CHANNEL STABILITY AND DOWNSTREAM CHANGES IN PARTICLE SIZE ON THE SQUAMISH RIVER, B.C.

by

Gary J. Brierley

B.A. (Hons.), University of Durham

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE
in the Department
of
Geography

SIMON FRASER UNIVERSITY

November, 1983

APPROVAL

Name: Gary J. Brierley

Degree: Master of Science

Title of Thesis: Channel Stability and Downstream Changes in Particle Size on the Squamish River, B.C.

Examining Committee:

Chairman: Roger Hayter

Edward J. Hickin
Senior Supervisor

Michael C. Roberts

Michael A. Church
Associate Professor
External Examiner
Department of Geography
University of British Columbia

Date Approved: 21 December, 1983

PARTIAL COPYRIGHT LICENSE

Title of Thesis/~~Project/Extended Essay~~

Channel Stability and Downstream Changes in Particle Size on the Squamish River, B.C.

Author:

(signature)

Gary J. Brierley

(name)

January 25, 1984

(date)

ABSTRACT

This study examines the hypothesis that 'the morphology and sedimentology of the contemporary Squamish River channel may be explained only by considering processes on several timescales'. The literature reviewed focuses upon processes affecting, and the resulting scales of, sediment order. Differentiation is made between available (or Holocene) time, an intermediate timescale determined by intermittent sediment inputs, and contemporary time. Analysis of sediment order at different spatial scales is used to evaluate post-glacial adjustments of the Squamish River. Focus is placed upon the downstream gradation of particle sizes.

Methods of field sampling coarse sediment upon bars are discussed. The sampling design adopted measures particle 'b' axes along transects and within quadrats. Relative performance of these two sampling strategies is assessed.

The data show marked discontinuities in the downstream decline in particle size. These trends correlate with changes in channel pattern and slope. The smooth gradational pattern initially derived by Sternberg (1875) is found not to apply and the profile is better divided into unit sections. While individual reaches may have attained an equilibrium condition over short time intervals, the system as a whole has not. A distinction is made between short-term disequilibrium in the sediment balance, in response to temporary sediment inputs from landslide debris and neoglacial moraines, and longer term nonequilibrium produced by paraglacial sedimentation.

The various non-equilibrium conditions have resulted in a sediment wedge, on which is formed the braided section of the study reach. Downstream passage of this wedge is conditioned by the balance between upstream and downstream river control. As energy conditions have declined in the post-glacial period, so the rate of downstream translation has been reduced. It is speculated that present movement is determined more by en masse sediment mobilization during extreme events, while other processes merely redistribute material within the wedge.

It is concluded that river development in such high energy, alpine environments has been dominated by past events, and that contemporary processes are responsible for few of the significant geomorphic elements of the present fluvial landscape.

DEDICATION

To my parents

ACKNOWLEDGEMENTS

The assistance of many people must be acknowledged in completion of this thesis. Firstly, the guidance of my senior supervisor, Dr. E.J. Hickin, was most gratefully received. With a delicate balance of prompting and patience, the direction of study was resolved. Completion was aided by allowing freedom of style - and hence all inadequacies herein reflect upon me, not him. His approach to my research has been excellent and I thank him most sincerely.

The comments of Dr. M.C. Roberts were always helpful. The critical reading of the external examiner, Dr. M. Church, greatly resolved many of the structural writing problems. Discussion with fellow graduates, at both S.F.U. and U.B.C., aided in resolving many conceptual issues.

Studies of this nature depend heavily upon field assistance, and the labours of many people were appreciated with this regard. The encouragement and help of many members of the Geography Department at S.F.U., both in writing the thesis and drafting the diagrams, are warmly acknowledged. In particular, I wish to thank Steve Gardner for the many general discussions, his assistance with the computer and his friendship throughout.

Finally, financial assistance for this research has been gratefully received from an NSERC Grant, awarded to Dr. Hickin, and an Open Graduate Scholarship from S.F.U.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1 : Introduction

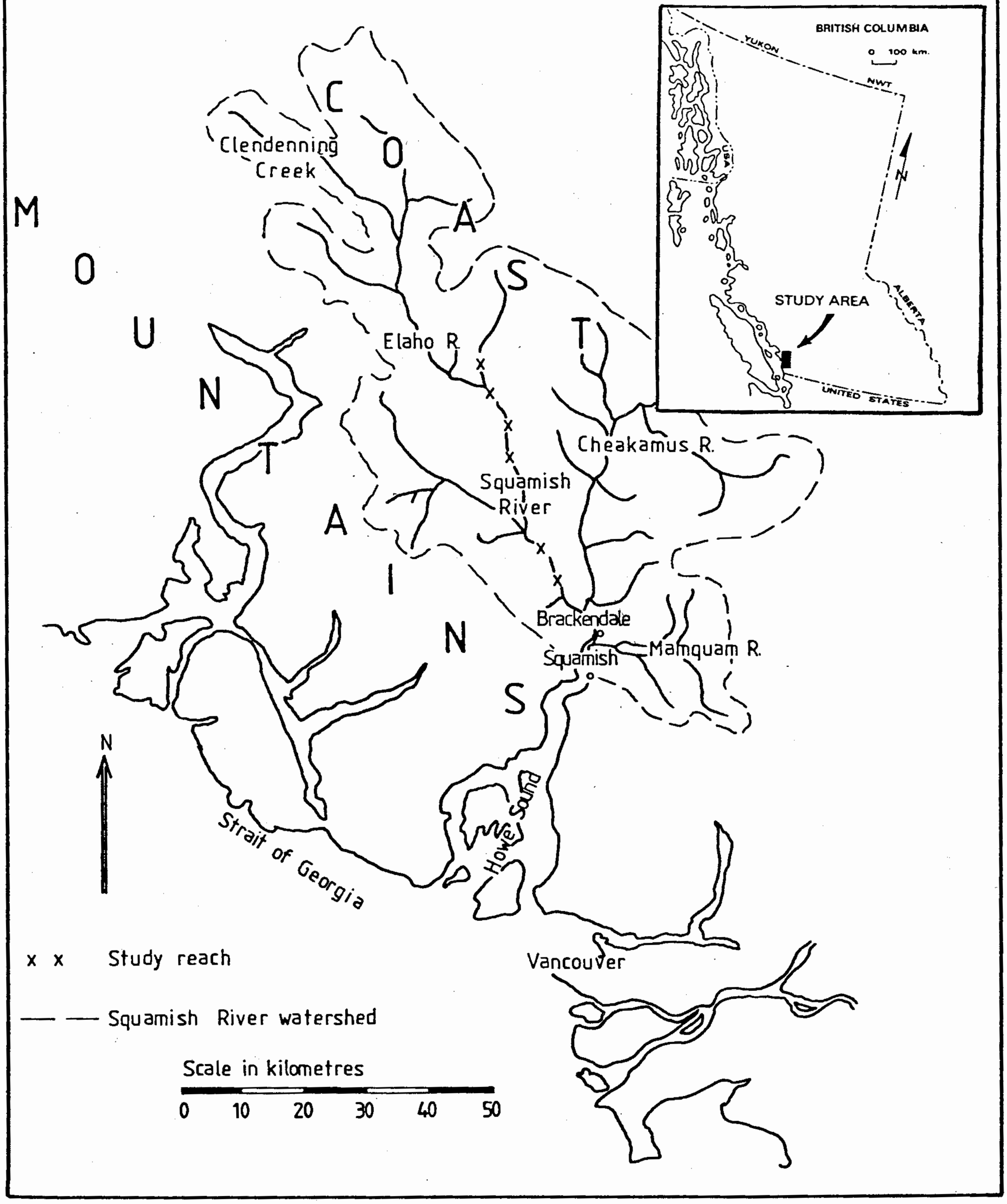
1 : 1 Context of the study

This study examines the hypothesis that 'the morphology and sedimentology of the contemporary Squamish River channel may be explained only by considering processes on several timescales'. Located 80km north of Vancouver, this high energy fluvial system lies within the Coast Mountain Ranges (see Figure 1.1). In the relatively brief 'geologic' time interval since the retreat of the last major mountain ice sheets in the region, the system has undergone marked changes in the sedimentologic balance among supply, storage and redistribution. In considering this balance at least three timescales appear to be important : contemporary, available (or Holocene), and an intermediate temporal scale associated with intermittent sediment inputs of varying magnitude and frequency.

Discontinuities in the downstream trends of planform type and slope, and the extreme coarseness of channel bed material in various reaches, prompted evaluation of contemporary rates of fluvial adjustment of the Squamish River. The equilibrium condition of the system can be evaluated by analysis of sediment transfer through a reach over a particular timescale (see Section 1 : 4). In order to examine river behaviour in the post-glacial period, elements that reflect geomorphic processes

Figure 1.1

THE REGIONAL SETTING



at different timescales had to be selected. Incorporating field observation and measurement with air photo interpretation, sediment volume has been qualitatively assessed in relation to downstream changes in channel pattern, gradient and particle characteristics (as described in Section 1 : 3). For practical reasons and time limitations, field measurement was restricted to analysis of the downstream gradation of particle characteristics.

Some of these issues are examined as secondary objectives of the study, namely :

1. To review the processes affecting sediment order at various timescales, and
2. To consider the various scales and implications of sediment organization in gravel bed rivers and design an appropriate sampling procedure for examining the downstream gradation of particle characteristics.

Various practical problems were encountered in completion of the study. Although logging roads provide excellent access to the valley, collection of samples was extremely time consuming, which posed difficulties in attaining equivalent samples. To minimize variability, most samples were collected during winter low flow conditions, when gravel bars were best exposed. Initial surveillance trips were carried out in Spring, 1982 and various pilot studies were completed in the summer. Following these studies the sampling design was adjusted and further samples collected in Fall, 1982.

A review of relevant literature is presented in Chapter 2. Two themes are considered : the fluvial processes operative at different timescales and the resulting scales of sediment order. The various components of the regional physical setting are described in Chapter 3, with particular attention given to sediment-related issues in the post-glacial period. Field methods and sampling design are documented in detail in Chapter 4, graphical presentation of results follows in Chapter 5, and the final chapter includes interpretations, implications and conclusions of the study, and suggestions for future research.

1 : 2 Timescales of reference

The condition of the Squamish system in the immediate post-glacial period provides the setting for subsequent changes. Extreme sediment supply following the retreat of extensive ice sheets at the end of the Fraser Glaciation produced a system out-of-phase with present environmental conditions. This paraglacial period (Church and Ryder, 1972) had marked effects upon the nature of the system, significantly affecting subsequent processes. A sediment wedge in mid-system reflects these processes in the Squamish system. Hence, activities acting throughout the Holocene interval are responsible for the macro-scale sediment order within the system. As this period is the maximum time unit during which adjustments to paraglacial sedimentation can occur, this has been termed the scale of 'available' time.

The second time interval of relevance to this study is the contemporary time frame. This refers to the period required for within-reach internal adjustment to recent changes, such as flood events. Hence, while floods may be the most important agent of change, abrasion and sorting processes continually redistribute sediment until environmental balance has been attained over a particular channel reach or floodplain unit. These events are reflected both in contemporary gravel bars and in the floodplain depositional environment. Clearly, examination of the surface gravel component of contemporary bars cannot be expected to provide insight into sedimentation activities over the last 10,000 years, as this smaller scale sediment organization reflects recently active processes.

The final temporal unit of significance can best be described as 'intermediate'. Although this refers to no precise timescale, the role of intermittent sediment inputs may be of great significance in the fluvial development of a system. These inputs may be of widely differing magnitude, character and consequence at sporadic or random time intervals. In this study two different processes are of relevance at this intermediate time frame : the placement of neoglacial moraines (Ryder, 1981) and landslide activity (particularly the Dusty Creek landslide; Clague and Souther, 1982).

1 : 3 Evaluation of methods for examining river behaviour at different timescales

Although fragmentary and often inconclusive, the sedimentologic record provides the most extensive source of information for examining past events within a geomorphic system. Accordingly, the degree of sediment organization is indicative of the state and stage of development of a fluvial system and the downstream gradation of particle size can be used as an interpretive tool for examining river development. As Rana et al (1973, 1967) noted,

> "The temporal and spatial distribution of bed material are needed to understand the fluvial morphology and hydraulics of the system. ... The bed sediment size distribution ... can provide insight into the hydrologic and hydraulic circumstances under which sediments are transported and deposited."

This relatively easily measurable feature is also of major significance for engineering applications. Most computational procedures in fluvial studies and river engineering require bed material size as an input parameter (Church and Kellerhals, 1978), as it provides a useful guide to channel energy, efficiency and competence.

This study follows the contention of Kellerhals et al (1976, 813, 824) that :

> "... the bias of most engineers towards readily quantifiable topics has lead to a serious gap in ... work (on river related processes); the neglect of

> interpretive work on river-related landforms. ... (Channel bars) ... probably contain more information on channel processes and bed load sediment transport in particular than any other river feature, but due to the unfortunate preoccupation of river-related research with two-dimensional flume experimentation much of this information remains undeveloped."

As an operationally adaptive sampling method was required, this study was restricted to examination of the coarsest fraction on the surface of presently active channel bars.

While field measurement was restricted primarily to analysis of the downstream gradation of particle characteristics, various other sources of information were used to substantiate the results. Sediment supply sources and downstream changes in planform type and gradient have been evaluated in a qualitative sense from air photography, map and field evidence.

1 : 4 The applicability of the equilibrium concept

Whatever terms are applied, nature appears to operate according to various negative feedback, self-regulatory mechanisms, yet at the same time is said to evolve. This 'equilibrium' condition implies both stability and the ability to make adjustments (Miller, 1958). According to Le Chatelier's principle, if any stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction which will tend to absorb the effects of the stress. Essentially this implies a fluctuating condition, or state of flux about some norm. Equilibrium, therefore, involves either equivalence of inputs and outputs or invariance of certain components, within a definable system over a particular time span.

Many conceptual problems in the use of the equilibrium concept were clarified by the three fold temporal division of Schumm and Lichty (1965) into cyclic, graded and steady state time. Various landscape elements were seen to be independent at these different timescales. Many millenia are involved in cyclic time and therefore it has little relevance to this study. The graded time span is sometimes referred to as geomorphic time and operates over centuries. Conditions of dynamic equilibrium prevail, as every slope and channel in an erosional system adjust to each other and all elements of the topography are downwasting at the same rate (Hack, 1960). Over steady state time, measured in decades, changes may not be discernible. This may be termed engineering time (e.g. Hickin, 1983).

Before examining the appropriateness of these timescales in the development of the Squamish River system, it is necessary to isolate components of channel character which are indicative of the equilibrium condition. To be useful, the features measured should also have some geomorphic significance. Applying the simple input/output concept, the rate of sediment transfer through a particular reach, over a particular timescale, can be used to evaluate the equilibrium condition of a system. Sediment transfer reflects the balance among supply, storage and redistribtion and is controlled by fundamental agents, such as competence and capacity of the flow. Competence is a mechanical flow property, whereas capacity reflects both flow regime and the nature of the sediment mix.

Sediment transfer can be analysed by the methods described in Section 1 : 3 and then applied to evaluate the equilibrium condition for the timescales described in Section 1 : 2. The character of downstream changes in channel planform can be used to test whether the system has fully adjusted over Holocene (available) time. The same planform may be expected if the total reach is dominated by the same controls and an equilibrium condition has been attained. Changes in channel pattern during the Holocene have been demonstrated by Rose et al (1982), who showed the tendency for a persistent planform to develop.

Examination of the downstream gradation of particle sizes within a particular reach provides further insight into the equilibrium condition. The Sternberg (1875) model can be used to test the nature of the contemporary sedimentologic balance by examining the downstream regularity in the grain size of valley fill sediments. Hence, a smooth gradational pattern would be indicative of some form of equilibrium condition.

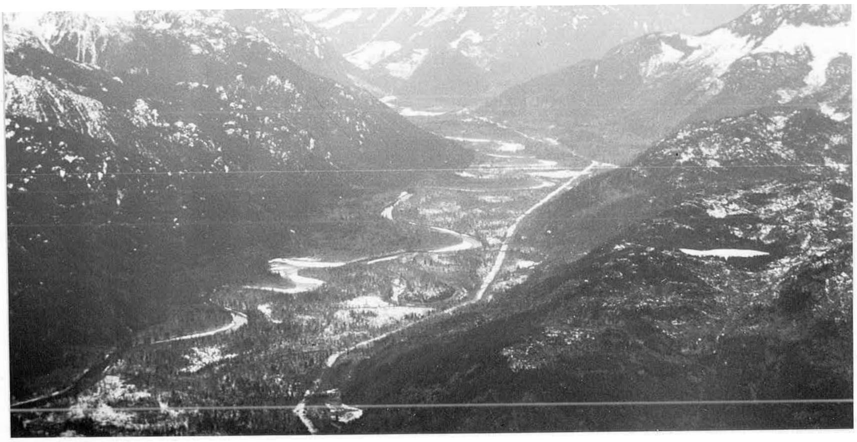
In this study the Squamish Valley is used as a laboratory to examine geomorphic responses to environmental changes at different timescales. The timescales described by Schumm and Lichty (1965) are not applicable to this system. This probably reflects the different environmental setting of the Squamish River in comparison to the regional setting of many 'classic' fluvial geomorphology papers, which were based upon stable landmasses in mid-eastern United States. These areas have been little affected by external changes such as climatic variability or a recent glacial history.

As the Squamish Valley is in a high energy alpine environment, which reflects the 'recent' effects of pronounced glacial activity, timescales of reference have been defined somewhat differently (Section 1 : 2). The accentuated relief has been greatly affected by the mountain ice sheets of the Fraser Glaciation, which resulted in deep valleys with steep valley side slopes (see Figure 1.2). Processes over the 'available' time span, especially in the paraglacial interval, have dominated subsequent activity. The extent and nature of valley infill have been so pronounced that these conditions are still recorded in the system today. Intermittent sediment inputs have further disrupted the sedimentologic balance. Hence, present environmental conditions are out-of-phase with contemporary processes and a state of non-equilibrium prevails.

As rivers are always in a process of adjustment, at some scale, definition of the equilibrium concept is exceedingly difficult (Kesseli, 1941). Not all reaches of a river are necessarily at grade (Mackin, 1948) and degrees of variability from a balanced condition can be suggested. For example, Howard (1982) attributed causes of disequilibrium to three types of

Figure 1.2

Aerial view of the Squamish Valley



fluctuation :

1. rapid trends,
2. recent step changes or pulse inputs, and
3. intermediate frequency inputs.

While the disequilibrium condition is relatively transient in character, the term nonequilibrium is better applied to systems in a more permanent state of sedimentologic imbalance. This may result from the flood history (Stevens et al, 1975), climatic changes during the Holocene (Knox, 1976), or simply from channel bed characteristics such as particle size and the degree of packing or paving (e.g. Kellerhals, 1967; 1982).

In summary, fluvial processes affecting sediment order are evaluated at differing timescales. The equilibrium concept provides a useful method for describing the state and stage of fluvial development. Differentiation is made between the equilibrium condition, operative over decades at contemporary time, the disequilibrium condition, in response to pulse-like temporary sedimentologic imbalances over timescales varying from decades to centuries, and more permanent nonequilibrium, resulting from massive sediment inputs in the early post-glacial period with an insufficient period of time for redistribution, or outputs, to be complete. This nonequilibrium condition is operative over thousands of years.

Chapter 2 : Literature review

The literature review for the study is divided into two sections. The first examines the processes affecting sediment order at different timescales. Consideration of the changing nature and effectiveness of processes in the post-glacial period supports the hypothesis that the contemporary morphology and sedimentology of the Squamish River can only be explained with reference to activities of former eras. Discussion of the resulting sedimentologic order follows, focusing upon planform type, the gravel bar depositional environment and the downstream gradation of particle size. These were important considerations in determining how the thesis was to be examined.

2 : 1 : 1 Available time : Paraglacial sedimentation

Variations in sediment supply during the Holocene may be attributed to the interaction of several factors, such as climate and/or vegetational change and human interference. A period of intense geomorphic activity immediately followed deglaciation. This 'paraglacial sedimentation' refers to non-glacial processes directly conditioned by glaciation (Church and Ryder, 1972). Sparse vegetation, glacially oversteepened slopes, and the proximity to glacial meltwater outlets with large, flashy discharges resulted in vast quantities of material being made available to rivers. Large temporary storage features, such as alluvial fans and cones, resulted (e.g. Ryder, 1971).

As ice margins retreated, peak discharges were reduced, and glacially derived materials became more inaccessible. Vegetation became established and the nature of processes changed from rapid paraglacial sediment supply conditions immediately following deglaciation to gradual reworking and removal of these deposits by fluvial and slope processes. Since paraglacial sediments formed the surface for subsequent flow interaction, they have exerted pronounced control upon fluvial activity. As Kellerhals et al (1976, 816) noted :

> "During much of the (Holocene) period ... rivers have been moving, sorting and redepositing the major 'slug' of glacially derived sediments; today many rivers flow over lag deposits of glacial till or outwash that they are now not competent to move."

2 : 1 : 2 The role of intermittent sediment inputs

Intermittent sediment inputs are considered to affect the sediment balance over an intermediate timescale. These pulse inputs can be of varying nature and consequence, occuring at sporadic intervals. Their effectiveness depends upon both the calibre and quantity of the sediment mix and the return period of activity. In this study there are two important intermittent sources. Ryder (1981) commented on the role of sediment inputs from neoglacial moraines which produced 'waves' of downstream sediment movement. Secondly, landslide debris may produce pulse sediment inputs. In both instances the supply mechanisms to the main channel are important considerations. In their discussion of the role of paraglacial sediment inputs, Jackson et al (1982) isolated two related issues which remain to be resolved :

1. the time required for a coarse-sediment pulse to pass a given location downstream from the sediment source, and
2. the rate of diffusion of the pulse with distance from the source area.

These issues can be applied equally to the role of intermittent sediment supply events. The regional periodicity of neoglacial advances and discussion of local landslide activities are presented in Chapter 3.

2 : 1 : 3 The effectiveness of contemporary processes

Present day activities within valleys such as the Squamish have been conditioned largely by past events, as current processes merely act upon the surface of former sediment accumulations. Processes operative over the contemporary time interval reflect sediment adjustments to flood events by abrasion and sorting processes.

Abrasive processes can be divided into two types : in transit and in situ. The effectiveness of in transit mechanisms has been demonstrated both experimentally (e.g. Wentworth, 1919; Schoklitsch, in Graf, 1971; Krumbein, 1941; Kuenen, 1956) and from field evidence (e.g. Bradley, 1970; Shaw and Kellerhals, 1982). In situ chemical weakening of particles may occur either on the channel bed or on the bar surface (e.g. Bradley, 1970; Adams, 1979a). Various mechanisms have been suggested, such as grinding as particles vibrate in situ (Schumm and Stevens, 1973) and pot-holing (Shaw and Kellerhals, 1982).

Processes of selective transportation can be divided into two scalar components : local and progressive downstream sorting (Russell, 1939; Rana et al, 1973). Local sorting occurs over distances shorter than a bedform length. For example, coarser particles accumulate upon riffles in riffle/pool sequences (Leopold et al, 1964; Church, 1972; Hirsch and Abrahams, 1981; Milne, 1982) probably due to velocity reversals (Keller, 1971; Lisle, 1979). Progressive downstream sorting occurs over far greater distances and results from cumulative local sorting, along with changes in flow competence along the stream (Knighton, 1980). The effectiveness of sorting processes has been confirmed by field studies (e.g. Plumley, 1948; Bradley et al, 1972; Davies et al, 1978). While each size fraction undergoes differential downstream sorting, the greatest changes occur in the coarsest fraction, with relatively less sorting of each progressively finer fraction (Smith, 1974).

The relative importance of abrasion and sorting processes depends upon a combination of factors. One significant characteristic affecting process effectiveness is the channel condition in relation to 'grade'. Abrasion is seen to dominate under degraded or graded conditions, whereas differential transport is the most important process under aggrading conditions (Mackin, 1963; Rogers, 1964; Bradley, 1970; Shaw and Kellerhals, 1982). Flow regime and calibre of bed material greatly influence process effectiveness. Sorting cannot control the size distribution as this process merely moves grains around and does not produce them (Rogers, 1964). Scheidegger (1961, 175) commented that :

> "The most likely mechanism of pebble gradation in rivers consists of pebbles becoming contriturated due to the action of frictional forces, but being assigned their position along the stream bed by a sorting process due to differential transportation."

Knighton (1982) identified three regimes in which these different processes are dominant :

1. abrasion and size sorting in the headwater area,
2. shape and size sorting in the middle reaches, and
3. sorting and breakage towards the downstream reaches.

In low frequency flood events sediments are mobilized en masse; in some instances the basal portion moves as a viscous, subaqueous flow (e.g. Stewart and LaMarche, 1967; Scott and

Gravlee, 1968). Highly complex depositional arrangements, with limited internal sorting, may result from hindered settling during the waning stage of floods (Middleton and Southard, 1978).

This prompts enquiry into geomorphic effectiveness in relation to the magnitude and frequency of floods. Wolman and Miller (1956) stated that most of the work of moving sediment from the drainage basin is done by frequent flows of moderate magnitude. However, from their review of flood effectiveness under differing environmental circumstances, Wolman and Gerson (1978, 189) conceded that :

> "Exceedingly rare floods of extreme magnitudes ... may exceed thresholds of competence unattainable in the 'normal' record resulting in 'irreparable' transformations of valley landforms."

Many recent case studies have demonstrated the geomorphic effectiveness of extreme flood events. In his recent review of river channel changes, Hickin (1983, 71) commented that :

> "extreme events, part of the normal process system, may cause significant departures from equilibrium channel morphology that may persist for long periods of time."

From this viewpoint, Dury (1980) called for a re-enquiry into 'Neocatastrophism'. The history of extreme events may be preserved within the sedimentologic record. Dott (1983) suggested that uniformitarian and cyclic principles of sedimentation should be rejected, and considered episodic, although not necessarily catastrophic, events to be of far greater significance.

In summary, processes operative at the contemporary timescale are redistributing sediments which were supplied over various time intervals. Local scale sediment order results from sorting and abrasion in situ processes, while downstream trends reflect progressive sorting and abrasion in transit. Hence, interactions over various timescales have resulted in several degrees of sedimentologic order.

2 : 2 Scales of sedimentologic order

Within the Squamish floodplain the range in particle sizes is great, but sediment order is apparent at a variety of scales. Simple examination of individual bars reveals spatial organization of particle size fractions from silt through to coarse gravels. However, sediment organization is also apparent for channel pattern and the overall longitudinal profile.

2 : 2 : 1 Planform type

Channel pattern is a reflection of physical meaning which has tended to be overlooked in the past (Kellerhals et al, 1976). Downstream changes in planform type, and changes over time, are indicative of changes in controlling conditions and energy relations. A braided to meandering transition occurs within the study reach on the Squamish River. The character and significance of such transitions are described in this section.

The braided river depositional environment has been reviewed by Miall (1977). Braiding occurs under high energy depositional conditions, when sediment load is either too voluminous or too coarse for the river to transport frequently (e.g. Fahnestock, 1963; Ore, 1964; Church, 1972). The incidence of bar intitiation, flow diversion and creation of new channels is high.

The fundamental difference between the depositional mechanisms in meandering and braided environments is the lateral nature of bar development in meandering sections. Recently reviewed by Callander (1978), a meandering planform reflects lower energy conditions than braided sections. Leopold and Wolman (1957) differentiated meandering from braided patterns by combinations of slope, discharge and width/depth relations. Henderson (1961) added bed material size to this function.

Other things being equal, rivers with coarse grained beds are wide, shallow and braided, and rivers with fine grained beds are narrow, deep and meandering (Wilson, 1973). While bedload transport predominates in braided channels, sediment moves as mixed and suspended load in meandering reaches (Miall, 1977). Due to higher current velocities and turbulence, braided deposits tend to be coarser and less well sorted (Glaister and Nelson, 1974). Hence, braiding is more characteristic of upstream reaches, while meandering is more common downstream, where the slope is gentler and particles less coarse (Walker and Cant, 1979).

The braided/meandering transition can be viewed in a temporal as well as a spatial sense (e.g. Leopold and Wolman, 1957). Since the extreme sediment supply of the paraglacial period, many rivers have been working towards a degradational, quasi-stable meandering regime (e.g. Fisk, 1947; Schumm, 1971; Jackson et al, 1982). Braided sections in the upper courses of streams may move downstream or disappear over time, dependent upon local conditions of sediment supply, quantity and calibre. Channel planform, therefore, reflects large scale sediment order. Changes in pattern, both in space and time, are indicative of differing energy relations and depositional conditions.

2 : 2 : 2 The gravel bar depositional environment

Within a floodplain unit various depositional zones can be defined in relation to channel position (e.g. Williams and Rust, 1969). Sediment order varies for each zone. In gravel bed rivers the greatest degree of sorting is found in the active channel zone. This can be further divided into two units : the channel itself, and the gravel bar depositional environment. As measurements within the channel were considered impractical, this study has been restricted to evaluation of gravel bars.

Gravel bars are the macro- and megaforms in the hierarchical continuum of bedform scales (Jackson, 1975). These channel-scale features adopt many different forms which differ in both morphology and growth pattern (Bluck, 1976). Church and Jones (1982) differentiated between 'storage element' bars, which adopt a relatively passive role with channel flow, and 'hydraulic element' bars, which serve as important energy dissipators by increasing flow resistance. Gravel bars are the most conveniently adjusted aspect of channel form when it becomes necessary to make changes in resistance characteristics to accommodate different flow levels.

Smith (1974) divided bars into two main types : 'unit' bars of distinctive form and relatively simple structure, and compound bars, which have undergone a complex erosional and/or depositional history. Only those bars whose existence depends more on the long term position and shape of the channel than on short term variations in flow and sediment supply are likely to maintain a more-or-less stable form over a long period. The character and form of these bars reflect their energy relations of deposition. Hence, trends of downstream organization of bar type may be discernible (Church and Jones, 1982).

Since gravel bars are formed initially from coarser lag material they tend to be relatively stable features while finer sediments move through the system as irregular, often indistinct, smaller bedforms (Hein and Walker, 1977). Usually bars are composed of material smaller than the channel bed surface (Smith, 1974). Each bar itself shows some degree of sediment size organization, reflecting different depositional conditions over the bar surface. Leopold (1970) termed zones of similarly sized material 'locales'. The presence of such features has important implications for the sampling design. Bluck (1982) observed that most gravel bars have a coarse upstream portion and a comparatively fine downstream portion. This has been substantiated by field studies upon various bar types (e.g. Bluck, 1971; 1976; Doeglas, 1962; Levey, 1978; Nanson, 1980). Compound bars, however, rarely exhibit simple patterns of grain size or structure, either internal or superficial (Smith, 1974; Miall, 1977).

In summary, gravel bars adopt a wide range of forms, ranging from simple unit bars to complex, compound features expressing diverse erosional and depositional histories. Bar type reflects channel planform, sediment size, and local circumstances. While deposits in meandering sections exhibit a certain degree of order, the continual shifting of channels in braided sections produces heterogenous bar surfaces, with patches of material of different size and different degrees of sorting (Leopold and Wolman, 1957).

2 : 2 : 3 The downstream gradation of particle size

Differing scales of sediment order are reflected within channel planforms and upon individual bar surfaces. A more general guide to the condition of the system is provided by the overall downstream decline in particle size. For practical reasons, this summary measure must be restricted to one part of the sedimentologic suite, in this case the coarsest active gravel fraction.

While many studies have concentrated upon processes producing the downstream gradation of particle characteristics, relatively few have commented on the nature and implications of the trends. The smooth nature of the downstream gradation of particle sizes was first characterized by the abrasion law of Sternberg (1875), which showed that the weight of a stream pebble is directly proportional to the work done in overcoming friction over the distance travelled. As stream competence decreases, there is an according reduction in particle size carried.

The ′rational equation of the river bed profile′ developed by Shulits (1941) considered wear phenomena to logically reflect downstream changes in channel slope. Similarly, Sundborg (1956, 194) commented that :

> "Study of the relation between the bed material and the longitudinal profile of a river has led to the view that the gradient of a river in equilibrium is directly proportional to the grain size in stretches where the river does not undergo marked change, for instance owing to the confluence of a tributary. Since it has been found empirically that particle size on the whole follows Sternberg′s abrasion law ... a river in equilibrium should therefore have an exponential longitudinal profile."

Subsequent work has shown Sternberg′s equation to be a reasonable description of the downstream decrease in grain size in rivers flowing on alluvial gravels (Church and Kellerhals, 1978). Particle size and shape at any point on the longitudinal profile reflect both initial conditions and the rate of subsequent modification. Since the flow conditions which influence the rate of movement vary with distance downstream, systematic changes in the size, sorting and shape of bed material can be expected in that direction (Knighton, 1975; 1980; 1982).

A smooth downstream gradation in particle size reflects changes in flow properties such as its power, efficiency and competence. Hence, although the exponential Sternberg decline function may not be apparent, concurrent smooth trends for particle size and channel gradient may be indicative of an equilibrium condition.

Miller (1958) demonstrated that the nature of the downstream transition is dependent upon the assumptions inherent in Sternberg's study. Various disturbances, such as tributary inputs, lithologic contacts and sediment sources in areas other than the headwater region, may markedly affect the overall particle size gradation (e.g. Mackin, 1948; Hack, 1957; Miller, 1958; Shaw and Kellerhals, 1982). These sediment-related imbalances may affect the equilibrium condition of the system.

Chapter 3 : Regional Setting

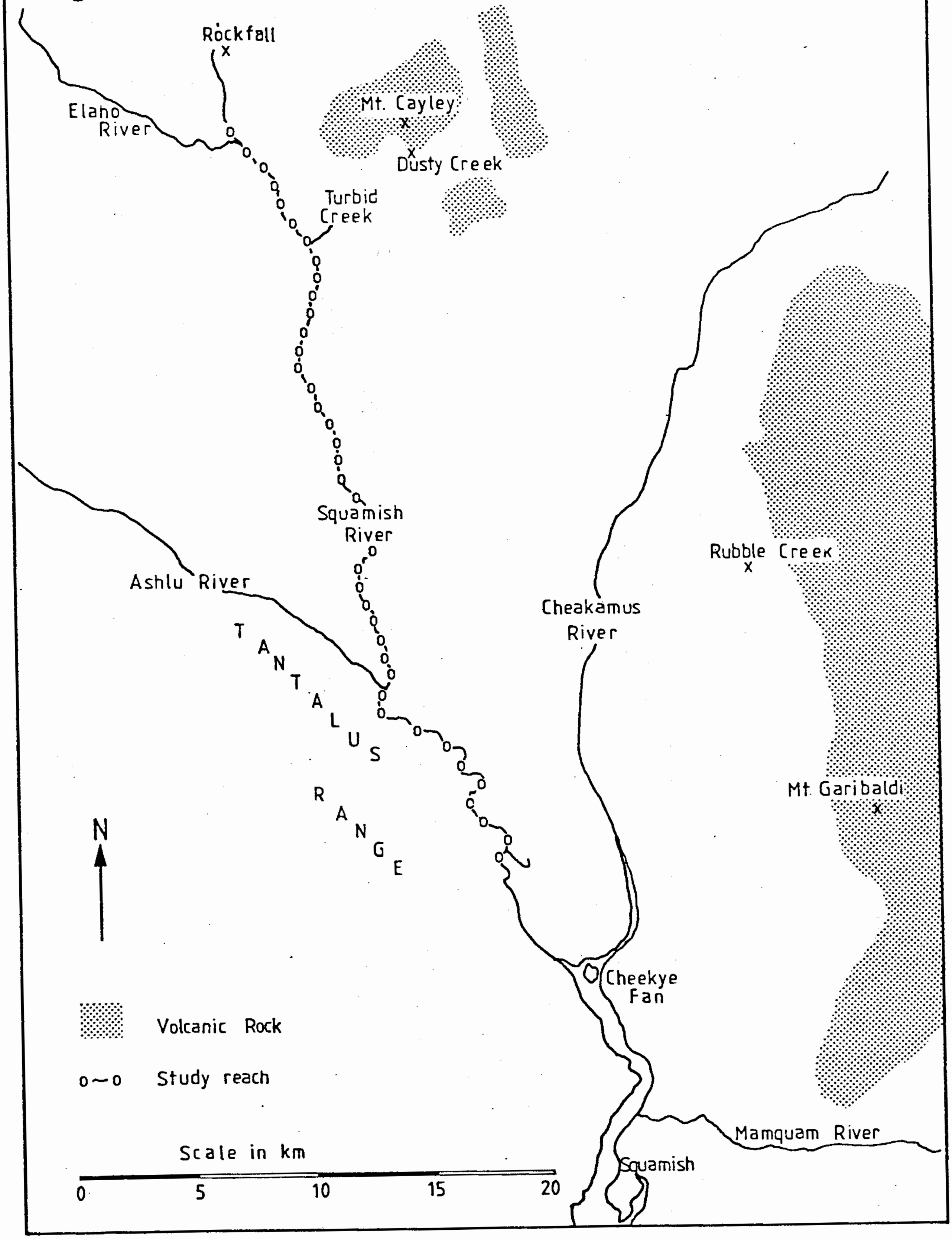
In the southern coastal region of British Columbia major linear structures have been excavated by glacial and fluvial processes to form striking alignments and grid-like patterns of valleys and fjords parallel to regionally developed sets of joints or faults. Over 150km long, and draining an area of about 3,600km^2, the Squamish River follows the trend of the Tantalus Range Mountains before flowing into Howe Sound fjord. This study focuses on the channel section between the Elaho and Cheakamus tributaries (see Figure 3.1). The physical geography of the region is described in this chapter.

3 : 1 : 1 The present climate

British Columbia is in the zone of the westerly atmospheric circulation of the northern hemisphere. The Squamish region exhibits a typical maritime coastal climate, with marked ameliorating effects of the Pacific Ocean.

In winter the northerly portion of the airstream flow prevails giving cool, wet conditions. As the moisture-laden air in successions of frontal systems rises in contact with the northwest/southeast aligned mountains, the western side of the Coast Ranges displays high precipitation totals. Due to the

Figure 3.1 LOCAL DETAIL OF THE STUDY AREA



abrupt nature of uplift and the transition from ocean to land surface, precipitation increases dramatically with elevation, and large snowfalls occur in the mountains. Frequent cold air intrusions from the interior assist in the freezing process.

In summer the prevailing westerlies weaken and the climate becomes dominated by the southern section of the airstream associated with large, semi-permanent Pacific anticyclones. There are frequent spells of fine, sunny weather with bright, dry and warm conditions.

The region is characterized by a wet winter and a dry summer regime. In Squamish itself, precipitation reaches a maximum in fall and winter, with monthly totals in excess of 250mm from October to January, while there is less than 80mm monthly precipitation between May and August. Mean annual precipitation is just over 2,000mm, with a mean winter snowfall of almost 1,500mm. In some cases upland areas experience precipitation totals in excess of 5,500mm. Temperature and precipitation normals for the Squamish meteorological station are presented in Figure 3.2.

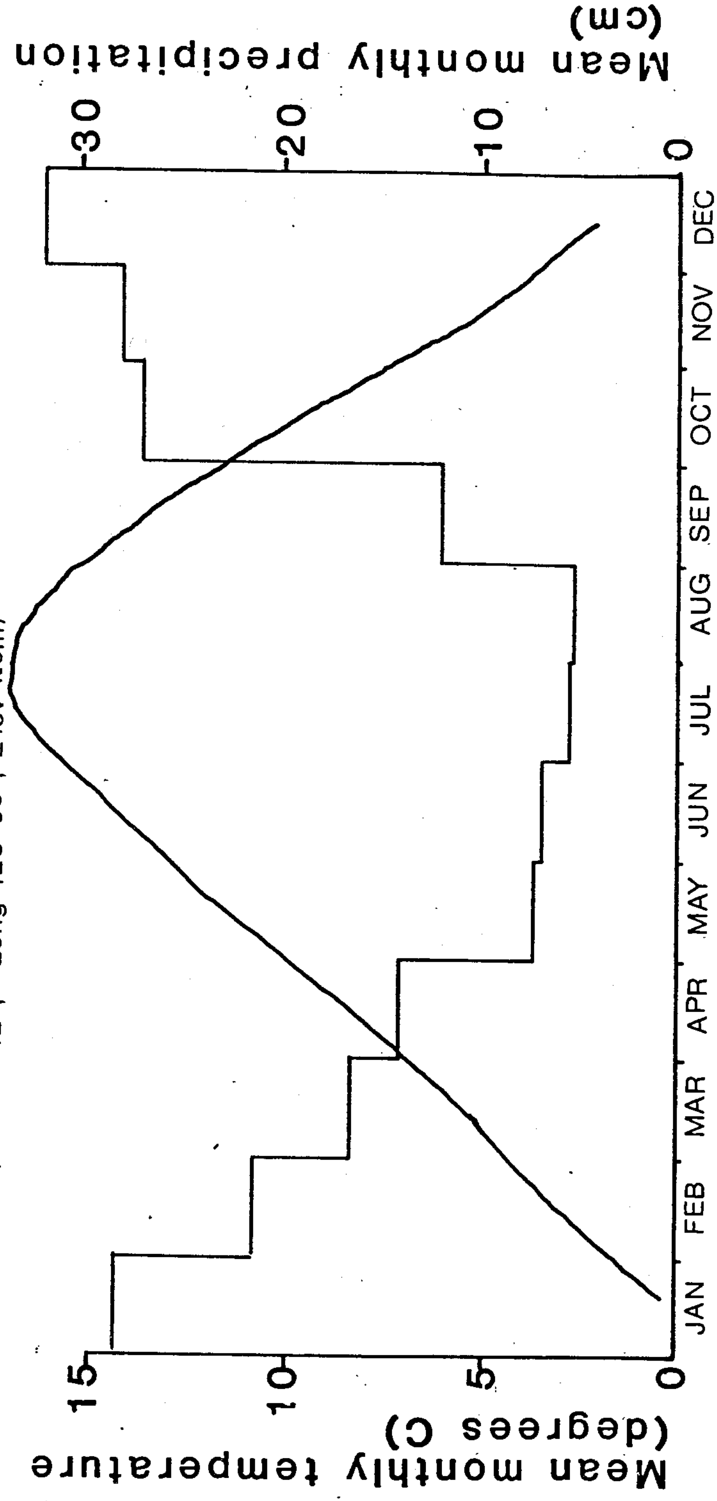
An Indian word, 'Squamish' refers to the strong winds which are channeled down the valley. The location of the Squamish estuary, in a deep cleft in the Coast Mountains, has a marked effect on its climate, as does the north/south orientation of the valley inland from its estuary. The frequent storms of fall and winter tend to be funneled up Howe Sound, accentuating the wind and precipitation regimes. The high peaks which surround

Figure 3.2

TEMPERATURE AND PRECIPITATION NORMALS

AT SQUAMISH, B.C.

(Lat 49°42'; Long 123°09'; Elev 1.6m)



the area augment the development of summer convective showers (Hoos and Vold, 1975).

3 : 1 : 2 Holocene climatic fluctuation

Immediately following the Fraser Glaciation, the climate of the region was cool and moist. Gradually conditions became more mild, culminating in the hypsithermal conditions of relative warmth which prevailed from 10,000 to 6,500 years ago (Fulton, 1971). In southern British Columbia, arboreal vegetation became established shortly after deglaciation, indicating a rapid transition to a nonglacial climate without an intervening stage of tundra vegetation (Clague, 1981).

Cooler and wetter conditions have followed to the present day. During this period minor climatic fluctuations have occurred, although they were by no means spatially synchronous. Short lived cool and moist intervals have coincided with temporary expansions of mountain glaciers, referred to as neoglacial advances.

3 : 2 Geology of the Squamish Valley region

The regional geologic history is outlined in Table 2.1. According to the classification of Holland (1964), the Squamish Valley lies within the Pacific Ranges of the Coast Mountain area in the western system of the Canadian Cordillera. The ranges

Table 3.1

THE GEOLOGICAL CONTEXT IN SOUTHWESTERN B.C.

Period	Epoch	Geological scenario
Quaternary		Pleistocene Glaciation and Volcanic Intrusion of the Garibaldi Volcanic Belt
Tertiary	Pliocene	Destruction of early Tertiary surface; Trenching along major valleys and tributaries following 2,000m of differential uplift in the Coast Mountains
	Miocene	Erosion surface of low relief (600m)
Early Tertiary		Erosion along major valleys following differential uplift, which separated the Insular and Coast Mountains by the Coastal Trough
Cretaceous		Erosion of low relief, resulting in sedimentation in basins
Jurassic		Coast plutonic Complex batholiths intruded in Late Jurassic/Early Cretaceous

have a width of 125-160km between their western boundary along the Coastal Trough and their eastern boundary with the Interior System. Within this major physiographic unit are a series of deep cut, fault oriented and glacially excavated valleys. Accelerated fluvial erosion due to pre-Pleistocene uplift of the Coast Mountains produced well defined valleys which largely conditioned glacier patterns.

The Coast Plutonic Complex is mainly granitic (quartz diorite and granodiorite) in composition, with minor occurrences of gneiss and schist. A more comprehensive guide to these basement rocks is given by Souther (1980). Major andesitic volcanoes (such as Mount Garibaldi, 2678m, and Mount Cayley, 2393m) rise 500-1,000m above the glacially-eroded surface of the southern Coast Mountains. Mount Cayley, the largest volcano in the central Garibaldi belt, is a composite pile of dacite lavas formed during at least three distinct stages of activity, between 0.3-0.7M years ago (Souther, 1980). Although the geological history of the area is quite confused, with complex lithological associations, the outcome is relatively straightforward (see Figure 3.1).

3 : 3 Geomorphology of the Squamish Valley region

The geologic past provides the general topographic framework upon which contemporary geomorphic processes mould and reshape the surface constituents. This reworking is examined under three subheadings, namely glacial activity, fluvial activity, and landslides and related phenomena.

3 : 3 : 1 Regional glacial chronology

During the Pleistocene Epoch the region was subjected to several major glacial episodes but stratigraphic evidence is such that the picture may be by no means complete. The maximum glacial extent of the Fraser Glaciation has been termed the Vashon Stade and lasted from 18,000 to 13,000 years ago in the southern Coast Mountains (Clague, 1976). Ice depth in the Squamish Valley was greater than 1,950m, with the ice surface at 2,100m in the Garibaldi region and 1,800m in the Tantalus Ranges (Mathews, 1951). Ice recession occurred relatively rapidly and lowland adjacent to the southern Coast Mountains was ice free by 13,000 years ago (Armstrong and Hicock, 1976).

During the period in which the lowland was emerging, minor glacial advances occurred, which reworked former deposits. The most notable readvance has been termed the Sumas Stade, which reached its climax about 11,300 years ago. A large submarine moraine at Porteau Cove in Howe Sound marks the maximum stand of Sumas ice (Mathews et al., 1970), indicating that a major valley glacier occupied the Squamish system after the ice sheet phase (Ryder, 1981). However, low level cirques were not reoccupied at that time (Mathews, 1951). Recession of Sumas piedmont glaciers was very rapid.

Armstrong and Hicock (1976) determined that every major ice advance and retreat in the region was accompanied by eustatic and isostatic sea level changes of up to 230m. Post-glacial readjustment was very rapid, and only minor regional changes have taken place over the last 11,000 years. Indeed, the shore has stood close to its present level for the past 5,500 years in all parts of the area (Mathews et al, 1970; Clague et al, 1982; Clague and Luternauer, 1983).

About 10,500 years ago closed temperate forest communities became established in the lowland areas, subordinating or replacing pioneer species and those adapted to cooler, more moist conditions. By 9,500 years ago mountain glaciers had shrunk to almost their present size (Fulton, 1971). Cirques are currently glacierized at 1,500m on northerly slopes, and over 1,800m on southerly slopes. Cool and moist intervals have produced neoglacial advances.

Regionally three episodes of neoglacial advance have been identified at 5,800-4,900 and 3,200-2,300 years ago, and during the last 1,000 years. Ryder et al (pers. comm., 1981) noted that these regional scale events were not synchronous. Mathews (1951) determined that three of four glaciers studied in the Mount Garibaldi area reached their maximum post-glacial extent in the early part of the C18th and the middle part of the C19th. In the Tantalus Range large compound cirques, commonly containing lakes, with elevations between 900-1,200m, occupy large areas of the western part of the Pacific Ranges, and trunk glaciers terminate well below snowline (Ryder, 1981).

3 : 3 : 2 The fluvial scene

In late glacial and post-glacial times rivers carried vast quantities of debris from the waning glaciers, and deposited it to great depths on valley floors and at the head of fjords (Davis and Mathews, 1944). Between 90-120m of alluvial deposits have accumulated on the post-glacial floor of the Squamish Valley (Mathews, 1952), largely in response to high rates of paraglacial geomorphic activity (see Chapter 2). The fall in base level due to glacio-isostatic uplift and resultant changes in land/sea positions led to entrenchment and terracing of late-glacial and older deposits (Clague, 1981).

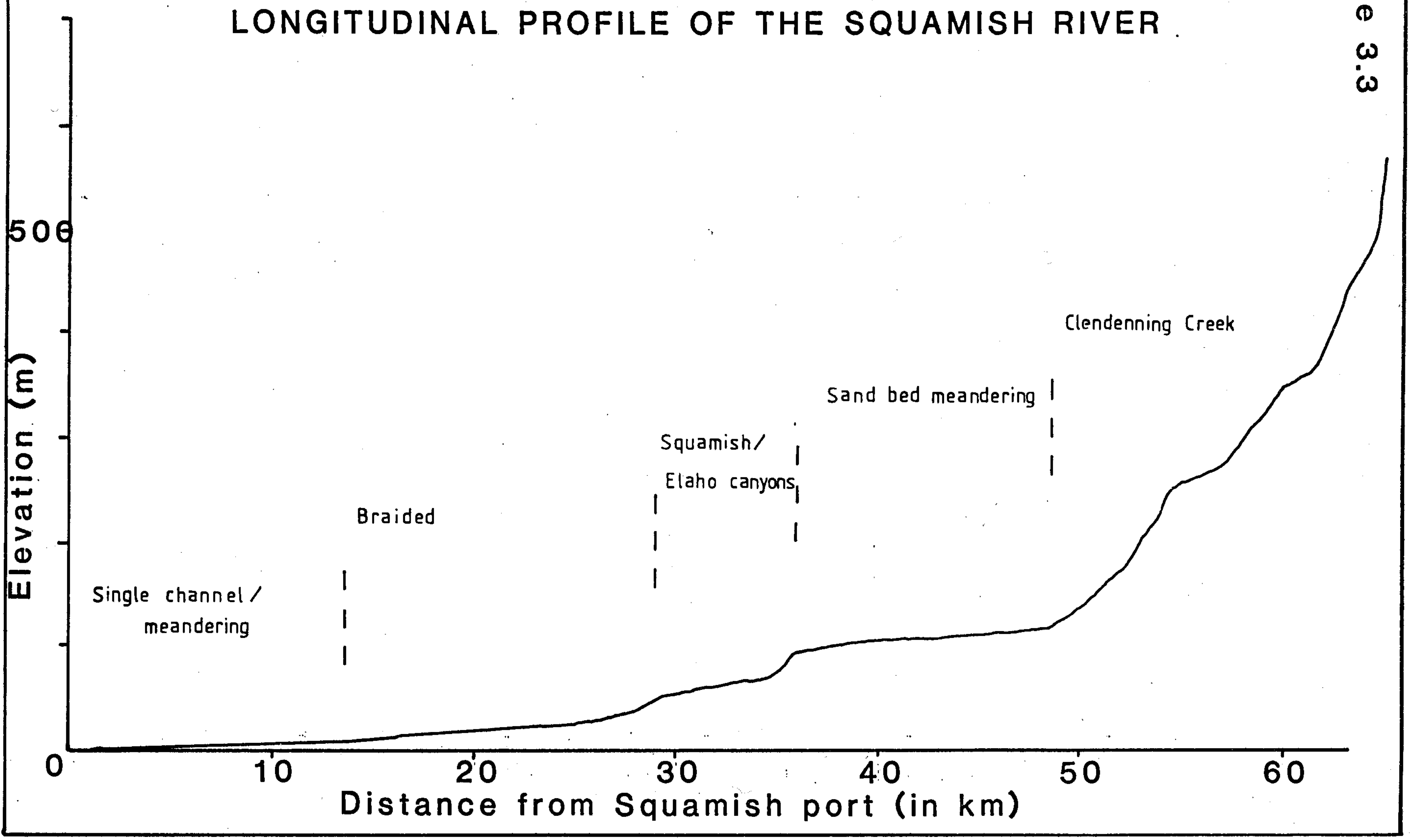
As slopes stabilized and vegetation became established following the paraglacial interval, sediment supply rates diminished. Many alluvial fans in the Squamish basin reflect these former sediment supply conditions, and now present major sediment storage units within the system. For example, the Cheekye Fan, in the lower course of the Squamish River, has an estimated volume of 2.5km^3. The fan developed at the end of the last glacial episode, as runoff was forced to flow between glacier ice and the adjacent mountainside. Immediately downstream of the Cheakamus junction the Squamish River has eroded the toe of the fan, exposing a 13m section of five units. Eisbacher (1983) described the section as two cycles of rapid aggradation, each characterized by the emplacement of a massive debris flow, and a subsequent phase of fluvial deposition in braided channels. The lowest unit revealed a ^{14}C date of 5,890 ±100 years B.P.

Over 150km from Squamish, the glacier fed Clendenning Creek falls steeply to the Elaho River. Several large alluvial fans actively supply sediment to the river and the Elaho River degrades for a few kilometres upstream of the Clendenning/Elaho junction. Downstream, the sand-bed Elaho River adopts a single channel meandering regime. The channel gradient is fairly gentle in this reach (see Figure 3.3), but becomes very steep as the river enters a canyon, several kilometres upstream of the confluence with the Squamish River.

Large volumes of material have accumulated at the Squamish/Elaho confluence. Following several kilometres of divided channel with large mid-channel bars, the Squamish River enters its canyon. Within a short distance three highly sediment-charged tributaries enter the Squamish system from the eastern flank, transporting easily erodible volcanics from the Mount Cayley landslide debris.

Downstream of the canyon the Squamish Valley widens considerably, and the Squamish River adopts a braided pattern.

Figure 3.3



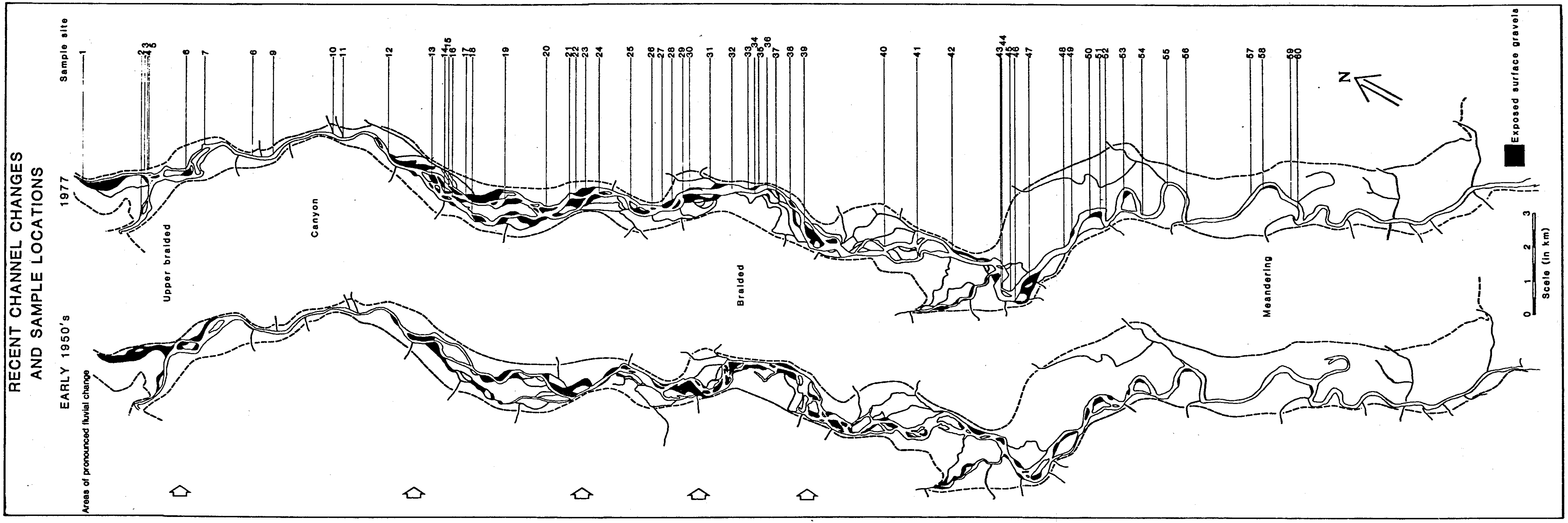
LONGITUDINAL PROFILE OF THE SQUAMISH RIVER

Map and air photographic evidence demonstrate the continuing history of channel shifting in this section of relatively modest gradient (see Figure 3.4). This dynamic geomorphic reach is the primary focus of study.

At its confluence with the Ashlu River the Squamish River channel pattern changes abruptly. The river has been pushed to the eastern side of the valley by a low-lying accumulation of fairly fine material, in a shallow fan form. This restriction imposes a single channel meandering pattern, which is retained downstream. Flow conditions in the lower course have been markedly influenced by the terraced Cheekye Fan. This fan effectively pushed the Cheakamus River against the opposite bedrock bank, resulting in over 9km of upstream aggradation (Mathews, 1952). Similarly, the Squamish River was pushed to the extreme western wall of its valley.

The main channel of the Squamish River has become well entrenched in the flatter lower reaches. Stathers (1958) compared 1899 land surveys with those of 1958 and determined that the general form of meanders on the Squamish had not changed, but that there was a tendency for them to move downstream. Levings (1974) determined that width relations had changed. Hickin (1978, 1979) examined mean flow structures around a variety of bends with different radii of curvature, and described the development of concave bank benches immediately upstream of sharply curved bends.

Figure 3.4


RECENT CHANNEL CHANGES AND SAMPLE LOCATIONS
1977
EARLY 1950's
Sample site
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60
Upper braided
Canyon
Braided
Meandering
N
Exposed surface gravels
0 1 2 3
Scale (in km)
Areas of pronounced fluvial change

Prior to its junction with the Cheakamus, the Squamish River adopts a fairly straight course. Conditions of over-supply of sediment prevail downstream. The river pattern has been largely controlled by man, protecting the communities of Brackendale and Squamish.

As the Squamish River enters Howe Sound a delta has formed. Composed of glacial flour and silts deposited from suspension, the delta has an estimated area in excess of 380,000m^2, and currently is growing at an average rate of 6.5m per annum on its western and central fronts, and 2.5m per annum along its eastern front (Hoos and Vold, 1975).

3 : 3 : 3 Landslides and related phenomena

The relationship between slope and channel processes largely conditions sediment supply to a river. Ryder (1981) considered present slope and channel processes in the Squamish region to be in equilibrium, with glaciers constituting the major natural source of sediment. Locally, human activities have affected this environmental balance. For example, logging disturbances have increased rates of sediment supply from slopes (O'Loughlin, 1972).

O'Loughlin maintains that, in comparison with landslide densities in other mountainous areas, the Coast Mountain densities are relatively small. However, in the presence of an impermeable till substratum and heavy seasonal rainfall, these slopes are prone to catastrophic failure. Slope instability in the area is largely geologically controlled. Weakly consolidated agglomerates and tuffs, and closely jointed lavas, are highly susceptible to mechanical weathering and loss of competence.

The best documented landslide in the study area was the 1963 Dusty Creek landslide on the western flank of Mount Cayley. Well researched by Clague and Souther (1982), this landslide had an estimated volume of 5 x $10^6 m^3$. The landslide debris consists largely of angular, poorly consolidated porphyritic rhyodacite blocks, up to 3m in diameter. Deposits are massive to weakly stratified, poorly sorted to non-sorted diamicton, with angular to subrounded clasts in a matrix of silt and sand. Clasts range widely in size but average 50-200mm in diameter. Both Turbid and Dusty Creeks became re-established very soon after the landslide, with over 30m of re-entrenchment.

As the landslide moved downslope, sediments from former flows were mobilized, indicating a continuing history of local instabilities. Lower, oversteepened slopes of the Mount Cayley complex, particularly on the western flank, are prone to small rock-avalanches in summer and mixed rock and snow avalanches in winter. Material accumulates in narrow canyons and is periodically flushed out during periods of flood by catastrophic debris flows. A fill, 15m thick, fans out over much of the lower Turbid Creek valley and forms a benchland in Squamish River Valley. Mature forest has developed atop, indicating that events over recent centuries largely have been restricted to the incised channel (Souther, 1980).

The Rubble Creek landslide in the Cheakamus Valley was of a similar nature. The 1855 landslide, with an estimated volume of 25 x $10^6 m^3$, was seemingly a response to catastrophic failure of the steep slope of ice-contacted dacite lavas (Moore and Mathews, 1978).

A large rockfall is also found in the Upper Squamish. Tree-ring evidence indicates that the event took place over 300 years ago. Debris is found on both sides of the river, suggesting that the fall temporarily may have dammed flow. A steep-sided canyon cuts the bedrock and a surface accumulation of large angular clasts remains at this point.

Finally, evidence of several avalanche trails is apparent in the upper reaches of the area, particularly upon the surface of tributary fans. These may present further localized sediment sources.

Ryder (1981) summarized landscape development in the southern Coast Mountains at three distinct spatial and temporal scales :

1. Tertiary tectonic processes : a period of tectonic processes and subaerial denudation. The resulting structural lineaments, and fragments of relict erosion surfaces, provide the overall framework within which more localized forms subsequently developed.
2. Pleistocene glacial erosion : a period of alpine glaciation and rapid, final glaciation during which valleys and mountain ridges were modified.
3. Holocene modifications : recent reworking of

glacially-derived sediments. Accumulations of fluvial sediments have been largely conditioned by the availability of glacially-modified sediment. Furthermore, this has been a period of minor modifications to valley sides, due to frost shattering, avalanches and rockfalls, in accord with local structural and lithological controls. The overall effects of Holocene denudational processes have been relatively small, especially on plutonic rocks.

3 : 4 Hydrology

The Squamish system drains an area of about 3,600km^2, of which 2,300, 950 and 330km^2 are contributed by the Squamish, Cheakamus and Mamquam Rivers respectively (Water Survey of Canada, 1973; see Figure 1.1). The hydrological records of greatest relevance to this study have been collected at the Brackendale station, located 1.6km upstream from the mouth of the Cheakamus River. Figure 3.5 shows the mean daily discharge by month for the available post-1955 data. The average monthly flow of 245cumecs masks marked seasonal variations, with a July maximum over 500cumecs and a March minimum of 92cumecs. This emphasizes the rapid rise in discharge at the time of the Spring freshet.

Flood events in the Squamish system can be divided into two basic types. Snowmelt produces large numbers of small floods in spring. In periods of mild temperature and severe rainfall such events may be quite pronounced. However, the most drastic flood events, with daily discharges in excess of 1,000cumecs, tend to occur in fall and winter (see Figure 3.6), when a sharp rise to flood peak results from rapid runoff in periods of short, intense rainfall. A plot of flood recurrence interval, for

Figure 3.5

ANNUAL HYDROGRAPH AT BRACKENDALE

(1956-1980)

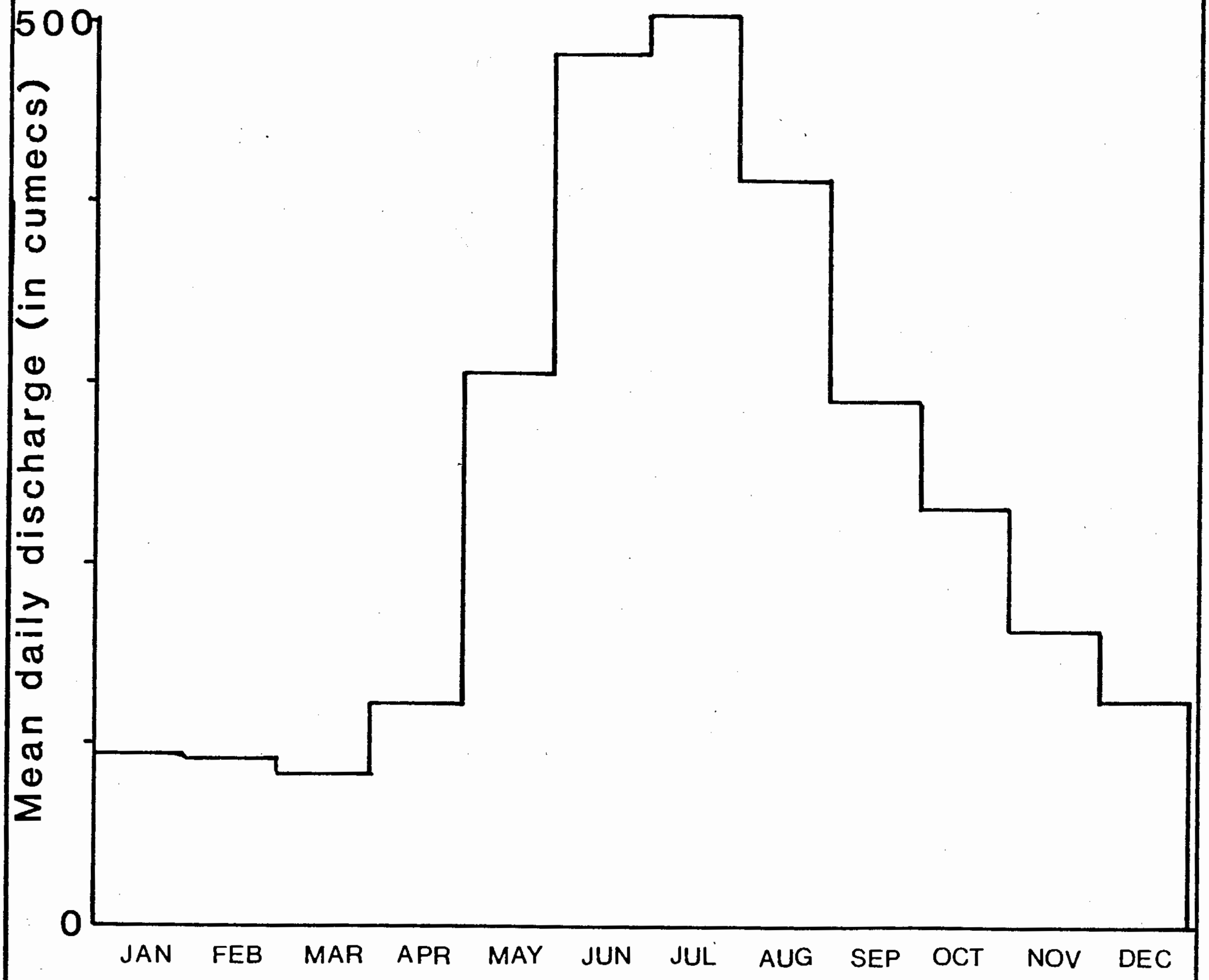
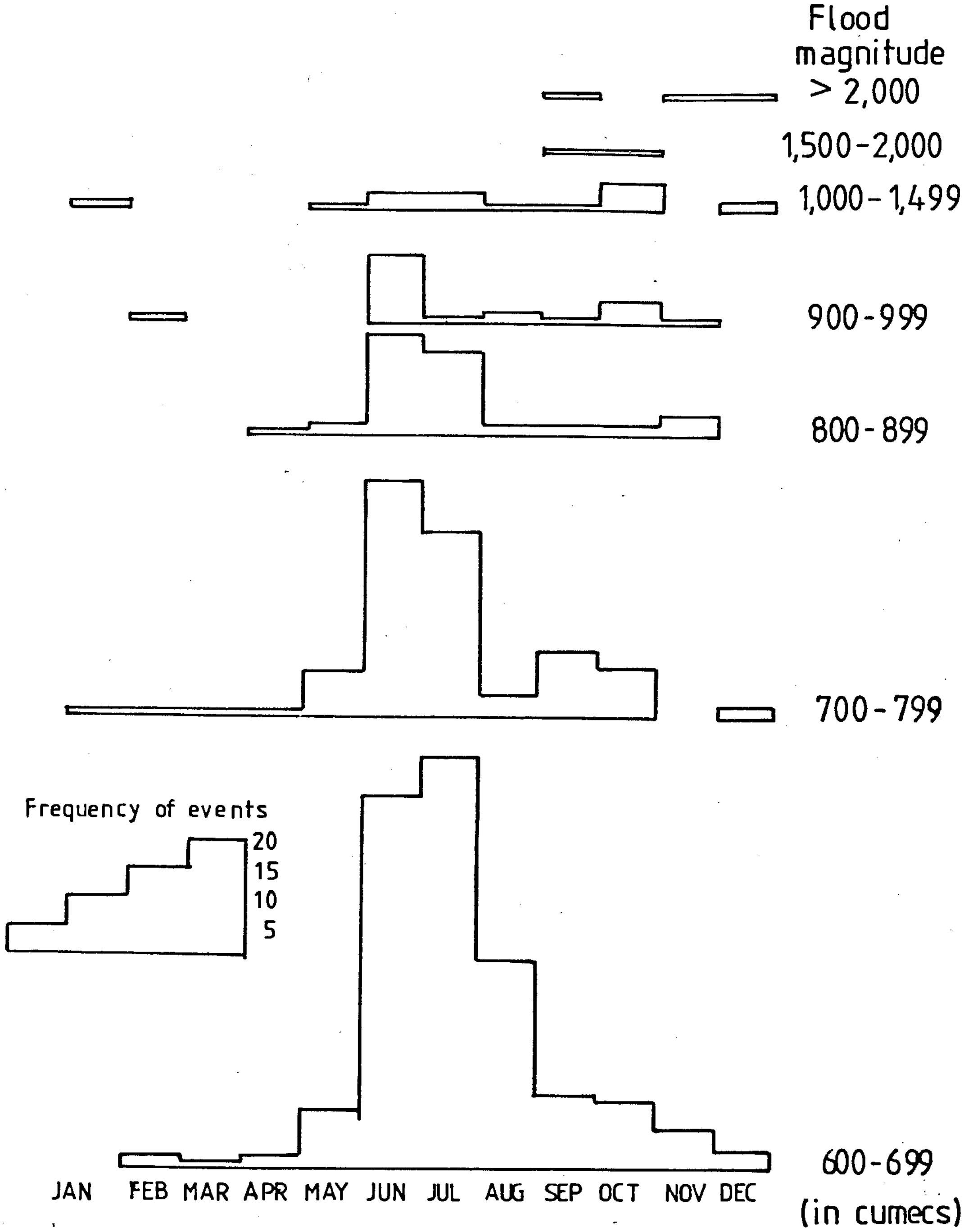


Figure 3.6

FLOOD FREQUENCY BY MONTH

AT BRACKENDALE (1956-1980)



maximum instantaneous discharges between 1958-1982, is presented in Figure 3.7.

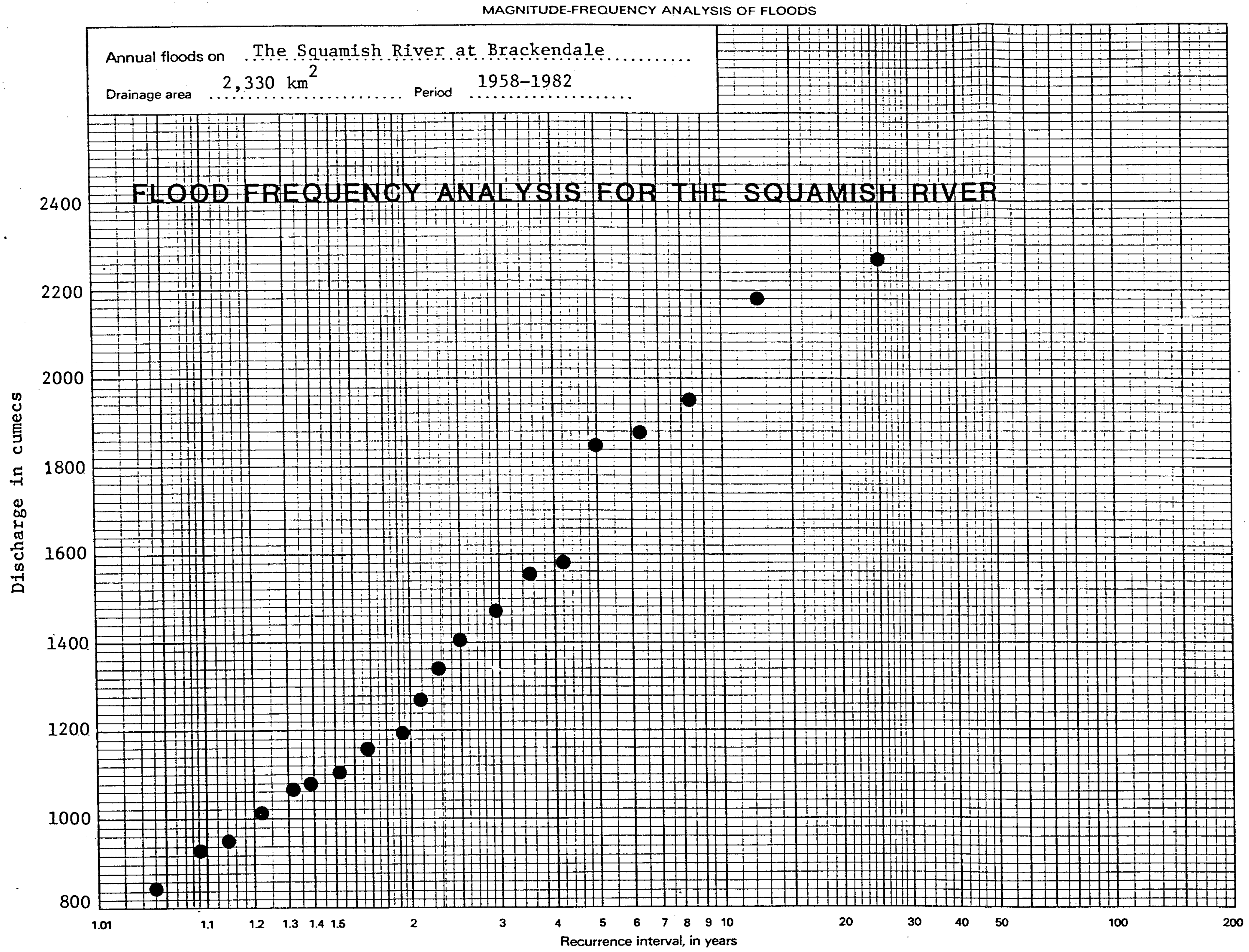
3 : 5 Biogeography

The Squamish Valley lies within the Pacific Coast Mesothermal Forest Region. The biogeoclimatic zoning of Krajina (1965) characterizes this zone as one of western and mountain hemlock, while floodplain areas exhibit a mixed forest of conifers and deciduous trees, with spruce and cedar common. In most places these are interspersed with maple, alder and cottonwood, the latter two being the primary colonizers of channel bars.

Slaymaker (1972) noted the large accumulations of sediments and logs in the Squamish River. These log jams are instrumental in gravel bar growth and affect channel form and location. The effect of vegetation in stabilizing bars is quite pronounced in the meandering section, where accumulations of finer particles permit vegetation development. In the more active river reaches vegetation is seemingly relatively transient.

Vegetation on the valley side slopes is divided altitudinally. At lower levels the subalpine forest subzone is both dense and productive. Between 900-1,000m this zone intergrades with the Pacific coastal subalpine parkland subzone, characterized by mountain hemlock. At higher elevations, above 1,500m, the alpine coastal subzone, with tundra conditions,

Figure 3.7


MAGNITUDE-FREQUENCY ANALYSIS OF FLOODS
Annual floods on The Squamish River at Brackendale
Drainage area 2,330 km^2
Period 1958-1982
FLOOD FREQUENCY ANALYSIS FOR THE SQUAMISH RIVER
Discharge in cumecs
2400
2200
2000
1800
1600
1400
1200
1000
800
1.01
1.1
1.2
1.3
1.4
1.5
2
3
4
5
6
7
8
9
10
20
30
40
50
100
200
Recurrence interval, in years

predominates.

Soils in the region are classified as ferro-humic podzols. These are highly leached, acidic, and reddish-brown in colour (Department of Environment, 1973). Organic content increases with elevation, as oxidation is retarded by increased precipitation and lower temperatures. Alluvial stream deposits have produced regosolic soils, varying to gleysolic in areas of poor drainage. Hence floodplain areas are characterized by young, fertile soils subject to periodic flooding and fluctuating water tables (Department of Environment, 1973).

Chapter 4 : Methodology and field design

In order to examine the hypothesis presented in the Introduction, methods had to employed to determine sediment order at various scales. Macro-scale sediment organization at the level of channel planform, and channel gradient are easily determined from mapping and air photographic evidence, although some field surveying was required. Determining the downstream gradation of particle sizes, however, raised many problems of field sampling of gravels. This is a highly significant question in sedimentologic analysis of gravel bed rivers. To qualify the attained results, the sampling methodology must be explicitly stated in detail.

Following a general introduction to the sampling context, this chapter reviews the various techniques used in sampling coarse gravels. The selected sampling procedure is then outlined, with particular emphasis on method, site and sample size.

4 : 1 The Sampling Context

Regardless of the topic under investigation, poor data collection techniques cannot be overcome by sophisticated analysis. Sampling designs can be either extrinsic (i.e. independent of the field of study) or intrinsic (i.e. related to the criteria being studied). A combination of random, systematic and stratified procedures is usually chosen. The aims of the selected method include :

1. to give minimal systematic or random errors,
2. to be sufficiently precise with as few measurements as possible, and
3. to be both controllable and replicable.

In essence the procedure seeks reliable conclusions about the parent population with as small an output of effort as possible.

In striving for a representative and comprehensive sample design one must decide whether to aim for a few, high-quality samples, or to compromise precision for 'reasonable' approximations and collect a large number of samples. Various pilot studies can help make this decision. As outlined by Carson (1967), the optimum sample size depends upon :

1. the degree of information wanted,
2. the degree of confidence wanted in the conclusions, and
3. the variability within the individual populations.

In sampling coarse gravels absolute precision is unattainable, and sampling methods generally entail a simple method repeated many times.

4 : 2 Review of techniques for size analysis of gravels

Data required in this study pertain to the sediment characteristics of gravels upon river bar surfaces. A sampling technique was sought which allowed reasonable estimation of sediment size and sorting while permitting evaluation of secondary issues, namely particle shape and lithologic composition.

The vast array of sediment sizes necessitates the use of a size classification which condenses the size groupings, yet still retains a meaningful degree of differentiation between sizes. The geometric system of Wentworth (1922) is the most utilized technique, herein referred to by the phi classification of Krumbein (1934).

In technical terms, sampling procedures are either volumetric or size-by-frequency in nature. These methods are not dimensionally equivalent (Kellerhals et al, 1975) and various mathematical transformations have been developed (e.g. Sahu, 1964; Kellerhals and Bray, 1971; Potter, 1979). In practice there are three suitable methods for size analysis of surface bar gravels : analysis by measurement of individual particle axes, weight analysis and photographic measures.

4 : 2 : 1 Field measurement of individual particle axes

Two alternative, yet dimensionally equivalent, methods exist, sampling on either a transect or at-a-point quadrat basis. The transect method was first proposed by Wolman (1954) and involves the following steps:

1. Isolate the sample area and establish a transect grid.
2. At a predetermined interval pick up individual stones from the surface directly beneath the grid ... i.e. beneath the toe after one or more steps (Wolman, 1954), or reaching down with eyes closed and outstretched finger (Leopold, 1970).
3. Measure the length of each a, b and c axis. In many instances the b axis alone will suffice. This is defined by the orthogonal to the longest axis in the principal axis plane (Church and Kellerhals, 1978).
4. Place each pebble into a 1/2phi size class and plot the frequency distribution, from which size characteristics can be extrapolated.

The Wolman (1954) method is quick and fairly efficient; it is a simple, reasonably reliable and easily replicable field technique when consistently applied by an individual operator. The at-a-point quadrat method follows essentially the same steps, the quadrat being placed at a predetermined or random location and particles picked up directly beneath the intersections of strings. In this way sediments are collected in both longitudinal and lateral directions.

4 : 2 : 2 Bulk sieve analysis

Sieving can be carried out in either the field or the laboratory, and size analysis often involves the combination of both. A predetermined volume, dependent upon the coarsest fraction, is collected from a designated location. The sample size recommended by the American Society for the Testing of Materials (test C136-71) is related to the size of the largest pebble by :

$$W = 0.082\ B_{max}^{0.54} ,$$

in which W is sample mass in kilograms, and B_{max} is the maximum intermediate axis in millimetres (Adams, 1979b).

Weights for each 1/2phi fraction are derived by sieving. An arbitrary cut off is defined between field and laboratory operations (generally at 8mm), and correction factors are applied to make the two sets of sieve data equivalent.

Although bulk sieve analysis is an accurate and reliable technique there are several drawbacks to its general use. The technique is extremely time consuming and, if large particles are found, the sample size soon reaches astronomical proportions if it is to be representative. For example, with a maximum intermediate axis of 300mm, a sample of over 400kg is required. Some error is found in the method, as sieving actually measures a size between the a and b axes, because particles may pass diagonally through square sieve holes. Furthermore, volumetric analysis draws samples from both the surface and subsurface populations, which are not equivalent.

One alternative, suggested by Carling and Reader (1981), is to collect a sample by core-freezing of gravels, returning the sample to the laboratory for analysis. Restraints are imposed by limiting particle size and accessibility problems for the required equipment.

4 : 2 : 3 Size analysis by photographic techniques

The use of photographs provides a very rapid method for evaluation of sediment size characteristics, but its accuracy is questionable. Having designated the sample area a quadrat frame is placed on the gravel surface, a scale placed alongside, and a photograph taken from directly above. Many samples can be collected, and replication is easy. However, as with the other techniques, the size fraction under consideration is critical. There are problems of definition for smaller gravels, while boulders impose major scaling difficulties.

Having taken the photographs two interpretive methods are available. Either all particles within the quadrat (or a fraction thereof) can be counted and their mean size derived on an areal basis (Church, 1967), or a transparent grid can be placed over the photograph and the long and short axis of each particle beneath an intersection measured. The former technique is not very accurate, and does not permit evaluation of secondary statistics. Adams (1979b) derived correction factors for the axes measured in the latter method. He determined that estimates of the mean were good, but the scatter was large for the standard deviation, and estimates of skewness and kurtosis did not show any useful accuracy.

In conclusion, application of correction factors makes photographic measures a useful addition to sampling techniques, but some practical difficulties may be encountered. Pebbles in the photographs may be partly concealed by other pebbles or fines, or they may be in shadow so that actual pebble axes are not visible. Tilting and pebble orientation may further influence the derived statistics.

Palmer and Traves (1973), in a comparison of gravel sampling methods, determined that samples collected by bulk sieve analysis and grid-by-number techniques (whether in the field or from photographs) were drawn from the same population. Smaller variations were noted, such as :

1. Values derived from the field grid-by-number technique were slightly larger than those attained by bulk sieve analysis and results from photographs, and
2. values derived from bulk sieve analysis were slightly larger than results from photographic measures for larger particles, but slightly smaller for smaller particles.

Bray (1972) concluded that the grid-by-number technique is the most acceptable manner in which to analyse a gravel surface since it is equivalent to customary bulk sieve analysis for the surface population. Results from photographs were found to be 20-40% smaller than results attained by field grid-by-number methods, and about 10% smaller than bulk sieving results.

4 : 2 : 4 Rationale for technique selection

Initial field surveillance trips in Spring, 1982 revealed a wide range of sediment sizes and depositional environments in the Squamish Valley. Hence an intrinsic and adaptive sampling design was required to provide representative data of the downstream gradation of sediment characteristics. As Bray (1982) commented, it is unlikely that a common procedure for data collection for gravel bed rivers will ever be adopted.

Data had to be collected fairly quickly, yet be sufficiently accurate to permit evaluation of secondary statistics. While sampling upon the active channel bed would be desirable it was deemed impractical, and the study was restricted to surface bar gravels.

In bulk sieve analysis samples are drawn from both surface and subsurface populations. As large samples are required, and time for data collection was limited, the technique was felt to be inappropriate for this study. The extreme coarseness, and range of sediment sizes posed major difficulties for representative and reliable sampling by photographic measures, and hence the more adaptive grid-by-number technique was selected.

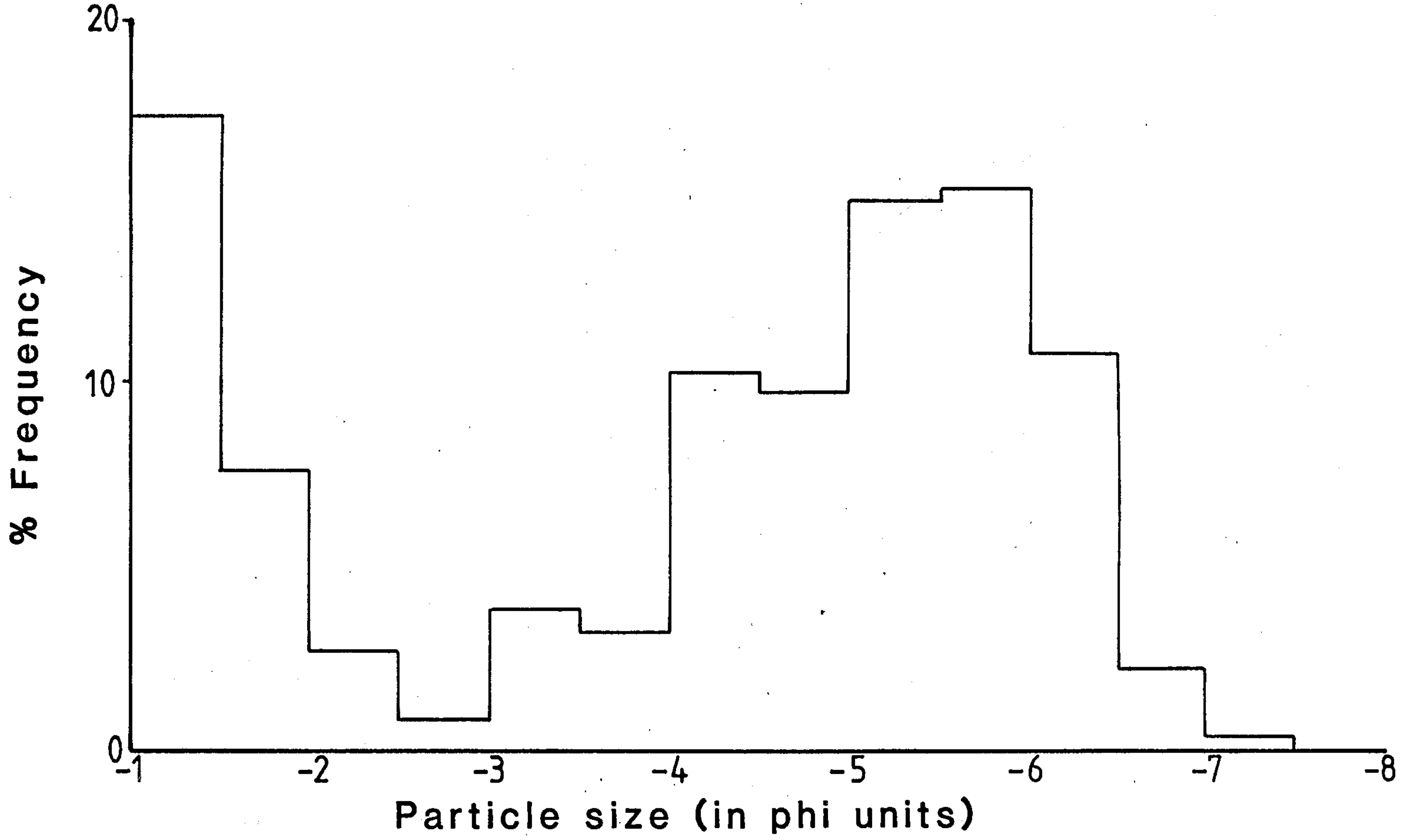
The grid-by-number technique provides the most suitable manner for dealing with large surface particles, as axes can be measured in place, and the sample interval is easily adjusted. However, limits are posed at the lower end of the size scale, due to practicalities of field measurement. Pilot studies were therefore carried out to determine the lower practical particle size limit. Four different bars were sampled by the quadrat at-a-point method during June, 1982. A size analysis frame, measuring particle b axes at 1/2phi interval was used, and samples of 400 particles taken at two or three locations (dependent upon the gravels area) upon each bar. A $1m^2$, 10 x 10 string quadrat was turned over four times in clockwise fashion at each point.

The results (Figure 4.1) indicate that less than 1% of the particles fall in the size class 5.66-8mm. Indeed, 8mm appears to be the most suitable cut-off interval within this bimodal distribution. This discontinuity is a common feature of the sedimentologic suite of gravel bed rivers, generally lying between 2-8mm. As this study concentrates upon the gravel population the size fraction larger than 8mm is of greatest relevance, although note is always made of the presence of smaller material.

Hence, sampling was restricted to currently active gravel bar surfaces, with data collection carried out by grid-by-number techniques for the size fraction greater than 8mm. The following section outlines the location of actual sample sites.

Figure 4.1

THE OVERALL SIZE DISTRIBUTION WITHIN GRAVEL LOCALES



4 : 3 Determination of sampling sites

As described in Chapter 2, various scales of sediment organization are apparent within fluvial deposits. Particle size variations may be gradual or abrupt, continuous or discrete. Three particular scales are of relevance to this study: the sample reach, the selection of sampling bars, and sample location upon bars.

Downstream changes on the Squamish River are notable in terms of channel pattern, bar type and sediment size. As Figure 3.1 shows, the study reach extends over a distance of 50km, from the Elaho-Squamish confluence to the end of the meandering section on the Squamish River. From air photo and map analysis of downstream channel changes, three distinct sampling zones were isolated and alternative sampling strategies employed in each case. It was felt that while the sampling design must be well defined, it must also be adaptive to changes in field conditions. In all cases, however, dimensionally equivalent grid-by-number methods were used.

4 : 3 : 1 Selection of sampling bars

Initial field surveillance revealed a wide variety of bar types in the study reach. The braided section is dominated by complex, compound features (exemplified in Figure 4.2), with isolated examples of unit bars. These are primarily longitudinal, lateral and diagonal types. The meandering section

Figure 4.2 An example of a complex bar

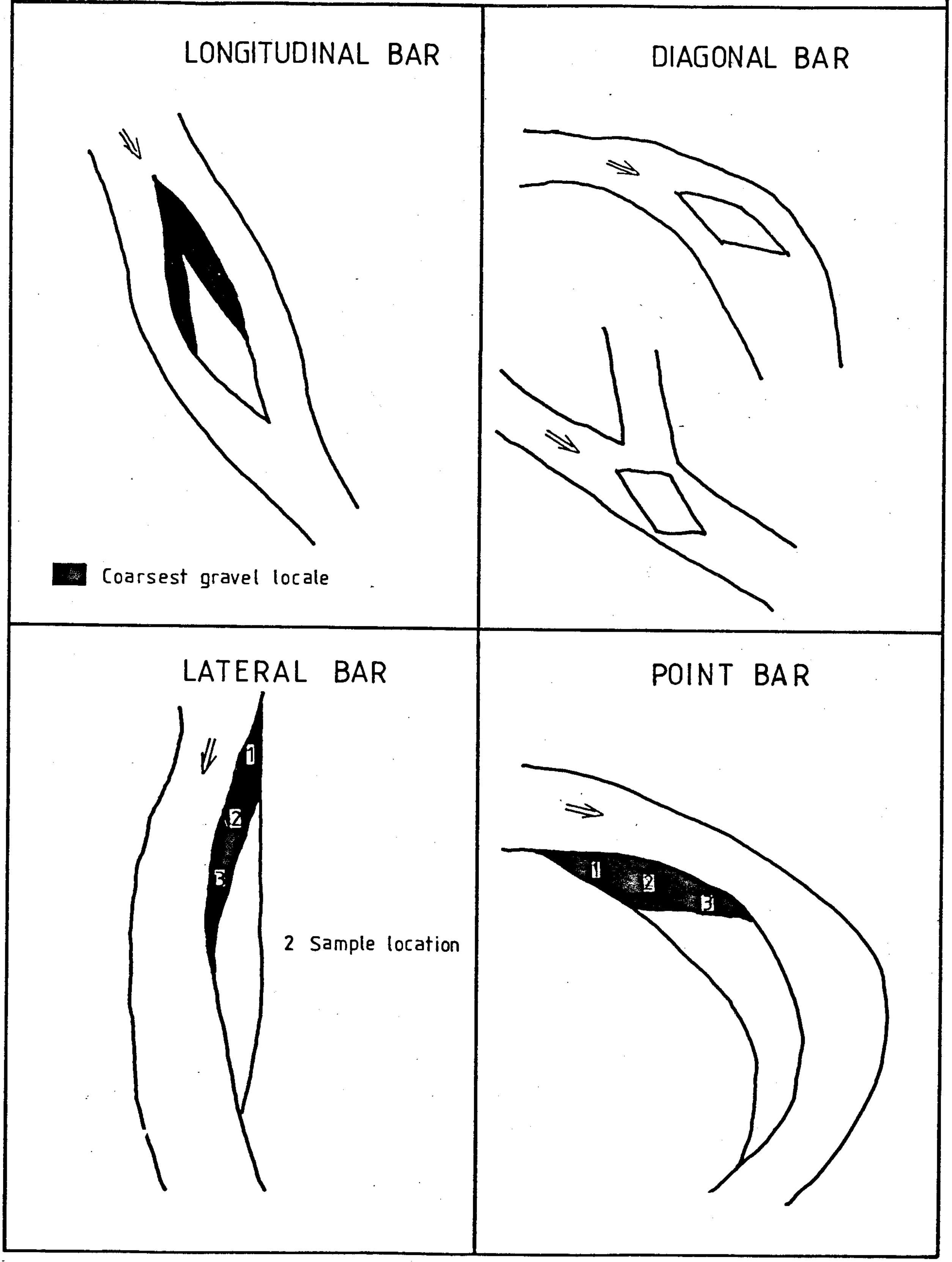
demonstrates a simple pattern of alternating point and lateral bars. A simple graphical representation of these unit bar types is given in Figure 4.3.

In reviewing the selection of sampled bars attention is drawn to Figure 3.4, which shows the field sites. The upstream section of the study reach may be viewed as the sediment source zone, influenced not only by contributions from the Upper Squamish and Elaho Rivers, but also by a series of intensively active sediment transporting tributaries. Upstream of the Squamish canyon seven bars were sampled. A major compound bar composed of well-rounded (fluvioglacial?) material, located in the Upper Squamish as the floodplain widens, provides insight into materials which may be supplied from upstream. This bar is part of an extensive accumulation of coarse gravels and reflects a confused erosional and depositional history.

A lateral bar on the Elaho River was also sampled to determine its role as a contributing source. Located immediately downstream of the Elaho canyon, this coarse gravel bar has formed as the floodplain widens, and lies alongside a large mid-channel bar.

Three small bars were sampled at the Elaho-Upper Squamish confluence. Seemingly of temporary nature, these bars are of indistinct form and are probably 'units' of a divided compound bar. Finally, samples were collected from two mid-channel bars between the Elaho junction and the Squamish canyon.

Figure 4.3 GRAVEL BAR 'TYPES'



While bars were sampled at an interval sufficient to accurately define the downstream gradation in sediment characteristics, limitations were imposed by their location and accessibility. In the canyonized reach bars are both infrequent and with limited access. Consequently only four bars were sampled in this section; three are lateral bars at tributary outlets, the fourth is a bar of point bar form, which appears to reflect a secondary flow origin rather than being associated with the main flow.

Although a general downstream trend from mid-channel through diagonal to lateral bars may be discerned in the braided section, this implies an order which is rather misleading. As samples should be collected at geomorphologically similar locations, priority listings based upon site equivalence are often drawn up (e.g. Bray, 1972; Palmer and Traves, 1973; Church and Kellerhals, 1978). In the braided section of the Squamish River it was felt that the confused sediment pattern could not be analysed by a rigorously imposed sampling design, and recourse to the constraints of 'field sense' had to be adopted. Hence samples were collected from the coarsest active gravel bar accumulations within any particular reach. Comparison of recent (1978/1980) air photographs with actual field conditions quickly demonstrated the rapidity of local-scale changes and the futility of imposing a rigid sampling design within such a dynamically adjusting system.

In accordance with this strategy, samples were collected from thirty-one bars at a fairly regular downstream interval within this 25km stretch, during Fall, 1982. In many instances it was impossible to classify the bar type other than to describe it as a 'complex, compound feature'.

Determination of sample sites was much simpler in the meandering section, which was defined to be the reach downstream of the Ashlu confluence. Point and lateral bars consistently alternate downstream, and each major active gravel accumulation (a total of eighteen sites) was sampled during Summer, 1982. These bars become increasingly more widely spaced downstream, and the final sample was collected at the northern limit of the Cheakamus Indian Reserve. The section of the Squamish River downstream of this point is characterized by a well-developed, almost straight channel, with few active gravel bars prior to the confluence with the Cheakamus River.

In summary, while there are pronounced downstream changes in channel pattern on the Squamish River, the associated changes in bar type are not so straightforward. Hence, sampling procedures have been designed which are adaptive to local field conditions. Bars in the upstream reaches are seen to be supply oriented, braided channel bars exhibit complex forms as they are continually reworked, and bars in the meandering section alternate between lateral and point bars. In total sixty bars were sampled (see Figure 3.4).

4 : 3 : 2 Sample location upon each bar

In accordance with the policy of sampling the coarsest gravel bar in any section, the coarsest locale upon each selected bar was sampled. This enabled downstream consistency in sampling. As noted in Chapter 2, the coarsest locale tends to be in the proximal zones of bars, usually at the upstream end.

4 : 3 : 3 Specifics of the sampling method

As the degree of particle size organization varies with channel planform, it was decided to adopt slightly different sampling strategies for each section. Dimensionally equivalent grid-by-number techniques were used throughout.

In the braided and upstream section the Wolman (1954) transect method was employed. This is the most suitable technique when sampling a wide range of particle sizes, as it smooths out local scale variations upon the gravel surface, and provides a summary estimate of sediment characteristics within the coarse gravel locale.

Individual particles were sampled at a regular interval along a tape positioned at the water's edge (see Figure 4.4). The spacing of sampled particles was determined by the size of the coarsest fraction. To draw an independent sample, avoiding complications of imbrication, at least two pebbles should separate selected particles. In most instances a 1/2m interval

Figure 4.4 Tape position on the bar surface

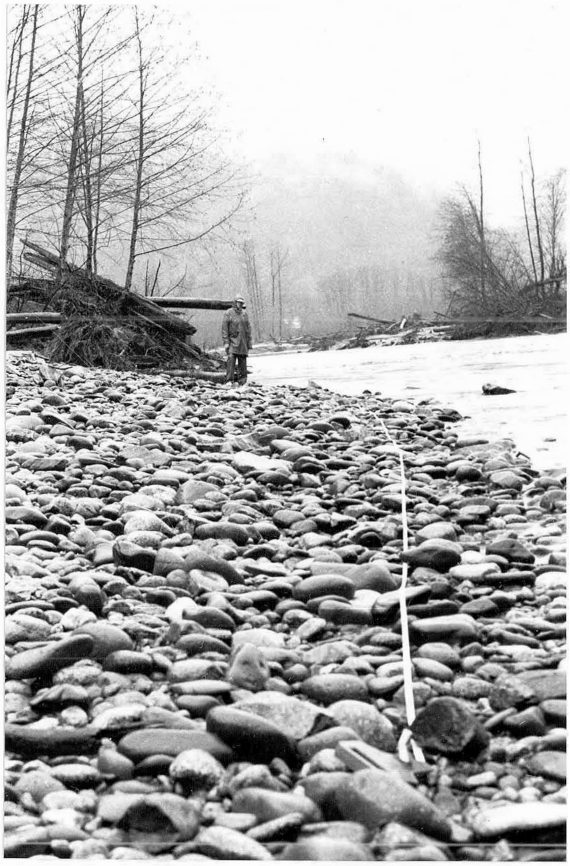
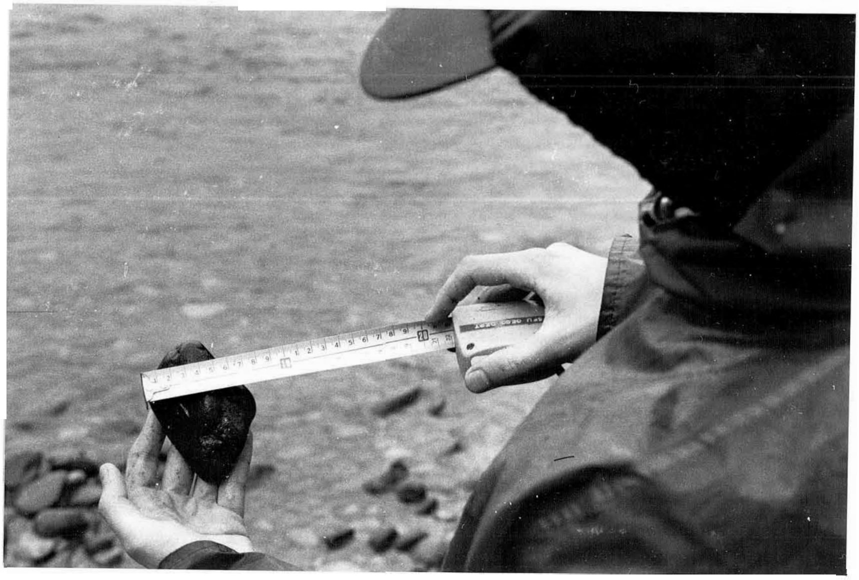


Figure 4.5 Measurement of the particle 'b' axis



was sufficient, but in some cases this had to be increased to 1m.

To test the representativeness of the transect sample parallel samples of 100 particles were collected from four bars of widely differing particle sizes. Samples were collected along a water's edge and 1m inshore transects. If a particle smaller than 8mm was at a sample interval its presence was noted, but the nearest larger particle was selected and recorded. The b axis of each particle was measured in mm (Figure 4.5). This was then converted to 1/2phi frequency and cumulative frequency curves plotted. Student's t-test revealed no significant differences between the two samples at the 5% confidence level (see Table 4.1). However, the water's edge samples were consistently slightly coarser and better sorted than the samples from 1m inshore (see Figure 4.6). In summary, while sample designs based upon flow levels are conceptually compelling, local scale differences may be so pronounced that downstream consistency of sampling position cannot be attained. To minimize such variation samples were collected over as short a time interval as possible, during low flow conditions in Fall, 1982.

Isolation of locales by size fraction is relatively straightforward for bars in meandering reaches. However, little has been written about size variation within the gravels locale, and the surface size distribution has not been described. When working in the field, size differentiation within the smaller sized gravels population is not very easy, as judgements of both

Table 4.1

Analysis of transect position using Student's t-test

Comparison of 100particle transect samples collected at water's edge and 1m inshore locations; mean and standard deviation calculated from ½phi frequency data and presented in phi units

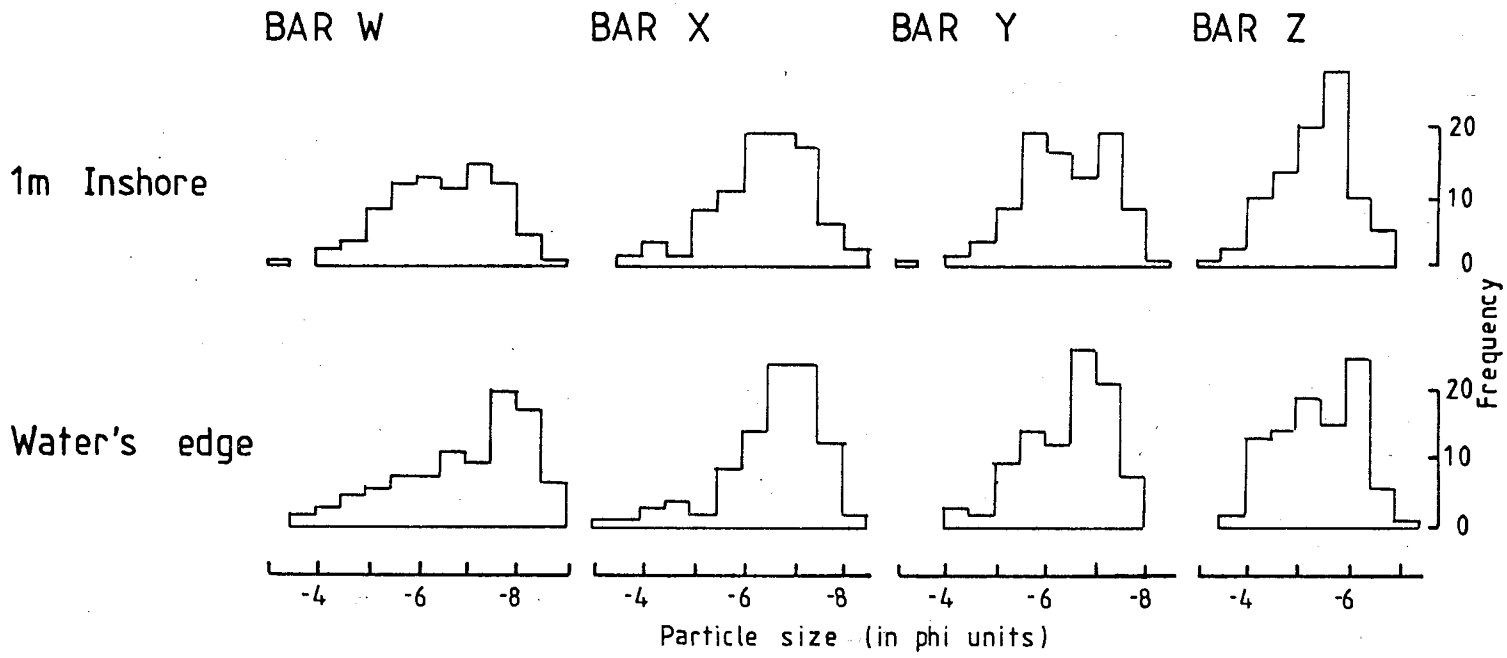
	BAR W		BAR X		BAR Y		BAR Z	
	W.E.	1m I	W.E.	1m I	W.E.	1m I	W.E.	1m I
Mean	-6.975	-6.890	-6.620	-6.400	-6.460	-6.360	-5.455	-5.355
Standard Deviation	1.293	1.257	0.976	0.973	0.852	0.937	0.810	0.753
Student's t	0.471		1.596		0.790		0.905	

W.E. = water's edge; 1m I = 1m inshore samples

There are 198 degrees of freedom. As t is less than 1.96, the 95% confidence interval, in all cases, there is no statistically significant difference in mean values between the two sample locations.

Figure 4.6

HISTOGRAMS COMPARING 2 x 100 TRANSECT SAMPLES



maximum particle size and the sediment mix have to be made. Consequently, problems were faced in determining sample location.

The essential principle adopted throughout the sampling design was to sample the coarsest gravel fraction. Hence, when sampling on the lateral and point bars of the meandering section it was decided to collect samples at three 'representative' locations, rather than use the summatory transect method at some predetermined location. Samples were collected from the centre of the active gravels locale, as upstream, midstream and downstream locations (see Figure 4.3).

The quadrat at-a-point method was selected, and a $1m^2$, 10 x 10 string quadrat used. Particles were selected from directly beneath string intersections (Figure 4.7), and b axis sizes were recorded at 1/2phi interval by the size analysis frame (Figure 4.8). To be equivalent with the measurement of individual axes described for the transect method, circular holes were cut in the size analysis frame. At each point the quadrat was turned over four times. The presence of particles smaller than 8mm was noted, but measurements not taken. Particles covering two or more intersections were included only once. Ideally the quadrat frame should be larger under such circumstances, as two pebbles should separate all sampled particles. Samples were collected during a one week period of moderate flow during Summer, 1982.

The results of the three sample locations were compared, but no consistent trends were apparent for either bar type or

Figure 4.7 Particle selection for the quadrat method

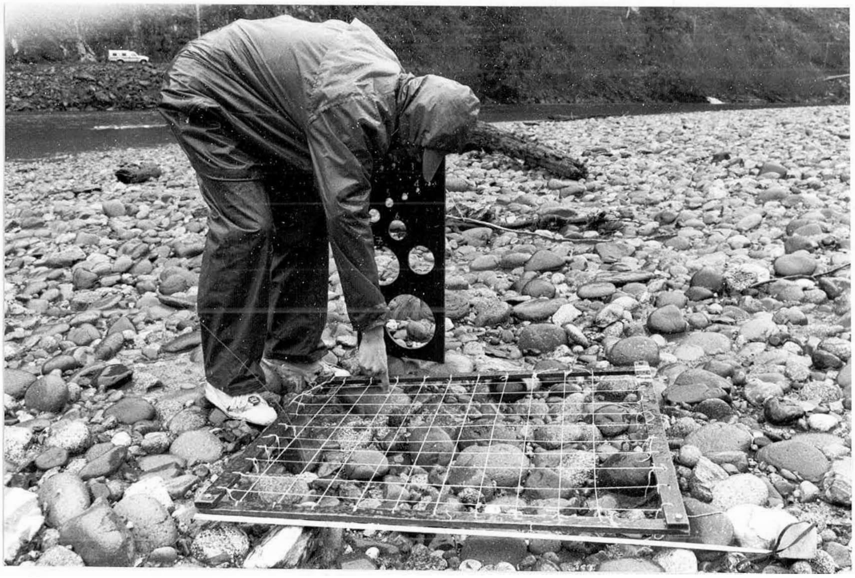


Figure 4.8 Measurement of the 'b' axis in the size analysis frame

position downstream (Table 4.2). Hence it was concluded that internal variation within the active gravel locale of lateral and point bars on the Squamish River was essentially random.

The equivalence of the two sampling methods used was assessed by carrying out both techniques upon four bars in the meandering section during March, 1983. Student's t-test revealed significant differences at the 1% level of confidence for all quadrat positions on one of the bars, while results for the other three bars were far more consistent, with significant differences restricted to two downstream quadrat positions, one at the 1% and the other at the 5% confidence level (see Table 4.3)

In general the transect method appears to give a slightly higher estimate of mean size than is obtained by sampling at-a-point. This seemingly results from the inclusion of a larger proportion of finer gravels (from 8-32mm) in the at-a-point samples (as shown in Figure 4.9), whereas water's edge transect samples are more likely to have been winnowed. As the closest approximation to results obtained by transect methods is attained by using the coarsest at-a-point sample, this study has been restricted to analysis of the coarsest of the three quadrat samples. Of these, eight were collected at upstream locations, five at midstream locations and five at downstream locations. Comparison of coarser grain size statistics (D84, D90, D95) for the transect and the coarsest at-a-point samples reveals a strong degree of equivalence (Table

Table 4.2

Comparison of sampling positions on bars in the meandering section
(Squamish River pilot study, July, 1982)

Samples collected from central locations at upstream, middle and downstream sites in the active gravel locale. Data presented by ½phi frequency.

Bar	Bar	Sample	Particle size in phi units											Standard
No.	Type	location	-3	-3½	-4	-4½	-5	-5½	-6	-6½	-7	-7½	Mean	Deviation
43	Point	Upstream	5	2	8	8	14	20	17	22	3	1	5.69	1.03
		Middle		1	10	14	15	27	21	8	4		5.61	0.81
		Downstream		7	13	29	29	17	2	3			5.02	0.66
44	Point	Upstream		1	5	8	21	19	18	18	7	3	5.91	0.88
		Middle			3	5	18	25	22	12	12	2	6.02	0.79
		Downstream		1	6	12	15	17	27	12	8	1	5.84	0.86
45	Side	Upstream		6	20	20	19	24	7	4	1		5.13	0.78
		Middle	1	6	17	17	19	21	13	5			5.19	0.82
		Downstream	4	11	19	22	14	20	3	6	1		4.94	0.89
46	Point	Upstream	2			10	9	28	25	20	4		5.94	0.76
		Middle	1	2	15	14	15	18	19	13	3		5.51	0.91
		Downstream	1	2	4	10	22	22	22	14	3		5.71	0.79
47	Side	Upstream		3	7	12	11	24	22	13	8		5.77	0.88
		Middle		4	8	10	15	26	22	12	3		5.65	0.83
		Downstream	1	3	9	15	29	17	14	9	3		5.44	0.84
48	Side	Upstream	1	1	10	14	28	37	6	3			5.34	0.64
		Middle		1	3	10	19	30	27	7	2	1	5.75	0.69
		Downstream		1	5	15	17	25	24	8	2	2	5.69	0.79
49	Point	Upstream	4	7	16	13	18	16	16	10			5.23	0.97
		Middle	5	6	19	12	21	20	15	2	1		5.11	0.91
		Downstream	7	8	13	13	32	20	5				4.94	0.80
50	Point	Upstream	1	4	7	8	26	27	19	8			5.51	0.77
		Middle	2	3	8	16	20	20	21	10			5.47	0.84
		Downstream	5	5	9	12	18	17	27	9			5.41	0.94
51	Point	Upstream	2	2	11	21	28	14	13	6	3		5.32	0.84
		Middle	2	10	20	11	13	15	14	1			5.23	1.03
		Downstream	1	3	14	13	12	14	18	21	3	1	5.63	1.01
52	Point	Upstream	6	7	19	24	23	11	13	2			4.95	0.85
		Middle	2	6	11	26	28	23	3	1			5.04	0.68
		Downstream	4	6	12	19	28	18	12	1			5.09	0.79

Table 4.2(cont.)

Bar No.	Bar Type	Sample location	-3	-3½	-4	-4½	-5	-5½	-6	-6½	-7	-7½	Mean	Standard Deviation
			Particle size in phi units											
53	Side	Upstream	3	5	13	23	30	19	10				5.07	0.72
		Middle	1	6	13	27	27	15	10	1			5.07	0.71
		Downstream	1	6	16	18	24	18	13	4			5.17	0.80
54	Side	Upstream			6	3	13	21	38	12	1		5.90	0.67
		Middle		1	5	3	17	32	33	8	2		5.81	0.65
		Downstream	1	1	7	7	17	31	27	9	1		5.69	0.74
55	Point	Upstream	2	2	5	13	17	24	20	15	2		5.65	0.86
		Middle		6	13	12	19	17	26	5	2		5.43	0.87
		Downstream	1	2	8	16	21	31	13	8			5.45	0.75
56	Side	Upstream	1	2	7	9	31	28	15	6			5.47	0.70
		Middle	2	2	4	6	33	25	19	7			5.54	0.73
		Downstream		1	6	7	20	32	21	11	1		5.70	0.70
57	Side	Upstream		2	6	17	17	26	21	9	2		5.59	0.77
		Middle		7	5	13	29	23	13	5	3		5.41	0.81
		Downstream		2	6	15	20	31	14	10	2		5.57	0.75
58	Point	Upstream	1	1	8	17	21	25	17	8	2		5.51	0.79
		Middle	5	6	15	19	15	21	10	9			5.16	0.94
		Downstream	3	11	24	17	12	20	12	1			4.94	0.87
59	Side	Upstream	1	1	15	11	34	20	13	5	1		5.33	0.75
		Middle	3	2	5	18	21	26	17	7	1		5.45	0.81
		Downstream	2	7	14	21	18	21	11	5			5.15	0.84
60	Point	Upstream	2	6	11	24	24	25	7	1			5.10	0.72
		Middle	1	4	14	19	26	29	5	1			5.14	0.68
		Downstream	2	3	16	11	31	30	6	1			5.18	0.70

Table 4.3

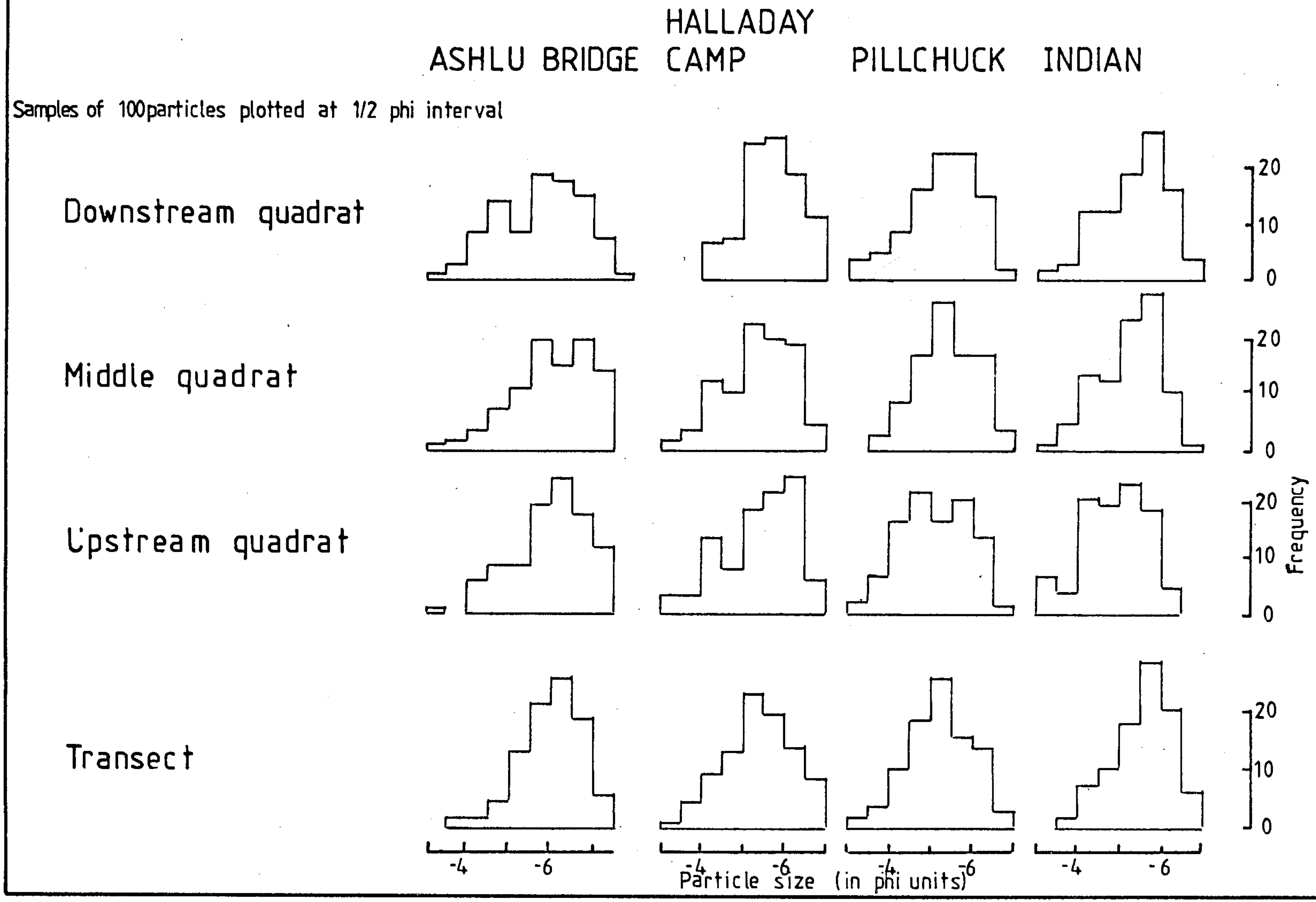
Statistical comparison of transect and quadrat methods
(Squamish River pilot study, Spring 1983)

Samples of 100 particles analysed by ½phi frequency using Student's t-test. Data presented in phi units.

Bar	Sampling Method	Mean	Standard Deviation	Student's t	Statistical significance (198 d.f.)
Ashlu Bridge	Transect	-5.990	0.747		
	Upstream Quadrat	-5.985	0.880	0.043	No
	Middle Quadrat	-6.000	0.936	0.084	No
	Downstream Quadrat	-5.730	0.992	2.094	Yes, at 5%
Halladay Camp	Transect	-5.375	0.827		
	Upstream Quadrat	-5.415	0.876	0.332	No
	Middle Quadrat	-5.345	0.831	0.256	No
	Downstream Quadrat	-5.655	0.684	2.609	Yes, at 1%
Pillchuck	Transect	-5.220	0.768		
	Upstream Quadrat	-5.087	0.807	1.194	No
	Middle Quadrat	-5.357	0.722	1.300	No
	Downstream Quadrat	-5.230	0.818	0.089	No
Indian	Transect	-5.565	0.713		
	Upstream Quadrat	-4.885	0.775	6.457	Yes, at 1%
	Middle Quadrat	-5.225	0.733	3.325	Yes, at 1%
	Downstream Quadrat	-5.340	0.799	2.101	Yes, at 1%

COMPARISON OF TRANSECT AND QUADRAT SAMPLING METHODS

Figure 4.9



Samples of 100particles plotted at 1/2 phi interval

4.4).

In summary, while the two methods are not completely statistically equivalent, any differences can be explained in terms of either local circumstances or inclusion of finer constituents within the gravel size fraction. Since the quadrat at-a-point method overestimates particle sizes for the bars of the meandering section and, as average sizes are smaller in this reach, any differences are insignificant in analysis of the overall downstream trend. Although samples were collected at different times of the year using these different methods, it was felt that this adaptive sampling framework most appropriately evaluated the downstream variation in particle size.

4 : 3 : 4 Sample size analysis

Despite its importance, there are few published guidelines for sample size analysis. In aiming to derive reliable statistical estimators of population characteristics from a minimum of field data, each study tends to develop its own procedure. While the sample aims to be 'acceptably' reliable, attempting to collect a larger sample may necessitate sampling within adjoining sedimentologic zones (i.e. the degree of internal variability may increase as the areal basis for sampling increases). Both sample size and the degree of internal variability are examined in this section. Transect and

Table 4.4

Comparison of graphic estimates of D84, D90 and D95 for transects and the coarsest quadrat sample

Samples of 100particles recorded at ½phi interval. Presented in mm.

Bar	Sample method and position	D84	D90	D95
Ashlu Bridge	Transect	99.0	109.9	130.7
	Middle Quadrat	128.0	135.3	145.0
Halladay Camp	Transect	75.1	87.4	97.7
	Downstream Quadrat	81.6	93.7	101.8
Pillchuck	Transect	66.3	73.5	83.3
	Middle Quadrat	70.0	75.1	82.1
Indian	Transect	75.1	83.3	94.4
	Downstream Quadrat	69.6	78.8	93.1

at-a-point methods are considered separately.

Transect methods

Church and Kellerhals (1978) determined the relative precision of the mean (the range within which the true mean probably lies, expressed as a percentage of the sample mean) by the standard statistical measure :

$I = \pm (t_{\alpha} / \sqrt{N}) (S/\bar{x})$, where

t_{α} = value of Student's t for the desired confidence interval,

N = sample size, and

$S/\bar{x}$ = coefficient of variation of the sample.

In a pilot study of eight bars on the Squamish River such analysis revealed average estimates of ±5.3% and ±4% for samples of 50 particles at the 1 and 5% confidence levels. Little variation was noted for any of the bars, the worst cases being ±6.74% and ±5.13% respectively. For the samples of 100 particles average estimates improved to within ±3.8% and ±2.9% (Table 4.5). Derivation of D50, D65 and D90 statistics for the 50 and 100 particle samples determined that the level of agreement between sample sizes is fairly good throughout the coarser fraction, with estimates being very similar in all cases (see Figure 4.10).

To examine internal variability within transect samples, 100 particle samples from the eight pilot study bars were split into 2 x 50 samples. The two samples were shown to be fairly

Table 4.5

The relative precision of 50particle and 100particle transect samples

100particle transect samples divided into 2 X 50particle samples

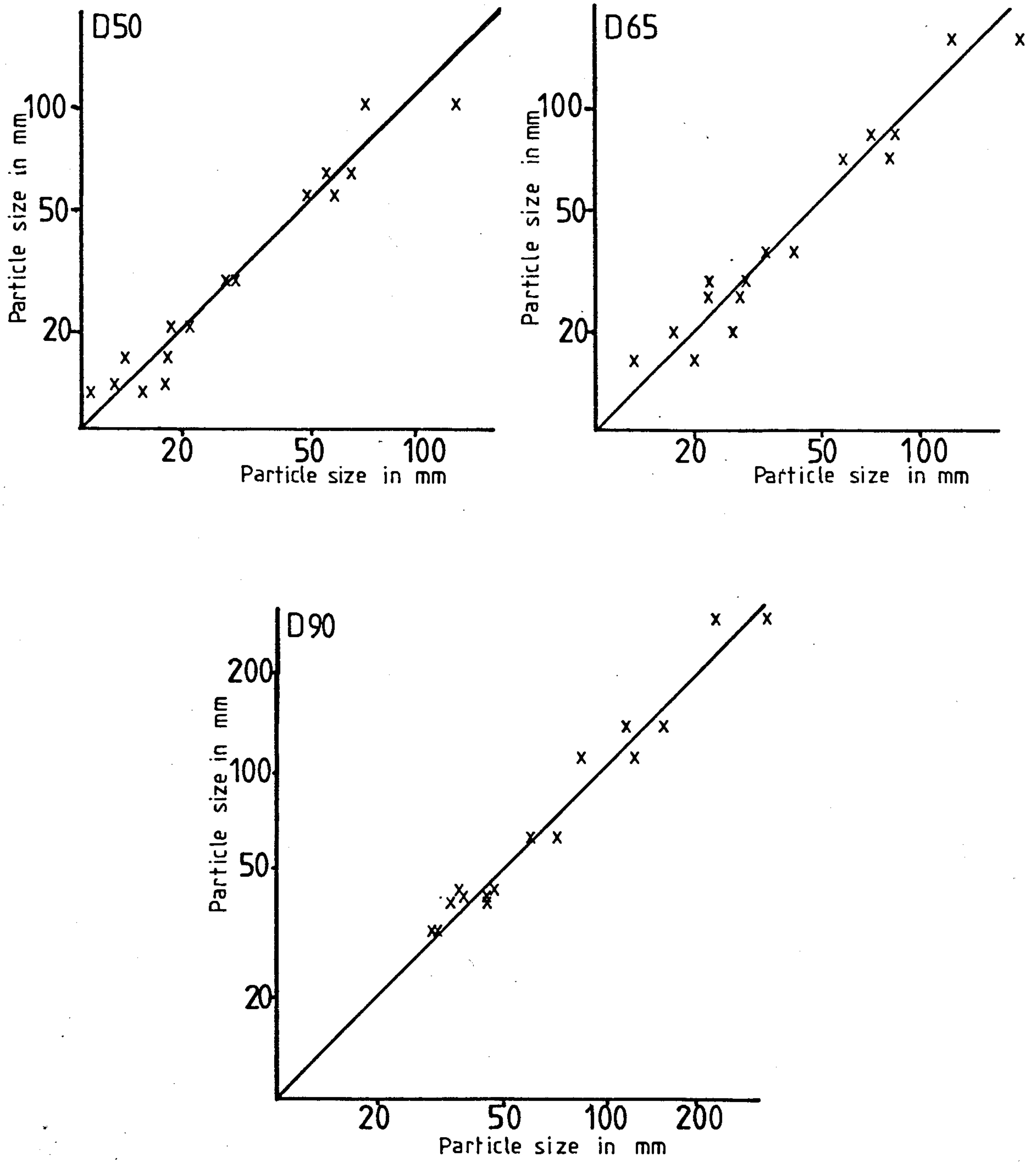
Bar	Sample	Coefficient of Variation	5% Relative Precision	1% Relative Precision
W	1st 50	0.178	± 4.93%	± 6.48%
	2nd 50	0.185	± 5.13%	± 6.74%
	Total	0.185	± 3.63%	± 4.77%
X	1st 50	0.157	± 4.35%	± 5.72%
	2nd 50	0.140	± 3.88%	± 5.10%
	Total	0.147	± 2.88%	± 3.79%
Y	1st 50	0.125	± 3.46%	± 4.55%
	2nd 50	0.136	± 3.77%	± 4.95%
	Total	0.132	± 2.59%	± 3.40%
Z	1st 50	0.148	± 4.10%	± 5.39%
	2nd 50	0.151	± 4.19%	± 5.50%
	Total	0.148	± 2.90%	± 3.81%
Ashlu Bridge	1st 50	0.127	± 3.52%	± 4.63%
	2nd 50	0.125	± 3.46%	± 4.55%
	Total	0.125	± 2.45%	± 3.22%
Halladay Camp	1st 50	0.169	± 4.68%	± 6.16%
	2nd 50	0.137	± 3.80%	± 4.99%
	Total	0.154	± 3.02%	± 3.97%
Pillchuck	1st 50	0.136	± 3.77%	± 4.95%
	2nd 50	0.153	± 4.24%	± 5.57%
	Total	0.147	± 2.88%	± 3.79%
Indian	1st 50	0.117	± 3.24%	± 4.26%
	2nd 50	0.140	± 3.88%	± 5.10%
	Total	0.128	± 2.51%	± 3.30%

	50samples	100samples
Average relative precision at 5%	± 4.026%	± 2.86%
Average relative precision at 1%	± 5.291%	± 3.75%

Figure 4.10

COMPARISON OF COARSE GRAINED PARAMETERS

2 x 50 transect samples



consistent, as t-test results revealed significant differences in only two cases, one at the 1% and one at the 5% confidence level (Table 4.6). In no case does the ratio of variance differ significantly from 1.00 at the 1% level, but one sample differs at the 5% confidence level. Finally, these eight transect samples of 100 particles were split into 4 x 25 samples, and the variability of each 1/2phi frequency distribution was analysed by the non-parametric Kolmogorov Smirnov test. A significant difference is noted in only one case, this at the 5% level (Table 4.7), indicating that a certain degree of consistency prevails over the length of the transect samples.

Quadrat at-a-point methods

To determine the smallest representative sample size for the at-a-point method the $1m^2$, 10 x 10 string quadrat was turned over four times at each of ten locations (from four different bars), giving samples of 400 particles. Particles beneath two intersections were included only once, as re-inclusion artificially raises the mean particle size. Particles smaller than 8mm were not included in the analysis, and larger particles were measured at 1/2phi interval by the size analysis frame.

Analysis of variance was used to test whether it was necessary to turn the quadrat over four times at each sample location, or whether one positioning would suffice. In four of the ten cases a significant difference (at the 95% confidence

Table 4.6

Statistical comparison of 2 x 50particle transect samples drawn from the same gravel locale

Data presented in phi units

Bar	Mean 1st 50	 2nd 50	Standard deviation 1st 50	 2nd 50	Student's t	Significance (98 d.f.)
W	-6.74	-7.17	1.197	1.330	1.699	no
X	-6.62	-6.62	1.039	0.930	-	
Y	-6.63	-6.29	0.830	0.856	2.016	5%
Z	-5.51	-5.40	0.816	0.816	0.674	no
Ashlu Bridge	-5.98	-6.00	0.757	0.751	0.133	no
Halladay Camp	-5.44	-5.31	0.920	0.726	0.784	no
Pillchuck	-5.40	-5.04	0.737	0.770	2.642	1%
Indian	-5.50	-5.63	0.641	0.786	0.906	no

Table 4.7

Analysis of internal variability along transect samples using the Kolmogorov-Smirnov test

Cumulative frequencies of pilot study transect samples calculated at ½phi interval for the 100particle samples divided into 4 x 25 samples.

	Cumulative frequency by ½phi interval												Max.	
Bar	-3	-3½	-4	-4½	-5	-5½	-6	-6½	-7	-7½	-8	-8½	Diff.	Sig?
W														
1st 25		1	2	4	5	8	10	13	17	22	24	25	8	no
2nd 25			1	2	3	6	7	12	15	21	24	25		
3rd 25				1	4	5	8	10	12	18	23	25		
4th 25		1	2	3	4	5	7	9	10	14	22	25		
X														
1st 25	1	1	1	2	2	6	10	19	21	24	25		8	no
2nd 25		1	1	3	3	3	8	14	19	24	25			
3rd 25			2	3	4	6	8	11	22	25				
4th 25			1	1	2	5	9	16	23	25				
Y														
1st 25				1	3	8	11	15	22	25			7	no
2nd 25					3	5	9	14	21	25				
3rd 25			2	2	5	9	13	21	25					
4th 25			1	2	4	8	10	20	24	25				
Z														
1st 25		1	5	6	10	16	23	24	25				6	no
2nd 25			4	7	12	16	25							
3rd 25		1	6	12	14	17	22	25						
4th 25			1	6	15	18	23	25						
Ashlu Bridge														
1st 25			1	3	9	13	21	25					11	yes, at 5%
2nd 25		1	1	1	5	10	13	24	25					
3rd 25				1	1	7	16	21	25					
4th 25		1	2	4	8	16	24	25						
Halladay Camp														
1st 25		3	4	5	12	17	23	25					8	no
2nd 25	1	2	6	7	11	19	21	25						
3rd 25		1	5	13	19	22	23	25						
4th 25			1	5	13	18	24	25						
Pillchuck														
1st 25	1	2	3	8	16	19	23	25					9	no
2nd 25			2	5	11	20	25							
3rd 25	1	2	7	12	20	23	25							
4th 25		2	5	12	18	20	24	25						
Indian														
1st 25			2	3	7	19	24	25					8	no
2nd 25			3	8	13	22	24	25						
3rd 25		1	3	6	11	16	21	25						
4th 25		1	2	4	9	14	24	25						

level) was noted between the four positions (Table 4.8). This indicates the high degree of local scale variability, and suggests that samples should be collected over at least $4m^2$.

To examine the minimum acceptable sample size particles were systematically drawn from each of the four positions, and both mean and standard deviation determined following the successive addition of four particles. Graphs plotting estimates of mean and standard deviation against sample size appear to stabilize for samples of between 80 and 100 particles (an example is shown in Figure 4.11). While statistically significant differences were apparent for the samples of 80 particles, no discernible differences were noted for the samples of 100 particles. Consequently particles were measured in the field at alternate string intersections giving a sample of 25 particles for each of the four quadrat positions. For each particle smaller than 8mm, alternative particles were collected systematically from intervening rows and columns.

4 : 3 : 5 Particle shape and lithologic variation

As considered to be of secondary importance in this study both particle shape and lithologic composition were merely 'added' to the aformentioned sampling designs. Particle shapes may be extremely complex, and are usually assessed in one of two ways :

1. quantitative derivations from measurements of a, b and c

Table 4.8

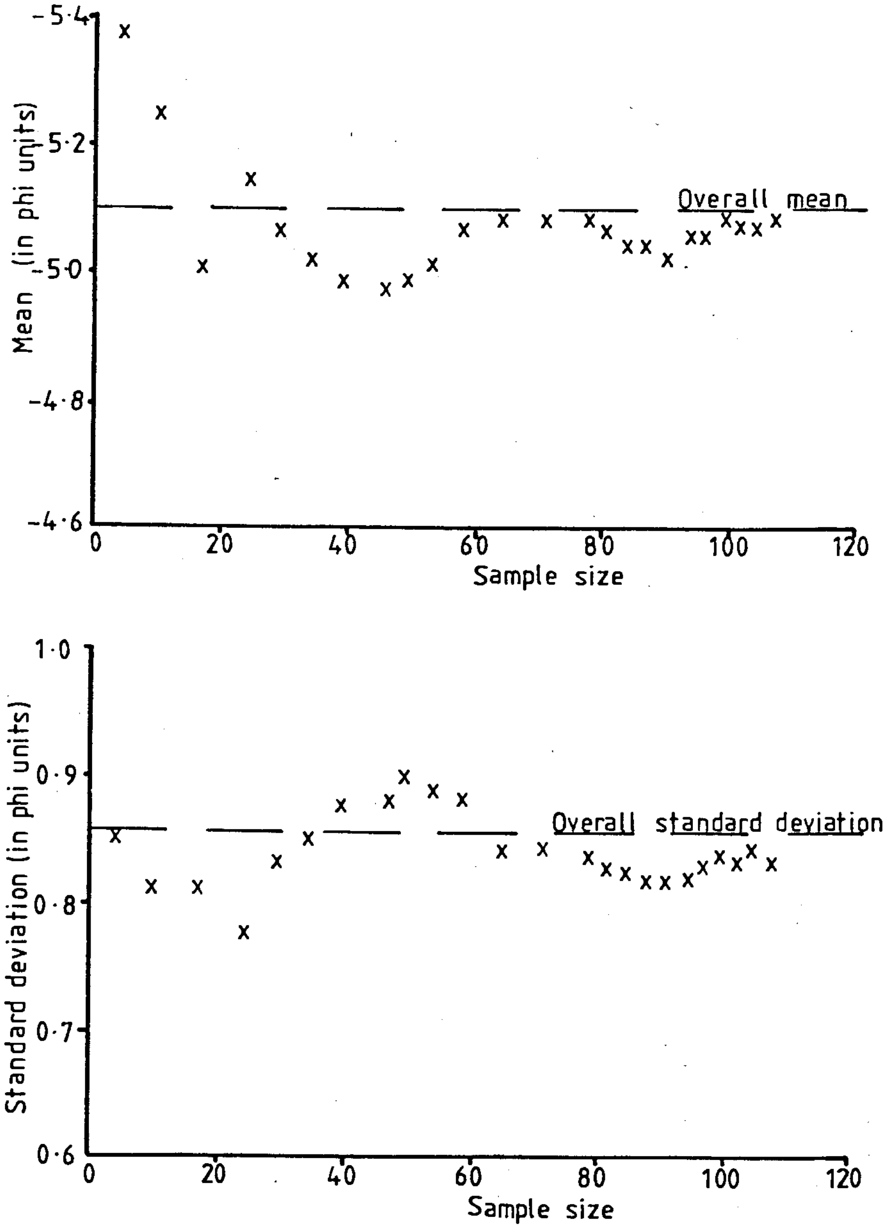
Statistical testing of the significance of quadrat positioning using Analysis of Variance

Squamish River pilot study, June 1982. 4 x 100 quadrat samples collected using the size analysis frame at ½phi interval.

Bar	Type	Sample position	ANOVA Source	Sum of squares	df	Estimate of variance	F ratio	Sig?
R	Side	Upstream	Total	280.8066	327			
			Between	1.1484	3	0.3828		
			Within	259.6501	324	0.8039	0.4762	no
		Middle	Total	220.6680	284			
			Between	0.5039	3	0.1680		
			Within	220.1541	281	0.7863	0.2136	no
		Downstream	Total	206.2031	280			
			Between	2.7969	3	0.9323		
			Within	203.4063	277	0.7370	1.2650	no
S	Point	Upstream	Total	142.7617	265			
			Between	2.4063	3	0.8021		
			Within	140.3555	262	0.5378	1.4915	no
		Downstream	Total	133.1641	240			
			Between	4.3789	3	1.4596		
			Within	128.7852	237	0.5457	2.6748	yes
T	Point	Upstream	Total	240.4883	269			
			Between	15.6328	3	5.2109		
			Within	214.8555	266	0.8108	6.4271	yes
		Middle	Total	290.5469	318			
			Between	0.4047	3	0.1016		
			Within	290.2422	315	0.9243	0.1099	no
		Downstream	Total	245.7227	297			
			Between	9.9509	3	3.3203		
			Within	235.7517	294	0.8045	4.1264	yes
U	Side	Upstream	Total	206.9375	287			
			Between	5.1250	3	1.7083		
			Within	201.8125	284	0.7131	2.3956	no
		Downstream	Total	168.9375	256			
			Between	6.6289	3	2.2096		
			Within	162.3086	253	0.6441	3.4307	yes

Figure 4.11

SAMPLE SIZE ANALYSIS



axes, and

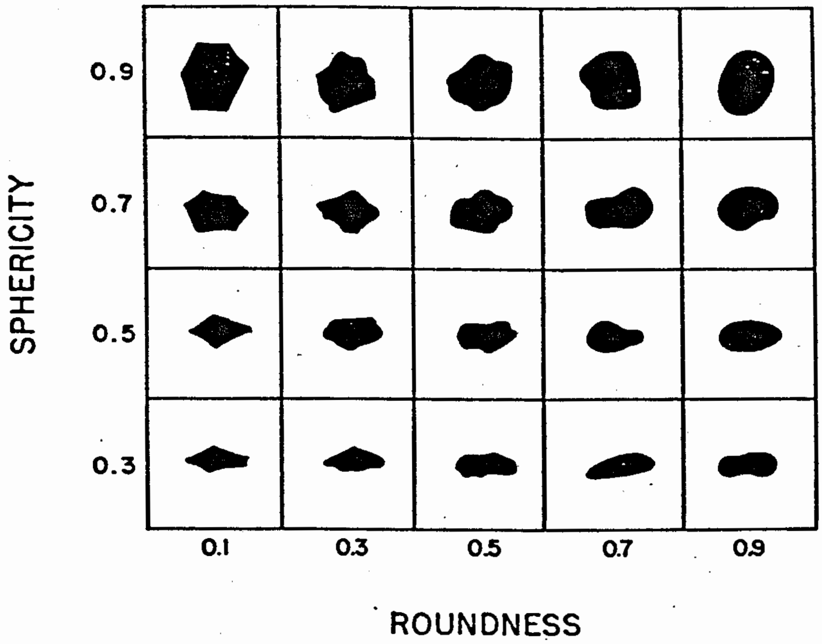
2. field comparison of selected particles with various characteristic 'types'.

As this study focused upon measurement of b axes only, the latter method was selected and both roundness and sphericity were estimated by comparing sampled particles with the silhouette 'type' images (Figure 4.12) redesigned by Krumbein and Sloss (1963, 111) from the original half-tones of Powers (1953). Using this method, Folk (1955) found little operator variance for sphericity, but commented that differences may be quite marked for roundness. To maintain consistency all samples were collected by the same operator.

As described in Chapter 3, complex lithological variations are found in the Squamish Valley. To avoid complication, and in response to time limitations, a simple differentiation of compositional types was made between plutonic and volcanic rocks. For the transect method all 100 particles were analysed in terms of shape and lithology, while for the at-a-point method the first quadrat position (i.e. 25 particles) provided a summary of these characteristics for the meandering reach bars.

Figure 4.12

Silhouette images of particle shape



(Krumbein & Sloss, 1963, 111)

4 : 4 Summary of sampling techniques employed

Kellerhals and Bray (1971) list five major difficulties in gravel sampling :

1. lateral and longitudinal variations in bed material composition,
2. time variations,
3. vertical variations,
4. wide bimodal size variations, and
5. use of non-equivalent sampling procedures.

In selection of the most appropriate sampling technique all the above factors must be considered. Points 1, 4 and 5 have been largely resolved by procedural arrangements, which sufficiently ensure controllability and replicability.

Lateral and longitudinal variations have been accounted for by the adaptive qualities of the design, as samples were consistently drawn from the coarsest active gravel locale. Surface transect methods were employed in the braided section, where local size variations were pronounced, while at-a-point methods were used in the meandering section in an attempt to describe internal variations within the gravel locales.

The wide bimodal gap in the size distribution has effectively been acknowledged but ignored. Sampling was restricted to particles with b axes greater than 8mm, although the presence of smaller particles was noted.

The issue of using non-equivalent sampling procedures did not arise, as both transect and at-a-point methods fall into the dimensionless grid-by-number category of Kellerhals et al (1975). Controversial issues, such as the lower size limit and counting of particles which fall beneath two intersections only once, have been treated consistently.

Time and vertical variations present more substantial changes which confound issues such as controllability and replicability. Time variations may be significant at a variety of scales, and samples were therefore collected over as short a time interval as was practically possible, in all cases attempting to ensure that flow levels were similar.

Vertical variations have essentially been avoided, as the sampling was restricted to the surface population. Consistency of method ensures that the difficulties postulated by Kellerhals and Bray (1971) are minimized but, when encountered, are equally distributed.

In conclusion, the wide range of sediment sizes makes taking representative photographs impossible, while bulk sieving is clearly impractical. Hence, measurement of the b axis of individual particles has been selected as the most appropriate technique for this study. Whether to sample at-a-point or by transect methods was determined by channel morphology, and the associated sedimentologic order of the gravel bars. The former method was used on the point and lateral bars of the meandering section, while the latter method was used for the more disturbed bars upstream. Sample location was oriented to the coarsest unit within the active gravels locale. Step-by-step summaries of the two sampling procedures are presented in Tables 4.9 and 4.10 and examples of field data sheets are presented in Appendix 1.

Table 4.9

Summary of transect method used in braided and upstream sections

1) Isolate the study reach, dividing the section into units for sampling. In this study the main sampling requirement was that sufficient samples be collected for the downstream gradation of particle characteristics to be fairly well defined.
2) Walk into the designated sampling unit, and locate the coarsest active gravel bar.
3) Place the transect tape along the water's edge within the coarsest gravels locale.
4) Assess the coarsest particle size, and determine the sampling interval allowing two particles between selected individual pebbles.
5) At a regular interval (usually ½m or 1m) pick up the particle directly beneath the tape, and record the b axis in mm.
6) Determine whether the particle is plutonic or volcanic in nature.
7) Assess particle shape by comparison with the silhouette image.
8) If particles less than 8mm in diameter are found at the sample location, make note of such and take the nearest particle greater than 8mm.
9) Continue this process until a sample of 100 particles has been obtained.

Table 4.10

Summary of Quadrat at-a-point method used in meandering section

1) Locate gravel bar accumulations from air photographs.
2) In the field determine the limits of the active gravel locale at the bar surface, and locate the sample points along a central axis, with equal distances between upstream, middle and downstream samples.
3) At each sample point randomly throw the $1m^2$, 10 x 10 string quadrat to the bar surface.
4) At alternate string intersections pick up individual particles.
5) Record the particle size on a frequency table by placing the pebble into a size analysis frame divided at ½phi interval. Note particle shape in comparison to the silhouette image, and record lithology on separate tables.
6) If particles smaller than 8mm are encountered, note their presence, and collect alternative particles from intervening rows and columns until a sample of 25 stones has been collected.
7) Upon completion of the first quadrat position, flip the quadrat over in clockwise fashion, repeating the size analysis only. Collect 25 stones, and repeat for two further positions of the quadrat completing a $4m^2$ square. Hence a sample of 100 particles is obtained from each quadrat at-a-point sample site.

Chapter 5 : Results and statistical summary

5 : 1 Graphic presentation of results

The basic choice in derivation of grain size statistics is between graphic measures and measures of moments (Folk, 1965; 1966). In this study all statistics have been derived from graphic probability plots, using the methods proposed by Folk and Ward (1957). Swan et al (1978) concluded that two possible sources of error in grain size statistical parameters are :

1. grouping of data into size classes, often truncating distributions, and
2. application of graphic statistical measures, defined in terms of a normal distribution, to distributions which are non-normal.

In response to the first consideration, the Squamish data have been artificially truncated at 8mm, for reasons described in Chapter 4. The standard phi size classificatory system has been applied throughout. Approximations to normal distributions are confirmed by the linear nature of all probability plots, and the fact that 89% of kurtosis values lie in the narrow range between 0.71 and 1.19.

Various size parameters derived from graphic probability plots are presented in Appendix 2. Graphic expressions of both simple and summary statistics of the downstream transitions in particle characteristics are presented in this section.

5 : 1 : 1 1/2phi frequency data

Figure 5.1 shows the 1/2phi frequency histograms for all sampled bars, presented in downstream manner. All transect data and the coarsest quadrat samples are included. The figure demonstrates a fairly continuous decrease in particle size downstream. Three major units can be isolated, in accordance with the noted trends in channel pattern.

The first eight bars of the upstream section show a pronounced decline in the frequency of occurrence of the size class above 256mm, while the interval from 64-256mm is maintained fairly consistently throughout. Hence, reduction in particle size can be attributed to the reduction of the very coarsest fraction.

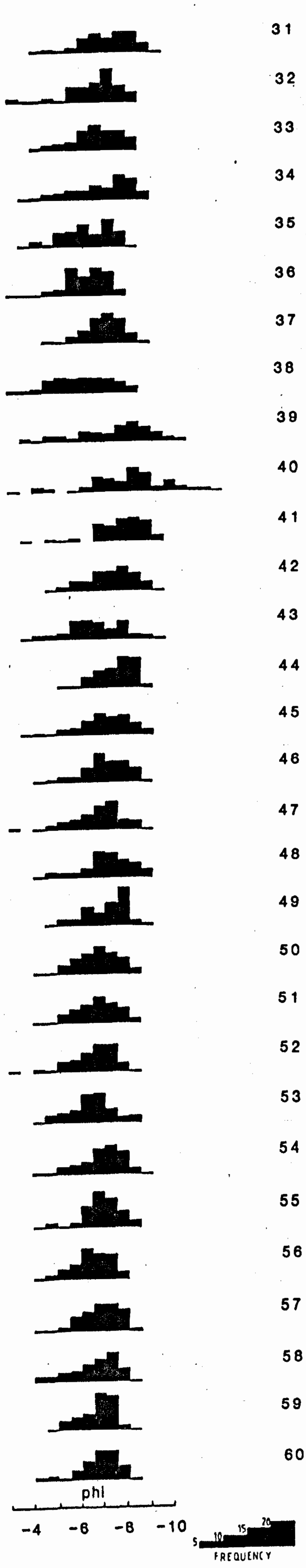
The source regions at the head of the braided section (bars 9 and 10, at the outlet of tributaries fed by landslide debris), are characterized by extreme ranges of particle sizes. These very poorly sorted materials reflect the proximity to source. They represent the coarsest size fraction found in the study reach. Largely composed of shattered volcanics, these deposits are prone to rapid disintegration, both in situ and with distance downstream. As large numbers of fragments and flakes are produced, the range of sediment sizes is extremely large.

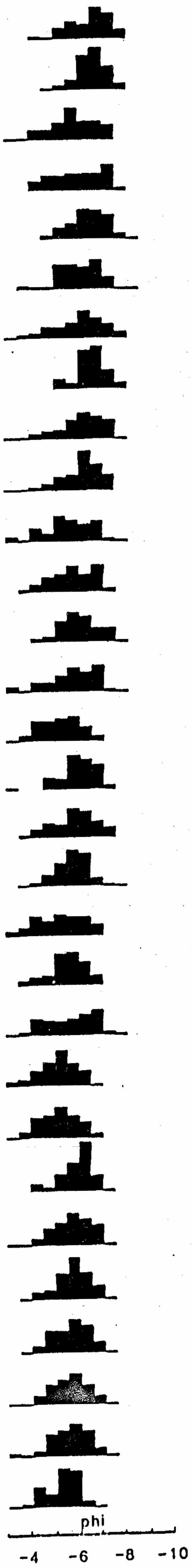
Downstream of this braided input, size fractions above 128mm demonstrate a regular decrease in their proportion of the gravel population. The size fraction from 64-128mm is

SIZE FREQUENCY HISTOGRAMS AT 1/2PHI INTERVAL FOR ALL BARS STUDIED

Figure 5.1

Bar number	Distance from Squamish port	Bar type	Bar number	Distance from Squamish port	Bar type
1	70.9	lateral	31	50.0	complex
2	69.6	longitudinal	32	49.2	point
3	69.1	lateral	33	48.8	point
4	68.9	complex	34	48.4	lateral
5	68.6	complex	35	48.2	lateral
6	67.8	longitudinal	36	47.7	complex
7	66.9	longitudinal	37	47.2	longitudinal
8	64.8	lateral	38	46.5	diagonal
9	64.3	point	39	46.1	lateral
10	62.4	lateral	40	43.5	lateral
11	61.9	lateral	41	41.8	point
12	60.6	lateral	42	40.9	lateral
13	58.7	complex	43	37.9	point
14	58.7	lateral	44	37.9	point
15	58.5	complex	45	37.4	lateral
16	58.2	complex	46	37.0	point
17	57.7	complex	47	36.4	lateral
18	57.1	longitudinal	48	35.4	lateral
19	56.5	longitudinal	49	34.9	point
20	56.3	lateral	50	34.1	point
21	54.0	complex	51	33.6	point
22	53.8	longitudinal	52	32.7	lateral
23	53.5	complex	53	31.7	lateral
24	53.0	complex	54	30.5	lateral
25	51.7	complex	55	29.0	point
26	51.5	complex	56	26.9	lateral
27	51.2	lateral	57	24.8	lateral
28	50.5	longitudinal	58	24.3	point
29	50.2	complex	59	23.4	lateral
30	50.0	complex	60	22.9	point





consistently maintained as the modal group, although the proportion of sizes smaller than 64mm increases in the downstream direction. The bars of the meandering section demonstrate a fairly wide distribution in modal groups, although a general tendency for sizes to decrease downstream is once more apparent. In most cases the modal class is smaller than 64mm.

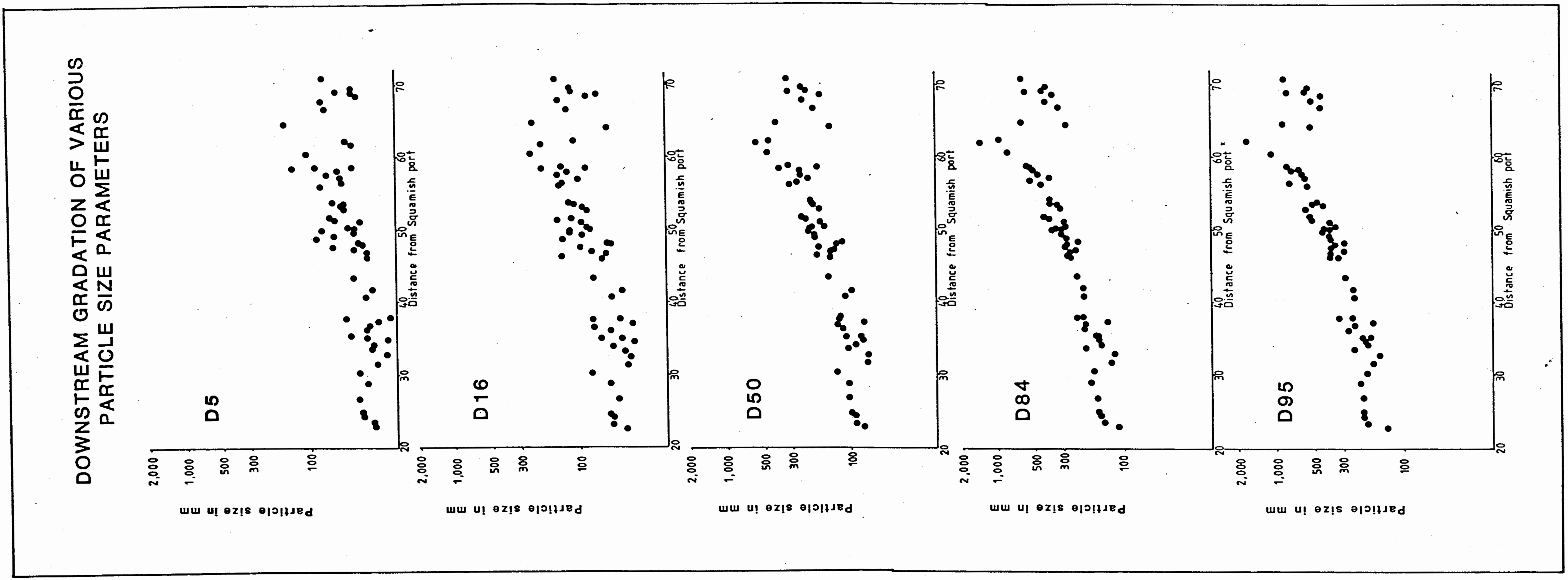
5 : 1 : 2 Graphic percentile data

The downstream trends of various percentile values are presented semi-logarithmically in Figure 5.2. Distances are given from Squamish port, in kilometres. As noted for the frequency histograms, channel pattern appears to dominate trends in the data. However, effects are somewhat variable for the different percentile values.

The patterns of downstream gradation in Figure 5.2 can be divided into three types. The smaller particle size parameters (D5 and D16) vary little downstream, although there is a general tendency for the proportion of finer particles to increase in the meandering reach. Lowest D5 values were recorded on bars at the head of the braided section, where coarse sediments overlie the smaller size fraction.

D50 values demonstrate the closest approximation to Sternberg's principle. The fairly smooth downstream trend does show some imbalances, especially at the head of the braided section (km62.5) where a coarse sediment input has been noted.

Figure 5.2


DOWNSTREAM GRADATION OF VARIOUS
PARTICLE SIZE PARAMETERS
D5
D16
D50
D84
D95
Particle size in mm
2,000
1,000
500
300
100
Distance from Squamish port
20
30
40
50
60
70

The reach downstream of the canyon shows a near-linear relationship (on the semi-logarithmic axes).

The coarsest gravel fraction percentiles (D84 and D95) demonstrate rather different patterns. This was to be expected as the size frequency histograms (Figure 5.1) indicated a sharp downstream decline in the proportion of coarser gravels, while the central proportion of the size range exhibited more gradational change and lower values were locally variable. Downstream changes in the coarsest fraction demonstrate a disturbed and exaggerated gradational decline. Upstream sections of the study reach have widely variable upper percentile values. In the braided section a rapid and smooth downstream particle size decline is apparent. This does not extend through the meandering section. A different linear gradation is found, with markedly reduced steepness (i.e. the coefficient of size reduction is far smaller).

Considering the manner of data collection, particularly regarding the truncation of the particle size range, determination of 'lines of best fit' for all curves is of limited relevance, as they have little physical meaning. Fortunately trends can be distinguished easily from Figure 5.2, and it is apparent that downstream trends are inconsistent for lower percentile values, smoothly gradational for median values, and closely accord with channel planform, in a linear sense, for coarser percentiles.

5 : 1 : 3 Summary statistical measures

Figure 5.3 presents downstream changes in graphic mean and graphic standard deviation (or sorting index). As the coarser samples also demonstrate the widest ranges of particle sizes, the two graphs show a close direct relationship. Hence, the apparent larger standard deviations in the braided reach can be attributed as much to larger mean particle sizes as to channel position.

The trends of the graphs in Figure 5.3 once more reflect the influence of channel pattern. The dominating effect of the Turbid Creek tributary at 62.5km, and the abrupt nature of subsequent downstream changes, are confirmed. The braided reach adopts the form of a coarser sediment unit. The downstream limit, at 35km, marks the beginning of the single channel, meandering reach.

Downstream changes in skewness (Figure 5.4) and kurtosis (Figure 5.5) demonstrate no discernible downstream trend, and in both cases little variation is noted. Virtually all skewness values lie between 0.1 and 0.4, indicating slightly positively skewed distributions, as is apparent from the bias of the frequency histograms to larger particle sizes. Most kurtosis values lie between 0.8 and 1.2, indicating mesokurtic distributions (Folk and Ward, 1957). Hence, while samples approximate to normal distributions, the degree of 'peakedness' is not pronounced.

Figure 5.3

DOWNSTREAM GRADATION OF MEAN AND STANDARD DEVIATION

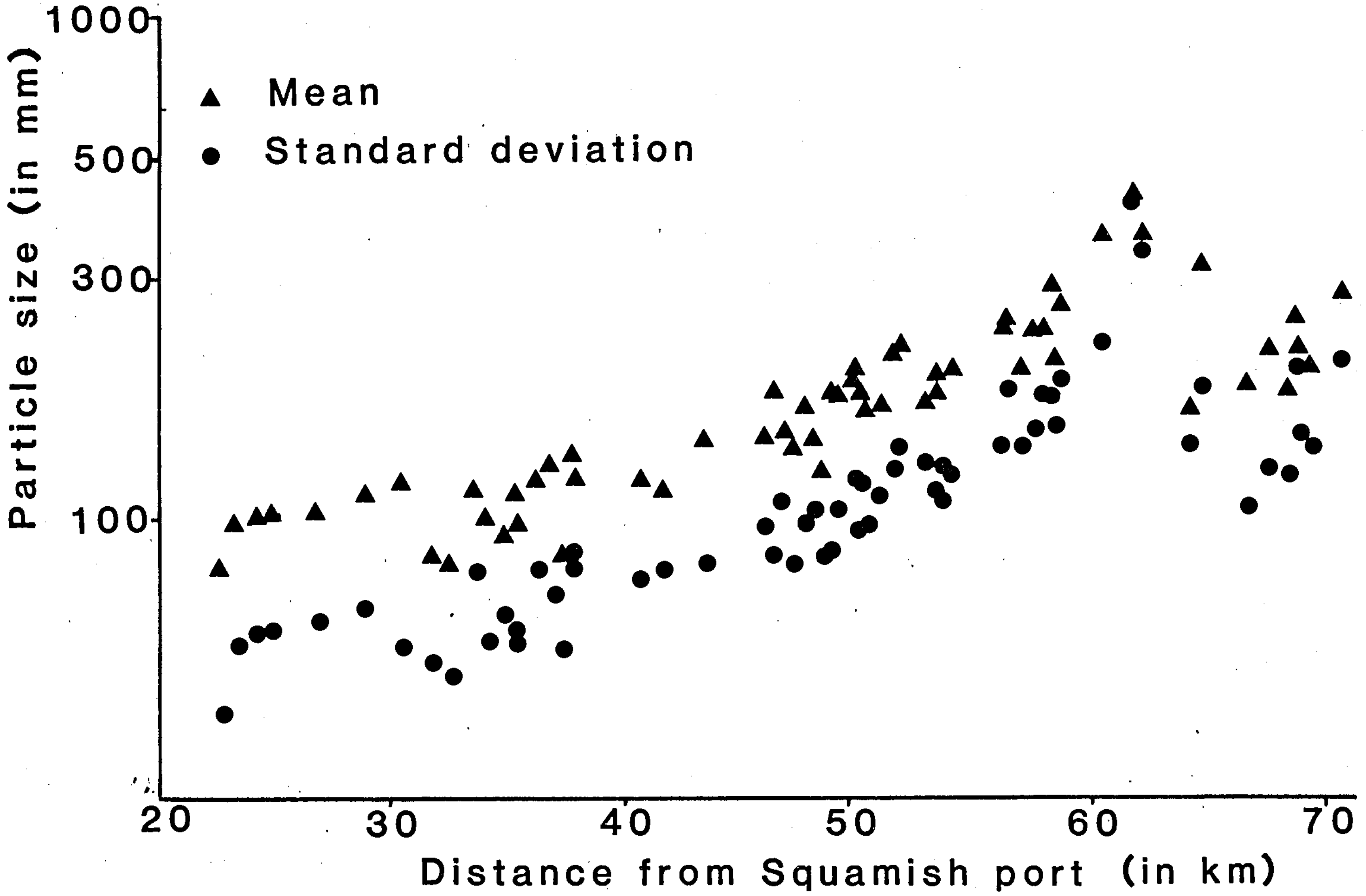


Figure 5.4

DOWNSTREAM GRADATION IN GRAPHIC SKEWNESS

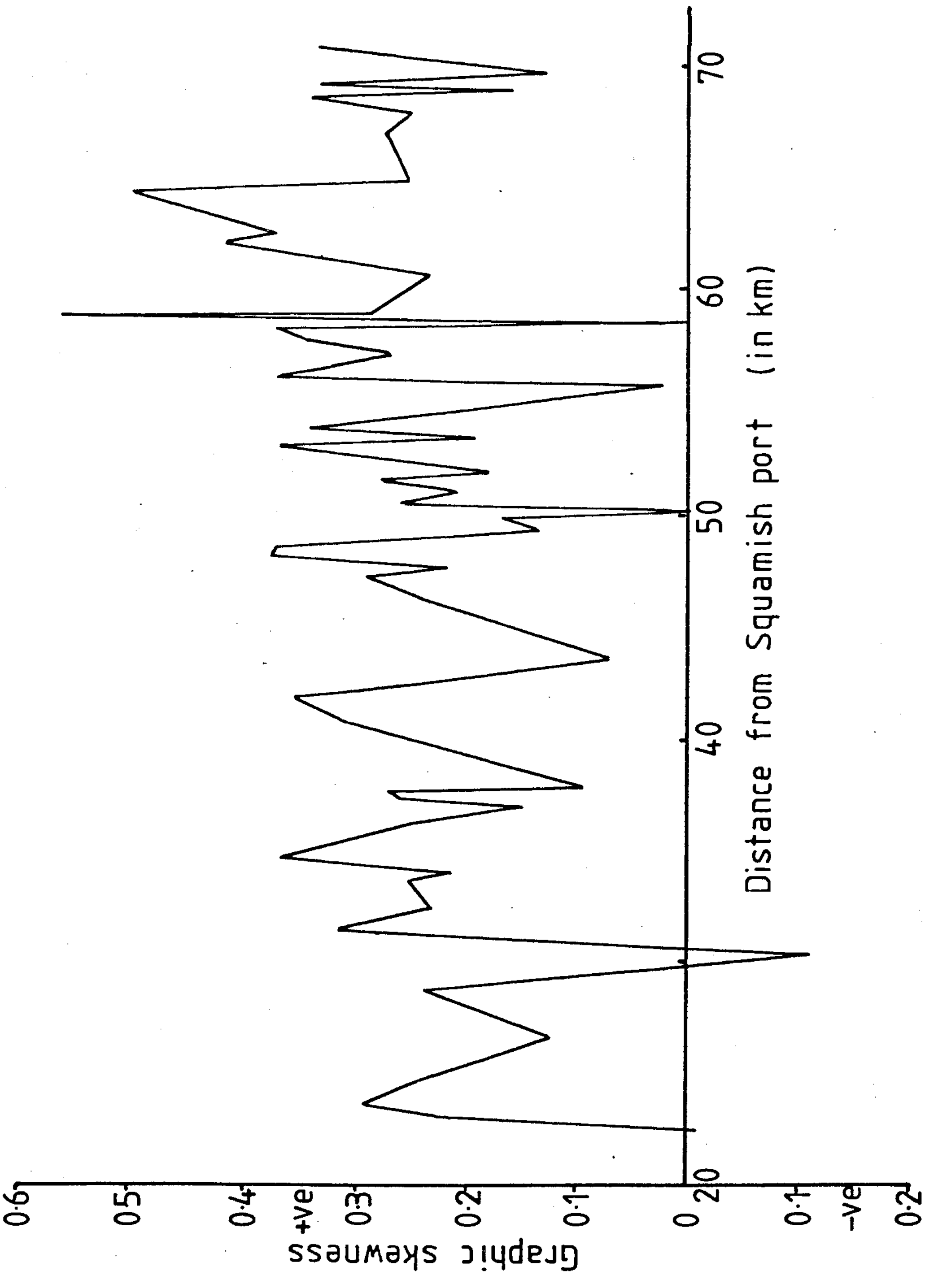
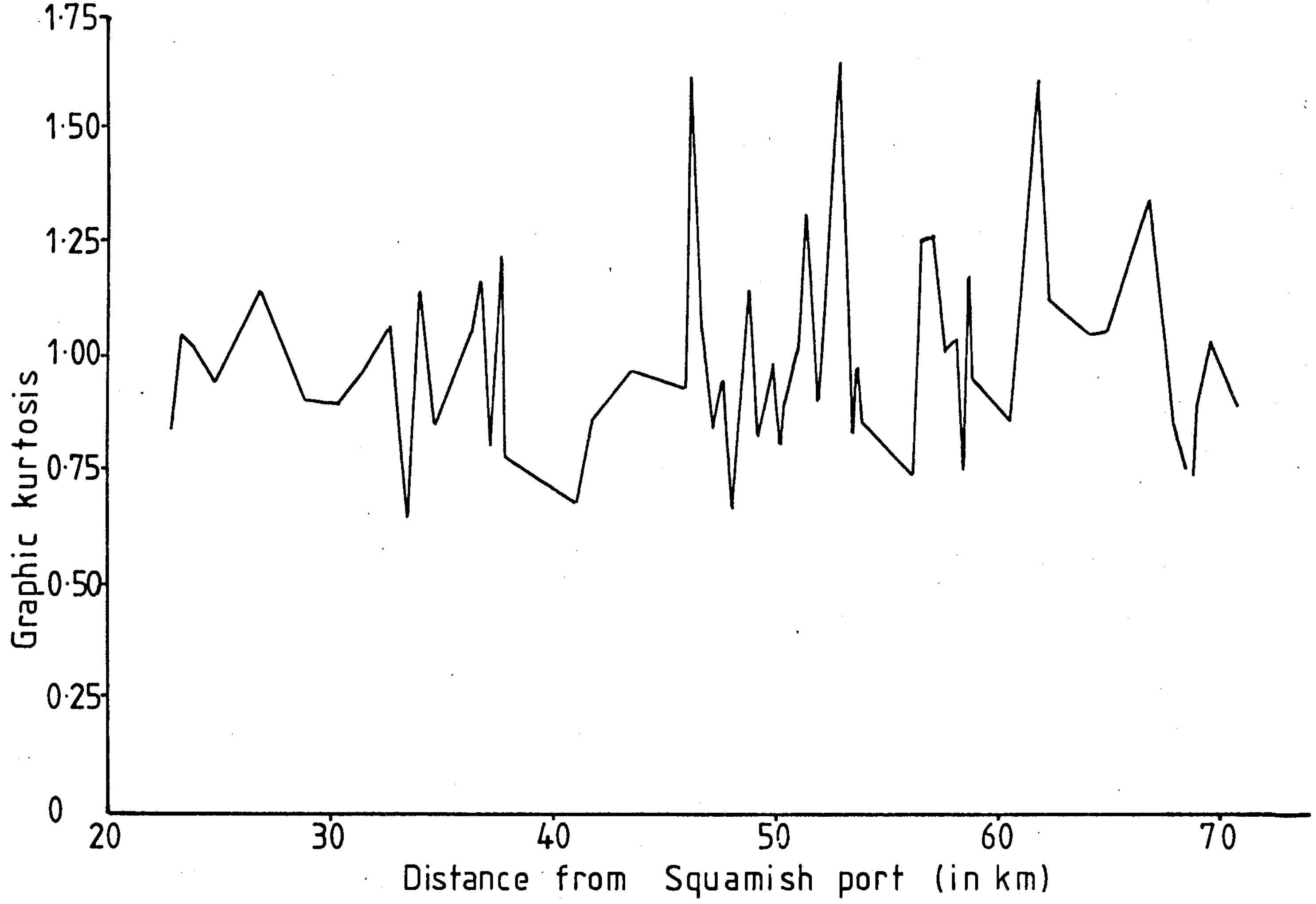


Figure 5.5



DOWNSTREAM GRADATION IN GRAPHIC KURTOSIS

5 : 1 : 4 Particle shape variations

Downstream changes in roundness (Figure 5.6) are dominated in large part by the Turbid Creek tributary input at 62.5km. Many of the large angular blocks supplied at this point break down into flaky fragments, reducing the proportion of well-rounded particles in the overall downstream trend. Particles tend to become more rounded downstream of the Turbid Creek sediment input. This may be attributed to either the decreasing influence of the tributary material, or rounding by fluvial activity.

Sphericity of particles appears to increase slightly downstream throughout the study reach, although much local variation is noted (Figure 5.7).

5 : 1 : 5 Changes in lithologic composition

The simple differentiation between rocks of volcanic and plutonic origin is seemingly well justified by examination of Figure 5.8. The proportion of volcanic rocks is relatively small (less than 30%) until the outlet at Turbid Creek, which is fed by debris from landslides within the Mount Cayley volcanic pile. There is a relatively smooth decline in the percentage of volcanic material downstream of this point, with local scale variation reflecting both vagaries of the sampling design and further tributary inputs.

Figure 5.6

DOWNSTREAM GRADATION IN PARTICLE ROUNDNESS

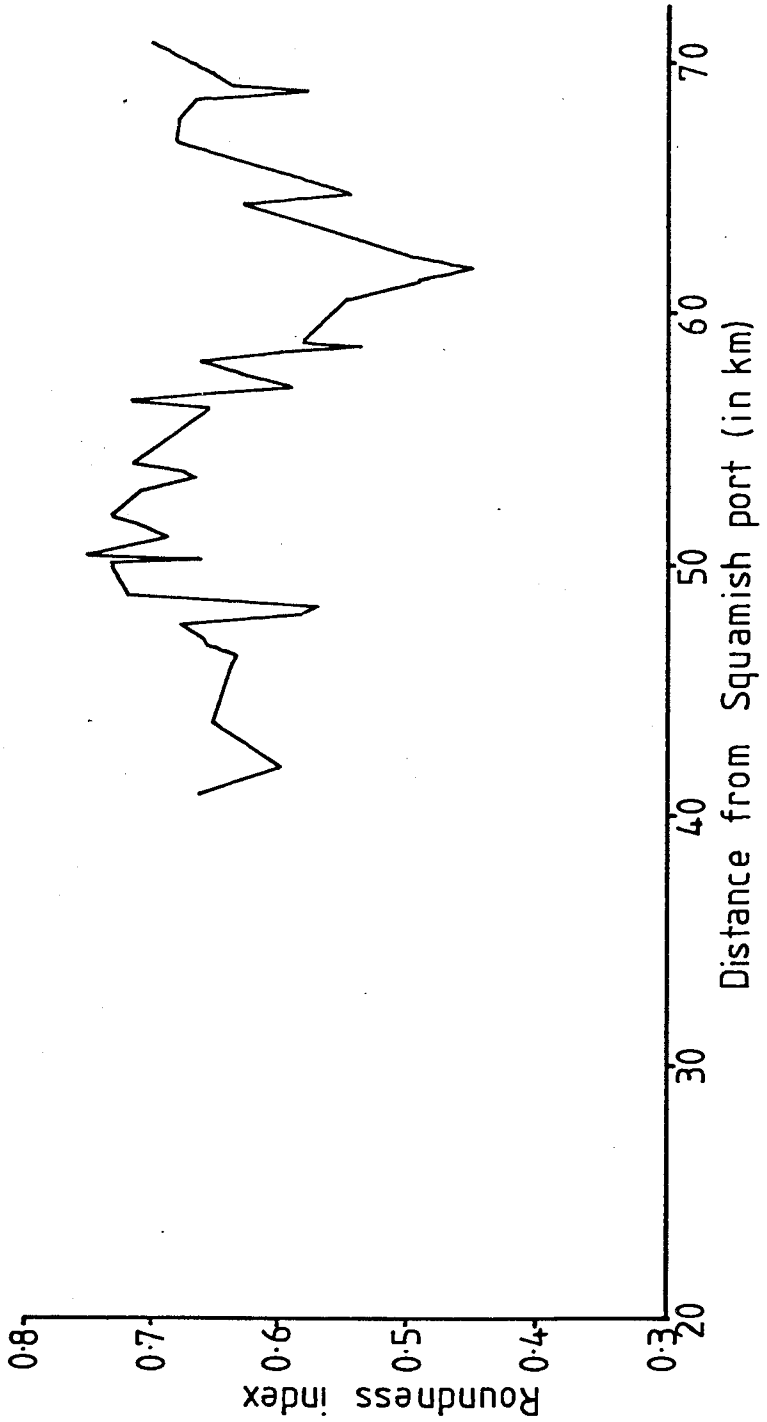
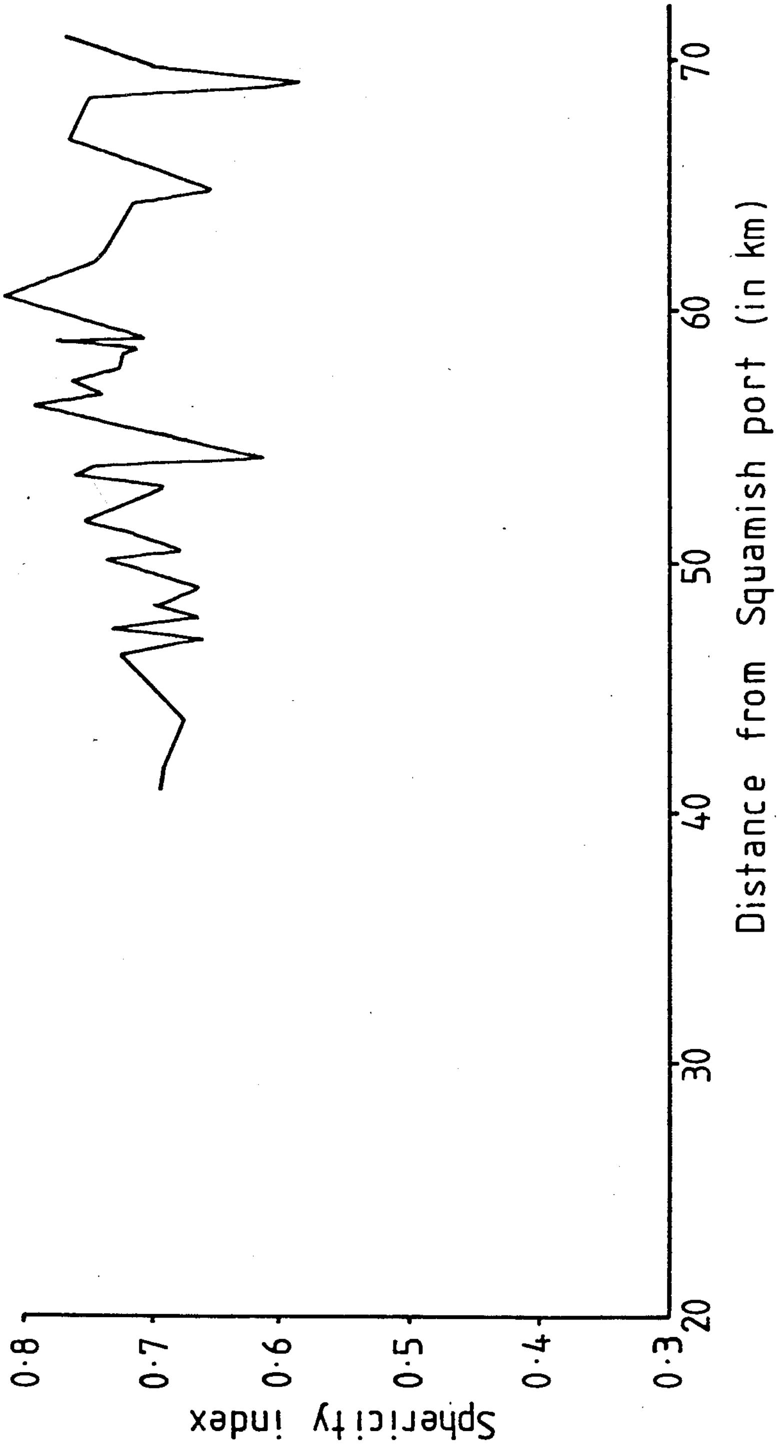


Figure 5.7

DOWNSTREAM GRADATION IN PARTICLE SPHERICITY



DOWNSTREAM GRADATION IN PERCENTAGE VOLCANICS

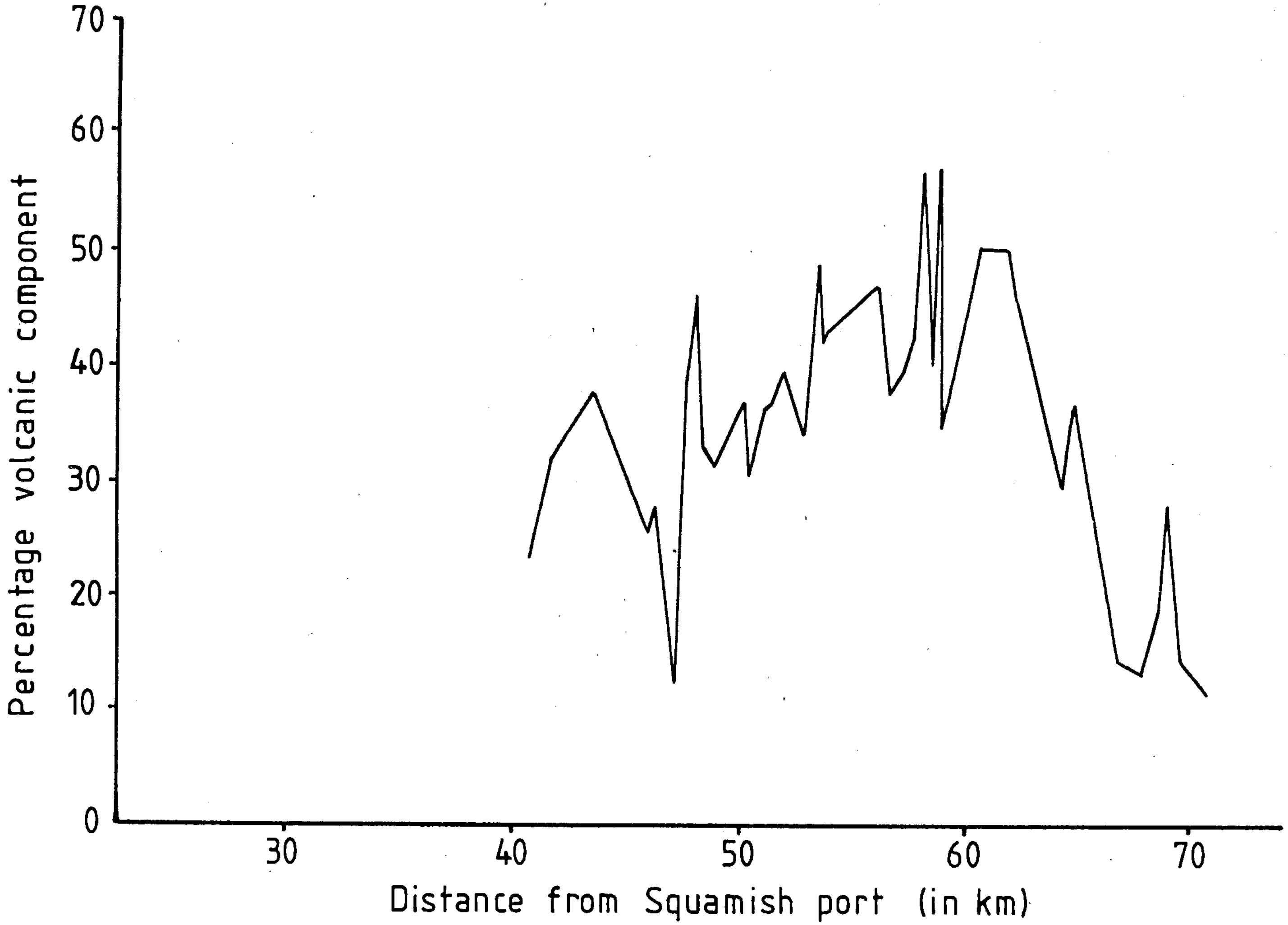
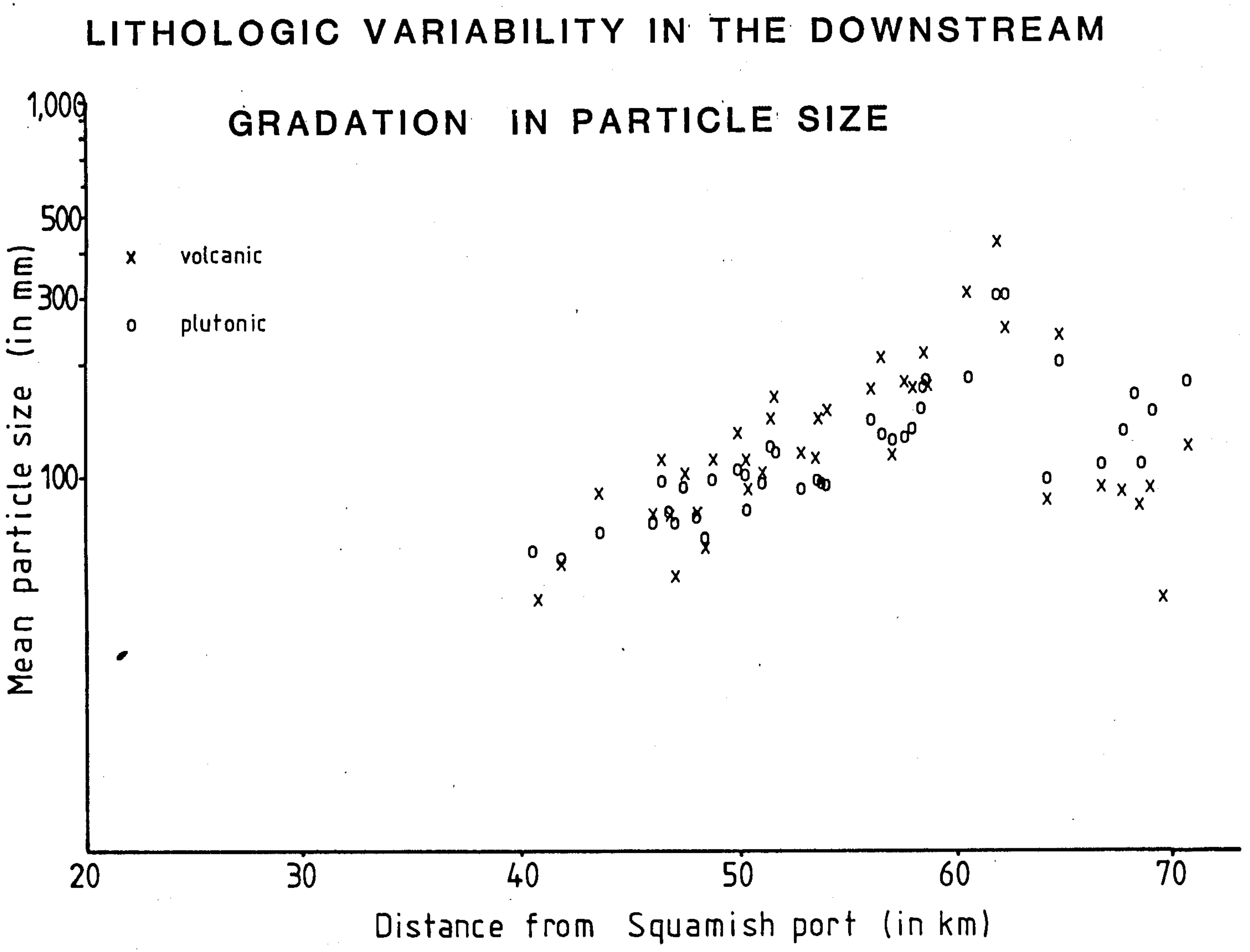


Figure 5.8

Figure 5.9 plots the downstream gradation in mean particle sizes for both the volcanic and plutonic components. Only samples of 30 particles or more are included, with means calculated from 'absolute' data. The trends for both rock types are relatively similar, but the downstream gradational effects are more pronounced for the volcanic component. Being of weak structure, the volcanic rocks are readily prone to disintegration and the exponent of size reduction downstream is much more pronounced than for the plutonic component.

Figure 5.9



LITHOLOGIC VARIABILITY IN THE DOWNSTREAM GRADATION IN PARTICLE SIZE

Chapter 6 : Interpretation, implications and conclusions

The downstream trends in particle characteristics described in Chapter 5 demonstrate discontinuities in association with planform type. These trends are examined in relation to the various geomorphic processes described for different timescales in the literature review. The coarser sediment unit of the braided section is interpreted as a sediment wedge, the downstream passage of which is guided by the balance between downstream and upstream river control. The post-glacial history of the system is evaluated in terms of its equilibrium context and the balance between sediment supply, storage and redistribution.

6 : 1 Fluvial processes affecting the downstream gradation

Although this study has not focused on the processes affecting the downstream decline in particle sizes, various observations have been made in this regard. Contemporary processes affecting sediment order are conditioned by flow regime. Downstream trends in particle characteristics of the Squamish River (Figures 5.1 to 5.9) reflect the combined effects of various processes.

6 : 1 : 1 Mechanisms of particle wear considered

The downstream increase in sphericity and roundness of particles within the study reach is indicative of the ability of the Squamish River to abrade particles. Further evidence is provided by the rapid breakdown of volcanic materials (see Figure 5.9). The volcanic component is very poorly sorted, with large quantities of fragmented particle flakes and chips being particularly notable near the Turbid Creek confluence. Abrasion in situ of these weakly bonded dacite lavas was apparent upon many bar surfaces. Effects of particle wear are less obvious for the sediments of plutonic origin, indicating the importance of particle composition and inherent structural weaknesses in affecting downstream sediment trends.

6 : 1 : 2 Effectiveness of sorting mechanisms

The fact that a wide range of particle sizes within the coarsest gravel locale is not apparent for bars downstream of the Turbid Creek confluence is testament to the sorting abilities of the Squamish River. Indeed, principles of selective transportation are well evidenced by the smooth nature of the downstream gradation of particle sizes in the braided reach (Figure 5.1).

Results from this study have shown a more rapid downstream change in the proportion of coarse gravels than is apparent for medium-sized gravels. At the lower end of the particle size range a certain size fraction is frequently flushed through the system (see Figure 4.1). Large quantities of finer materials remain intact within floodplains, however, having been deposited by waning floods.

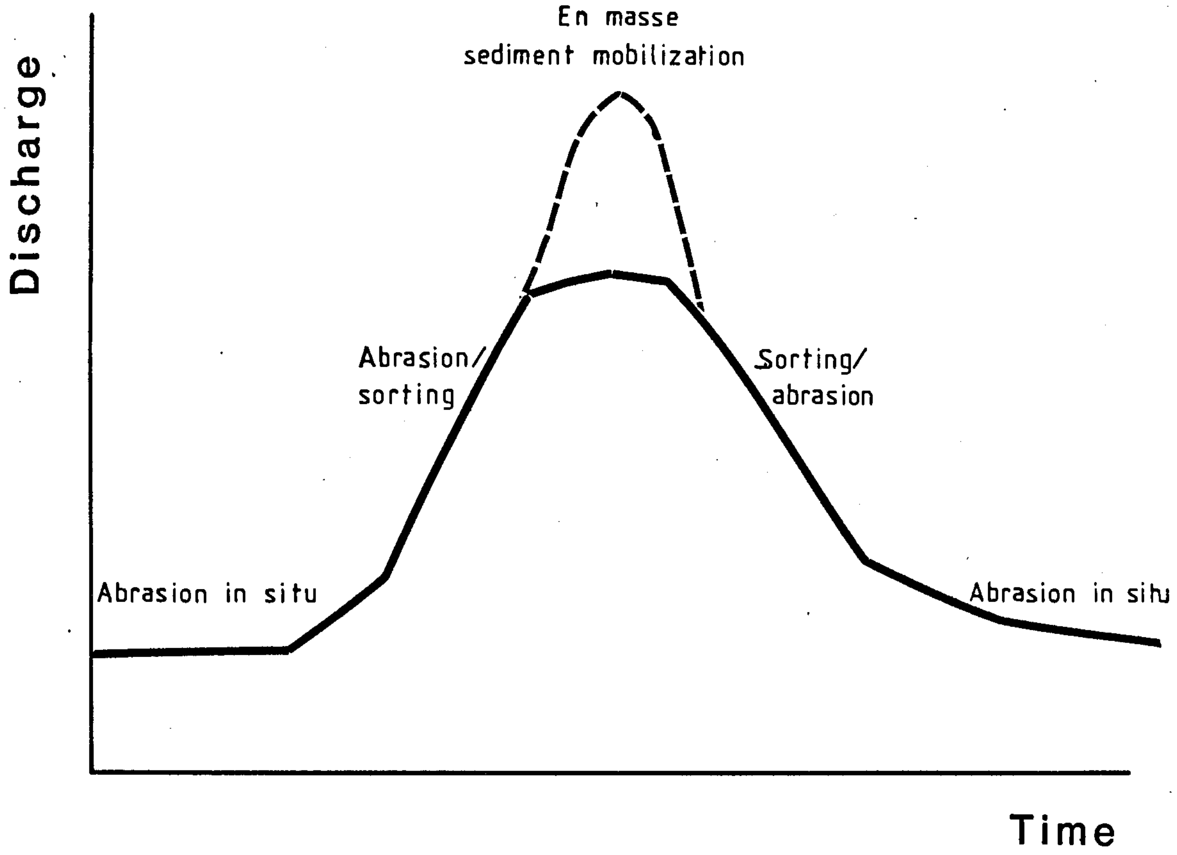
6 : 1 : 3 En masse sediment mobilization : The role of extreme events

The role of flow regime in conditioning process effectiveness is presented schematically in Figure 6.1. At low flow levels the coarsest size fraction cannot be mobilized and only a small proportion of floodplain deposits is affected. Processes of abrasion in-situ predominate, resulting in surficial rounding, rather than splitting and fracturing of particles. Under higher flow and energy conditions impact and abrasion forces are more effective, and selective transportation of particles occurs. The poor sorting of gravels on the coarsest bars confirms the limited ability of selective transportation mechanisms. Sorting processes are better regarded as lower flow redistributing agents, rather than the major determinant of downstream trends.

The low frequency of events able to mobilize all sediments leads one to question the overall effectiveness of abrasion and sorting processes. Simple evaluation of the primary forces affecting sediment transport leads one to conclude that, as

Figure 6.1

PROCESS EFFECTIVENESS IN RELATION TO DISCHARGE



discharge increases the sediment load increases in an exponential manner until some limiting capacity is attained. Positive forces, such as shear stress, lift forces and impact (momentum) forces are all maximized at higher flows, while negative packing forces are overcome beyond some critical threshold limit. Sediment movement proceeds very rapidly once the surface armour has been broken (see, for example, Parker et al, 1982). Channel bed resistance also is reduced under mobile bed conditions.

With high flows, coarser debris traps and entrains finer debris in its path, producing sediment movement in a slug-like fashion. Under such conditions sediment mobilization is capacity-limited, rather than competence-limited, and vast quantities of material are moved downstream en masse, with a limited degree of internal sorting.

The nature of sediment organization in the study reach implies that competence-limited processes must be operative. For example, as the Squamish River leaves its canyon, channel width increases dramatically, competence is reduced, and the coarser fraction of the sediment load is deposited. Frequency of fluvial reworking of this coarsest fraction is necessarily limited.

Baker and Ritter (1975) related maximum particle size transported to the critical mean shear stress required for mobilization by the expression :

$D90 = 65 \tau_0^{0.54}$.

where D90 is the 90th percentile of the cumulative particle size distribution, and τ_0 is mean critical shear stress. As derived from other studies in high energy gravel-bed depositional environments, this expression can be applied reasonably to the Squamish data. Costa (1983) confirmed the applicability of using boulder deposits to evaluate peakedness of former flow conditions.

Application of this relationship to the coarsest gravel bars sampled (numbers 9 and 10, with D90 values of 625 and 820mm respectively) reveals that flow depths in excess of 8m are required for mobilization (as demonstrated in Appendix 3). The channel width in this reach averages between 80-100m, and hence approximate discharges required to initiate movement of this coarse fraction can be determined for varying flow velocities. Results of such analysis are shown in Table 6.1. Extremely high discharges are required for mobilization. Comparison of these discharges with the flood hydrology data (Figure 3.5) determines that even under minimum conditions for mobilization there have been very few events of sufficient magnitude to affect this coarsest fraction upon the coarsest active gravel bars. Indeed, there have been a maximum of only five events of sufficient magnitude to mobilize D90 particles on Bar 10 in the 24 years of record.

Local scale sediment reorganization follows the passage of an extreme flow. The poorly-sorted waves of material are reworked and sorted to a degree limited by flow competence within any particular reach. Hence, the complete picture of

Table 6.1

Discharge computations to mobilize the largest size fraction

(After Baker & Ritter, 1975; Appendix 3)

From Appendix 3 it is known that formative discharges for mobilizing D_{90} particles in the upper braided/canyonized reach had a flow depth between 8 and 13m. Using these as estimators, required discharges can be determined for various velocities as width estimates can easily be derived from photographs. Hence, for a width between 80 - 100m, discharges are given by :

$Q = w\ d\ v$, as follows :

Velocity (m/s)	Discharge (m^3/s)	
	Depth 8.2m, width 80m	width 100m
2	1312	1640
3	1968	2460
4	2624	3280
5	3280	4100
	Depth 13.5m	
2	2160	2700
3	3240	4050
4	4320	5400
5	5400	6750

sediment size organization is conditioned by events of markedly different magnitudes and frequencies.

6 : 2 Channel pattern changes : Passage of a sediment wedge

As noted in the regional setting, the major feature of the study reach is the downstream changes in channel morphology. Associated with these abrupt transitions in flow characteristics are pronounced breaks in the slope of the longitudinal profile and the curve of downstream particle size decline. The braided section is considered to represent a sediment wedge which is slowly moving downstream.

6 : 2 : 1 Evidence of fluvial instability and the sediment wedge

The limits of the sediment wedge, defined by the braided section of the study reach, are apparent both in the field and from air photographs. Evidence for the sediment wedge is obtained from three inter-related sources : changes in channel morphology, slope, and particle size organization. The sharp breaks in downstream trends of these characteristics reflect downstream changes in the nature and energy of flow.

The bedrock floor of the canyon acts as a local base level for fluvial processes in the upstream braided and canyonized sections of the Squamish River. While sediment is flushed through the canyon itself, the valley upstream is infilled with glacially-derived coarse gravels, to a depth in excess of 60m (B.C. Hydro, pers. comm.). Although steep slopes in this area ensure high shear stresses, and particle sizes are sufficiently small to enable rapid sediment mobilization, it is likely that transport capacity is soon attained, because the channel remains choked with material. As the canyon itself remains virtually sediment free, upstream and downstream sections can be regarded as separate entities.

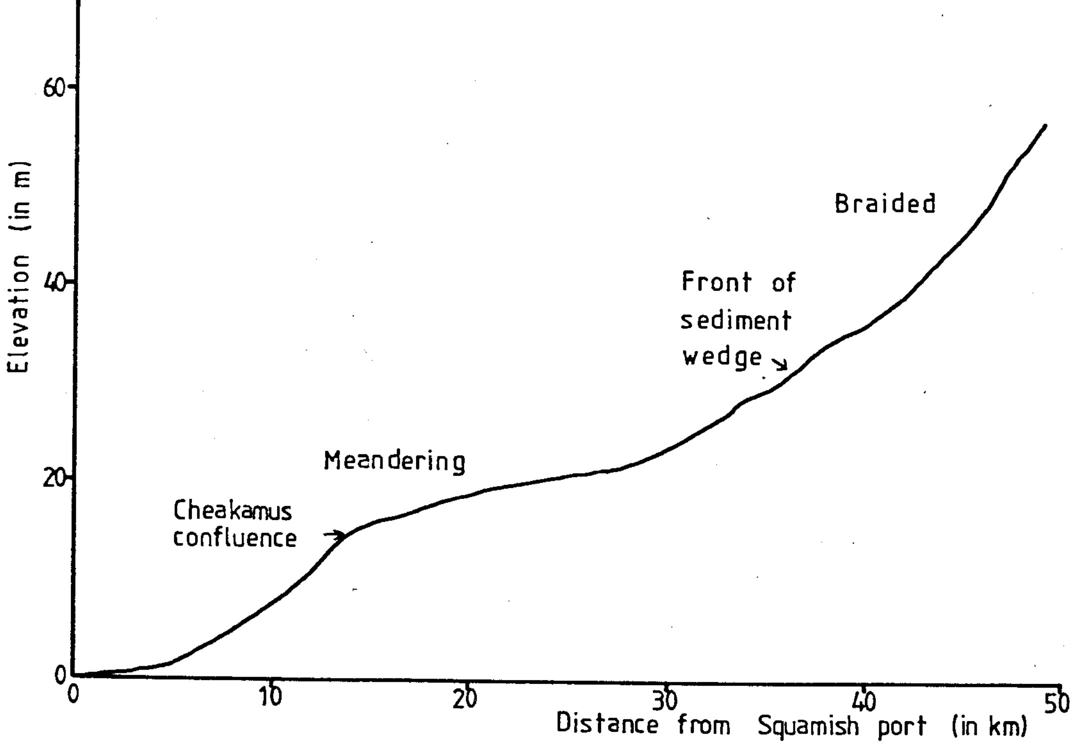
As the Squamish River leaves its canyon, large volumes of material are supplied by tributaries. The valley widens considerably and fluvial competence is reduced greatly. Sedimentation proceeds at great rates, resulting in a braided river pattern.

While energy conditions vary gradually within the braided section, drastic changes occur at the Ashlu River confluence. Over a distance of just 2km, the Squamish River changes from a wide active channel, with a width of 120-200m and floodplain width of 1,000-1,200m, to a single channel about 140m wide upon a 1,700m wide floodplain. At the Ashlu junction channel pattern and flow morphology change. Extremely sharp bends downstream of the junction indicate marked differences in energy conditions and depositional environment from those in the upstream section. The coefficient of particle size decline becomes considerably smaller in the downstream section. There is a pronounced break in slope (Figure 3.2), which upon closer field survey revealed the steepness of the front of the sediment wedge (Figure 6.2).

Figure 6.2

CHANNEL BED SLOPE

AT THE SEDIMENT WEDGE FRONT



Possible causes of the wedge, and of its downstream translation, are considered in the following section.

6 : 2 : 2 Evaluation of possible causes of the sediment wedge

Paraglacial sediment supply

Glacially-derived sediments provide the most notable source for present fluvially-worked gravels. Large amounts of paraglacial material remain within present floodplains in storage forms with varying degrees of permanence.

Extremely high flows immediately following glacial retreat infilled the glacially-cut Squamish Valley with gravels to considerable depth. Indeed, the channel section upstream of the Squamish canyon is choked with glacially-derived material. Some paraglacial deposits are stored within alluvial fans. Although fans in the upstream reaches of the Squamish Valley have not been dated, Eisbacher (1983) determined the Cheekye Fan to the south of the study reach to be older than 5,800years B.P. These fans are covered by established, stable vegetative communities. Presently several fans are being undercut, re-supplying material to the main river channel.

Rivers in high energy paraglacial environments undoubtedly had the competence and capacity to move the coarsest of materials presently found within the Squamish system.

Redistribution of these deposits has been limited by the lower energy available for sediment transport of subsequent flows.

Neoglacial sediment supply

Accumulations of glacially derived materials are not solely restricted to events occurring over 10,000 years ago. As stated in the regional setting, the Squamish Valley is flanked by mountains currently supporting alpine glaciers. Fluctuations in climatic conditions have resulted in neoglacial advances in the post-glacial era. These events are recorded by accumulations of morainal debris. Dating of one moraine in the Ashlu tributary yielded a tree-ring age in excess of 350 years. This may record the most recent in a series of neoglacial events.

Ryder (1981) stated that the most recent neoglacial episode is still detectable in some rivers in the form of glacial accumulations that have destabilized successive reaches as they move slowly toward the sea. The periodicity of advances suggests that sediment inputs occurred in short, pronounced waves. Short term activism added to the massive sediment infilling of the Squamish Valley. Fluvial adjustment to these inputs probably resulted in downstream migration of these waves.

Supply and effect of landslide debris

Structural instabilities within the recent volcanic lavas of the Pacific Coast Ranges have led to many regional landslides of substantial proportions. Debris from the 1963 Dusty Creek landslide (described in Chapter 3) has been supplied to the Squamish River by the tributary Turbid Creek. The location of Turbid Creek, at the head of the braided section, and the volcanic nature of the sediment input (see Figure 5.8), suggest that this source has been a major contributor to the sediment wedge.

The Dusty Creek landslide is part of the continuing history of regional slope-related instabilities. Large volumes of material have been made available for removal, and much remains stored between the present channel and the valley wall. Effects upon local fluvial activity are minimal unless supply mechanisms transport this material to active areas of the channel floodplain.

As well as the major landslide events, a variety of other slope instabilities have been noted. Avalanches supply some materials to the steeply inclined tributaries, there is evidence of debris flows upon alluvial fans, and a large rockfall has been noted in the Upper Squamish Valley. The total of these sediment contributions, however, is relatively insignificant in the light of the paraglacial and neoglacial sources.

The role of logging activities

Although large volumes of timber have been extracted from the Squamish Valley, effects upon sediment supply to the main channel probably are of limited significance. There are two major forms of disturbance. Firstly, surface clearance may lead to increased slope wash production. Such materials are very fine in texture and of little relevance to this study. Secondly, various logging activities may cause slope instabilities, although there was limited field evidence of such in the Squamish basin.

6 : 2 : 3 The sediment wedge reviewed

The braided section, or sediment wedge, of the study reach reflects conditions of over-supply of sediments. The combined effects of various supply mechanisms, at different time intervals, must be invoked.

Consideration of the relative scales of sediment supply leads one to presume that most of the material presently on the Squamish Valley floor reflects extremes of sediment mobilization during the paraglacial era. High energy depositional conditions are inferred from the coarseness of materials. As equivalent conditions are required for subsequent reworking and vast quantities of material remain stored in the system, long-term conditions of sediment excess in available time are ensured.

Additional sediment loads have been generated by intermittent events, such as neoglacial advances and landslides. In adding to an already overloaded sediment system, further imbalances have resulted. However, the character of sediment supply is different for these two different mechanisms. Neoglacial events are specific to certain time phases, while landslides have a sporadic history of activity. One can speculate that neoglacial morainal materials probably move through the system as sediment waves, whereas landslide debris is greater in volume and has resulted in the more permanent sediment wedge.

While the initiation of the braided section was conditioned largely by sediment supply rates, its persistence reflects subsequent storage properties and the inability of contemporary processes to redistribute all materials provided. The rate of fluvial reworking is controlled by the energy available for sediment mobilization.

The balance between downstream and upstream river control (Mackin, 1948) exerts great control upon contemporary sedimentologic order in the Squamish River system. The local base level of the study reach has been produced by sediment accumulations at the Cheakamus junction. As the downstream reaches of the Squamish River have become choked with sediment, channel slope has been reduced. Accordingly fluvial energy has been reduced and the rate of particle redistribution decreased. A single-channel meandering pattern has been adopted with relatively small particle sizes.

Conversely, the excessive sources of material in the upper reaches have resulted in upstream control in the canyonized and braided reaches. This has been termed channel control by Church (1972). Steeper channel slopes and greater channel competence result in mobilization of coarser particles in these upper sections. The braided planform demonstrates a relatively smooth downstream transition in particle size. As the zone of predominantly upstream control meets the zone of predominantly downstream control, channel pattern changes, channel slope becomes less steep and the rate of downstream particle size decline is reduced.

The Ashlu River confluence appears to represent the point in the Squamish system at which downstream control from the Cheakamus sediment input mingles with upstream controls from the higher energy conditions and sediment input of the upper braided and canyonized sections. As sediments have been supplied continually from upstream sources, yet their passage has been delayed by downstream control, they remain within the system in the form of the braided pattern. This may be considered to represent a sediment wedge. As regional sea levels have been essentially constant for over 5,000 years, it is postulated that upstream controls have gradually become more significant. Given this scenario, the sediment wedge should gradually move downstream.

Evidence that the sediment wedge has moved downstream is provided by its sharply defined downstream limit, with changes in channel pattern, slope and particle size. Downstream translation of the sediment wedge may be affected by en masse sediment mobilization during extreme events. To date, downstream passage of the wedge is incomplete and it remains lodged in mid-system, guided by the balance between upstream and downstream control and the frequency of extreme flows. Eventually the downstream translation will be complete. The equilibrium nature of these effects, and the temporal framework for analysis and interpretation of this dynamic, high energy gravel bed river, are considered in the following section.

6 : 3 Implications of the study

The exponential particle decline function predicted by Sternberg (1875) has been found not to apply to the Squamish system, as plots on semi-logarithmic paper are not rectilinear. Rather, downstream trends in particle characteristics are better analysed in units, according to changes in channel pattern and slope. Deviation from expected downstream trends is attributed to some form of sedimentologic imbalance within the Squamish River system. Hence, while individual channel sections may be in equilibrium, downstream adjustment of the whole study reach is incomplete. These discontinuities in energy relations are indicative of a system in a non-equilibrium condition.

Although the present geomorphic environment of the Squamish Valley is extremely active, conditions have been dominated by events in the past, producing a nonequilibrium condition. Recent, smaller scale sediment inputs have resulted in further river adjustments of a more temporary, disequilibrium nature. The braided section of the study reach represents such a temporary state.

Interpretation of relevant time scales of activity, and associated lag effects, allows distinction to be drawn between nonequilibrium and disequilibrium conditions, and provides insight into the present state of rivers and their adjustments in the post-glacial era. Sedimentologic imbalance in the Squamish system can be attributed to extreme over-sediment supply, long term sediment storage, and the inability of the river to redistribute all materials.

As large volumes of material remain within the Squamish system, redistribution in available time is incomplete. Since sediments supplied in the paraglacial period have not been transferred through the system, a nonequilibrium condition is apparent. The permanence of sediment storage presents a sedimentologic context out-of-phase with present environmental conditions; one that will persist for some time. Indeed, present rivers such as the Squamish may not possess the competence to mobilize the stable gravel beds upon which they flow.

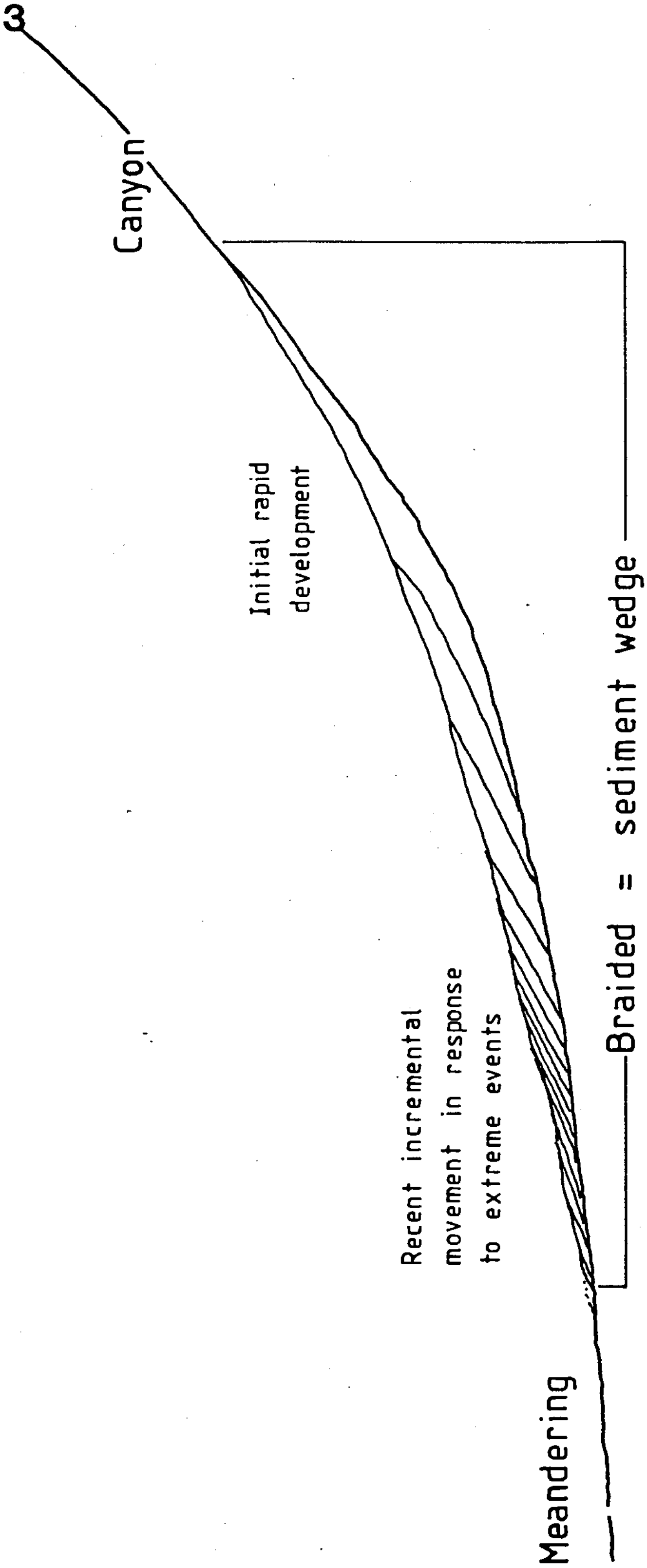
Intermittent supply of material from neoglacial moraines and landslide debris has produced more temporary, disequilibrium effects. These events have lesser significance to the whole system, as sediment transfer occurs over an intermediate time interval conditioned by the nature of the sediment input. The sediment wedge in the Squamish system exemplifies this disequilibrium condition. The coarse composition of the wedge, and the balance between upstream and downstream river control, have resulted in this wedge being lodged in mid-stream, only able to move under extreme flow conditions. As it passes downstream, valley width increases, ensuring that downstream translation of the wedge is hindered. This has possibly resulted in step-like downstream movement over time (see Figure 6.3).

Recent changes in channel morphology and configuration suggest that fluvial reworking is incomplete and reorganization of particle sizes continues. However, the character of the materials involved and the nature of present-day flow regimes ensure that river channel changes are now guided more by extreme events and en masse sediment mobilization. Hence the contemporary timescale presents an equilibrium condition, with long periods of small scale sediment redistribution following intervals of catastrophic change.

In summary, linkages between the sediment balance and temporal phases of post-glacial fluvial adjustment have implied that various non-equilibrium conditions are apparent within the Squamish system. Long term nonequilibrium, associated with paraglacial sediment supply, has been supplemented by shorter term disequilibrium phases.

Figure 6.3

DOWNSTREAM MOVEMENT OF THE SEDIMENT WEDGE



6 : 4 Concluding comments

Given the scarcity of other sources of information on the sedimentologic nature of river channel changes over the past 10,000 years, the degree of sediment order provides a suitable starting place for enquiry. As it reflects the summary effects of former activities, it provides insight into the nature, role and consequences of past events. However, many problems in analysis result from insufficient knowledge of the dating and magnitudes of activity.

Although sedimentologic order exists on the Squamish River, with close correlations between particle size, channel pattern and slope, this is an order imposed by former conditions and does not reflect an equilibrium balance with present environmental conditions. The degree of permanence of the sediments in the braided section is conditioned by the capacity and competence of subsequent flows to remove the imbalancing wedge. As yet, the the time for particle redistribution has been insufficient. As Holland (1964, 15) stated :

> "In the short interval since the disappearance of the bulk of the Pleistocene ice, stream erosion has once again become an active agent of landscape development. The time interval is too short to result in extensive modification of the landscape."

The study has drawn attention to the rate at which fluvial adjustment takes place. The Squamish system has been dominated by short bursts of activity in the immediate post-glacial era. Sediments supplied have remained within the system, largely in semi-permanent storage units. Redistribution has been relatively slow; dominated by extreme events, with local scale redistribution under lower flow conditions. Hence, principles of catastrophism apply to fluvial development in such high energy mountainous environments. Similar conclusions have been reached by workers in other environments. For example, extreme flows are seen to be the major agents of geomorphic change in arid fluvial geomorphology (e.g. Baker, 1977; Graf, 1983). This prompts further enquiry into the role of magnitude/frequency relations in flood effectiveness and river development under different environmental conditions.

Finally, several questions have been prompted about fluvial development in the post-glacial era. The mechanisms of sediment supply need more in-depth analysis, and estimates of the volumes of material supplied by each need to be evaluated. Only then can the temporal framework be seen more clearly. The storage forms adopted and their permanence in relation to varying flow conditions have to be reviewed. Dating of alluvial fans, for example, would provide guidelines for stability of storage units. Climatic and vegetative variability in the post-glacial era also requires further analysis, so that the picture of fluvial adjustment can become more complete. Just as Langbein and Schumm (1958) schematized sediment yields for different environmental regions, so the sediment balance in any one particular region should be evaluated throughout the post-glacial era. For example, what effect did the hypsithermal climatic conditions have? Similarly, what were the consequences of cooling during periods of neoglacial advance?

The study has demonstrated the importance of clearly defining the environmental context in evaluating the nature of geomorphic processes. As geomorphologists, we need to look beyond the present scene, adjusting our time frames of observation and reference, to gain deeper understanding of the state of fluvial systems and how they are likely to adjust in the future. However, as Leopold et al (1964, 107) lamented :

> "A major problem common to many processes affecting the earth's surface ... is that genesis must be inferred from an analysis of the end results with little or no direct knowledge of what actually happened or of the time that it took."

Appendix 1

Example of field data sheet for the transect method

Bar : 36
Date sampled : 15/12/82; A. Dobud
Type : Longitudinal
Location : 48·1km from Sq. post
Field notes : New bar (?); possibly reworked from large former accumulation; Finer sediments at head - sample from middle ½m interval

b axis	lith	shape	b axis	lith	shape	b axis	lith	shape	b axis	lith	shape
25	V	C3	276	V	B4	108		A5	376	V	A4
364	V	B4	397	V	B4	255	V	A3	72		B3
21		A4	x157		B3	30		C3	62		B5
129		A4	354	V	B4	x23		A3	190		C2
162		A3	346	V	B3	70		C3	134		A4
x91		B2	318		C5	94	V	B4	124		A4
44	V	B3	145		A3	254		B3	x78		A5
105		A4	21		B3	66		B5	44		B3
134	V	B4	168	V	B3	140	Br	B4	214		A4
328		B3	29		B3	184		B5	182	V	B4
111	V	C3	84		C3	97		A5	31	V	A5
105		A3	x141		B4	x130		B4	140		A4
x230		B4	224	V	B3	95		C4	113		B3
95		C5	214		B3	101		A5	216		B5
74		B3	131		B2	230		C5	354		C4
101		C5	x58		A4	290	V	A5	214		C5
416	V	A3	466	V	A3	92	V	C5	134		A4
77	V	A3	122	V	B4	328		A4	208	V	B3
25	V	C3	135		B3	126		A5	152		B5
375	V	A5	160		B3	223		C2	261		C2
x108	V	C5	152	V	B5	382		A4	131		A5
64		A4	105		B4	128		B5	112	V	A3
x108		C4	132		A4	142	V	A4	45		A3
353	V	A1	281	V	B4	342	V	A5	87		B4
131	V	A5	109		C3	60		B4	92		B5

Appendix 1 (cont.)

Example of field data sheet for the quadrat method

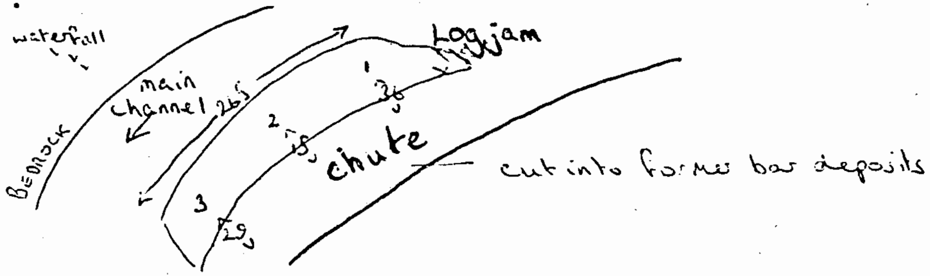
Bar : 9

Type : Point (separated by chute)

Date sampled : 13/7/82, D.Halladay

Location : 28.6km from Sq. point

Field notes :



Example of actual sample point (Point 1 above) :

phi	NW	NE	SW	SE
-3	𝍷𝍷𝍷	𝍷		𝍷𝍷𝍷
-3.5	𝍷	𝍷		
-4	𝍷𝍷𝍷𝍷	𝍷	𝍷𝍷	𝍷
-4.5	𝍷	𝍷𝍷𝍷	𝍷𝍷𝍷	𝍷
-5	𝍷𝍷	𝍷𝍷𝍷𝍷	𝍸𝍷	𝍷𝍷
-5.5	𝍸𝍷𝍷𝍷	𝍸𝍷	𝍷𝍷	𝍷𝍷𝍷𝍷
-6	𝍷𝍷𝍷	𝍷𝍷𝍷	𝍷𝍷𝍷	𝍸𝍷𝍷𝍷
-6.5	𝍷𝍷𝍷	𝍸𝍷	𝍸𝍷𝍷	𝍸𝍷
-7	𝍷		𝍷𝍷	𝍷
-7.5				
<-3	𝍷	𝍷𝍷		𝍸

Shape

			𝍷	𝍷
			𝍸𝍷𝍷	𝍷𝍷𝍷
		𝍷𝍷	𝍷𝍷𝍷	
𝍷	𝍷	𝍷𝍷	𝍷𝍷𝍷𝍷	

Lithology

Volcanic	𝍸 𝍸 𝍷
Plutonic	𝍸 𝍸 𝍷𝍷𝍷𝍷

Appendix 2

Summary data for all bars studied at ½phi frequency

Bar No.	-3	-3½	-4	-4½	-5	-5½	-6	-6½	-7	-7½	-8	-8½	-9	-9½	-10	-10½	-11
1			1	3	2	5	14	16	13	18	18	9	1				
2	3	1	1	3	1	13	13	16	27	14	8						
3			2	4	6	7	16	21	17	16	11						
4		2	3	5	6	8	8	12	10	21	18	7					
5		1	5	2	12	13	19	11	23	13	1						
6		1	1	1	4	6	23	16	23	20	5						
7					2	1	6	11	22	26	21	9	2				
8	3	3	4	11	13	12	13	13	12	10	6						
9		3	1	5	5	3	9	8	7	14	17	13	8	4	3		
10	1		4	3		1	5	12	11	8	19	15	5	9	5	3	4
11		1		2	1	3		15	14	19	21	18	6				
12				1	4	9	9	17	16	20	15	8	1				
13		1	4	4	6	16	17	15	10	16	5	4	2				
14					2	2	10	15	17	26	25	3					
15		1	2	1	6	7	13	19	16	18	11	6					
16			1	2	5	5	12	25	18	18	12	2					
17	2		1	4	7	9	14	21	24	9	8	1					
18			2	5	4	4	8	22	21	15	12	7					
19				1	6	6	16	11	20	32	6	2					
20	1	1	1	2	4	11	22	16	23	15	3	1					
21			1	1	8	13	17	23	18	14	5						
22	1		3	2	10	11	16	23	23	9	2						
23			1	7	9	11	23	24	12	6	7						
24			2	2	7	8	11	21	23	19	6	1					
25			1	4	2	5	17	28	23	14	6						
26			2	4	9	12	25	21	20	7							
27			2	4	13	16	22	22	18	3							
28			5	5	5	10	15	19	25	11	1						
29				1	8	11	14	31	29	5	1						
30	1	1	3	4	2	9	15	25	25	13	2						
31			3	2	10	15	13	27	22	8							
32				1	4	9	27	34	19	6							
33	1		8	9	14	26	15	15	12								
34	1	1	8	12	12	14	14	14	21	3							
35			1	3	10	11	25	24	20	5	1						
36		3	2	2	20	20	18	23	10	1	1						
37	1	3	5	10	10	13	23	17	12	6							
38					8	6	31	34	15	6							
39	2	2	5	7	9	16	22	19	16	2							
40	1	1	3	6	11	13	31	21	13								
41	4	1	11	7	21	18	15	18	3	2							
42		3	7	13	15	21	15	22	4								
43			3	5	18	25	22	12	12	2							
44	5	2	8	8	14	20	17	22	3	1							

Appendix 2 (cont.)

Bar No.	-3	-3½	-4	-4½	-5	-5½	-6	-6½	-7	-7½	-8	-8½	-9	-9½	-10	-10½	-11
45	1	6	17	17	19	21	13	5									
46	2			10	9	28	25	20	4								
47		3	7	12	11	24	22	13	8								
48		1	3	10	19	30	27	7	2	1							
49	4	7	16	13	18	16	16	10									
50	1	4	7	8	26	27	19	8									
51	1	3	14	13	12	14	18	21	3	1							
52	4	6	12	19	28	18	12	1									
53	1	6	16	18	24	18	13	1									
54			6	3	13	21	38	12	1								
55	2	2	5	13	17	24	20	15	2								
56		1	6	7	20	32	21	11	1								
57		2	6	17	17	26	21	9	2								
58	1	1	8	17	21	25	17	8	2								
59	3	2	5	18	21	26	17	7	1								
60	2	3	16	11	31	30	6	1									

Appendix 3

Derivation of competence intervals for coarse sediment mobilization

(after Baker & Ritter, 1975)

$D_{90} = 65\tau_o^{0.54}$, (Baker & Ritter, 1975),

where D_{90} = 90th percentile particle size,

τ_o = critical mean shear stress for initiating particle transport,

= γRS,

where γ = specific weight of water = 1000kgm^{-3},

R = hydraulic radius,

S = energy slope.

Assuming that R approximates flow depth, and with a general slope of 0.00805 in the upstream/braided reach, one can determine flow depth for transport of the coarsest particles from D_{90} sizes.

Thus, $D_{90} = 65\ (1{,}000 \times d \times 0.00805)^{0.54}$,

where d = flow depth.

For Bar 10, D_{90} = 625mm. Hence, d = 8.2m.

For Bar 11, D_{90} = 820mm. Hence, d = 13.6m.

References

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

Adams, J., 1979b, Gravel size analysis from photographs, Journal of the Hydraulics Division, American Society of Civil Engineers, 105, HY10, 1247-1255.

Armstrong, J.E., and S.R. Hicock, 1976, Quaternary multiple valley development of the lower Coquitlam Valley, Coquitlam, British Columbia, Geological Survey of Canada Paper, 76-1B, 197-200.

Baker, V.R., 1977, Stream-channel response to floods, with examples from Central Texas, Geological Society of America Bulletin , 88, 1057-1071.

Baker, V.R. and D.F. Ritter, 1975, Competence of rivers to transport coarse bedload material, Geological Society of America Bulletin , 86, 975-978.

Bluck, B.J., 1971, Sedimentation in the meandering River Endrick, Scottish Journal of Geology, 7, 93-138.

Bluck, B.J., 1976, Sedimentation in some Scottish rivers of low sinuosity, Transactions of the Royal Society of Edinburgh, 69, 425-456.

Bluck, B.J., 1982, Texture of gravels in braided streams, In : Hey, R.D., J.C. Bathurst and C.R. Thorne, (Eds.), Gravel-Bed Rivers : Fluvial Processes, Engineering and Management, Wiley, Chichester, 339-356.

Bradley, W.C., 1970, Effects of weathering on abrasion of granitic gravel, Colorado River, Texas, Geological Society of America Bulletin, 81, 61-80.

Bradley, W.C., R.K. Fahnestock and E.T. Rowekamp, 1972, Coarse sediment transport by flood flows on Knik River, Alaska, Geological Society of America Bulletin, 83, 1261-1284.

Bray, D.I., 1972, Generalized regime-type analysis of Alberta rivers, Unpublished PhD thesis, University of Alberta, Calgary.

Bray, D.I., 1982, Flow resistance in gravel-bed rivers, In : Hey, R.D., J.C. Bathurst and C.R. Thorne, (Eds.), Gravel-Bed

Rivers : Fluvial Processes, Engineering and Management, Wiley, Chichester, 109-138.

Callander, R.A., 1978, River meandering, *Annual Review of Fluid Mechanics*, 1978:10, 129-158.

Carling, P.A. and N.A. Reader, 1981, A freeze-sampling technique for coarse-river bed-material, *Sedimentary Geology*, 29, 233-239.

Carson, M.A., 1967, The magnitude of variability in samples of certain geomorphic characteristics drawn from valley-side slopes, *Journal of Geology*, 75, 93-100.

Church, M., 1967, A relatively painless method of obtaining mean cobble size data on coarse clastic surfaces, *Unpublished paper*.

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

Church, M. and D. Jones, 1982, Channel bars in gravel-bed rivers, In : Hey, R.D., J.C. Bathurst and C.R. Thorne, (Eds.), *Gravel-Bed Rivers : Fluvial Processes, Engineering and Management*, Wiley, Chichester, 291-338.

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

Church, M. and J.M. Ryder, 1972, Paraglacial sedimentation : A consideration of fluvial processes conditioned by glaciation, *Geological Society of America Bulletin*, 83, 3059-3072.

Clague, J.J., 1976, Quadra Sand and its relation to the late Wisconsin glaciation of southwest British Columbia, *Canadian Journal of Earth Sciences*, 13, 803-815.

Clague, J.J., 1981, Late Quaternary geology and geochronology of British Columbia, Part 2 : Summary and discussion of radiocarbon-dated Quaternary history, *Geological Survey of Canada Paper*, 80-35, 41pp.

Clague, J., J.R. Harper, R.J. Hebda and D.E. Howes, 1982, Late Quaternary sea levels and crustal movements, coastal British Columbia, *Canadian Journal of Earth Sciences*, 19, 597-618.

Clague, J.J. and J.L. Luternauer, 1983, Late Quaternary geology of southwestern British Columbia, *Field Trip Guidebook*, Trip 6, Geological Association of Canada, Victoria, B.C., 112pp.

Clague, J.J. and J.G. Souther, 1982, The Dusty Creek landslide on Mount Cayley, British Columbia, Canadian Journal of Earth Sciences, 19, 524-539.

Costa, J.E., 1983, Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range, Geological Society of America Bulletin, 94, 986-1004.

Davies, D.K., R.K. Vessell, R.C. Miles, M.G. Foley, and S.B. Bonis, 1978, Fluvial transport and downstream sediment modifications in an active volcanic region, In : Miall, A.D., (Ed.), Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir 5, Calgary, 61-84.

Davis, N.F.G. and W.H. Mathews, 1944, Four phases of glaciation with illustrations from southwestern British Columbia, Journal of Geology, 52, 403-413.

Department of Environment, 1973, The Burrard Inlet-Howe Sound area : preliminary description of existing environmental conditions, Department of the Environment Report, 69pp.

Doeglas, D.J., 1962, The structure of sedimentary deposits of braided streams, Sedimentology, 1, 167-190.

Dott, R.H., 1983, 1982 S.E.P.M. Presidential Address : Episodic sedimentation - How normal is average? How rare is rare? Does it matter?, Journal of Sedimentary Petrology, 53, 5-23.

Dury, G.H., 1980, Neocatastrophism? A further look, Progress in Physical Geography, 4, 391-409.

Eisbacher, G.H., 1983, Slope stability and mountain torrents, Fraser Lowlands and southern Coast Mountains, British Columbia, Field Trip Guidebook, Trip 15, Geological Association of Canada, Victoria, B.C.

Fahnestock, R.K., 1963, Morphology and hydrology of a glacial stream - White River, Mount Rainier, Washington, United States Geological Survey Professional Paper, 422-A, 70pp.

Fisk, H.N., 1947, Fine-grained alluvial deposits and their effects on Mississippi River activity, Mississippi River Commission Waterways Experiment Station, Vicksburg, Mississippi, 82pp.

Folk, R.L., 1955, Student operator error in determination of roundness, sphericity and grain size, Journal of Sedimentary Petrology, 25, 297-301.

Folk, R.L., 1965, Petrology of Sedimentary Rocks, Hemphill's, Austin, Texas, 159pp.

Folk, R.L., 1966, A review of grain size parameters, *Sedimentology*, 6, 73-93.

Folk, R.L. and W.C. Ward, 1957, Brazos River bar - A study in the significance of grain size parameters, *Journal of Sedimentary Petrology*, 27, 3-26.

Fulton, R.J., 1971, Radiocarbon geochronology of southern British Columbia, *Geological Survey of Canada Paper*, 71-37, 28pp.

Glaister, R.P. and H.W. Nelson, 1974, Grain size distributions, an aid in facies identification, *Bulletin of Canadian Petroleum Geology*, 22, 203-240.

Graf, W.H., 1971, *Hydraulics of Sediment Transport*, McGraw Hill, New York, 513pp.

Graf, W.L., 1983, Flood-related channel change in an arid-region river, *Earth Surface Processes and Landforms*, 8, 125-139.

Hack, J.T., 1957, Studies of longitudinal stream profiles in Virginia and Maryland, *United States Geological Survey Professional Paper*, 294-B, 45-97.

Hack, J.T., 1960, Interpretation of erosional topography in humid temperate regions, *American Journal of Science*, 258-A, 80-97.

Hein, F.J. and R.G. Walker, 1977, Bar evolution and development of stratification in the gravelly, braided Kicking Horse River, British Columbia, *Canadian Journal of Earth Sciences*, 14, 562-570.

Henderson, F.M., 1961, Stability of alluvial channels, *Journal of the Hydraulics Division, American Society of Civil Engineers*, 87, HY6, 109-138.

Hickin, E.J., 1978, Mean flow structure in meanders of the Squamish River, British Columbia, *Canadian Journal of Earth Sciences*, 15, 1833-1849.

Hickin, E.J., 1979, Concave-bank benches on the Squamish River, British Columbia, Canada, *Canadian Journal of Earth Sciences*, 16, 200-203.

Hickin, E.J., 1983, River channel changes : retrospect and prospect, *International Association of Sedimentologists, Special Publications*, 6, 61-83.

Hirsch, P.J. and A.D. Abrahams, 1981, The properties of bed sediments in pools and riffles, *Journal of Sedimentary Petrology*, 51, 757-760.

Holland, S.S., 1964, Landforms of British Columbia, a physiographic outline, British Columbia Department of Mines and Petroleum Resources Bulletin, 48, 138pp.

Hoos, L.M. and C.L. Vold, 1975, The Squamish River Estuary : Status of environmental knowledge to 1974, Report of the Estuary Working Group, Department of the Environment, Regional Board Pacific Region, Environment Canada, Special Estuary Series No.2, 178pp.

Howard, A.D., 1982, Equilibrium and time scales in geomorphology : Application to sand-bed alluvial streams, Earth Surface Processes and Landforms, 7, 303-325.

Jackson, L.E., G.M. MacDonald and M.C. Wilson, 1982, Paraglacial origin for terraced river sediments in Bow River, Alberta, Canadian Journal of Earth Sciences, 19, 2219-2231.

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

Keller, E.A., 1971, Areal sorting of bed-load material : The hypothesis of velocity reversal, Geological Society of America Bulletin, 82, 753-756.

Kellerhals, R., 1967, Stable channels with gravel-paved beds, Journal of the Waterways and Harbors Division, American Society of Civil Engineers, 93, WW1, 63-84.

Kellerhals, R., 1982, River regulation and channel stability, In : Hey, R.D., J.C. Bathurst and C.R. Thorne, (Eds.), Gravel-Bed Rivers : Fluvial Processes, Engineering and Management, Wiley, Chichester, 685-716.

Kellerhals, R. and D.I. Bray, 1971, Sampling procedures for coarse fluvial sediments, Journal of the Hydraulics Division, American Society of Civil Engineers, 97, HY8, 1165-1180.

Kellerhals, R., M. Church and D.I. Bray, 1976, Classification and analysis of river processes, Journal of the Hydraulics Division, American Society of Civil Engineers, 102, HY7, 813-829.

Kellerhals, R., J. Shaw and V.K. Arora, 1975, On grain size from thin sections, Journal of Geology, 83, 79-96.

Kesseli, J.E., 1941, The concept of the graded river, Journal of Geology, 49, 561-588.

Knighton, A.D., 1975, Channel gradient in relation to discharge and bed material characteristics, Catena, 2, 263-274.

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

Knighton, A.D., 1982, Longitudinal changes in the size and shape of stream bed material : evidence of variable transport conditions, Catena, 9, 25-34.

Knox, J.C., 1976, Concept of the graded stream, In : Melhorn, W.N. and R.C. Flemal, (Eds.), Theories of Landform Development, Proceedings, 6th Annual Geomorphology Symposium, Binghamton, New York, Allen and Unwin, London, 169-198.

Krajina, V.J., 1965, Biogeoclimatic zones and classification of British Columbia, Ecology of Western North America, 1, 1-17.

Krumbein, W.C., 1934, Size frequency distribution of sediments, Journal of Sedimentary Petrology, 4, 65-77.

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

Krumbein, W.C. and L.L. Sloss, 1963, Stratigraphy and Sedimentation, Freeman, San Fransisco, 660pp.

Kuenen, Ph.H., 1956, Experimental abrasion by pebbles, 2 : Rolling by current, Journal of Geology, 64, 336-368.

Langbein, W.B. and S.A. Schumm, 1958, Yield of sediment in relation to mean annual precipitation, Transactions of the American Geophysical Union, 39, 1076-1084.

Leopold, L.B., 1970, An improved method for size distribution of stream bed gravel, Water Resources Research, 6, 1357-1366.

Leopold, L.B. and M.G. Wolman, 1957, River channel patterns, braided, meandering and straight, United States Geological Survey Professional Paper, 282-D, 35-85.

Leopold, L.B., M.G. Wolman and J.P. Miller, 1964, Fluvial Processes in Geomorphology, Freeman, San Francisco, 522pp.

Levey, R.A., 1978, Bed-form distribution and internal stratification of coarse-grained point bars, Upper Congaree River, South Carolina, In : Miall, A.D., (Ed.), Fluvial Sedimentology, Canadian Society of Petroleum Geologists, Memoir 5, Calgary, 105-128.

Levings, C.D., 1974, River diversion and intertidal benthos at the Squamish River delta, British Columbia, In : Proceedings, Symposium on the Influence of Freshwater Outflow on Biological Processes in Fjords and Coastal Waters, Geilo, Norway, April, 1974, 18pp.

Lisle, T., 1979, A sorting mechanism for a riffle-pool sequence : Summary, Geological Society of America Bulletin, 90, 616-617.

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

Mackin, J.H., 1963, Rational and empirical methods of investigation in geology, In : Albritton, C.C., (Ed.), The Fabric of Geology, Addison-Wesley, Reading, Massachusetts, 135-163.

Mathews, W.H., 1951, Historic and prehistoric fluctuations in alpine glaciers in the Mount Garibaldi map area, Journal of Geology, 59, 357-380.

Mathews, W.H., 1952, Mount Garibaldi, a supraglacial Pleistocene volcano in southwestern British Columbia, American Journal of Science, 250, 81-103.

Mathews, W.H., J.G. Fyles and H.W. Nasmith, 1970, Post-glacial crustal movements in southwestern British Columbia and adjacent Washington State, Canadian Journal of Earth Sciences, 7, 690-702.

Miall, A.D., 1977, A review of the braided-river depositional environment, Earth Science Reviews, 13, 1-62.

Middleton, G.V. and J.B. Southard, 1978, Mechanics of Sediment Transport, Society of Economic Paleontologists and Mineralogists, Short Course No. 3, Binghamton, New York, March 29-30, 1977.

Miller, J.P., 1958, High mountain streams : effects of geology on channel characteristics and bed material, New Mexico State Bureau of Mines and Mineral Resources, Memoir 4, 53pp.

Milne, J.A., 1982, Bed-material size and the riffle-pool sequence, Sedimentology, 29, 267-278.

Moore, D.P. and W.H. Mathews, 1978, The Rubble Creek landslide, southwestern British Columbia, Canadian Journal of Earth Sciences, 15, 1039-1052.

Nanson, G.C., 1980, Point bar and floodplain formation on the meandering Beatton River, northeastern British Columbia, Canada, Sedimentology, 27, 3-29.

O'Loughlin, C.L., 1972, A preliminary study of landslides in the Coast Mountains of southwestern British Columbia, In : Slaymaker, H.O. and H.J. McPherson, (Eds.), Mountain Geomorphology : Geomorphological Processes in the Canadian Cordillera, British Columbia Geographical Series No.14, Tantalus, Vancouver, 101-112.

Ore, H.T., 1964, Some criteria for recognition of braided stream deposits, University of Wyoming Contributions to Geology, 3, 1-14.

Palmer, H.S. and D.C. Traves, 1973, Comparison of gravel sampling methods, Unpublished Senior Report, Department of Civil Engineering, University of New Brunswick, Fredericton, 67pp.

Parker, G., P.C. Klingeman and D.G. McLean, 1982, Bedload and size distribution in paved gravel-bed streams, Journal of the Hydraulics Division, American Society of Civil Engineers, 108, HY4, 544-571.

Plumley, W.J., 1948, Black Hills terrace gravels : a study in sediment transport, Journal of Geology, 56, 526-577.

Potter, K.W., 1979, Derivation of the probability density function of certain biased samples of coarse river bed material, Water Resources Research, 15, 21-22.

Powers, M.C., 1953, A new roundness scale for sedimentary particles, Journal of Sedimentary Petrology, 23, 117-119.

Rana, S.A., D.B. Simons and K. Mahmood, 1973, Analysis of sediment sorting in alluvial channels, Journal of the Hydraulics Division, American Society of Civil Engineers, 99, HY11, 1967-1980.

Rogers, J.J.W., 1964, Some applications of statistical models in geologic research, Texas Journal of Science, 16, 342-349.

Rose, J., C. Turner, G.R. Coope and M.D. Bryan, 1980, Channel changes in a lowland river catchment over the last 13,000 years, In : Cullingford, R.A., D.A. Davidson and J. Lewin, (Eds.), Timescales in Geomorphology, Wiley, Chichester, 159-175.

Russell, R.D., 1939, Effects of transportation on sedimentary particles, In : Trask, P.D., (Ed.), Recent Marine Sediments, American Association of Petroleum Geologists, Tulsa, 32-47.

Ryder, J.M., 1971, The stratigraphy and morphology of paraglacial alluvial fans in south-central British Columbia, Canadian Journal of Earth Sciences, 8, 279-298.

Ryder, J.M., 1981, Geomorphology of the southern part of the Coast Mountains of British Columbia, Zeitschrift fur Geomorphologie, 37, 120-147.

Sahu, B.K., 1964, Transformation of weight frequency and number frequency data in size distribution studies of clastic sediments, Journal of Sedimentary Petrology, 34, 768-773.

Scheidegger, A.E., 1961, Theoretical Geomorphology, Springer-Verlag, Berlin, 333pp.

Schumm, S.A., 1971, Fluvial geomorphology : channel adjustment and river metamorphosis, In : Shen, H.W., (Ed.), Fluvial Geomorphology in River Mechanics, Water Resources Publication, Colorado State University, Fort Collins, 5.1-5.22.

Schumm, S.A. and R.W. Lichty, 1965, Time, space and causality in geomorphology, American Journal of Science, 263, 110-119.

Schumm, S.A. and M.A. Stevens, 1973, Abrasion in place : a mechanism for rounding and size reduction of coarse sediment in rivers, Geology, 1, 37-40.

Scott, K.M. and G.C. Gravlee, 1968, Flood surge on the Rubicon River, California - Hydrology, hydraulics and boulder transport, United States Geological Survey Professional Paper, 422-M, 38pp.

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

Shulits, S., 1941, Rational equation of river bed profile, Transactions of the American Geophysical Union, 22, 622-631.

Slaymaker, H.O., 1972, Sediment yield and sediment control in the Canadian Cordillera, In : Slaymaker, H.O. and H.J. McPherson, (Eds.), Mountain Geomorphology : Geomorphological Processes in the Canadian Cordillera, British Columbia Geographical Series No.14, Tantalus, Vancouver, 235-245.

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

Souther, J.G., 1980, Geothermal reconnaissance in the central Garibaldi Belt, British Columbia, Current Research, part A, Geological Survey of Canada, Paper 80-1A, 1-11.

Stathers, J.K., 1958, A geographical investigation of development potential in the Squamish Valley region, British Columbia, Unpublished M.A. Thesis, Department of Geology and

Geography, University of British Columbia, 194pp.

Sternberg, H., 1875, Untersuchungen uber Langen - und Querprofil geschiebefuhrender Flusse, Zeitschrift fur Bauwesen, 25, 483-506.

Stevens, M.A., D.B. Simons and E.V. Richardson, 1975, Nonequilibrium river form, Journal of the Hydraulics Division, American Society of Civil Engineers, 101, HY5, 557-566.

Stewart, J.H. and V.C. LaMarche, 1967, Erosion and deposition in the flood of December 1964 on Coffee Creek, Trinity County, California, United States Geological Survey Professional Paper, 422-K, 22pp.

Sundborg, A., 1956, The River Klaralven - A study of fluvial processes, Geografiska Annaler, 38A, 127-316.

Swan, D., J.J. Clague and J.L. Luternauer, 1978, Grain-size statistics 1 : Evaluation of the Folk and Ward graphic measures, Journal of Sedimentary Petrology, 48, 863-878.

Walker, R.G. and D.J. Cant, 1979, Facies models 3 : Sandy fluvial systems, In : Walker, R.G., (Ed.), Facies Models, Geoscience Canada, Waterloo, Ontario, 23-31.

Water Survey of Canada, 1973, Flow data for the Squamish, Cheakamus, Mamquam and Stawamus rivers, Water Survey of Canada Unpublished data, 48pp.

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

Wentworth, C.K., 1922, A scale of grade and class terms for clastic sediments, Journal of Geology, 30, 377-392.

Williams, P.F. and B.R. Rust, 1969, The sedimentology of a braided river, Journal of Sedimentary Petrology, 39, 649-679.

Wilson, I.G., 1973, Equilibrium cross-section of meandering and braided rivers, Nature, 241, 393-394.

Wolman, M.G., 1954, A method of sampling coarse river-bed material, Transactions of the American Geophysical Union, 35, 951-956.

Wolman, M.G. and R. Gerson, 1978, Relative scales of time and effectiveness of climate in watershed geomorphology, Earth Surface Processes, 3, 189-208.

Wolman, M.G. and J.P. Miller, 1960, Magnitude and frequency of forces in geomorphic processes, Journal of Geology, 68, 54-75.