater than 50% probability may warrant consideration. At the other extreme, at the level of a law, probabilities in excess of 99.99% should be expected. Intuitively, at the exploratory stages something between 75% and 90% seems reasonable. The conventional 95% confidence level is thus a compromise between these two diverse purposes, and, as such, is really too rigorous for the initial stages and not rigorous enough for the definitive level.

A reason for its continued popularity is that it represents a good compromise between type I and type II errors for certain narrowly defined sampling situations. An additional attraction is that it may give an investigator a false sense of economy by suggesting that a single set of experiments can both explore and confirm. The use of a 95% level in the present work is based solely on popularity. A more reasonable 90% level would not alter any conclusion of this study.

B. FIELD METHODS

Flynn Creek channel deposits and the Quesnel bar were sampled after the surface layer had been removed, usually to the depth of the largest stone. This eliminated any bias due to surface armoring or winnowing of fines. At the bank sites the surface vegetation and organic layer were removed, typically 10 cm thick, and a sample was taken from this new surface to the water table, integrated over the entire depth, which was usually about 0.75 meters. The slope samples were taken in a manner similar to the bank samples: after the surface vegetation had been removed, the sample was integrated over a depth of about 0.75 meters.

For the bar and channel deposits, a single shovel full of sediment was removed, placed in a galvanized pail, and weighed on a tripod mounted spring balance. Weights were recorded to the nearest 0.25 kg. Next, the material was dumped into a rocker sieve 30 cm square and 10 cm deep with a 32 mm screen in the bottom. The empty bucket was weighed, and its weight was subtracted from the previous weight to give the net weight of the material sieved. Following a thorough shaking onto a 2 meter by 3 meter tarp, the stones remaining on the screen were hand fitted through an aluminium template with square holes ranging from 8 - 128 mm in half phi intervals. All of the stones on the 32 mm screen were checked, and in the hundreds of sievings done, less than 10 stones passed through the 32 mm hole in the template indicating that the rocker sieve is an accurate device. The hand fitting proved to be more enjoyable and more expedient than changing screens to use the rocker sieve to differentiate the material coarser than 32 mm.

The size of the largest stone in the initial shovel full determined the size of the sample, unless a larger stone was encountered during the sampling at that site. The weight of the largest stone did not exceed 3% of the total weight of the sample at any site, with one exception. The largest stone at site 10 on the Quesnel bar weighed 7.5% of the total. This particular site was under about a meter of water at the time of sampling; so the material removed was allowed to drain overnight before weighing. Consequently, the total weight of the sample was not known until the second day. In the interest of expediency, the sample was not enlarged.

The material less than 32 mm was split into a 10.5 kg or slightly larger sample which was bagged in plastic and sealed with duct tape for laboratory analysis. Splitting was accomplished by rolling the material back and forth from one end of the tarp to the other to thoroughly mix it. Then it was rolled into a concentric pile, and the tarp was raised along an imaginary line bisecting the mound, causing the material to fall into two approximately equal halves. Raising the tarp was difficult with large samples, but a shovel handle or long, stout stick expedited the procedure. Usually an arm was slowly worked under from each side, lifting and dividing material in the process. By using two tarps, any size pile could be obtained through a series of splits with one half remaining on the tarp and the other being temporarily stored on the second tarp. As soon as the split looked about right it was placed in a bucket and weighed. If the weight was between 10.5 - 12 kg, it was bagged; otherwise it was recombined and split again. The remaining material was weighed and then dumped back into the sampling hole, along with the stones that were larger than 32 mm.

At the Quesnel bar, if the sample contained no material larger than coarse sand, a single shovel full was bagged. All sampling at Quesnel was integrated over 25 cm, the depth of the shovel blade. If more material was needed, the pit was expanded horizontally rather than vertically.

The constant depth of all samples may be a complicating factor, since in the coarse textured areas 25 cm may represent only a portion of material deposited in a single event whereas in the silt and sand areas 25 cm may contain sediment from many depositional events. No simple method for isolating deposits of single events could be envisioned at the time so a uniform depth for all samples was used. This raises the question of time scales involved in determining the presence or absence of a gap. Is it a within event phenomenon, a single event phenomenon, a seasonal phenomenon, or a longer duration phenomenon? Klingeman and Emmett (1982) show that at least two rivers, the Tanana in Alaska and the confluence of the Snake and the Clearwater in Idaho, show gaps in both the bed load and bar material, but no study has shown if the mode in the sand region of the bar material occurs simultaneously with the coarse mode, or if it is deposited at lower flows.

C. LABORATORY METHODS

When the samples were ready to be analyzed, the bags were unsealed, and the material was placed in tared pans and weighed so the amount of material available for analysis was known. The pans were placed in drying ovens at 100° C for a minimum of 24 hours. After drying, the samples were allowed to cool for 24 hours to equilibrate to the room temperature and humidity, weighed to record the weight of water lost, and sieved through 22 mm, 16 mm, and 11.2 mm screens on a Fisher mechanical shaker. All stones retained on the screens were rubbed by hand if finer material was still clinging to them. Each of the three sieve fractions was weighed in tared pans to record the amount of material retained on the screens. The material less than 11.2 mm was split into a 600 - 800 gram sample for further analysis. The remaining material was weighed to give a total split weight which was used to calculate the split ratio. This weight also showed the amount of material lost in sieving and splitting.

The 600 - 800 gram split was wet sieved through a 2 mm and a 0.063 mm screen after soaking 1 - 30 minutes in a deflocculant of 5% solution of sodium metaphosphate mixed with 50 ml of water. The two sieve fractions were placed in separate pans and put into drying ovens at 100° C for 24 hours. After cooling for 24 hours both pans were weighed to calculate, if necessary, the material lost in wet sieving. The coarse fraction was sieved at half phi intervals to 2 mm for 10 - 20 minutes, and the pan material was added to the fine fraction, which was then split into a 50 - 100 gram sample. Repeated measurements of splits from the same sample showed little difference in size distributions between 10 - 15 minutes of shaking and no difference between 15 - 20 minutes of shaking, except for the Flynn Creek sandstone. It gave the most consistant results between 5 - 10 minutes of shaking. The Flynn Creek samples were sieved for 10 minutes; all others were sieved for 20 minutes. A test of all the possible methods of assigning losses showed less than 1%

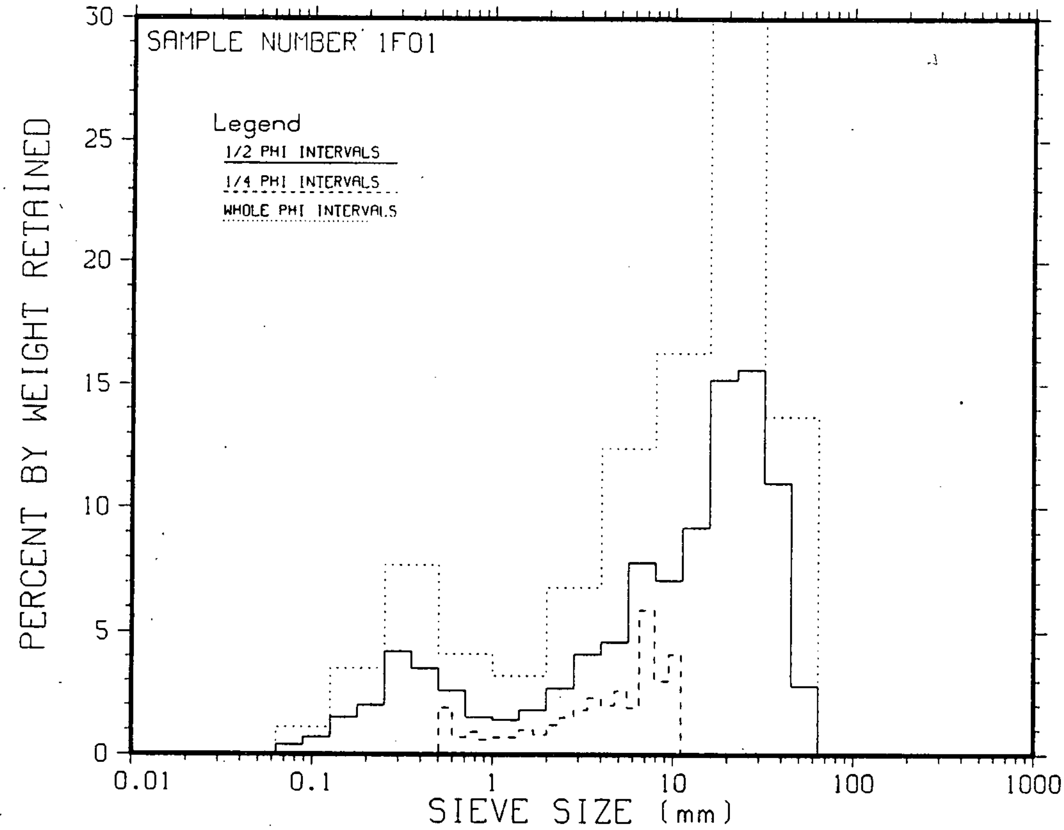

Figure 26. Various phi spacings (1/4 phi interval between 0.5 and 11.2 mm)

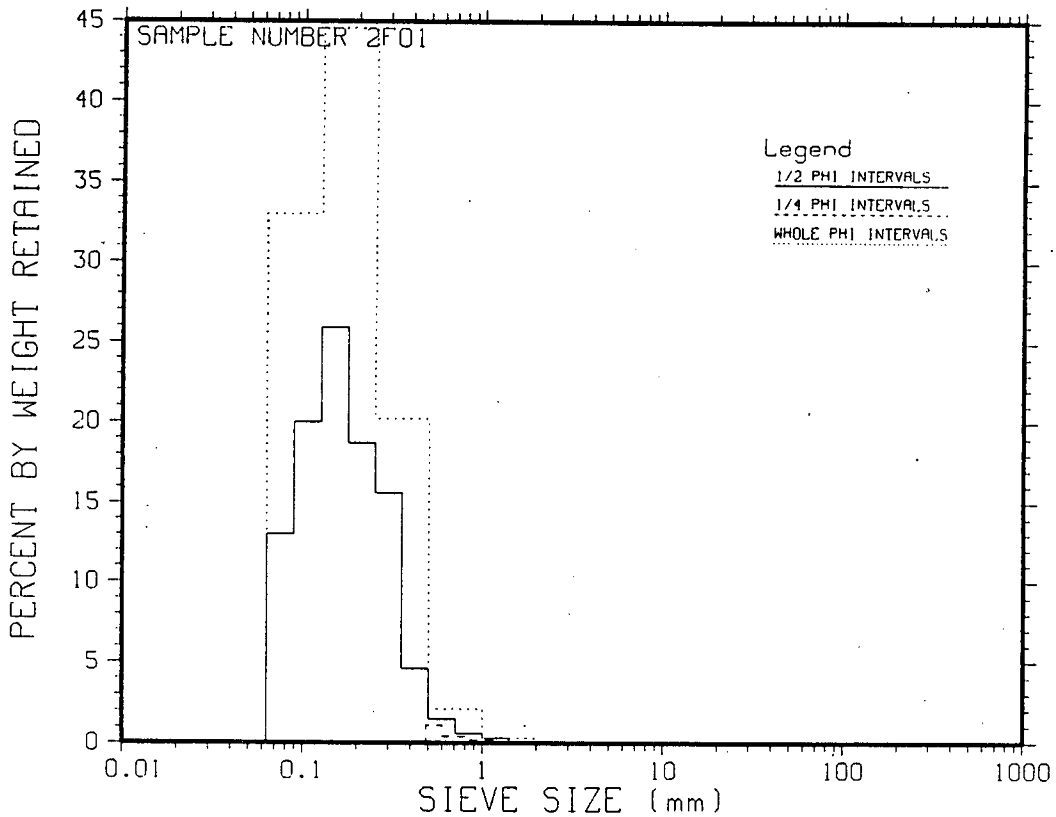

Figure 27. Various phi spacings (1/4 phi interval between 0.5 and 11.2 mm)

difference between the most extreme cases. Typical losses for the complete analysis of a 10.5 – 12 kg sample were 0.01% and never exceeded 0.02%.

To test the effects of closer screen interval spacing on the shape of the gap, all bank and bar samples from Flynn Creek were sieved at 1/4 phi intervals between 0.5 and 11.2 mm. These were then combined to give a uniform 1/2 phi spacing from 0.063 to 128 mm. Likewise, the 1/2 phi data may be combined to give whole phi spacings. Figures 26 and 27 shows the results of these different spacings on the gap between 0.5 and 10 mm for a unimodal and a bimodal sample. At some sufficiently large spacing, the gap will disappear. The results shown in Figure 26, however, suggest that even if each individual grain were measured, the resulting continuous distribution would still show a gap.

APPENDIX B

Table 2. Sample site locations

Sample	Location and description
OAK1	Last gravel bar, located 6.5 miles downstream on Oak Creek, under 35th street bridge
OAK2	Diagonal bar 5 miles downstream on Oak Creek, just north of bridge on Harrison Boulevard
OAK4	Left point bar 2.25 miles downstream on Oak Creek
OAK3	Small medial bar 2 miles downstream on Oak Creek, just below culvert at junction of West Fork Oak Creek Road (#6020) and Patterson Road (#600)
OAK6	Medial bar at log jam 1.5 miles downstream on Oak Creek
OAK7	Bank failure 1 mile downstream on Oak Creek
1F01	Right point bar sample located 30 meters upstream of USGS weir on Flynn Creek
2F01	Left bank sample located 30 meters upstream of USGS weir on Flynn Creek
3F01	Right slope sample located 30 meters upstream of USGS weir on Flynn Creek
2F02	Bar sample at log jam located 305 meters upstream of USGS weir on Flynn Creek
2F03R	Right slope sample located 305 meters upstream of USGS weir on Flynn Creek
2F04	Left point bar sample located 610 meters upstream of USGS weir on Flynn Creek
2F05	Right bank sample located 610 meters upstream of USGS weir on Flynn Creek
3F02	Right slope sample located 610 meters upstream of USGS weir on Flynn Creek
2F06	Right bank sample located 915 meters upstream of USGS weir on Flynn Creek

Table 2 (continued)

Sample	Location and description
2F07	Right point bar sample located 915 meters upstream of USGS weir on Flynn Creek
3F03	Left slope sample located 915 meters upstream of USGS weir on Flynn Creek
2F08	Left point bar sample located 1220 meters upstream of USGS weir on Flynn Creek
2F09	Right bank sample located 1220 meters upstream of USGS weir on Flynn Creek
3F04	Left slope sample located 1220 meters upstream of USGS weir on Flynn Creek
3F05B	Right bar sample located 1525 meters upstream of USGS weir on Flynn Creek
3F06	Right slope sample located 1525 meters upstream of USGS weir on Flynn Creek
QB01–QB46	See Figure 21

Table 3. Percent retained on sieves

Sample	OAK1	OAK2	OAK3	OAK4	OAK6	OAK7	1F01	2F01	3F01	2F02	2F03R
Dry wt. (kg)	50.969	54.035	30.110	57.664	47.232	40.326	42.328	11.596	64.900	95.836	50.615
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	0.2	0.2	0.2	0.3	0.3	0.2	0.4	20.0	3.5	0.2	2.0
0.090	0.5	0.4	0.2	0.4	0.4	0.4	0.7	25.9	5.1	0.4	2.9
0.125	0.7	0.6	0.3	0.5	0.6	0.7	1.5	18.9	7.1	0.8	3.3
0.180	0.9	1.0	0.4	0.5	0.7	0.7	2.0	15.6	5.1	0.11	4.2
0.250	1.7	2.5	0.7	0.9	1.2	0.9	4.2	4.6	7.9	2.0	4.7
0.354	1.8	2.9	0.8	0.9	1.0	0.7	3.5	1.5	5.9	2.1	4.3
0.500	2.6	3.8	1.2	1.1	1.1	0.7	2.6	0.6	4.3	2.0	3.8
0.710	2.8	3.4	1.4	1.1	1.0	0.7	1.5	0.3	2.0	1.4	2.1
1.00	3.4	3.4	1.9	1.3	1.0	0.9	1.4	0	1.3	1.4	1.1
1.40	4.2	6.1	2.6	2.8	1.2	1.4	1.8	0	1.3	1.11	0.9
2.00	4.2	4.0	3.0	1.6	1.4	1.7	2.7	0	2.3	2.3	2.3
2.80	5.9	5.0	3.9	2.3	1.9	2.2	4.1	0	3.5	3.0	2.6
4.00	6.9	5.3	4.4	2.5	2.9	2.5	4.6	0	3.7	2.6	3.7
5.66	10.3	8.0	6.4	3.4	5.3	3.8	7.8	0	4.1	3.4	3.8
8.00	11.9	8.7	7.3	4.9	9.0	5.2	7.1	0	3.7	3.6	3.1
11.2	14.9	11.3	7.6	5.3	11.8	5.5	9.2	0	2.7	4.6	2.4
16.0	12.5	13.5	10.4	5.3	14.4	10.1	15.2	0	2.2	6.0	1.5
22.5	9.6	10.9	16.5	8.2	16.8	8.7	15.6	0	1.4	8.0	2.0
32.0	3.3	6.3	19.5	14.8	15.0	7.2	11.0	0	1.4	10.5	1.9
45.0	0.7	2.5	8.6	18.5	10.9	14.2	2.8	0	1.9	8.0	4.4
64	0.8	0	3.0	23.1	2.5	22.0	0	0	5.5	7.0	1.4
90	0	0	0	0	0	10.2	0	0	15.0	3.1	13.2
128	0	0	0	0	0	0	0	0	7.6	10.3	4.2
180	0	0	0	0	0	0	0	0	0	14.3	24.3
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	2F04	2F05	3F02	2F06	2F07	3F03	2F08	2F09	3F04	3F05B	3F06
Dry wt. (kg)	43.382	69.789	36.673	45.057	53.854	49.710	74.897	21.894	32.912	81.685	43.490
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	0.4	0.8	5.4	1.8	0.4	3.7	0.3	3.3	9.8	1.0	0
0.090	0.6	1.8	7.6	2.8	0.8	5.5	0.5	6.1	15.0	1.6	5.6
0.125	1.2	4.1	10.2	4.1	1.6	7.4	1.0	9.8	17.6	1.9	7.8
0.180	1.5	5.3	7.7	3.5	1.8	5.7	1.1	9.3	12.9	2.6	10.6
0.250	3.5	10.2	10.1	5.0	3.7	7.4	2.2	11.8	15.0	3.2	8.2
0.354	4.9	8.5	7.8	4.2	3.4	5.5	2.3	7.7	10.5	2.8	11.1
0.500	5.6	6.5	6.4	3.7	2.7	4.2	2.4	5.8	7.4	2.4	8.2
0.710	3.6	3.9	3.2	2.6	1.9	2.2	1.8	3.7	2.8	1.6	6.3
1.00	3.4	3.4	2.6	2.6	2.4	1.7	2.1	3.2	1.4	1.5	3.4
1.40	4.2	4.2	3.3	3.2	3.8	3.0	2.8	2.7	1.2	1.2	2.6
2.00	5.2	5.0	4.4	4.1	4.9	6.2	3.2	2.9	1.3	2.4	2.8
2.80	7.8	6.4	5.2	5.9	6.6	7.2	3.9	3.6	1.5	2.8	3.6
4.00	7.1	5.6	4.8	6.9	6.5	6.6	3.9	4.3	1.2	4.2	4.6
5.66	8.3	7.1	4.2	7.8	7.4	9.7	5.2	5.6	1.5	5.7	3.7
8.00	7.7	4.9	2.7	8.3	7.4	9.8	4.6	4.5	0.2	5.3	3.3
11.2	9.5	5.7	3.7	9.6	12.7	6.0	6.8	5.7	0.3	7.6	1.3
16.0	8.5	5.3	2.9	8.6	10.4	3.5	7.1	4.1	0.1	6.9	2.8
22.5	8.5	5.6	2.0	4.3	7.9	1.3	8.1	3.8	0	7.6	1.6
32.0	6.7	4.3	3.7	5.9	4.9	3.3	15.6	2.1	0.3	9.5	1.1
45.0	1.6	1.3	2.1	5.1	1.5	0.2	13.3	0	0	7.9	4.1
64	0	0	0	0	0	0	11.8	0	0	9.7	2.8
90	0	0	0	0	0	0	0	0	0	2.8	1.7
128	0	0	0	0	0	0	0	0	0	7.9	3.0
180	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	QB01	QB02	QB03	QB04	QB05	QB06	QB07	QB08	QB09	QB10	QB11
Dry wt. (kg)	25.151	53.961	59.623	107.808	65.201	51.225	33.107	15.609	63.132	81.233	48.732
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	0.1	0.2	0.6	0.1	0.2	0.2	0.3	0.2	0.4	0.1	0.2
0.090	0.3	0.2	0.6	0.1	0.2	0.2	0.3	0.3	0.4	0.2	0.2
0.125	0.8	0.5	0.8	0.2	0.5.	0.4	0.5	0.6	0.5	0.4	0.4
0.180	1.6	0.7	0.7	0.3	0.6	0.5	0.6	0.9	0.5	0.6	0.5
0.250	4.9	1.9	1.3	0.7	1.6	1.0	1.4	2.0	0.9	1.5	1.1
0.354	5.8	2.9	1.8	1.3	2.7	1.6	2.5	2.6	1.1	2.2	1.6
0.500	4.8	3.5	3.0	2.6	5.3	3.4	5.7	5.4	2.0	3.5	3.9
0.710	2.7	2.3	3.3	2.7	5.7	3.7	5.4	6.8	2.1	2.8	5.0
1.00	2.8	1.8	3.7	2.9	5.8	3.6	4.6	8.6	2.6	2.5	5.6
1.40	3.8	2.0	4.1	3.4	5.9	3.4	4.1	8.2	3.2	2.2	5.6
2.00	6.0	2.4	4.5	4.1	6.5	4.2	3.6	7.4	3.9	2.0	5.2
2.80	8.9	3.5	5.0	4.9	7.4	5.6	4.1	7.1	5.7	2.5	5 .
4.00	9.4	4.7	4.1	4.9	6.3	5.4	3.9	5.7	5.9	2.5	4.1
5.66	11.6	6.0	5.0	5.2	7.0	7.0	5.4	7.4	8.4	4.2	5.4
8.00	14.0	6.4	4.0	5.6	7.0	8.1	5.5	7.0	8.0	3.3	5.8
11.2	12.1	10.7	6.3	5.8	8.1	8.6	6.2	12.2	9.8	4.4	7.1
16.0	6.0	14.3	7.4	5.2	6.6	10.7	8.0	11.9	10.8	5.7	6.8
22.5	2.3	11.8	6.3	4.4	4.2	14.7	13.5	4.2	14.5	5.5	8.2
32.0	2.0	15.7	11.4	9.1	7.4	13.1	15	1.6	11.5	5.7	11.7
45.0	0	6.5	12.2	13.7	7.4	2.5	7.9	0	5.5	11.1	16.6
64	0	0.7	8.8	13.3	3.6	2.1	1.3	0	2.3	14.5	0
90	0	1.2	5.0	6.2	0	0	0	0	0	8.1	0
128	0	0	0	3.3	0	0	0	0	0	14.6	0
180	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	QB12	QB13	QB14	QB15	QB16	QB17	QB18	QB19	QB20	QB21	QB22
Dry wt. (kg)	129.374	87.631	93.568	49.704	83.330	84.444	4.527	7.477	12.014	92.847	92.789
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	0.2	0.5	0.2	0.4	0.1	0.2	3.3	0.6	0.1	0.2	0.2
0.090	0.2	0.5	0.2	0.5	0.2	0.4	7.0	1.2	0.1	0.1	0.2
0.125	0.5	0.7	0.3	0.8	0.4	0.7	12.4	5.1	0.7	0.2	0.4
0.180	0.8	0.8	0.4	0.8	0.7	0.8	9.5	9.6	1.8	0.3	0.4
0.250	1.8	1.5	0.9	1.3	1.8	2.1	17.3	16.4	8.3	0.8	0.7
0.354	2.4	1.9	1.5	2.1	2.9	2.6	16.9	13.9	16.	1.3	0.9
0.500	3.2	2.9	3.0	3.2	5.0	2.8	16.5	15.0	18.	2.4	2.1
0.710	2.7	3.4	3.3	3.1	4.6	1.7	9.2	11.3	8.4	2.9	3.2
1.00	2.5	4.5	3.7	2.4	4.8	1.4	4.8	10.3	4.8	3.7	4.6
1.40	2.3	5.3	4.1	2.3	5.4	1.4	1.9	8.3	4.0	4.6	5.4
2.00	3.0	5.7	4.0	3.2	5.6	1.5	0.9	5.0	3.3	4.5	5.1
2.80	4.1	6.3	4.7	4.5	6.9	2.2	0.3	2.6	4.0	4.7	5.3
4.00	3.9	6.0	3.2	8.3	7.1	2.7	0	0.6	4.4	3.8	4.2
5.66	5.7	8.1	4.9	9.5	8.6	5.3	0	0.1	8.7	3.9	4.3
8.00	7.5	6.2	3.7	11.8	6.9	6.4	0	0	8.0	5.1	5.3
11.2	6.8	6.8	5.1	13.1	7.5	10.0	0	0	6.9	4.8	6.9
16.0	10.0	5.4	5.2	13.7	6.8	12.6	0	0	1.9	6.3	6.7
22.5	15.6	4.0	9.3	10.5	6.1	22.3	0	0	0	9.7	4.6
32.0	11.0	10.2	7.1	7.2	4.2	12.9	0	0	0	10.3	8.8
45.0	12.7	9.3	10.8	0	4.9	7.1	0	0	0	11.2	11.8
64	2.9	10.1	9.9	0	6.2	2.8	0	0	0	17.5	13.4
90	0	0	10.7	0	3.3	0	0	0	0	1.6	5.6
128	0	0	4.0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	QB23	QB24	QB25	QB26	QB27	QB28	QB29	QB30	QB31	QB32	QB33
Dry wt. (kg)	26.172	80.403	81.270	41.952	8.470	6.178	90.874	38.285	15.762	21.025	4.646
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	0.2	0.3	0.3	1.0	1.1	1.5	0.1	0.4	0.1	0.1	9.9
0.090	0.2	0.3	0.5	0.9	1.7	1.5	0.1	0.5	0.2	0.2	10.
0.125	0.4	0.4	0.5	1.2	4.5	3.2	0.3	1.1	0.4	0.9	7.4
0.180	0.5	0.5	0.8	1.4	6.3	4.8	0.4	1.4	0.5	1.6	3.1
0.250	1.3	1.3	1.9	2.3	12.8	11.7	1.1	3.2	1.3	4.4	6.1
0.354	2.0	1.9	2.7	2.5	14.3	15.4	1.7	4.4	1.8	6.2	12.
0.500	3.3	3.2	4.4	4.8	19.0	21.0	2.5	6.1	3.6	7.5	24.
0.710	3.4	3.7	3.4	8.6	15.8	16.5	2.6	5.6	4.4	5.3	13.
1.00	3.5	4.8	2.2	16.7	12.0	12.8	2.8	5.2	5.3	4.7	5.0
1.40	3.7	5.3	1.6	20.3	7.7	7.5	3.2	5.1	5.8	4.7	3.3
2.00	4.7	5.0	1.8	11.3	3.3	2.6	3.6	5.3	5.7	4.4	2.9
2.80	7.0	5.4	2.6	4.0	1.5	1.2	3.4	6.0	5.9	5.3	2.0
4.00	8.1	4.4	3.1	1.4	0.1	0.3	3.0	6.1	5.2	5.3	0.6
5.66	11.1	6.1	4.8	1.3	0	0.1	4.5	10.3	7.5	6.6	0
8.00	10.	7.5	6.2	1.9	0	0	6.1	9.8	5.9	6.3	0
11.2	10.6	7.6	6.8	1.5	0	0	6.9	11.0	8.2	8.7	0
16.0	10.3	8.5	7.3	2.9	0	0	7.0	6.7	8.2	10.9	0
22.5	14.6	8.2	9.9	2.3	0	0	5.4	8.9	11.4	11.4	0
32.0	4.3	15.7	10.9	3.0	0	0	8.7	0.7	15.1	3.8	0
45.0	0.9	9.1	15.7	10.8	0	0	10.5	2.1	3.7	1.5	0
64	0	0.8	7.3	0	0	0	10.1	0	0	0	0
90	0	0	5.1	0	0	0	12.1	0	0	0	0
128	0	0	0	0	0	0	4.1	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	QB34	QB35	QB36	QB37	QB38	QB39	QB40	QB41	QB42	QB43	QB44
Dry wt. (kg)	4.140	3.509	63.200	29.769	5.915	31.289	39.497	2.758	10.322	9.258	61.168
Sieve (mm)	%	%	%	%	%	%	%	%	%	%	%
0.063	23.5	10.0	0.3	3.5	28.6	0.5	0.1	63.0	0.7	0.1	0.2
0.090	18.3	6.3	0.4	3.7	25.3	0.5	0.1	27.9	1.2	0.2	0.3
0.125	14.3	6.0	0.8	4.5	19.6	0.6	0.1	6.5	3.1	0.5	0.7
0.180	5.6	3.7	1.0	3.8	7.8	0.7	0.1	0.8	4.4	0.6	1.0
0.250	5.4	4.3	2.4	5.5	5.2	1.8	0.4	0.4	7.4	0.6	2.2
0.354	8.2	9.3	3.7	5.1	3.4	3.2	1.1	0.4	8.2	0.5	2.5
0.500	14.6	19.3	6.4	6.6	3.7	5.8	3.6	0.4	12.3	4.4	3.6
0.710	8.0	16.4	6.5	5.6	2.9	5.4	5.8	0.4	10.3	4.8	3.3
1.00	1.8	12.4	7.1	5.0	1.6	5.0	7.6	0.4	8.7	7.5	3.6
1.40	0.3	7.4	7.3	4.1	0.8	5.4	8.6	0	9.6	9.9	3.7
2.00	0.1	3.2	7.5	3.6	0.2	5.9	7.3	0	9.9	11.7	4.6
2.80	0	1.3	8.2	4.1	0.2	7.7	6.7	0	10.8	12.6	6.0
4.00	0	0.4	6.3	3.5	0.3	8.0	6.1	0	7.3	10.4	6.1
5.66	0	0.1	7.7	4.5	0.4	8.7	6.9	0	5.1	12.6	9.6
8.00	0	0	7.1	5.9	0	8.6	6.9	0	0.7	8.9	11.1
11.2	0	0	7.0	6.2	0	8.7	7.2	0	0.1	8.3	9.4
16.0	0	0	7.7	6.4	0	9.0	7.5	0	0	5.0	7.1
22.5	0	0	4.4	10.2	0	8.8	9.5	0	0	1.3	6.9
32.0	0	0	5.7	7.3	0	3.7	9.7	0	0	0	7.2
45.0	0	0	1.6	0.8	0	2.1	4.7	0	0	0	6.7
64	0	0	1.0	0	0	0	0	0	0	0	4.4
90	0	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	0	0	0	0	0	0	0
256	0	0	0	0	0	0	0	0	0	0	0

Table 3 (continued)

Sample	QB45	QB46
Dry wt. (kg)	5.981	8.048
Sieve (mm)	%	%
0.063	1.7	0.3
0.090	1.6	0.6
0.125	2.2	1.7
0.180	2.4	3.0
0.250	7.7	6.4
0.354	13.8	6.4
0.500	21.1	8.4
0.710	15.4	8.1
1.00	11.9	9.4
1.40	7.2	9.9
2.00	4.9	10.1
2.80	2.6	11.2
4.00	2.1	9.3
5.66	2.5	9.1
8.00	1.6	5.0
11.2	0.7	1.0
16.0	0.3	0.1
22.5	0	0
32.0	0	0
45.0	0	0
64	0	0
90	0	0
128	0	0
180	0	0
256	0	0