LAKE SEDIMENTS AS RECORDS OF PALAEOENVIRONMENTAL CHANGE:
KWOIEK CREEK, COAST MOUNTAINS, BRITISH COLUMBIA

By

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ABSTRACT

It has been suggested that the dominant controls on alpine sediment transfers during the Holocene Epoch relate to climate change, specifically paraglacial sedimentation and Neoglacial activity. Alpine lakes with appropriate geometry and hydraulic conditions trap a high proportion of sediments inflowing from their surrounding drainage basins. Thus alpine lake sediments have the potential to yield a comprehensive, integrated signal of drainage-basin geomorphic activity through time, which may be interpreted as a proxy record of Neoglacial activity.

This study is concerned with the interpretation of alpine lake sediments in glacierized drainage basins as records of Neoglacial activity. It adopts an explicitly geomorphological approach that integrates an understanding of the drainage basin sedimentary system, specifically sediment sources and transfers, with the interpretation of lake sediment deposits and extends existing models of alpine sedimentary response down-valley, away from the immediate proglacial environment.

A down-valley sequence of four valley bottom lakes, Kha, Klept, Kokwaskey and Kwoiek, within the Kwoiek Creek watershed, southeastern Coast Mountains of British Columbia, were studied. Sub-bottom sounding and multiple cores from each lake allowed identification of lake-wide changes in sediment input through time; in addition terrain mapping and characterisation of sediment sources provided a framework within which to identify the sources of the lake sediments and their fluctuations through time.

Preliminary characterization of the sediments broadly separated organic and clastic components. Detailed laboratory analyses revealed organic matter content to be a good inverse indicator of sedimentation rates. Grain size analyses revealed three distinct textural populations.
Graphical partitioning of the cumulative grain size distributions identified each fraction for further analysis. The provenance of the coarsest and intermediate fraction was determined through SEM surface texture analysis of a statistically representative number of grains. The coarsest fraction was derived from localized colluvial sources. The intermediate fraction was derived from glacial sources and strongly filtered downsystem. The finest fraction was characterised as glacial in origin because of consistent trends in its variability at the drainage basin scale through time. Fluctuations in the total influx of the intermediate and finest fractions are interpreted as a proxy record of Neoglacial activity in the watershed. Analysis of persistence in the sedimentation data indicates history of the order 100 yrs, which is interpreted as an index of the relaxation time of sedimentary stores.

Basal dates on the sediments provide the earliest dates for deglaciation in the southern Coast Mountains, suggesting that extensive areas of southwestern British Columbia were ice free prior to 11 500 B.P. Three phases of Neoglacial activity centred 6000 to 5000 B.P., 3500 to 2900 B.P. and post 750 B.P are suggested by increased sedimentation rates for glacially-derived material. When compared with reconstructions from a pollen study conducted within the watershed and regional chronologies reported in the literature, there is remarkable consistency.

The major advantage of the lake sediment approach as developed in this study is the continuity and apparent sensitivity of the derived proxy records. These records permit a consideration of both the magnitude and frequency of palaeoenvironmental change, specifically Neoglacial activity, at one site. Such a record has not been found elsewhere in British Columbia, where discontinuous terrestrial records have been used.
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CHAPTER 1  INTRODUCTION

This study is concerned with the interpretation of alpine lake sediments in glacierized drainage basins as records of palaeoenvironmental conditions over timescales of $10^2$-$10^3$ yrs. The study adopts an explicitly geomorphological approach which integrates an understanding of the drainage basin sedimentary system, specifically sediment sources and transfers, with the interpretation of lake sediment deposits. The emphasis is both methodological, the development of techniques and analyses to document and interpret changes in the palaeo-sediment system through sediment source and sink analysis; and substantive, in its interpretation of a variety of sedimentary signals to obtain a greater understanding of Holocene palaeoenvironmental history of southern British Columbia.

1.1 The alpine sediment system as a framework for timescales of $10^3$ yrs

The movement of sediment through a drainage basin may be envisaged as a cascade of material moved episodically between storages by a suite of transfer processes. The "alpine sediment system" provides a conceptual framework within which to view the associated processes of weathering, erosion, transport and deposition, emphasising sediment transfer processes and incorporating glacial, fluvial, aeolian and slope processes. A highly schematic representation highlighting sediment sources and storage points is presented in Figure 1.1 (adapted from Church, 1980). As a framework it enables integration between processes (climatological, biological, geomorphological, hydrological) and between places (supraglacial, glacial, subglacial, proglacial) (Gurnell & Clark, 1987).

Alpine sediment transfers vary in time, the nature of the variability depending on temporal scale. At the Holocene timescale the dominant controls relate to climate change, specifically paraglacial sedimentation
Figure 1.1 Schematic representation of main sediment transfer patterns and storages in alpine watersheds (adapted from Church, 1980). Emphasis on sediment sources and sinks. The transfer pathways are greatly simplified.
from late Wisconsinan glaciation and Neoglacial activity (Church, 1980). During the second half of the Holocene Epoch many mountain areas, particularly in mid-latitude and mid-altitude locations, have undergone repeated periods of glacial advance and retreat (Grove, 1988), with associated contrasts in the glacio-hydrological (Rothlisberger & Lamb, 1987) and sediment systems (Johnson, 1982). The general phasing of changes in a glaciated sediment system has been codified by Church and Ryder (1972) in the framework of paraglacial sedimentation. This model focuses attention on the importance of considering sediment dynamics and interpreting the sedimentary record against a background of glacial forcing and relative chronology. The underlying assumption of the paraglacial concept is that glaciation represents a fundamental change in the terrestrial erosional environment such that major quantities of sediment are produced in the form of glacial drift. This material may have attained stability within the glacial depositional environment, but is unstable with respect to the fluvial environment that succeeds the glacier spatially and temporally. Thus the proglacial and postglacial rivers evacuate the glacial sediment at a rate that is far in excess of the "normal" material supply expected in nonglacial environments. For periods up to several thousand years, sediment yield of large regions is unrelated to the concurrent primary production of debris by non-glacial processes (Church & Slaymaker, 1989). Thus a change from glacial to non-glacial conditions initiates a series of significant changes as the various components of the system adjust at different rates to the altered and altering environment. Inevitably there will ensue marked changes in the rate and pattern of sediment production and transfer, reflecting the sensitivity of the system in a phase of disequilibrium, that should be
recorded in the deposits in sediment stores. Over the Holocene Epoch, at timescales of the order $10^2$ to $10^3$ yrs, sedimentary records in glacierized alpine drainage basins should provide a continuous palaeoenvironmental record that reflect variations in Neoglacial forcing of the sediment cascade and paraglacial reworking.

Downstream from the immediate proglacial environment it becomes important to consider the fact that changes in sediment properties reflect both a direct glacial effect and a secondary geomorphic control, namely other sediment transfer processes and sediment traps operative in the drainage basin (see Figure 1.1). Sediment sources other than glacial meltwater streams may contribute significantly to the sedimentary record as a consequence of subaerial weathering and episodic mass movement events. In steep terrain, mass movements (slumps, earthflows, creep, debris avalanches etc) provide sediment to the fluvial system where entrainment by flowing water may occur. In other instances, more rapid flow phenomena (debris flows, debris torrents etc) are significant sources of material for a channel system. These introduce considerable variability to the sediment record at timescales $10^0$-$10^1$ yrs.

Interpretation of sediment records in terms of palaeoenvironmental conditions is possible only if the full range of processes governing sedimentation at appropriate temporal and spatial scales is understood. This permits the sedimentary signals of interest to be isolated, and models of sedimentary response with suitable forcing functions, boundary conditions and lags can be formulated. The nature of the variability of alpine sediment transfers, and more generally, the effect of reworking of glacial and colluvial deposits on down-valley sedimentation over timescales of the order $10^2$-$10^3$ yrs has been little considered, and is the
focus of this study.

1.2 Alpine sedimentary records

The late Quaternary stratigraphic record of British Columbia is largely a product of brief depositional events that were separated by long periods of non-deposition and erosion (Clague, 1986). At the broadest regional scale glaciation has been characterised by deposition and non-glacial periods by non-deposition and erosion. When viewed in a spatial framework, geologically significant sedimentation i.e. that which produces deposits capable of being preserved in the stratigraphic record, has been restricted to particular parts of the British Columbia landscape. The main terrestrial sediment "sinks" have been valleys and coastal lowlands, while mountains and uplands have been areas of erosion (Clague, 1986). As a consequence, the stratigraphic record of the Holocene Epoch in alpine environments is restricted to lakes and mountain valleys. Many investigators (see for example the pioneering work of de Geer (1912), Antevs (1922); and more recently Schytt (1963), Cewe and Norbbin (1965), Norbbin (1973), Karlen (1976, 1981), Davis et al (1979), Leonard (1986 a,b) and Zelinski & Davis (1987)) have suggested that the glacial sedimentary records in alpine lakes exceed the sensitivity, resolution and continuity of the terrestrial record upon which Quaternary stratigraphers have traditionally relied.

The basic premise of such studies is that lakes with appropriate geometry and hydraulic conditions trap a high proportion of inflowing particulates from their surrounding catchments, thus yielding a comprehensive, integrated signal of drainage-basin scale geomorphic activity (Oldfield, 1977). The location and size of a lake relative to its contributing area, in addition to the hydraulics of the system, dictate
the sensitivity and resolution of the record. When considered in this context lake sediments may be viewed as the most significant sediment store in the watershed sediment cascade. If their study is combined with a consideration of sediment sources and transfer processes, lake sediments provide an opportunity to determine temporal variability of sediment movement in a catchment in terms of both volume and provenance, thereby providing a basis for integrated insight into variations of the alpine sediment system at several timescales.

Attempts to model the sedimentary response of alpine lakes have been largely restricted to the immediate proglacial environment. Many studies have been conducted on controls of annual, and to a lesser degree, daily sediment yield variations, for example Ostrem (1975), Perkins & Sims (1983), Weirich (1985) and Gilbert & Desloges (1987). These investigations stress the importance of hydroclimatic factors, specifically runoff, which is largely a function of snow and ice melt rates. At longer timescales ($10^1$-$10^2$ yrs), available data indicate that sedimentation rate variations bear a close relation to ice extent, suggesting that these longer term changes are of value for reconstructing glacial activity (Karlen, 1976, 1981; Leonard, 1986 a,b). At these timescales, rates of glacial erosion have much more influence on downvalley sedimentation rates, and the availability of meltwater for sediment transport is less of a limiting factor (Leonard, 1981). Given the logistical constraints of obtaining long sediment records in proglacial environments, Karlen (1976) suggests that it is expedient to study deposits in lakes with a lower input of glacial sediment. These may be lakes in drainage basins where the area covered by glaciers is small in comparison with the area where the glacial sediment will eventually settle, or downvalley lakes where there has been some
attenuation of the glacial signal of interest. Such downvalley lakes are the focus of this study.

Lake sediments "in situ" are a consequence of complex interactions between mechanisms of deposition, resuspension, chemical and biogenic transformation, and longer term diagenesis. Moreover sediment accumulation in open lakes is a function of the relation between input and loss through the outflow: this is in turn related to sediment type, residence time and lake morphometry. Changes in the mode of sediment input to a lake may affect the dispersal of incoming sediment and have profound effects on deposition patterns. These may arise, for example, as a consequence of changes in the distributary pattern on a delta, or different modes of sediment delivery (see for example, Smith et al., 1982). Alterations in the relative contributions of overflows or underflows result from changes in the physical limnology and stratification regime of a lake, possibly as a consequence of changes in the bathymetry of the lake due to sedimentation and infilling.

Thus in developing a descriptive, downvalley, drainage basin scale model of lake-sediment character it becomes necessary to consider two scales of controls: those operating on sediment sources in the watershed (i.e. driving forces of transfer processes and resistance of the terrestrial materials); and those related to the nature of the depositional environment. The approach proposed in this study to resolve and understand these controls at timescales of $10^2$-$10^3$ yrs, is to document sedimentary changes at a drainage basin scale by studying a number of lakes in a downvalley sequence, with multiple cores taken from each lake (c.f. Dearing, 1982). This approach permits basin-wide chronologies to be constructed ensuring that localised changes not be misinterpreted.
1.3 Objectives

It is the contention of this study that fluctuations in the glacially driven sedimentation signal and its attenuation by non-glacial inputs at the drainage basin scale can be identified within the framework of the alpine sediment system, by analysis of sediment source, pathway, and lake-sediment sink. Characteristic physical and chemical processes in sediment production, transfer and storage impart distinctive traits to the sediments which, if identified, can be used to reconstruct, quantify and interpret flows of material. Thus an understanding of the palaeo-sediment system can be attained, which is important not only for a contingent understanding of the functioning of the contemporary alpine sediment system, but is fundamental to the use of alpine sedimentary records for palaeoenvironmental reconstructions.

Specifically this study involves:

1. Analysis of drainage basin sediment sources in conjunction with the lake sedimentary record in order to develop a methodology to document and interpret changes in characteristics and processes of sedimentation in a chain of alpine/sub-alpine lakes during the Holocene Epoch in southern British Columbia. This permits isolation of the glacial sediment signal of interest from colluvial, fluvial and aeolian sediment inputs.

2. Development of a descriptive model for the Holocene Epoch of lacustrine sedimentary response to fluctuations in Neoglacial forcing in downvalley lakes in alpine/subalpine watersheds at timescales of the order $10^2$ to $10^3$ yrs. From the model of paraglacial sedimentation it would be expected that the rate of sedimentation and the relative contribution of glacial sediment has fluctuated through time, decreasing
down-system, with an associated decrease in sensitivity and increase in lag time of sedimentary response.

3. Comparison of these patterns/processes with a local palynological study conducted within the basin, and glacial and climatic history derived from literature sources, in order to assess their consistency with more conventional lines of evidence.

The structure of the thesis is designed to highlight these objectives. Chapters 2 and 3 provide contextual information in terms of the study area, identification of sediment sources, and establishment of continuity in the contemporary sediment cascade. Chapter 4 outlines the methodology developed to interpret the sedimentary signal, which identifies distinct components of the lake sediment record and documents their source. Chapter 5 presents the temporal trends and develops a descriptive model of palaeoenvironmental change which is assessed for consistency with regional data from more conventionally used lines of evidence in Chapter 6. Chapter 7 presents the methodological and substantive conclusions of the study. Appendix I presents the lithostratigraphies of lake cores and their cross-correlation, Appendix II the techniques used to develop a chronology, and Appendix III lists data and results. Details of methods are introduced into the text where appropriate rather than being separated into a separate chapter in order to make the arguments for the sequencing of the analyses undertaken in the study clearer.
CHAPTER 2  THE STUDY SITE

This chapter presents the rationale for the selection of the study area, its physiography, geology, vegetation, hydroclimate and contemporary geomorphology. The dominant sediment sources and transfers that deliver sediment to each of the lakes studied are identified in order to provide the framework pursued in Chapter 4 for the characterization of sediment sources.

2.1 Selection of the Kwoiek Creek watershed

Not all lakes provide equally continuous or sensitive records of environmental change. Therefore the selection of the study site was a critical step in the investigation. The Kwoiek Creek watershed (latitude 50°03'N to 50°12'N, longitude 121°35'W to 122°00'W) (Figure 2.1) was initially selected for three reasons. First, within the watershed there are two chains of lakes that are glacially fed, and through which, in principle, it is possible to document changes in sedimentation downstream from glacial to non-glacial environments. Second, approximately 10% of the catchment is currently glacierized, and glaciers would be expected to have existed throughout the Holocene Epoch (as will be demonstrated later). Third, the drainage basin is relatively accessible as a consequence of extensive logging activity in the last two decades.

This study required a watershed with a strong glacial signal. For this reason the southern portion of the drainage basin, fed by Kwoiek Glacier, was selected for investigation (Figure 2.1). It was also important that sedimentation be continuous over the Holocene Epoch with no unconformities in the lake sediment record. This is more likely in lakes constrained at their outlet by a rock sill, than in those dammed by a moraine, or a colluvial or alluvial fan. Fans may have blocked the valley, and thus
Figure 2.1 The Kwoiek Creek watershed
formed the lake, at any stage during the Holocene. Furthermore they may have been susceptible to episodic failure resulting in lake drainage, erosion of the sediments, and unconformities in the record. In addition, the resolution and length of the sedimentary record encompassing the Holocene is important, given the logistical constraints of retrieving long cores and the difficulties of working in very deep lakes, within a mountain watershed. Ideally, lakes with steep-sides and flat bottoms, conditions conducive to minimum post-depositional slumping, and lakes which do not mix to their base, thereby minimising post-depositional disturbance of the sediments, are desirable. For all these reasons the chain of lakes Kha, Klept, John George and Kwoiek was selected. Kokwaskey Lake was also studied in an attempt to document the signal from the Haynon, Chochiwa, Kokwaskey Lake chain (see Figure 2.1) and to isolate this chain's effect on the sedimentary record of the distal Kwoiek Lake.

2.2 The catchment

The Kwoiek Creek watershed is a 250 km$^2$ drainage basin, located on the eastern side of the Coast Mountains (Figure 2.1). Approximately 40% of the watershed currently is above tree line and 10% is glacierized. Kwoiek Creek flows a linear distance of 32 km, west to east, originating in the Kwoiek and Chochiwa glaciers, with a number of smaller nonglacial tributaries, the most important of which are shown on Figure 2.1.

The topography of the watershed is characteristic of the eastern Coast Mountains. It has high relative relief, with most summits and ridge crests above 2000 m. The highest peak is Skihist Mountain (2944 m), on the divide with the Stein watershed; the lowest point, approximately 150 m, the valley floor at the confluence with Fraser River. The valley-side slopes are steep, average gradient 31°, (0.6 m m$^{-1}$) (determined randomly using a
1 cm grid overlay) although they may be much steeper over short distances, with vertical rock faces common.

2.3 Geology

Bedrock of the Lytton map area was mapped by Duffell and McTaggart (1952) and Monger (1980-1982). The generalised geology for the Kwoiek Creek watershed is shown in Figure 2.2. Much of the Kwoiek Creek basin is underlain by coarse grained granodiorite of the Coast Plutonic Complex. The granodiorite is not homogeneous, but varies with regard to mineralogy, content and lithology of inclusions (granite, schist, and others), and degree of foliation. It is typically massive with widely spaced joints. Mechanical weathering produces large, blocky fragments and extremely coarse debris. In some places sheet structures resulting from unloading are well developed and give rise to smooth, slightly convex rock faces upon which exfoliation is occurring, for example, the northern valleyside in the Kwoiek Creek watershed, upstream from Fraser River.

Areas of the drainage basin are underlain by low-grade metamorphosed stratified rocks. The largest of which are belts of northwest-southeast striking rocks of the Relay Mountain Group, consisting primarily of thinly bedded or laminated, slightly dipping phyllite, argillite, conglomerate and greywacke, and low grade greenschist of the Bridge River complex (Figure 2.2) (for full description see Monger 1982). In most places rounded ridges and summits have developed on these rocks, but some fresh glacial forms persist, for example, Kwoiek Needle.

2.4 Physiography and regional glacial history

The extensive plateaus north of Stein Mountain, as well as the accordant summits to the northwest of the catchment are relics of the original
Figure 2.2 Bedrock geology of the Kwoiek Creek watershed
(Source information: Monger, 1982; GSC Open File 980, Ashcroft)
uplifted land surface of low relief that was dissected by late Tertiary rivers (Mathews, 1968). Evidence of glacial erosion within the catchment is marked. Most valleys are typically glacial troughs, with cirques, horns, aretes and tarns common above 1800m.

At the onset of Fraser glaciation the Kwoiek icefield area probably was an ice accumulation and dispersal zone. Advancing glaciers flowed eastward to Fraser River valley. During the glacial maximum, however, ice was deflected to the south or southeast across the Coast Mountains by a broad zone of southerly and southeasterly flowing ice that occupied the Fraser and Thompson plateaus. The presence of erratics in the Coast Mountains near Kwoiek Creek drainage basin indicates the surface of Pleistocene ice sheets at elevations up to 2300 to 2500 m (Duffell and McTaggart, 1952). At this time the flow directions were controlled more by ice sheet surface topography than by the underlying valleys (Davis & Mathews, 1944). Because of their proximity to the ice divide the glaciers in the vicinity of the Kwoiek watershed during Pleistocene glaciations were relatively incapable of extensive erosion or transportation at the time of the glacial maximum. Deglaciation in this area probably was characterised by recession of active valley glaciers, not downwasting, which predominated further from the source (Fulton, 1971). A more precise chronology of deglaciation is discussed later in the context of new data collected as part of this study (section 6.1).

Glacial fluctuations during the Holocene Epoch have been documented for a number of locations in the southern Coast Mountains (Ryder and Thomson, 1986) based on moraine chronologies (see more detailed discussion in Chapter 6). Evidence for an early Neoglacial advance (Garibaldi Phase) approximately 5000 years B.P. in southwestern British Columbia has been
found only in the mountains of the Garibaldi Park region. Investigators have documented a second advance between 3000 and 1800 years ago (see for example, Ryder & Thomson, 1986). This varied in intensity, duration and timing between regions but it is evident throughout the coastal region from Alaska to Oregon. Ice advances that commenced about 1000 years B.P., with maximum positions attained in the nineteenth century, were the most pronounced during the Holocene Epoch in most regions. A regionally synchronous response of glaciers seems to have occurred during recession from these Little Ice Age maxima, beginning 100 to 350 years ago. Only the moraines of the most recent Neoglacial event are found in Kwoiek Creek watershed. The Holocene Epoch Neoglacial fluctuations are documented in greater detail in Chapter 6 (Table 6.3).

2.5 Contemporary climate

The watershed lies in the lee of the Coast Mountains, climatically intermediate between the mountain and interior systems. The relative aridity of the eastern side of the Coast Mountains dampens the glacial activity seen in the Pacific Ranges further to the west. Precipitation decreases eastward and increases with elevation. No climate data have been collected from within the watershed but the range of precipitation and temperature can be estimated from stations in the region (see Table 2.1; locations shown on Figure 2.3). Extensive glaciers and snow fields lie in the southwest of the Kwoiek Creek watershed, where a relatively large névé with several glacier tongues occupies an area of approximately 26 km$^2$. Winter frontal precipitation predominates. Compounding the effects of synoptic-scale circulation are local and regional topographic controls on temperature and precipitation.

No river gauges are operative within the watershed. The hydrology is
### Table 2.1 A summary of selected climate statistics for stations closest to the Kwoiek Creek watershed

<table>
<thead>
<tr>
<th>Station</th>
<th>Mean T</th>
<th>Max T</th>
<th>Min T</th>
<th>Rain</th>
<th>Snow</th>
<th>Total</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alta Lake</td>
<td>5.7</td>
<td>22.9</td>
<td>-7.7</td>
<td>836.9</td>
<td>608.6</td>
<td>1420.3</td>
<td>226.1</td>
</tr>
<tr>
<td>(50 09° N 122 59° W 59 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bralorne</td>
<td>4.1</td>
<td>22.7</td>
<td>-12.0</td>
<td>375.3</td>
<td>271.3</td>
<td>636.3</td>
<td>132.1</td>
</tr>
<tr>
<td>(50 47° N 122 49° W 1015 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chilliwack</td>
<td>10.2</td>
<td>24.3</td>
<td>-1.5</td>
<td>1750.7</td>
<td>129.4</td>
<td>1880.4</td>
<td>349.0</td>
</tr>
<tr>
<td>(49 07° N 122 06° W 6 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hells Gate</td>
<td>9.2</td>
<td>26.8</td>
<td>-4.8</td>
<td>1009.1</td>
<td>188.5</td>
<td>1198.9</td>
<td>201.8</td>
</tr>
<tr>
<td>(49 47° N 121 27° W 122 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hope</td>
<td>9.7</td>
<td>24.4</td>
<td>-3.1</td>
<td>1539.5</td>
<td>192.6</td>
<td>1715.8</td>
<td>346.9</td>
</tr>
<tr>
<td>(49 22° N 121 29° W 39 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lytton</td>
<td>10.0</td>
<td>29.4</td>
<td>-6.3</td>
<td>326.8</td>
<td>162.5</td>
<td>467.3</td>
<td>80.4</td>
</tr>
<tr>
<td>(50 14° N 121 34° W 175 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pemberton Meadows</td>
<td>7.0</td>
<td>26.2</td>
<td>-9.0</td>
<td>638.3</td>
<td>283.4</td>
<td>990.2</td>
<td>184.0</td>
</tr>
<tr>
<td>(50 27° N 122 56°W 223 m)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 Mean annual temperature - average of the 12 monthly values
2 Mean monthly maximum - mean of all daily maximum temperatures recorded for a particular month (in all cases data for July)
3 Mean monthly minimum - mean of all daily minimum temperatures recorded for a particular month (in all cases data for January)
4 Rainfall (mm)
5 Snowfall - water equivalent (mm)
6 Total precipitation (mm)
7 Standard deviation of precipitation
8 Station location - Latitude, Longitude, Elevation

Data from Environment Canada (1982) Canadian Climate normals, 1951-1980
Figure 2.3 Location of climate stations referred to in Table 2.1

1. Alta Lake
2. Bralorne
3. Chiliwack
4. Hells Gate
5. Hope
6. Lytton
7. Pemberton Meadows
strongly influenced by spring snowmelt, modulated by storage in the lakes, the levels of which fluctuate approximately 0.3 - 0.5 m over the course of a year. Discharge peaks in late April to July due to snowmelt. An estimate of maximum snowmelt, assuming all available radiant energy is utilised (further assumptions outlined by Church, 1988), is of the order 43 mm/day, or a discharge $75 \text{ m}^3 \text{ s}^{-1}$ at the head of Kwoiek Lake. This is undoubtedly a very high estimate for the catchment given the steep slopes and tree cover. An estimate of $50 \text{ m}^3 \text{ s}^{-1}$ may be more realistic. A mean annual flood of $22.5 \text{ m}^3 \text{ s}^{-1}$ and a maximum daily flow of $97.5 \text{ m}^3 \text{ s}^{-1}$ for flows entering Kwoiek Lake were computed using regional envelope curves for the Cascade Mountains (Church, personal communication). The curves for the Cascade Mountains were selected to be more representative than those for the Coast Mountains because of the location of the Kwoiek Creek watershed in the lee of the Coast Mountains. Undoubtedly these values are overestimates for Kwoiek Creek because of the storage effects of the lakes.

2.6 Vegetation

Three major biogeoclimatic zones can be identified within the watershed (see Figure 2.4). Source information is derived from Ministry of Forests, Research Branch 1:125 000 map sheets of biogeoclimatic zones, and Ministry of Forests, Inventory Branch, 1:20 000 Forest Cover maps. In the valley bottom subcontinental Interior Douglas Fir (*Pseudotsuga menziesii*) predominates (IDF zone) with Engelmann spruce (*Picea engelmannii*), ponderosa pine (*Pinus ponderosa*), lodgepole pine (*Pinus contorta*), mountain hemlock (*Tsuga mertensiana*), western hemlock (*Tsuga heterophylla*), birch (*Betula*) and *Populus*, with an understorey of *Ribes*, *Acer circinatum*, *Paxistima myrsinites*, *Arctostaphylos uva-ursi*, and *Ceanothus velutinus*. At mid elevations subcontinental Engelmann spruce and
Figure 2.4 Vegetation cover of the Kwoiek Creek watershed
(Source information: Ministry of Forests, Forest Service Research Branch, Biogeoclimatic units, July 1980, Lytton Sheet, 1:125 000).
subalpine fir (Abies lasiocarpa) predominates (ESSF zone), with lodgepole pine and Douglas fir, and an understorey of Vaccinium, Ribes, Rhododendron, Equisetum, Juniperus, Valerian sitchensis, Paxistima myrsinites, Veratrum viride. Tree line elevation is approximately 1700 m, but it varies with changes in aspect, slope stability and microclimate and may be as high as 2000 m on south-facing slopes. At the highest elevations in the basin there is an association of alpine tundra/englemann spruce/subalpine fir parkland, with Lupinus arcticus, Potentilla flabellifolia, Pulsatilla occidentalis, Phyllodoce empetriformis, Erigeron peregrinus, Valerian sitchensis. Logged slopes are revegetated primarily by shrubs, herbs, bryophytes and young conifers, while logged stream banks of valley flats support a dense cover of black cottonwood (Populus balsamifera) and alder (Alnus rubra) interspersed with young conifers and an understorey of shrubs and herbs.

2.7 Contemporary geomorphology and sediment transfer processes

As a prerequisite to interpreting changes in lake basin sedimentation the sediment sources and processes of sediment transfer within the watershed were examined. A map of surficial materials is presented (Figure 2.5), adapted from Ryder (1976), from which it is possible to identify primary sediment sources and transfer processes delivering sediment to the lakes. Map units (see Figure 2.5) are delimited according to the character of the surficial materials. The emphasis is thus on sediment stores and their genesis. Materials are divided according to the mode of origin (genesis) and surface expression in accordance with the system developed by the B.C. Ministry of Environment (Ryder & Howes, 1984). Essentially four units are identified on Figure 2.5: rock outcrops/cliffs; talus/debris cones; colluvial blankets and veneers; and moraine/till.
Figure 2.5 Surficial geology of the Kwoiek Creek watershed (adapted from Ryder, 1976)
Rock outcrops/cliffs refers to bedrock outcrops or sites where rock is covered by only a thin mantle of drift or colluvium. Colluvium includes most postglacial accumulations of mass wasted materials. This unit is subdivided into talus/debris cones and blankets/veneers on the basis of surface expression. The talus/debris cones are composed of coarse angular fragments which have either fallen or crept downslope and usually have an obvious source above. In the Kwoiek Creek watershed the veneers/blankets of colluvial material typically occur on steeper (20° to 33°) slopes than those covered by till.

The local mantle of till is of local provenance. Generally it is discontinuous and restricted to valley-sides at relatively low elevation and gradients, but in many places it underlies avalanche deposits and rubbly postglacial colluvium on slopes of intermediate elevation and steepness (for example, in the vicinity of Kha and Klept Lakes). Granitic rocks underlying the headwaters of the watershed have given rise to coarse grained tills and moraines that are pale grey to white in colour, with subrounded boulders and cobbles in a matrix of gritty sand and minor silt. Little Ice Age moraines at the head of the Kwoiek Creek watershed are composed of blocks up to 1 m in diameter.

Valley-fill includes glacial, glacio-fluvial and alluvial facies. Prominent late glacial recessional moraines are not present. In the vicinity of creeks, especially on the north side of the watershed, ice-contact gravels are evident. In other locations crude bedding indicates material of glacio-fluvial origin. Given the resolution of the terrain map drawn in this study these are not mapped as a separate unit and are found primarily in those areas mapped as moraine/till. The alluvial materials are moderately well sorted and consist chiefly of bedded gravel with
interstitial sand. Clasts are rounded or subrounded and vary in size from pebbles to boulders, with sand and minor silt interbedded. The stream channels are floored with cobbles and gravels. The surficial materials sustain poor soil development with orthic regosols to poorly developed eutric brunisols present.

Three generalised sources of sediment for the lakes can be identified: recent (Little Ice age) glacial deposits; in situ weathered bedrock (eluvium) which may be mobilised (colluvium); and, "older" clastic material (for example, till, glacio-fluvial deposits) which mantle the hillslopes and infill gullies, which were deposited during the late Pleistocene Epoch. These materials may be mobilised by mass wasting (rockfall/rockslide, avalanche, debris flow, gully wash, soil creep) and fluvial processes, and delivered to the fluvial system and thus to the lakes. Evidence of aeolian transport and deposits is rare. An important common characteristic of all the sediment sources is their coarse sand to silt texture.

Storage of material occurs in small fresh morainal ridges close to present glacier termini, colluvial deposits, Fraser Glaciation drift, floodplains and partly infilled lakes. Associated with each sedimentary environment are specific chemical and physical processes that impart distinct characteristics to the sediments. If identified, these can be used to reconstruct, quantify and interpret provenance of material. This approach is exploited in Chapter 4 in order to characterise the sources and transfer pathways of sediments deposited in the lakes.

2.8 Anthropogenic activity

The major anthropogenic disturbance within the catchment that has influenced the flux of clastic sediment has been logging by BC Forest
Products (Fletcher Challenge) since 1971. The chronology of logging road construction is presented in Appendix II, as it provides a means of dating disturbed sediments within the lakes.
CHAPTER 3 COLLECTION OF FIELD DATA AND PRESCREENING OF CORES

This chapter presents information on the contemporary physical limnology and sedimentation patterns in the lakes, the selection of sampling sites to obtain the sediment cores, the coring procedures, and the methodology subsequently used to analyse the cores. The methodology followed was similar for all lakes; any specific differences are noted.

3.1 The lakes

Physical sedimentation in small mountain lake basins is influenced by a large number of variables. These include basin morphometry, discharge and density of inflow, quantity and variability of sediment input, circulation and vertical density structure of the water body, presence or absence of winter ice, and biological factors such as burrowing and sediment-ingesting organisms. Data, in various forms, were collected for each of these characteristics in order to describe the contemporary limnology of the lakes and to learn something of present day dispersal and sedimentation patterns, and the nature of the continuities in the contemporary sediment system.

3.1.1 Morphometry

The bathymetry of each of the lakes was mapped with a 50 kHz RayJeff MX2550 echo sounder. Multiple transects were run in each lake, with navigation by "dead reckoning" between known points identified on aerial photographs. Intersecting transects were made wherever possible to cross check profile locations by comparing similar bottom features and configurations. The morphometric characteristics of each of the lakes are presented in Figures 3.1 to 3.4 and Table 3.1. The areas and volumes of the lakes shown in Table 3.1 were determined by planimetry of the
Figure 3.1  Bathymetry of Kha Lake and coring locations
Figure 3.2 Bathymetry of Klept Lake and coring locations
Figure 3.3 Coring and Ekman sampling sites within Kokwaskey Lake. Problems with sounding equipment prevent bathymetry of the lake from being determined. The values next to each of the core sites indicate water depths determined with a plumb line.
Figure 3.4 Bathymetry of Kwoiek Lake and coring locations
Note different scale to earlier lakes
Table 3.1 Physical characteristics of the lakes

<table>
<thead>
<tr>
<th></th>
<th>Kha Lake</th>
<th>Klept Lake</th>
<th>Kokwaskey Lake</th>
<th>Kwoiek Lake</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>50°08'00&quot;N</td>
<td>50°08'00&quot;N</td>
<td>50°07'00&quot;N</td>
<td>50°07'30&quot;N</td>
</tr>
<tr>
<td>Longitude</td>
<td>122°52'45&quot;W</td>
<td>122°51'45&quot;W</td>
<td>122°50'00&quot;W</td>
<td>122°45'10&quot;W</td>
</tr>
<tr>
<td>Area (x10^3 m^2)</td>
<td>83.5</td>
<td>89.4</td>
<td>406.6</td>
<td>244.6</td>
</tr>
<tr>
<td>Max length (m)</td>
<td>440.0</td>
<td>460.0</td>
<td>1279.0</td>
<td>1062.5</td>
</tr>
<tr>
<td>Max width (m)</td>
<td>290.0</td>
<td>230.0</td>
<td>460.0</td>
<td>300.0</td>
</tr>
<tr>
<td>Max depth (m)</td>
<td>10.6</td>
<td>9.7</td>
<td>-</td>
<td>7.1</td>
</tr>
<tr>
<td>Mean depth (m)</td>
<td>4.9</td>
<td>4.5</td>
<td>-</td>
<td>2.7*</td>
</tr>
<tr>
<td>Volume (x10^3 m^3)</td>
<td>415.7</td>
<td>405.1</td>
<td>-</td>
<td>646.4</td>
</tr>
<tr>
<td>Altitude* (m a.s.l.)</td>
<td>1120</td>
<td>1120</td>
<td>1050</td>
<td>835</td>
</tr>
<tr>
<td>Contributing area (km^2)</td>
<td>54.0</td>
<td>62.0</td>
<td>42.0</td>
<td>152.25</td>
</tr>
<tr>
<td>Residence time# (h)</td>
<td>7.7</td>
<td>7.4</td>
<td>-</td>
<td>7.9</td>
</tr>
</tbody>
</table>

* This number is rather low because of the extensive deltaic area included in the computations

+ At lake outlet

# Minimum residence time based on mean annual flood derived from regional envelope curves 1965-1984 (see section 2.5). The mean annual flood was used for residence time computations because most sediment enters the lakes during the spring freshet.

N.B. The values for Kokwaskey Lake are incomplete because of problems with the sounding equipment. Given the apparent size of the lake the residence time would be expected to be longer than for the other 3 lakes.
bathymetric maps. The residence time computations are based on the discharges calculated for the mean annual flood obtained from regional envelope curves (section 2.5). In alpine systems of the Coast Mountains of southern British Columbia most sediment is moved through the fluvial system during the spring freshet. Given the way the mean annual flood was calculated there are some inherent uncertainties in the calculations. However, what is important in this study is the order of magnitude of the residence times for each of the lakes, i.e., that for most of the year they are of the order of hours to days and not longer. Simple calculations of settling times based on Stokes’ law indicate that for Kwoie Lake, assuming a non-stratified water column, material >16 µm would settle out during the mean annual flood. Finer material would be deposited during the rest of the year when residence times are greater.

Kwoiek and Kokwaskey lakes are impounded at their outlets by bedrock sills, and Klept and Kha by fans which encroached across the valley. These fans are now relatively inactive, with no evidence of recent deposition on their now well vegetated surfaces. All the lakes are aligned along the valley topographic axis, which has important implications for orientation relative to prevailing katabatic winds and thus mixing and dispersal patterns.

In cross section, all of the lakes are relatively steep sided with a flat floor. They are all composed of one major basin, although in Kwoiek Lake there is a pronounced longitudinal trough (see Figure 3.4) which is important in controlling the distribution of sediments. In two of the lakes, Kwoiek and Kokwaskey, a well developed headwater delta occupies the western end. In all of the lakes, with the exception of Kokwaskey which is fed through both the Chochiwa Glacier chain and the Kwoiek Creek chain,
the majority of the water and sediment enters through Kwoiek Creek, with small side streams having no discernible effect on lake temperature or turbidity profiles.

3.1.2 Vertical density structure and circulation

All the data presented on the physical limnology of the lakes are intended solely for descriptive purposes. The emphasis is on the order of magnitude of the various characteristics, not the specific values per se. Although collected in a standard manner the data were not collected on a continuous basis, but when trips were made into the field between 1986 and 1988. There are no marked differences between the years. Data are presented for 1986 to illustrate important trends.

Thermal stratification plays an important role in the distribution of fine sediment entering any lake because it influences the pattern in which inflowing water mixes with the lake water, thereby affecting the subsequent transport and deposition of all but the coarsest bedload. The highly seasonal and weather-dependent nature of glacial-river discharge, temperature and suspended sediment concentration variations, together with the normal seasonal evolution of lake thermal structure, results in changing and often complex mixing patterns at different times of the year. Temperature profiles are documented and summarised for the lakes of the Kwoiek Creek watershed (Figure 3.5). All the lakes may be classified as cold dimictic or polymictic. In general, the lakes have weak thermal stratification during the summer months (least well developed in Kha lake and not developed until late in the summer in Klept Lake), becoming isothermal in the fall and spring, resulting in full lake turnover. The lakes are ice covered during winter (November to April). The temperature profiles at this time are unknown.
Figure 3.5 Thermal profiles for the lakes of the Kwoiek Creek watershed. Data from 1986. Note different depth scales.

a) Kha Lake 1: June 28
   2: July 17
   3: August 12
   4: October 2

b) Klept Lake 1: June 16
   2: July 17
   3: August 12
   4: October 2

c) Kokwaskey Lake 1: June 17
   2: July 16
   3: August 14
   4: October 3

d) Kwoiek Lake 1: June 15
   2: July 15
   3: August 13
   4: October 4
Thermal effects on water density are usually overwhelmed by turbidity differences during maximum melt periods. In large lakes, the intervals of strongest underflows are often triggered by high suspended sediment loads. In small lakes with small inflows, strong underflows may be triggered by anomalously high suspended sediment loads supplied suddenly to the stream, for example, as a consequence of bank collapse or colluvial activity. For the lakes of the Kwoiek Creek watershed sediment inflow was not monitored on an annual basis. A knowledge of the sediment within the water column was obtained through vertical profiles at a number of stations within each lake, illustrated in Figure 3.6. The data are quite variable, with a strong attenuation in concentration down system. Ranges of depth-integrated values are presented in Table 3.2. When compared with data for glacial, alpine lakes the values are generally low (see Table 3.2). This is consistent with the fact that the lakes studied in the Kwoiek Creek watershed are not ice contact lakes and other sedimentary stores exist within the watershed. There is a strong, seasonal, May to July, snow-melt pulse of sediment into the system, documented in the measurements and visually observed in the field.

3.2 Selection of core sites

Likens & Davis (1975) introduced the term "sediment focusing" to describe the phenomenon of greater sediment accumulation in the deepest part of lakes. Much work has been directed towards predicting where the sediment will be focused (see for example Hilton, 1985), but this has met with limited success. A strategy of sub-bottom sounding and multiple coring enables definition of lake-wide changes in sedimentation patterns which permits an assessment of the extent to which observed variations represent large scale changes in sediment input, rather than localised
Figure 3.6 Suspended sediment profiles for the four lakes under investigation. Data from 1986. Note different scales.

a) Kha Lake: 1. June 28
   2. August 12
   3. October 2

b) Klept Lake: 1. June 16
   2. August 12
   3. October 2

c) Kokwaskey Lake: 1. June 17
   2. August 14
   3. October 3

d) Kwoiek Lake (Proximal): 1. June 15
   2. October 4
   (Distal): 1. June 15
   2. October 4
Table 3.2 Maximum recorded concentration of suspended particulate matter in the waters of glacial lakes (adapted from Gilbert & Desloges 1987).

<table>
<thead>
<tr>
<th>Lake</th>
<th>Concentration (mg l(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasikutaaq Lake, Baffin Island</td>
<td>5.7</td>
<td>Lemmen (1984)</td>
</tr>
<tr>
<td>Ape Lake, B.C. (before draining)*</td>
<td>28.7</td>
<td>Gilbert &amp; Desloges (1987)</td>
</tr>
<tr>
<td>Garibaldi Lake, B.C.</td>
<td>30.0</td>
<td>Mathews (1956)</td>
</tr>
<tr>
<td>Lillooet Lake, B.C.</td>
<td>49.0</td>
<td>Gilbert (1975)</td>
</tr>
<tr>
<td>Lake Wakatipu, N.Z.</td>
<td>57.0</td>
<td>Pickrill &amp; Irwin (1983)</td>
</tr>
<tr>
<td>Cascade Lake, Washington*</td>
<td>110.0</td>
<td>Campbell (1973)</td>
</tr>
<tr>
<td>Hazard Lake, Yukon</td>
<td>120.0</td>
<td>Liverman (1980)</td>
</tr>
<tr>
<td>Unnamed lake, Purcell Mtns, B.C.</td>
<td>140.0</td>
<td>Weirich (1985)</td>
</tr>
<tr>
<td>Sunwapta Lake, Alberta</td>
<td>380.0</td>
<td>Gilbert &amp; Shaw (1981)</td>
</tr>
<tr>
<td>Malaspina Lake, Alaska</td>
<td>723.0</td>
<td>Gustavson (1975)</td>
</tr>
</tbody>
</table>

This study +

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
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<td>13.8</td>
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<tr>
<td></td>
<td>- Min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klept lake</td>
<td>- Max</td>
<td>21.2</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>- Min</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kokwaskey lake</td>
<td>- Max</td>
<td>19.1</td>
<td>17.3</td>
</tr>
<tr>
<td></td>
<td>- Min</td>
<td></td>
<td></td>
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<tr>
<td>Kwoiek lake</td>
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<td>9.0</td>
<td>6.2</td>
</tr>
<tr>
<td></td>
<td>- Min</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* ice contact lake

+ from water profile data presented in Figure 3.6

max: maximum integrated value documented in measurements;
min: minimum integrated value documented in measurements

Obviously these do not represent the true maximum and minimum values for the year, rather the range for the period of measurements.
changes.

Thus as a precursor to coring, bathymetric sounding with a 50 kHz echo sounder, and sub-bottom sounding at 3.5 and 7 kHz were conducted with the objective of describing the bathymetric and sedimentary characteristics of each lake. There were two reasons for determining the sub-bottom stratigraphy of the lakes. First, to provide a basis for selecting coring sites in zones of greatest accumulation and potentially greatest resolution, and second, once the cores were obtained, to permit cross-correlation of results between point cores, where distinct sediment layers could be observed in both cores and sub-bottom traces.

Sub-bottom sediment profiles were obtained using a Raytheon RTT-1000A, portable, low-frequency sonar. Unfortunately for reasons that could not be resolved the sub-bottom sounding was largely unsuccessful. The results are not pursued further in this study.

3.3 Lake sediment sampling

Surface samples were collected with an Ekman sampler at multiple sites in each of the lakes (Figures 3.1 - 3.4) in order to document spatial variability in the facies and to determine coring sites. An undisturbed core from each surface sample was preserved in a 0.12 m diameter tin and allowed to become partially dry to strengthen and consolidate the sediment before shipment. The silty nature of most of the sediments allowed approximately the upper 20 cm to be recovered.

Based on a consideration of the patterns of sedimentation determined by the Ekman samples and bathymetry, multiple cores were taken from each lake (for locations see Figures 3.1 - 3.4). In this study any sample referred to with the prefix E was taken with an Ekman sampler, C is from a core, with the core/Ekman number referenced to Figures 3.1 to 3.4, and the depth
from which the sample was taken indicated. The abbreviation KWK refers to Kwoiek Lake, KOK to Kokwaskey Lake, KLP to Klept Lake and Kha is represented in full, KHA.

The corer that was used is a modified Wright (1967) square-rod piston corer built at UBC's Department of Geophysics & Astronomy, loaned by Dr. G.K.C. Clarke. The corer uses one of two 2.375 inch (6.03 cm) outer diameter (OD), 2.25 inch (5.72 cm) inner diameter (ID), 1/16 inch (0.16 cm) wall stainless steel tubes, 1.20 m long, one with a tempered steel serrated cutting edge, and one with a tempered bevelled cutting edge. Another similar core tube made of clear plexiglass, 2.25 inch (5.72 cm) ID and 1.20 m long which can be used in place of the stainless steel tubes proved useful for coring the surface sediments. Drive rods are 5 foot (1.52 m) lengths of 1 5/16 inch (3.33 cm) diameter zirconium-magnesium joined with coarsely threaded stainless steel couplings. These are standard rotary drill rods selected for rigidity and light weight. A T-extension handle was made to fit these.

A drilling platform 8' by 6'(2.44 m by 1.83 m) was built from 2 pieces of plywood and styrofoam floats. A drilling hole cut in the centre enabled work around the corer. Four anchors were deployed from the raft, one at each corner, to ensure a stable, immobile platform. Casing was made from 4 inch (10 cm) diameter ABS piping cut into 1, 2, and 5 foot (0.30, 0.61 and 1.52 m) lengths and fitted with ABS couplings so it could be assembled to the appropriate length for each drill hole. Samples were removed in one metre sections from a continuous borehole. A careful record was made of drive lengths and the length of core recovered. Discrepancies may be due to compression of sediment during the coring procedure, sediment lost from the corer bottom, and/or bore hole infilling between drives. At each site
two cores were taken within 2 m of each other. This meant that enough material was collected for all the analyses, and no part of the record was lost. The latter was achieved by ensuring that the depths of breaks in the core were not the same in adjacent cores i.e. that the drive lengths were different. The longest core obtained was 4.24 m (laboratory measurement) from Kokwaskey Lake (KOK5). In total 60 cores were collected from 30 sites (i.e. 2 at each "site"). The locations of each site are shown on Figures 3.1 to 3.4.

3.4 Description of the cores

After extrusion in the field and measurement of their lengths, the cores were wrapped in saran wrap and aluminum foil and transported in a core box to the laboratory where they were split length-wise. The cores were then air dried with careful observation during this process of stratigraphic units, contact types, sedimentary structures, texture, colour and other distinctive features, for example, inclusions of organics. Some cores were dried for 2 to 3 weeks before details of all structures and units became evident. Similar facies were repeated in the cores in all of the lakes.

As a precursor to selecting cores for more detailed analysis, a systematic characterization was undertaken based on a rigidly defined lithofacies scheme. Visual appraisal of grain size, bedding and sedimentary structures was used to subdivide the sedimentary sequence as outlined by Eyles et al. (1983) and adapted by Schmok (1986). This scheme and detailed logs of the cores are presented in Appendix I.

X-radiography, a fast and non-destructive scanning and recording technique, was undertaken to find sediment structures that may not be visible in the dried core. The radiographs were made in the Department of Radiology of the University of British Columbia with instrument settings
100 kV, 400 mA, phototimer 1.2 ms, 40" FFD, QIII screens. The technique is particularly valuable for studying the upper portions of the cores (0 - 20 cm) which had a high water content. Radiograph observations were used to supplement the visual observations and are incorporated into the core descriptions (Appendix I).

Central to any study documenting and interpreting changes through time is chronology. Radiocarbon dating, tephra identification and dated anthropogenic events in the sedimentary records were used to date the lake sediments. Appendix II outlines details of the techniques and results. All radiocarbon dates referred to in this study are uncorrected C-14 dates.

All the cores exhibit changes in their depositional records, the major features of which are alternations between massive and laminated silts, with incorporations of organic matter. The majority of the deposits are layers of massive sediments composed of particles ranging in size from fine sands to fine silts. This facies may represent periods when the sedimentation rate was sufficiently low that the layers were deposited without internal structure. Alternatively any structures may have been destroyed subsequently by bioturbation. The thinly laminated sediments consist largely of darker coloured silt with laminations of coarser, lighter coloured silt and fine sands. These deposits were observed in most cores. Detailed observation of these structures revealed no apparent sorting within the laminations. These deposits seem to represent periods of slightly greater sedimentation rates with periodic introductions of coarser material into the lakes. The more regular laminations, the rhythmites, observed only in the upper portions of Kokwaskey Lake sediments, are identified as varves (Appendix II). There is no evidence within any of the cores for flow structures, deformed beds or erosional
unconformities. The boundaries between facies are largely gradational.

The sediments of Kha Lake are predominantly laminated silts. The basal sediments, which prevented a longer record from being obtained, are coarse sands and granules with particles up to 5 mm in diameter. A radiocarbon date of 2350 ± 110 yrs B.P. (S-2936) was obtained on wood incorporated in laminated silts 17 cm above the contact between the coarse sands and overlying laminated silts. From the core obtained at site Kha2 (Figure 3.1) approximately 4.05 m of sedimentation has occurred in the last 2350 years. Above the laminated silts more massive silts with occasional beds of coarser material predominate. The sediments from 1.5 m to approximately 0.5 m depth are laminated silts, with massive silts overlying these. The upper 10 cm of record is distinct with many beds of coarser material. These are interpreted as the effect of logging and road construction in the vicinity of the lake.

Klept Lake is characterised by more massive deposits with frequent inclusions of organic material. Spatially the records are more variable than in Kha Lake, with many coarse beds of local origin. A basal date of 9640 ± 380 years B.P. (S-3011) was obtained on wood incorporated in massive silts approximately 17 cm above a contact with coarse sand. This is overlain by 2.26 m of fine sand/ silts which have been deposited during the Holocene Epoch. Two coherent tephra layers were identified in the sediments of Klept Lake, the lower at approximately 1.48 m depth, identified as Mazama tephra, the upper, approximately 0.52 m depth, identified as Bridge River tephra.

The sediments of Kokwaskey Lake are more uniform spatially although variable with depth. The basal sediments are laminated blue-grey clays. Organic material contained within these has been dated at 11,485 ± 185
years B.P. (S-2935), with approximately 4.15 m of sediment deposited over the postglacial period. The blue-grey clays are overlain by coarser sandy/silt deposits, which in the lower portions of the core are massive, becoming laminated in the mid-section and increasingly finer towards the surface. Two clearly defined tephras are evident in the Kokwaskey Lake sediments, the lower Mazama tephra, the upper Bridge River tephra. The uppermost sediments, encompassing approximately the last 250 years, are varved (see Appendix II).

The deposits in Kwoiek Lake would appear to be more uniform with depth. The basal sediments are coarse sands with a transition to fine silts mid-core, to laminated silts more recently. Approximately 2.49 m of sediment has accumulated over the postglacial period. The basal date on these sediments is 12,255 ± 770 years B.P. (S-3010). There is no Mazama tephra but Bridge River tephra is evident within the upper 0.60 m of sediments. The changes in sedimentary characteristics and their significance in each of the lakes through time are considered in much greater detail in subsequent chapters.

The cores within each lake were cross-correlated on the basis of their lithostratigraphy. Given the focus of this study on basin-wide changes in sedimentation over timescales $10^2$-$10^3$ years, preliminary screening of the data entailed discarding any beds which were obviously of local origin, for example graded beds due to localised mass wasting events at the edges of the lakes, and beds that only existed in one core. Specific cores were then selected for further study. These are identified where appropriate in the subsequent text. The cores were selected because they offer the greatest resolution and temporal coverage. However the shorter and/or younger cores have an important function in establishing spatial
variability of sedimentary characteristics and processes.
CHAPTER 4 INTERPRETATION OF THE LAKE SEDIMENT RECORD

The basic premise of this study is that during the Holocene Epoch variations in the alpine sediment system, at timescales $10^2-10^3$ years, have been largely controlled by fluctuations in Neoglacial activity and are recorded in the sediments of alpine lakes. This chapter presents a series of analyses to interpret the clastic component of the lake sediments in order to gain insight into the nature of the sediment sources and transfer processes delivering sediment to each of the lakes. These analyses and interpretations are based on lake wide sedimentary characteristics that were identified for each of the lakes. The first portion of this chapter presents data and interpretations of the organic component as an index of the volume of sediment influx through time; the second part presents textural analyses of the clastic component in order to identify different clastic sediment populations, which through source identification are shown to contain distinct palaeoenvironmental information. These analyses are used in Chapter 5 to document and interpret changes in the palaeo-sediment system through time, and to develop a chronology of Holocene palaeoenvironmental changes for the Kwoiek Creek watershed.

4.1 Organic matter content: an inverse indicator of sedimentation rates

Several workers have suggested that an inverse relation exists between clastic sedimentation rate and organic carbon content of sediments in glacial lakes (Karlen, 1976; Surgenor, 1978, Davis et al., 1979, Leonard, 1981). Similarly Oldfield (1977) notes that in non-glacial lakes total carbon content of sediments, reflecting organic carbon content, bears an inverse relation to total sediment input. This relation may be used to establish a strong co-variation between the two variables, and therefore permit organic matter content, which is easily measured, to be used as a
surrogate index of sedimentation rate.

It is proposed that the variations in clastic sediment input into the lakes in the Kwoiek Creek watershed will be closely related either to changes in rate of release of sediments by the glaciers, or to rates of re-entrainment of glacial, glacio-fluvial or colluvial deposits by meltwater streams. In either case such material is relatively deficient in organic material and changes in input of this material would likely be reflected inversely by changes in concentration of organic material, either autochthonous or allochthonous in origin. The relation may be complicated by the fact that the input into the lake of organic material from other sources may also be variable. However, the critical assumption is that the organic input is less variable than clastic sediment input, and thus variations in the organic content primarily reflect changes in clastic sedimentation.

In order to evaluate this assumption two independent tests were conducted. First, by using the upper sediments in Kokwaskey Lake, which are varved (see Appendix II) and therefore provide annual resolution of sedimentation rates; and second, comparing integrated values between dated tephra horizons within the cores of the lakes. Because of the number of samples that had to be analyzed, loss on ignition was used as a measure of total organic content in this study (combustion of the organic material in a muffle furnace for 3 hours at 450°). Samples of known volume, which represent approximately 1 cm depth of core, were used to determine both loss on ignition and minerogenic bulk density (mass clastic material per unit volume). The results for the organic matter are reported as percent by dry weight.

For two cores from the varved sediments of Kokwaskey Lake, samples were
taken for organic content determination every centimetre and compared with sedimentation rates in two cores K0K3 and K0K5 (see Figure 3.3). An average of 10 varves were represented in 1 cm of core, resulting in a temporal resolution for the test of the order $10^1$ yrs over a time period of approximately the last 250 years, the depth of core for which the individual varves could be resolved. It was expected that organic matter content and sedimentation rate would be negatively correlated. If there is a constant influx of organic material per year then the greater the annual sedimentation rate the lower the organic content per unit depth; conversely the lower the sedimentation rate the greater the organic content per unit depth. No significant variations in minerogenic bulk density are evident in the upper-sections of the cores studied, so this effect was neglected. The most recent part of the record with greater sedimentation rates due to anthropogenic activity within the catchment was not used in this analysis. The data are plotted in Figure 4.1 (K0K3 *, K0K5 +). Regression lines and equations were derived independently for the two cores analyzed in order to account for spatial variability in the organic content. Of interest is the consistency of the relation within a core. Significant ($\alpha < 0.01$) negative correlations ($r^2 = 0.90$ and 0.81; n= 21 and n=23 respectively) were obtained for the two cores:

Core K0K3: $S.R. = -0.92 \ (O.M.) + 3.10$

Core K0K5: $S.R. = -0.72 \ (O.M.) + 2.68$

S.R. sedimentation rate (mm yr$^{-1}$)

O.M. organic matter content (loss on ignition % by weight)

In down-core tests there may be significant serial correlation. In order to account for this effect the residuals were tested for first order
Figure 4.1 Relation between sedimentation rate and organic matter content of varved sediments for Kokwaskey Lake.
serial autocorrelation, $r_1$ (KOK3 $r_1 = 0.15$, n=20, not significant a 0.01; KOK5 $r_1 = 0.53$, n=23, significant a 0.01). The significance of serial correlation is considered further in section 5.3.

To ensure the consistency of this relation over the longer time periods of interest in this study, a second test was conducted. Clastic and organic sedimentation rates were determined for each of the lakes from all of the cores that penetrated tephra layers. Comparison of clastic and organic sedimentation rates during the known time intervals between the lower and upper tephra layers, and the upper tephra and the present, provides a means of assessing which component of sedimentation remains more nearly constant over timescales of $10^3$ yrs. The upper-most portions of the cores, which record the effects of logging within the catchment were not included in this phase of the analysis. Clastic sedimentation rates were determined from the weighted average of minerogenic bulk density data for the cores between layers of known age. Organic sedimentation was determined for the same core sections by multiplying the total sedimentation rate for each section of the core by its organic content (percent by weight). This provides sedimentation rates for both the clastic and organic material which can be expressed as mg cm$^{-2}$ yr$^{-1}$. The data on influx rates and ratios of their variability through time are presented in Table 4.1. The ratios of the variability in clastic sedimentation are much greater than those for the organic material. This lends further support to the hypothesis that clastic sedimentation rates have varied more than organic sedimentation rates in the lakes of interest and thus organic matter content of the lake sediments can be used as an inverse index of rates of sedimentation. The flux of organic material does vary through time. However, it is likely that it does so inversely with
Table 4.1 Assessment of variability of clastic and organic sediment influx over timescales of the order of thousands of years

<table>
<thead>
<tr>
<th></th>
<th>Clastic (mg cm(^{-2}) yr(^{-1}))</th>
<th>Organic (mg cm(^{-2}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Klept Lake (KLP1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2400</td>
<td>0.0240</td>
<td>0.0021</td>
</tr>
<tr>
<td>2400-6800</td>
<td>0.0186</td>
<td>0.0019</td>
</tr>
<tr>
<td>Variability</td>
<td>1.29 (0.78)</td>
<td>1.11 (0.90)</td>
</tr>
<tr>
<td>Kokwaskey Lake (KOK5)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0-2400</td>
<td>0.0429</td>
<td>0.0018</td>
</tr>
<tr>
<td>2400-6800</td>
<td>0.0325</td>
<td>0.0021</td>
</tr>
<tr>
<td>Variability</td>
<td>1.32 (0.76)</td>
<td>1.14 (0.88)</td>
</tr>
</tbody>
</table>

* Variability is defined as the ratio of the influx for the specified lake 0-2400 B.P. divided by that for 2400-6800 B.P. The value in brackets is the influx 2400-6800 divided by that 0-2400.

N.B. The values reported are point influx rates calculated from individual cores. They do not represent areally weighted values of sedimentation rates in the lakes.

Only the tephra horizons were used as chronological markers in this analysis to reduce potential errors because of dating uncertainty with the radiocarbon dates. Hence values for Kha and Kwoiek Lakes are not presented.
glacier activity, thereby enhancing the patterns of interest in this study. The relation between organic matter and sedimentation rates is used in Chapter 5 to document temporal variability in sediment influx in each lake.

4.2 Characterization of the clastic component

Grain size characteristics of selected cores (Kha C1 and C2; Klept C1 and C6: Kokwaskey C3 and C5; Kwoiek C6 and C15) and surface samples from all the Ekmans, were determined through a combination of standard wet sieving techniques and use of a SediGraph 5000 analyzer (see Stein, 1985 for description). Samples of approximately 5-6 g, representing 1 cm depth of core were lightly crushed with a pestle and mortar to break up large aggregates. To deflocculate the sediment, each sample was placed in approximately 50 ml of sodium hexametaphosphate solution and left for 24 hours with periodic stirring. Immediately prior to analysis each sample was placed in an ultra sonic bath to ensure complete disaggregation of material. The samples were wet sieved at 1/2 Φ intervals down to 63 μm, and then analysed using the SediGraph from 88 μm to 1 μm. The results were combined and cumulative grain size distributions plotted (see examples in Appendix III).

The most common sediments are silts, clayey silts and clays with a clearly distinct group of deposits composed of sand and silt (Figure 4.2). From inspection of the cumulative distribution plots (see Appendix III) it is evident that many of the sediments are polymodal. Histograms and cumulative curves reveal complicated distributions with the preponderance of curves (samples) consistently showing breaks of slope around 4Φ and 6Φ (see examples in Appendix III).

Numerous attempts have been made to relate a particular cumulative log
Figure 4.2  Textural triangle for lake bottom sediments, Kwoiek Creek watershed.
probability curve shape to a specific environment (see for example, Sly et al., 1983). Associated with this have been attempts to quantify curve interpretation by utilising statistical parameters to characterise the curve and bivariate plots of statistical measures to distinguish environments. However, given the polymodal nature of many of the grain size distributions in this study, such analyses of curve shape and statistical measures (such as skewness and kurtosis) may reflect only the relative magnitude and separation of modes and thus be of little interpretive value.

An alternative approach to the problem is to separate the constituent populations and to relate each of these to sediment transfer processes or sources. It has been suggested (see review in Middleton, 1976) that when cumulative curves are plotted on a log-probability scale, log-normal distributions appear as a straight line, and the component distributions of bimodal and polymodal sediments appear as straight line segments. There are three basic approaches to partitioning polymodal probability curves: analytical, numerical and graphical (Clark, 1976). Harding's (1949) graphical method provides a straightforward approach to partitioning distributions with up to four modes. The method is best described by Sinclair (1974). Inflection points on log-probability plots indicate the approximate proportions of, or the fraction (f) of, the total mixture that each mode represents. For example in Figure 4.3, a case of a bimodal distribution, the arrow indicates the point of inflection at approximately the 50th cumulative percentile, indicating the presence of 50% of a coarser population C, and 50% of a finer population F. When graphical partitioning is conducted on curves plotted on log-probability paper this approach assumes that each subpopulation has a log-normal distributions.
Figure 4.3 Example of separation of log-probability textural curves. This plot illustrates partitioning of a bimodal distribution with "Coarse" and "Fine" textural sub-populations intermixed. See text.
An extensive literature exists in fluvial geomorphology that supports this assumption for fluvially transported sediment. Given the prescreening of the data to remove deposits of obviously local origin most materials remaining were fluvially transported from their source. This is especially true for the material of interest within the lakes which is glacially-derived. This material must have been fluvially transported for some distance in order to be deposited in the lakes and thus the assumption of log-normality would seem to be realistic. Thus graphical partitioning of log-probability grain size plots was conducted for samples (cores KHA2, KHA5, KLP1, KLP5, KOK3, KOK5, KWK14, KWK15). When the component populations were separated, it became apparent that three well-defined populations are present, referred to subsequently as coarse (C) intermediate (I) and fine (F). These three component distributions were then analyzed for their mean, standard deviation and range. The higher order statistics, skewness and kurtosis, were not computed because of the greater uncertainty in the separation of the tails of the distributions which fall within the region of greatest graphical overlap. The average values for each core and their variability are presented in Table 4.2. It can be seen quite clearly that: there are three well defined modes: a coarser fraction (2.0 to 5.0\(\phi\), range defined \(\pm 2\) standard deviations, medium to fine sand) was found in all lakes, although this population in Klept Lake is finer and less well sorted; an intermediate fraction (3.0 to 7.0\(\phi\), fine sand to medium silt) in Kha Lake and Klept Lakes; and a finer fraction (6.0 to 9.0\(\phi\), fine silt) in all lakes. The mean characteristics of each of the sediment populations for each lake are shown schematically in Figure 4.4. In all lakes unimodal deposits exhibit the same characteristics as the finest fraction. There appear to be no systematic
Table 4.2 Summary of average characteristics of each of the three grain size populations by lake. C indicates coarse mode, I intermediate mode, and F finest mode.

<table>
<thead>
<tr>
<th>Mode</th>
<th>D$_{50}$ ($\phi$)</th>
<th>S.D. $D_{50}$ ($\phi$)</th>
<th>Sorting ($\phi$)</th>
<th>S.D. sorting ($\phi$)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kha Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.39</td>
<td>0.31</td>
<td>0.81</td>
<td>0.14</td>
<td>8</td>
</tr>
<tr>
<td>I</td>
<td>5.30</td>
<td>0.62</td>
<td>0.78</td>
<td>0.25</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>7.37</td>
<td>0.71</td>
<td>0.90</td>
<td>0.33</td>
<td>23</td>
</tr>
<tr>
<td><strong>Klept Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>4.03</td>
<td>0.75</td>
<td>1.09</td>
<td>0.46</td>
<td>15</td>
</tr>
<tr>
<td>I</td>
<td>5.40</td>
<td>0.69</td>
<td>0.70</td>
<td>0.19</td>
<td>8</td>
</tr>
<tr>
<td>F</td>
<td>7.42</td>
<td>0.56</td>
<td>0.78</td>
<td>0.31</td>
<td>22</td>
</tr>
<tr>
<td><strong>Kokwaskey Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.14</td>
<td>0.44</td>
<td>1.18</td>
<td>0.44</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>7.28</td>
<td>0.82</td>
<td>0.53</td>
<td>0.23</td>
<td>32</td>
</tr>
<tr>
<td><strong>Kwoiek Lake</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3.50</td>
<td>0.27</td>
<td>0.76</td>
<td>0.15</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>7.87</td>
<td>0.93</td>
<td>0.79</td>
<td>0.30</td>
<td>29</td>
</tr>
</tbody>
</table>
Figure 4.4 Characteristics of sediment sub-populations. Synthetic grain-size curves to illustrate the mean distribution of each sediment sub-population from each lake.

Kha Lake

Sand • Silt • Clay

Klept Lake

Sand Silt Clay

Kokwaskey Lake

Silt Clay

Kwoiek Lake

Sand Silt Clay
changes in either the mean size or the sorting of the coarsest fraction down-system. There is a slight fining of the finest mode but no systematic trend in sorting.

The first step in the interpretation of the physical significance of the breaks in the log-probability plots was to ensure that they are not a consequence of the analytical procedures used. As outlined above, every effort was made in the laboratory to ensure that this was not the case. Each sample was sieved over the sand/silt break and the SediGraph analysis started at 88 µm to ensure overlap.

In the sedimentological literature considerable discussion has been generated over the interpretation of different textural modes (see for example, Visher, 1969; Shea, 1974; Middleton, 1976). In general the size "breaks" or subpopulations may be related to either sources, mechanical breakage, or hydraulic sorting, either during transport or deposition.

In general in the lakes of the Kwoiek Creek watershed, sediment is deposited through settlement from suspension. No current structures, which are the only unequivocal evidence of underflows, are evident in the deposits (see Appendix I). This does not preclude weak underflows but suggests other transport mechanisms, such as overflows and interflows, and settling from suspension. Thus the differences in textural modes are unlikely a result of different depositional processes within the lakes.

A basic premise of this study is that during the Holocene Epoch there have been significant fluctuations in the relative contributions of different sediment sources. It is argued that the different sediment subpopulations are deposited concurrently and are thus a reflection of these sources. This hypothesis is supported by the fact that even when viewed under the binocular microscope no distinct beds with sorting are
visible which would indicate hydraulic sorting, a transport control. Furthermore there is little temporal synchronicity in the deposition of the coarsest fraction in the different lakes (this is discussed in greater detail in Chapter 5). It would be expected that at the spatial scale of the Kwoiek Creek watershed high magnitude hydrological events, whether related to snowmelt or synoptic events, would affect the entire watershed and thus there would be temporal synchronicity in terms of sedimentary characteristics, especially of the coarser fraction, if hydrologic/hydraulic processes were the control.

Thus the argument of a source control over sediment characteristics is pursued. The next major sections (4.3 and 4.4) present the results of two techniques to determine the sources of the different sediment fractions: surface texture analysis of the finest sand fraction using the scanning electron microscope, which encompasses the two coarser modes; and analyses of the mineralogy of the fine silt-sized fraction, the finer mode, in order to document and interpret changes in sources through time. These provide a foundation for the interpretation of the fluctuations in the fractions through time presented in Chapter 5.

4.3 Sediment source analysis: SEM analysis of the coarse fractions

One of the objectives in this study is to determine the sources of sediment deposited in the lakes, specifically to discriminate between sediment derived originally from glacial sources, sediment from contemporary colluvial sources, and sediment from old surficial deposits (of Fraser glaciation), all of which may have been reworked fluvially (see Figure 1.1 and section 2.7 for discussion of contemporary sediment sources and transfer mechanisms). It is proposed that one technique with which
this can be achieved involves characterization of the surface features of quartz sand grains, commonly termed surface textures, within the lake deposits using the scanning electron microscope (SEM).

The basic premise underlying work on grain surface texture is that given necessary time within distinct sedimentary environments characteristic chemical and physical processes modify the surface texture of sediment. The contention is that the modifying environment is sufficiently unique to impart distinctive suites of features of the surface on the sedimentary particles (Bull, 1981).

Essentially two branches of the work have evolved. First, those studies which are concerned with shape analysis of individual grains, primarily with the two-dimensional representation and numerical summary of grain outline using techniques such as Fourier analysis (Dowdeswell, 1982; Ehlrich, 1987). The basic premise of such work is that grain shape is extremely sensitive to abrasion. As a consequence rapid changes occur in roundness and angularity, which may thus be useful indices of sedimentary history. The second branch of work is concerned with specific surface characteristics, either presence/absence or intensity of development. The latter may be defined either as the number of grains exhibiting an effect, or as the percentage of the visible area covered on a single grain by a certain characteristic. Examples are found in the work of Margolis & Kennett (1971), Higgs (1979) and Bull (1985). This second stream of research has developed from the studies in which investigators were concerned with the association of single characteristics with a particular, unique environment (for example, Gravenor, 1979). At this stage of development the technique fell somewhat into disrepute as many "red herrings", as they have subsequently been termed, were published.
These arose largely because it was not recognised that it is not the transport pathways/ sedimentary environments per se but rather the processes operating within them that impart the surface features, and that such processes can be replicated in seemingly disparate environments. For example, V-shape pits are formed as a consequence of grain to grain impacts, which may occur whether the medium of transport is air or water, and thus may be found on both water and wind transported grains. Similarly chattermarks, which were formerly thought to be indicative of glacial-transported grains, have been shown to have mechanical or chemical origin (Bull et al., 1980). Consequently individual surface textures are rarely, if at all, useful indicators of palaeoenvironment. However, certain combinations remain highly diagnostic (Margolis & Kennett, 1971). This is the basic premise of the approach adopted in this study. Furthermore, environments and their associated processes are not 100% efficient in marking grains. Some grains may go through a transport cycle without receiving any new surface features. Therefore it is not inconsistent that modified and unmodified grains can co-exist in an environment. Hence, a number of grains, not a single grain, should be used to characterise an environment.

The processes that modify surface features within any environment can be broadly categorised into mechanical abrasion, chemical precipitation, and chemical solution. Figure 4.5 is a schematic representation of the sequential origin of quartz grain surface features (adapted from Trewin, 1988). Such a framework may be considered in a temporal context, i.e. the cycle of weathering and erosion, or a spatial context, for example in this study, the routing of sediment from source to lake-sediment sink. Surface textures observed on grains can be inherited from the source rock, altered
Figure 4.5 Origin of quartz grain surface features (adapted from Trewin, 1988)

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<tr>
<th>STAGE</th>
<th>PROCESSES</th>
<th>FEATURES</th>
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<tr>
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<td>by burial solution</td>
<td>Fractured &amp; distorted</td>
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<td>Subsequent cycle</td>
<td>Inherited diagenetic</td>
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<td>characteristics</td>
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Inherited characteristics

Tendency to uniformity during long transport

Large overgrowths & solution surfaces
by subsequent weathering and transportation, or subsequently derived by alteration as a consequence of depositional conditions i.e. diagenesis. The controlling factors are both endoscopic, pertaining to grain size, shape and particularly microstructure (Gomez et al., 1988), and exoscopic, pertaining to the environmental conditions of weathering and transport.

In general surface texture SEM work has not developed to a stage whereby suites of features can be used to define processes of sediment transfer in any environment. Thus in order to use surface characteristics diagnostically to classify the origin and subsequent transportational history of sediments, a methodology needs to be followed whereby materials are taken from known environments and then compared to material of unknown source, enabling the textural modification to be identified and inferences made about processes (Bull, 1981).

4.3.1 Methodology

In order to control the variety of influences on grain surface texture, the approach taken in this study was to characterise the surface features of a constant lithology, igneous monocrystalline quartz, from materials of known transportational history, residing in known sedimentary environments, and to use these "signatures" to develop a scheme whereby unknown lake deposits could be classified. This attempt to minimise lithologically inherited characteristics was possible because of the relative uniformity of the bedrock geology in the contributing areas to the lakes (see section 2.3). This is evaluated further below.

As a first step three replicate samples were collected from each of six known sedimentary environments within the watershed, resulting in a total of 18 samples. These sedimentary environments were identified in accordance with the generalised clastic sediment routing scheme (presented
in Figure 1.1; Figure 2.5). All the samples collected were surface samples from Quaternary surficial deposits, the origin of which was inferred from location, morphology, stratigraphy and sedimentology. All were of granodiorite provenance.

The deposits sampled were:

1. Contemporary glacial: Two samples were taken from the contemporary Kwoiek Glacier with no attempt to differentiate subglacial, englacial or supraglacial material, and one from Little Ice Age moraines.

2. Glacio-fluvial: Two samples from material from streams draining the Kwoiek Glacier and one from well sorted glacio-fluvial Little Ice Age deposits.

3. Colluvial: the products of mass wasting on the hillslopes in the upper portion of the catchment. One sample was taken from weathered in situ bedrock (eluvium), one from a talus slope, and a third from a debris flow deposit.

4. Colluvio-fluvial: products of mass wasting that have entered the fluvial system i.e. samples from non-glacial fed streams.

5. Deltaic: modern delta (2 from Kwoiek, 1 from Kokwaskey) to characterise an internal lake source with fluvial history to assess whether there is subaqueous imprint on the suite of surface textures.

6. "Old" surficial materials: the deposits of Fraser Glaciation (2 from till and 1 from a glacio fluvial deposit), all in the vicinity of Kwoiek Creek.

The last category is differentiated from the other environments by age. It was expected that the sediments would exhibit features indicative of longer exposure to subaerial weathering processes, specifically chemical
solution and precipitation.

Although this is a fairly crude subdivision these 6 units are thought to characterise the possible sources for the sediment adequately (see discussion in Chapter 2 of clastic sediment sources and pathways). As stated in Chapter 2 the evidence for aeolian deposits within the valley bottom is rare. In essence what is important in this study is to differentiate categories 1 and 2 i.e. recent glacier derived material from that sediment derived from all other sources.

The approach taken was to sieve the field sample to separate the fine sand, 63-250 µm, generally 63-125 µm. This fraction was selected to be representative of the two coarser fractions, identified from the initial grain size characterization of the sediments (section 4.2). It was important to ensure that the size fraction selected be present in all environments studied, such that the results from the known sedimentary environments be directly comparable with that work on the lake sediments, and that the size range is representative of the sediments in general i.e. that it constitutes a significant proportion of the grain size distribution (see section 4.2). Furthermore, most SEM work has been conducted on sand sized grains, for a variety of practical reasons in terms of sample preparation, and because such grains are generally believed to be transported independently and not as aggregates and would thus be expected to exhibit characteristics of particular transportation pathways. Therefore the results from this study could be compared with those in the literature.

The separated fraction was boiled in 10% HCl for 20 minutes on a hot plate to remove carbonates and organic stains, and subsequently dispersed in sodium hexametaphosphate to ensure that all grains were disaggregated.
A sonic bath was not used for dispersal since this might create new surface textures in the laboratory. The material was then cleaned in distilled water and air dried. Under a binocular microscope, 50 monocrystalline quartz grains were selected. Quartz was chosen because of its relative resistance to mechanical and chemical breakdown and its abundance. A minimum of 30 grains for each sample (following the recommendations of Tovey & Wong, 1978) were mounted on a SEM stub and coated with gold. Each stub was randomly coded and viewed non-sequentially on the SEM (Semko Nanolab 7, in the Department of Geological Sciences, University of British Columbia). To ensure that there were no variations in inherited characteristics sub-samples of the monocrystalline quartz grains were taken and used to make grain-mounts which were thin-sectioned and studied under polarised light with a petrographic microscope. In all cases the quartz grains analyzed were monocrystalline, unstrained, with little evidence of fluid inclusions.

The presence or absence of 34 characteristics were noted (see Table 4.3) for each grain on each stub. Although many investigators advocate the use of multiple characteristics, the actual surface textures used vary between studies. The textures observed in this investigation were selected after a literature search and preliminary observations of the samples from the Kwoiek Creek watershed to see the range of features evident. In the statistical analysis of the data some features were found to be of little discriminating value and were omitted from further consideration (see later discussion). Photographs of selected grains are presented in Figure 4.6 to illustrate the range of features observed. Krinsley and Doornkamp's (1973) "Atlas of quartz sand surface features" was used extensively in the early stages of this work to identify and define the surface features.
<table>
<thead>
<tr>
<th>Number</th>
<th>Surface texture</th>
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<tbody>
<tr>
<td><strong>Mechanical features</strong></td>
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<td>1</td>
<td>Complete grain breakage</td>
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<td>2</td>
<td>Edge abrasion</td>
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<td>3</td>
<td>Breakage blocks (&lt;10 µm)</td>
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<td>4</td>
<td>Breakage blocks (&gt;10 µm)</td>
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<td>5</td>
<td>Conchoidals (&lt;10 µm)</td>
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<td>6</td>
<td>Conchoidals (&gt;10 µm)</td>
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<td>7</td>
<td>Straight steps</td>
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<td>8</td>
<td>Arcuate steps</td>
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<td>Parallel striations</td>
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<td>10</td>
<td>Imbricate grinding</td>
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<td>Fracture plates</td>
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<td>Straight scratches</td>
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<td>15</td>
<td>Curved scratches</td>
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<td>16</td>
<td>Mechanical V-pits</td>
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<td>Dish-shaped concavities</td>
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<td><strong>Morphological features</strong></td>
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<td>18</td>
<td>Rounded</td>
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<td>Medium relief</td>
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<td>High relief</td>
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<td><strong>Chemical features</strong></td>
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<td>25</td>
<td>Oriented etch pits</td>
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<td>26</td>
<td>Anastomosis</td>
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<td>27</td>
<td>Dulled surface</td>
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<td>28</td>
<td>Solution pits</td>
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<td>29</td>
<td>Solution crevasses</td>
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<td>30</td>
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<td>31</td>
<td>Carapace</td>
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<td>32</td>
<td>Amorphous silica</td>
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<td>33</td>
<td>Euhedral silica</td>
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<tr>
<td>34</td>
<td>Chattermarks</td>
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</tbody>
</table>

* number used in text to reference the individual surface textures

Relative abundance recorded: 1 absent (< 1 grain)
2 present (2-7 grains)
3 common (8-21 grains)
4 abundant (> 22 grains)
Figure 4.6 Photographs of selected grains to illustrate surface textures

A: 1 Breakage blocks; 2 Edge abrasion (sub-rounded outline); 3 Conchoidal fractures

B: 1 Angular outline; 2 Adhering particles

C: 1 Breakage blocks; 2 Edge abrasion

D: 1 Adhering particles; 2 Conchoidal fractures
3 Precipitate of silica; 4 Breakage block
5 Impact pits

E: 1 Precipitate of silica predating grain breakage

F: 1 Solution hole; 2 Adhering particles
For each stub (i.e. each sample) the presence/absence data were summed and the percentage occurrence of each of the features for the 30 grains calculated and categorised for relative abundance (see footnote to Table 4.3). When conducted for the known sedimentary environments this provides a "finger-print" of surface textures for the major sedimentary sources and transfers of the Kwoiek Creek watershed. The results for the individual samples and the modes for each environment are presented in Table 4.4.

The environments exhibit some notable differences. The colluvial deposits contain very angular grains exhibiting breakage blocks and conchoidal fractures with little edge abrasion. Chemical features are present which indicate grain alteration by percolating water. The colluvio-fluvial deposits show minor evidence of fluvial action, slightly more rounded than the colluvial deposits but otherwise very similar. The glacial grains exhibit few effects of water rounding. They are angular with high relief, breakage blocks, conchoidal fractures, randomly oriented striations and semi-parallel step like features. There is very little precipitation or solution, and any that exists is a consequence of grain surface disruptions and/or fluid inclusions and the relative ease of alteration at these disrupted layers. The glacio-fluvial grains show alteration from their parent state, the glacial source, similar to that of the colluvial to colluvio-fluvial transition, with more pronounced edge abrasion and rounding; grains lack the high relief and sharp angular outlines typical of grains of primary glacial origin. The deltaic grains are similar to those from the glacio-fluvial deposits which are most probably their source (see later discussion). The most distinct grains are those from the "old" surficial deposits, with a relative abundance of chemical solution and precipitation features. These are undoubtedly a
Table 4.4 Relative abundance of surface textures for samples of known origin. First three samples for each sedimentary environment are modal abundance for each stub i.e. the individual samples, \(x\) is the mode of the modes i.e. it incorporates 90 determinations.

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1 Surface texture number refers to Table 4.3
C Colluvial
CF Colluvio-fluvial
G Glacial
GF Glacio-fluvial
D Deltaic
OSM Old surficial materials
function of time and increased contact with percolating soil water. It is conceivable that certain of these features, for example diagenetic overgrowths, may be destroyed during transport. However, solution effects, for example pits and crevasses (surface textures 28 & 29) are unlikely to be destroyed. Thus the sediments derived from this source and transported would be expected to remain distinct from those derived from other sediment sources.

4.3.2 Objective classification of the deposits

In order that the lake sediments of unknown origin be classified according to source some objective technique needs to be devised to assign unknowns to specific classes. Margolis & Kellner (1969) briefly describe a statistical evaluation of their binary data (present (1) absent (0)), whilst Bull (1978) attempted analysis of similar data sets by linear and multiple discriminant analysis. Culver et al (1983) undertook an evaluation of operator variance and differentiation between known environments using canonical variate analysis. This technique is concerned with the structure within the known groupings i.e. which surface textures contribute most to the characteristics of a particular environment, whereas multiple discriminant analysis is more concerned with the allocation of unknown samples to mutually exclusive categories. The problem arises that the relative abundance data compiled in this and in previous studies satisfy few of the requirements for the application of standard parametric statistics such as those previously used, which require the variables to be normally distributed, independent, and for the number of samples to exceed the number of characteristics.

With this in mind a Euclidean difference statistic (\(D_j\)), which uses the relative abundance data compiled in this study, is proposed to discriminate
objectively between samples, where:

\[ D_j = \frac{\sum_{i=1}^{n} (X_{ri} - X_{ji})^2}{n} \]

\( X_{ri} \) is the relative abundance for each of the characteristics (i) for the sample of the known reference environment.

\( X_{ji} \) is the relative abundance for each of the characteristics (i) for the sample to be classified.

\( n \) is the number of characteristics used.

This statistic provides a means to assess the differences between characteristics for individual samples and groups. An unknown sample is compared with signatures for known environments and is classified to that environment for which the difference statistic is minimised i.e. Min \( |D_j| \), \( j=1,6 \). The signatures take the form of the mode of the abundance categories for the 34 characteristics for the replicate samples taken from each of the known sedimentary environments sampled in this study (as in Table 4.4). Given the relative abundance, category data used in SEM studies, a root mean square difference statistic is preferred to a mean absolute difference statistic because it gives greater weighting to those differences greater than one category. This helps reduce potential problems of subtle differences in a number of categories between samples, possibly as a consequence of contamination by a small number of exotic grains, resulting in incorrect classifications.

The difference statistic permits a consideration of the relative importance of the individual surface characteristics in terms of their variability between replicate samples and their discriminating value between the different environments. It is important to establish the physical basis for the dissimilarities between environments in order to
establish that they are not solely a function of sampling strategy and unrepresentative signatures. Furthermore, some surface textures appear to be conservative, exhibiting little variation between the different sedimentary environments and thus can be removed from further consideration. The first step in the analysis was to identify these to improve the sensitivity of the statistic and to determine the optimal combination of characteristics to discriminate between sediments from the known environments.

The analysis was conducted in two stages. The first stage was to assess the degree of variability for each of the characteristics within the known environments. This was achieved by comparing each sample within a known environment against the mode for that environment and assessing the relative contribution (%) of each of the characteristics to the difference statistics (Figure 4.7a). This provides an index of the stability of each of the characteristics within each environment and identifies which characteristics are the most variable and therefore the least reliable in defining a particular environment. The second stage was to assess the relative contributions of the individual textures to the variability between environments. This was assessed in two stages. First, by comparing the modes of the six groups against one another and looking at the relative contributions of each surface characteristic (Figure 4.7b), and second, by comparing the individual samples against one another to assess the maximum between environment variability (Figure 4.7c). This second comparison is referred to subsequently as extreme range variability.

In general those characteristics that vary most within environments are also those that vary most between environments. In terms of differentiating between environments the most significant surface textures
Figure 4.7  Relative contribution of individual surface texture to difference statistics:

a) Within group

b) Between group

c) Extreme range
relate to morphology, edge abrasion, adhering particles, solution pits and crevasses. Cumulatively characteristics 1, 3, 6, 10, 17, 18, 25, 26, and 31 (see Table 4.3) contribute <10% to the difference statistic and were omitted from further consideration. All subsequent analyses were conducted with the reduced number of surface characteristics (n=25). Further reduction of the number of characteristics while increasing the differences between some paired comparisons, decreased the discriminatory power of the statistic for the reference samples overall.

In order to assess the confidence with which an unknown sample can be classified a number of independent tests were made. The first was to use the difference statistic to compare the samples from known environments against one another. This allows an assessment of both within (i.e. comparison of individuals against modes for each sedimentary environment) and between (i.e. modes for each environment compared against one another) environment variability. In addition extreme range statistics were computed as outlined above, for which the 18 individual samples were compared against one another to assess minimum and maximum variability within and between environments. The extreme range statistics were computed because the number of replicates for each environment (n=3) is small, with the modal scores for some of the characteristics relatively unstable (Figure 4.7a). The results from these analyses are presented in Figure 4.8. The solid lines represent the range of statistics for the mode comparisons, the dashed lines the extreme range comparisons. Ideally there would be a clear separation of the statistics, with the within environment difference statistics clustered close to zero, i.e. no differences, and the between environment values clustered much higher, with no numerical overlap between the two clusters. However, this is the case only for the
4.8 Difference statistics for samples from known sedimentary environments

a) Colluvial

b) Colluvio-Fluvial

c) Glacial

d) Glacio-fluvial

e) Deltaic (internal lake source)

f) Old Surficial materials - deposits of Fraser glaciation

Within group modal comparisons
Between group modal comparisons
Extreme range comparisons. Individual samples within and between groups respectively
samples taken from the old surficial materials.

In order to view the degree of dissimilarity/overlap more clearly cumulative frequency plots of the difference statistics are plotted in Figure 4.9. This graph illustrates the cumulative % of the difference statistics for paired comparisons less than a particular value, for the within and between environment comparisons with both modal and individual sample (i.e. extreme range) comparisons plotted separately. For each set of comparisons the difference statistics were calculated, ranked in ascending order and the cumulative % of difference statistics equal to or less than a certain number calculated. These numbers were then plotted. Some of the sample comparisons result in the same difference statistic. These points can be identified by steeper lines connecting them. Thus the number of points actually plotted on the ordinate scale equals, or is less than, the number of sample comparisons for each case of interest. Obviously the number of calculated difference statistics for within environment modal comparisons is less than for the individual sample (i.e. extreme range) comparisons, hence the lower number of points plotted.

The within group statistics cluster closer to 0 than the between group statistics. Rather than just illustrating the range limits of the difference statistics, evident in Figure 4.8, the cumulative curves enable an assessment of the probability of overlap. The vertical line drawn on the graph indicates the lowest values obtained for between group comparisons, which in this example is the same for both modal and extreme range comparisons. From these analyses for the Kwoiek Creek watershed it is proposed that the lowest of these values represents the minimum difference statistic that will be obtained when comparing a sample against a signature for an environment from which it is not derived. Therefore it
Figure 4.9 Cumulative distribution of difference statistics. M indicates modal comparisons; E.R. extreme range; see text for explanation

- **M - within**: Samples from each environment compared with the mode for that environment
- **M - between**: Modes from each environment compared against one another
- **E.R. - within**: Individual samples from each environment compared against replicates from that environment
- **E.R. - between**: Individual samples from one environment compared against those from other environments
is proposed when classifying unknown samples, guidelines be imposed whereby a sample is classified to that environment for which the difference statistic is minimised and the value must be less than 0.44 (when n=25) or an indeterminate result should be recorded. From the comparisons of known sedimentary environments outlined in this section using modal comparisons this would result in 69% of samples being correctly classified and 31% not classified.

When the individual data are studied, the differences for the comparisons of the glacial and glacio-fluvial environments, and the colluvial and colluvio-fluvial environments are seen to be amongst the smallest, and are in the graphical region of overlap. From the histogram plots earlier, and the descriptive comparison of the grains in the different environments outlined above, it is clear that the fluvial reworking of the parent glacial and colluvial grains introduces only subtle differences in characteristics. As the main thrust in this study is the identification of glacially derived grains regardless of fluvial reworking (which must occur at least for the glacially derived material in distal lakes) the second stage in the analysis was to pool the glacial and glacio-fluvial data, and the colluvial and colluvio-fluvial data, and to conduct a comparison between these two pooled groupings. These comparisons are presented in Figure 4.10 as cumulative distributions. These graphs indicate a much clearer differentiation of the environments with only 20% overlap (threshold $D_j 0.67$) on the cumulative curves for modal comparisons. When the within group statistics are broken down further (Figure 4.11), it can be seen that the variance within the colluvial environments is greater than that within the glacial environments (see both ER and modal comparison lines). This indicates that greater
Figure 4.10 Difference statistics - pooled glacial and colluvial
Figure 4.11 Difference statistics - pooled glacial and colluvial within and between group difference statistics
confidence can be attained when classifying glacial as opposed to colluvial sediments. For the colluvial deposits one sample in particular, the *in situ* eluvium, is most distinct and tends to bias the results, enhancing the apparent differences. However, as material can be delivered into the lakes by rockfalls etc, i.e. directly from such a source, this sample was retained in the analysis. It is not considered to be sufficiently distinct to create a separate category.

As an independent test of this scheme within the watershed, and in order to evaluate the additional influence of subaqueous post-depositional conditions on the lacustrine samples, signatures of sediments of known colluvial origin within the lakes (inferred from stratigraphic characteristics such as graded beds at the margins of the lakes) were compared with the terrestrial signatures (Figure 4.12). These results offer support for the use of this approach in the classification of lake deposits of unknown origin. All samples were correctly classified, although it is important to caution that this may provide a sense of over-confidence as such samples are the ones most likely to be derived from a single source and probably exhibit the strongest source signal.

In order to test the generality of the characteristics and classification procedure, data were compiled from the literature, primarily from the work of Bull (see Table 4.5), who has promoted this multi-parameter relative abundance approach, to compare against the data for the environments in this study. Such an approach is fraught with problems as a consequence of: variation in the selection of grains between different investigators; identification and nomenclature of specific features; and the great variability in both inherited characteristics (i.e. microstructural controls) and the processes operative in different
Figure 4.12 Classification of known subaqueous deposits (n=25)
All samples are classified as colluvial

- Glacial reference comparisons
- Colluvial reference comparisons
--- Within environment variance (modal)
---- Within environment variance (extreme range)
Table 4.5 Characteristic categories of abundance of surface features found on quartz grains from various environments of modification (Bull, 1985).

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<td>2</td>
<td>2</td>
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</tbody>
</table>

1 Surface texture number refers to Table 4.3
environments, nominally classified as the same. For example, the colluvial environments of Bull are ancient slopes of Swaziland, with a very different weathering regime to that of the Coast Mountains of British Columbia. The comparisons are reported in Table 4.6. It is important to note that for these comparisons the full range of surface textures was used i.e. n=34. As would be expected, differences do exist. As such at this stage it is cautioned that the classification scheme developed in this study is restricted to within-watershed discrimination of materials, although its utility has yet to be tested elsewhere in the Coast Mountains, or in alpine areas with a similar lithology.

From this first stage it was concluded that subtle differences in the combinations of surface characteristics are apparent in the known sedimentary environments of the Kwoiek Creek watershed which enable fine-sand material to be classified according to source. The analyses on the known sedimentary environments in this study indicate that these characteristic surface textures mostly are imparted during the weathering phase of the sediment's history and do not seem to be destroyed or altered during subsequent fluvial transport. This is undoubtedly a consequence of the spatial scale of this investigation and the distance the grains are transported. If the objective is to minimise the number of incorrect classifications i.e. minimise Type I errors, then to classify an unknown deposit within the Kwoiek Creek watershed, using the 25 surface characteristics employed in this analysis, a difference statistic, $D_j < 0.67$ should be obtained when compared to a reference sample. In the case of the known sedimentary environments analyzed in this study this would lead to >80% of the samples being correctly classified, and <20% not classified.
Table 4.6 Difference statistics for comparison of known sedimentary environment signatures determined for the Kwoiek Creek watershed with literature values of Bull (1985)

<table>
<thead>
<tr>
<th>Sedimentary environment</th>
<th>Difference statistic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Colluvial</td>
<td>0.65</td>
</tr>
<tr>
<td>Colluvio-Fluvial</td>
<td>0.80</td>
</tr>
<tr>
<td>Glacial</td>
<td>0.94</td>
</tr>
<tr>
<td>Glacio-Fluvial</td>
<td>0.99</td>
</tr>
<tr>
<td>Old Surficial materials/ Pedogenic sand</td>
<td>1.40</td>
</tr>
</tbody>
</table>

N.B. in this example n=34
4.3.3 Classification of the lake deposits

The objective of the SEM work was not to use it as a technique to characterise and describe samples down selected cores but to determine if the coarse and intermediate grain size fractions have a clear source signal such that fluctuations in these components could be used to make inferences about changing sediment sources through time. Thus the individual samples selected were specifically chosen from deposits where only one of these fractions is present i.e. to reflect either the coarse or intermediate sediment fraction, such that the respective sources of the two fractions could be identified with certainty. Samples approximately 1 cm in depth were taken from cores from all lakes at variable depths to ensure there had been no changes in the characteristics of the different fractions through time. The samples are described in Table 4.7.

The difference statistics for the comparisons of the lake sediments of unknown origin are presented in Table 4.7. Of the 20 samples analyzed 7 are classified as glacial in origin, 9 are colluvial, and 4 are indeterminate. No notable differences in classifications arose as a consequence of selecting the coarser or finer sand grains from an individual sample for analysis i.e. 125-250 μm compared to 63-88 μm. The coarse fraction of samples from the lower 2 lakes, Kokwaskey and Kwoiek, was classified as of colluvial or indeterminate origin. From the upper two lakes, Kha and Klept, the coarse fraction was classified as colluvial in origin and the middle fraction glacial in origin.

There are two probable explanations for the indeterminate results. It is important to stress these are the results for a bed and not for individual grains. First, given the low rate of sedimentation in the lakes and absence of sedimentary structures to identify deposits of individual
Table 4.7 Lake sediment samples classified as to origin using SEM

<table>
<thead>
<tr>
<th>Sample</th>
<th>Fraction</th>
<th>$D_j$-Colluvial</th>
<th>$D_j$-Glacial</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>KHA.C2.20</td>
<td>I</td>
<td>0.78</td>
<td>0.49</td>
<td>Glacial</td>
</tr>
<tr>
<td>KHA.C2.70</td>
<td>C</td>
<td>0.49</td>
<td>0.73</td>
<td>Colluvial</td>
</tr>
<tr>
<td>KHA.C2.90</td>
<td>C</td>
<td>0.52</td>
<td>0.71</td>
<td>Colluvial</td>
</tr>
<tr>
<td>KHA.C2.128</td>
<td>I</td>
<td>0.71</td>
<td>0.45</td>
<td>Glacial</td>
</tr>
<tr>
<td>KHA.C2.220</td>
<td>I</td>
<td>0.75</td>
<td>0.45</td>
<td>Glacial</td>
</tr>
<tr>
<td>KHA.C2.268</td>
<td>I</td>
<td>0.79</td>
<td>0.47</td>
<td>Glacial</td>
</tr>
<tr>
<td>KLP.C1.18</td>
<td>I</td>
<td>0.82</td>
<td>0.37</td>
<td>Glacial</td>
</tr>
<tr>
<td>KLP.C1.27</td>
<td>I</td>
<td>0.72</td>
<td>0.64</td>
<td>Glacial/Indeterminate</td>
</tr>
<tr>
<td>KLP.C1.93</td>
<td>C</td>
<td>0.43</td>
<td>0.79</td>
<td>Colluvial</td>
</tr>
<tr>
<td>KLP.C1.98</td>
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<td>0.79</td>
<td>Colluvial</td>
</tr>
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<td>KLP.C1.111</td>
<td>I</td>
<td>0.73</td>
<td>0.51</td>
<td>Glacial</td>
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<td>KOK.C5.60</td>
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<td>0.65</td>
<td>0.67</td>
<td>Indeterminate</td>
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<tr>
<td>KOK.C5.155</td>
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<td>0.53</td>
<td>0.75</td>
<td>Colluvial</td>
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<td>KOK.C5.240</td>
<td>C</td>
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<td>0.77</td>
<td>Colluvial</td>
</tr>
<tr>
<td>KOK.C5.315</td>
<td>C</td>
<td>0.43</td>
<td>0.82</td>
<td>Colluvial</td>
</tr>
<tr>
<td>KWK.C15.40</td>
<td>C</td>
<td>0.72</td>
<td>0.68</td>
<td>Indeterminate</td>
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<tr>
<td>KWK.C15.70</td>
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<td>0.75</td>
<td>0.67</td>
<td>Indeterminate</td>
</tr>
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<td>KWK.C15.135</td>
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<td>0.81</td>
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<td>KWK.C15.185</td>
<td>C</td>
<td>0.45</td>
<td>0.79</td>
<td>Colluvial</td>
</tr>
</tbody>
</table>

1 C - coarest fraction; I - intermediate fraction
events, many sedimentation events are represented in each unit of analysis. Thus the results are probably indicative of the integration of events and sources i.e. sediments of mixed origin. Second, the basal sediments in Kwoiek and Kokwaskey Lakes, given their coarse nature, are probably deposits reflecting colluvial, paraglacial sedimentation. The residence times of material on the slopes at this time, which were deposited by the retreating Fraser glaciation ice, were short; thus any signal characteristic of the old surficial materials, as determined today, would be poorly developed.

These results indicate that the coarsest fraction in many of the samples is colluvial in origin. The intermediate fraction is glacial in origin. When the results from the different lakes are compared they illustrate a strong filtering of the intermediate glacial signal down-system, as would be expected. The fraction is deposited in Kha and Klept lakes and does not reach the two more distal lakes. It is important to stress that the deposits analyzed here are ones selected to represent lake-wide changes in sedimentation i.e. deposits of an obviously localised, colluvial origin were discarded. The presence of glacially derived sediment at various depths in the sediments of Klept Lake supports the contention that glaciers have existed in the Kwoiek Creek watershed throughout the Holocene Epoch.

An interpretation of the significance of the changes in source of the coarser fractions through time is presented in Chapter 5 after consideration of the source and variability of the fine silt-sized fraction.

4.4 Sediment source analysis: The silt-fraction

The finest grain-size fraction (medium to fine silt; section 4.2) which
constitutes most of the sediment is not amenable to the same form of SEM surface texture analysis (see problems outlined by Krinsley, 1978). The size range of this fraction (presented in section 4.2) suggests that it may be "glacier rock flour" and thus be the sedimentary signal of specific interest in this study for reconstructions of glacial activity. A systematic examination of glacial rock flour by Keller & Reesman (1963) from a wide range of lithologies reported that particle sizes characteristically ranged 12 µm down i.e. the finest silt and clay. This generally corresponds to the fine sub-population identified in this study. In the lakes studied the lower size limit of this fine fraction may well be truncated as a consequence of the short residence times of the water and sediment in the lakes such that there is insufficient time for the finest sediment to settle out (see calculations in section 3.1).

The initial approach taken to characterise the source of the fine silt-sized material was by analysis of its mineralogy. An attempt was made to relate this to source characteristics, following a similar methodology of source-sink characterization outlined in the previous section for the SEM work. Samples of the 32 to 4 µm (5 to 8 φ) size fraction from samples of known genesis (see listing for SEM work) were ground into powder, fixed on unoriented mounts and analyzed on a Philips PW 1730 X-ray diffraction instrument, Department of Oceanography, U.B.C. using standard procedures. The dominant minerals were identified on the basis of the intensity of reflections using standard tables.

No clear distinctions between the mineralogy of colluvial environments and recent glacial deposits were evident. Both exhibited a predominance of quartz and feldspars in fairly regular proportions, with no minor minerals which would seem to be diagnostic of origin. One of the three contemporary
colluvial samples has a greater abundance of chlorite and phyllosilicate minerals, specifically vermiculite and smectite, which are present in only trace amounts in the glacial samples studied. This is undoubtedly a reflection of the greater subaerial exposure of the slope deposits and is consistent with the relative abundance of the incipient chemical features that were observed in the SEM work. This would suggest that if phyllosilicates are observed in the silt fraction of the lake sediments beyond trace amounts, the material was derived from a colluvial not a glacial source. However, if they are not present no conclusions can be drawn concerning provenance or history. The "old surficial materials" exhibited a much greater degree of weathering, with a greater abundance of smectite and vermiculite, and are the only deposits with appreciable kaolinite present. The distinctiveness of the Fraser Glaciation deposits (OSM) permits the differentiation of material derived from them and from material of contemporary colluvial and glacial sources.

The results from the lake sediments are ambiguous (see an example in Figure 4.13). There is no clear evidence for more than trace abundance of any minerals other than quartz and feldspar. This is not surprising given the bedrock geology, at least in terms of the contributing areas for the lakes under investigation, and the low residence times of many surficial materials before being deposited in the lakes. Previous studies have indicated that variations in the mineralogy of the non-clay clastic fractions of most lake sediments generally reflect variations in drainage basin geology (Jones & Bowser, 1978). Superimposed on this factor are the effects of selective settling and winnowing of finer grained sediments (Jones & Bowser, 1978). The absence of a strongly weathered silt fraction in the lake sediments suggests that there has been little reworking and
Figure 4.13 Example of XRD reflections of silt-sized fraction (lake sediment sample KWK Cl5-5)
deposition of the older surficial materials. Rather, the material deposited in the lakes appears to have been derived from contemporary glacial and colluvial deposits. However, using this technique it is not possible to identify confidently the source of the fine fraction.

One of the explicit reasons for choosing to work at a drainage-basin scale with a number of lakes was to permit a consideration of basin-wide as compared to localised, sedimentation patterns. This provides an alternative approach to identifying the source of the fine fraction by looking at the spatial and temporal coherence in its fluctuations. This approach is pursued in Chapter 5 through analyses which consider the coherence in the fluctuations of the silt-sized signal down-valley, i.e. between lakes, through time in conjunction with a consideration of the coherence of the colluvial signal as identified by the SEM technique. These are used to isolate the glacial sedimentary signal of specific interest in this study.

4.5 Summary

From the analyses presented in this chapter it is concluded that potentially important palaeoenvironmental information is contained in the clastic component of alpine lake sediments, both in terms of their rate of influx and provenance. Figure 4.14 is a schematic representation of the methodology adopted in this study to isolate this information.

Following initial characterization of the sediments into clastic and organic components, grain size analysis and subsequent partitioning of the cumulative probability curves revealed three distinct sub-populations that were mixed either prior to or during deposition. The technique of graphical partitioning allows "unmixing" and provides an opportunity to examine each population by itself in order to gain further insight into
Figure 4.14 Schematic representation of methodology pursued in this study to interpret palaeo-sediment record

Sub-bottom sounding/collection cores
Definition lake-wide sedimentary characteristics

Characterisation Lithostratigraphy

SEDIMENT FRACTIONS

Clastic fraction
Organic fraction

Textural analysis & graphical partitioning

Loss on ignition

SEDIMENT SOURCE IDENTIFICATION

Coarse Intermediate Fine

SEM XRD

Colluvial derived sediment Glacial derived sediment Glacial derived sediment

Synchronicity basin-wide changes Rate of sediment influx

PALAEO INTERPRETATION

Proxy signal glacial activity Holocene Epoch
origin. The provenance and history of the coarse and intermediate fractions can be determined by SEM surface texture analysis of a statistically representative number of grains and objectively classified as to origin using a Euclidean difference statistic. It has been shown that the coarse fraction in each of the lakes is derived from localised colluvial sources and the intermediate fraction in Kha and Klept lakes is of glacial origin. The silt grains are less easy to characterise using source-sink matching characteristics which are remarkably uniform across the basin in terms of weathering products. Further consideration of the origin of the lake sediments is presented in Chapter 5 by investigating the coherence of the silt signal down-valley through time.
CHAPTER 5 TEMPORAL CHANGES IN SEDIMENTARY RESPONSE

This chapter presents information on the fluctuations through time of sedimentation rates, identification of the glacial component and a consideration of its variability through time. This provides the basis for a model of Holocene Epoch glacial activity in the Coast Mountains of British Columbia which is assessed for regional consistency in Chapter 6.

5.1 Temporal variability in sedimentation rates

The inverse relation between organic content and clastic sedimentation rates that was established in section 4.1 is used as the basis for inferring changes in sedimentation rates through time in each of the lakes. Multiple cores from each of the four lakes were taken to represent the sedimentary environments within each of the lakes (see discussion in section 3.4). These cores are identified on each of the subsequent figures. Subsamples were taken at 5 cm intervals and analyzed for organic matter content (see section 4.2). A single core from each lake was then selected for more detailed analysis at 1 cm intervals. Any horizons which contained large fragments of organic material, for example those used for C-14 dating, were omitted from the analysis. The cores analysed at the lower temporal resolution (sample every 5 cm) were used to ensure that the results from the single cores selected for detailed analysis were representative of lake-wide changes through time. On average 1 cm of core represents 6 yrs of sedimentation in Kha Lake; 40 yrs in Klept Lake; 30 yrs in Kokwaskey Lake; and 60 yrs in Kwoiek Lake.

For each lake the data from each core are transformed to a standardised index:

\[ I = -\left(\frac{x_i}{\bar{x}} - 1.0\right) \]

I is the sedimentation index

\( x_i \) is organic matter content for the sample
\( \bar{x} \) the mean organic content for the core

A value greater than 0 (i.e. a low organic content) indicates above average sedimentation rates, a value less than 0 (i.e. a high organic content) below average rates, and 0 the average rate. This standardisation has the effect of accentuating fluctuations through time within the environments rather than variations in magnitude attributable to spatial variations in influx within each of the lakes.

The raw standardised data for the individual cores show generalised trends but are quite "noisy", with numerous outliers (see "spikes" on Figures 5.1 to 5.4). The potential origins of such outliers are numerous, but for the most part they are attributable to high magnitude clastic or organic sedimentation events. Hence they are not representative of integrated sedimentation episodes at the timescale of 10^2 years that are of interest in this study. For this reason the data were filtered to enable low frequency features to remain unchanged while damping higher frequency variations. This was achieved by using a 5 point running median. A running median rather than running mean was selected because it is not influenced by one or two outliers in a section of a core, but requires more persistent departures for a trend to be established. A 5 point running median was selected as it maintains the resolution of the data at a scale appropriate for this study, and more importantly, it is at least 3 points greater than any deposit that can be attributed to one event even in the lower portions of the record (maximum thickness of graded beds at the base of Kokwaskey 1.7 cm, see core logs in Appendix I).

In order to discriminate further the low frequency trends in sedimentation regime from higher frequency variations, a 21 point weighted running mean was
Figure 5.1 Standardised sedimentation data for Kha Lake

a) KHA.C2 (1 cm)
b) KHA.C4 (5 cm)
c) KHA.C3 (5 cm)
d) KHA.C5 (5 cm)
Figure 5.2  Standardised sedimentation data for Klept Lake

a) KLP.C1  
   (1 cm)  

b) KLP.C5  
   (5 cm)  

c) KLP.C6  
   (5 cm)  

d) KLP.C2  
   (5 cm)
Figure 5.3 Standardised sedimentation data for Kokwaskey Lake

a) KOK.C5
   (1 CM)

b) KOK.C3
   (5 CM)
Figure 5.4 Standardised sedimentation data for Kwoiek Lake

a) KWK.C15 (1 cm)
b) KWK.C14 (5 cm)
c) KWK.C6 (5 cm)
placed through the data, with weights which decrease outward in each
direction from a central weight (Hartwig & Dearing, 1983). The results of
this are presented in Figures 5.5 to 5.8. It can be seen quite clearly from
these figures that systematic changes in sedimentation rates have occurred
over the timescale of the Holocene in all of the lakes. The trends from the
cores analysed in greatest detail (i.e. 1 cm resolution) would appear to be
representative of lake-wide changes. The subsequent discussion focuses on
their interpretation.

The degree of variability in the sedimentation rate records may be assessed
through computation of the variance for each data set, or the complacency by
the standard deviation. These statistics were computed for the raw
sedimentation data and the raw data for the post 2400 yrs B.P. period (see
Table 5.1) and are interpreted below.

The sedimentation record from Kha Lake is relatively short, with a basal
date of 2350 +110 B.P. Two maxima are evident in the sedimentation record,
one in the upper sediments, at 0.7 m, and the other at the base of the core,
peaks at 3.25 and 3.90 m (see Figures 5.1 and 5.5). The upper, more organic
sediments may well be attributable to anthropogenic effects, specifically
road construction and logging in the immediate vicinity of the lake.

The record in Klept Lake (Figures 5.2 and 5.6) is much more "noisy". However, overall the range in magnitude in the sedimentation index and
variance is smaller than that for Kha Lake. The lake sediment record
indicates very high clastic sedimentation rates recently with low rates prior
to this. A road was constructed next to Klept Lake, but logging and
widespread removal of timber and disturbance of the vegetative cover has not
occurred. For much of the Holocene the lake sediments exhibit a remarkably
complacent record. The lake has not recorded recent (last 2400 years) changes
Figure 5.5 Standardised sedimentation data for Kha Lake (KHA.C2)

a) Raw standardised data
b) 5-point running median
c) 21-point weighted mean
Figure 5.6 Standardised sedimentation data for Klept Lake (KLP.C1)

a) Raw standardised data
b) 5-point running median
c) 21-point weighted mean
Figure 5.7 Standardised sedimentation data for Kokwaskey Lake (KOK.C5)
a) Raw standardised data
b) 5-point running median
c) 21-point weighted mean
Figure 5.8 Standardised sedimentation data for Kwoiek Lake (KWK.C15)

a) Raw standardised data
b) 5-point running median
c) 21-point weighted mean
<table>
<thead>
<tr>
<th></th>
<th>Variance</th>
<th>Standard deviation</th>
<th>(n)</th>
</tr>
</thead>
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<td><strong>Original data</strong></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Kha (KHA.C2)</td>
<td>0.081</td>
<td>0.285</td>
<td>410</td>
</tr>
<tr>
<td>Klept (KLP.C1)</td>
<td>0.047</td>
<td>0.216</td>
<td>258</td>
</tr>
<tr>
<td>Kokwaskey (KOK.C5)</td>
<td>0.127</td>
<td>0.356</td>
<td>429</td>
</tr>
<tr>
<td>Kwoiek (KW.K.C15)</td>
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<td>0.403</td>
<td>272</td>
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<tr>
<td><strong>Post 2400 B.P.</strong></td>
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</tr>
<tr>
<td>Kha (KHA.C2)</td>
<td>0.081</td>
<td>0.285</td>
<td>410</td>
</tr>
<tr>
<td>Klept (KLP.C1)</td>
<td>0.053</td>
<td>0.231</td>
<td>55</td>
</tr>
<tr>
<td>Kokwaskey (KOK.C5)</td>
<td>0.073</td>
<td>0.269</td>
<td>80</td>
</tr>
<tr>
<td>Kwoiek (KW.K.C15)</td>
<td>0.069</td>
<td>0.262</td>
<td>57</td>
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</tbody>
</table>
in sedimentation as pronounced as in Kha Lake just upstream, undoubtedly as a consequence of Kha's formation (see section 3.10) and filtering effect. Sedimentation rates in the lake do seem to decrease after 2400 B.P. (see Figure 5.6 at 55 cm depth) possibly as a consequence of Kha Lake's formation, however, a decrease is evident in all lakes within the watershed at this time. With the exception of the recent period the only pronounced high sedimentation rates are at the base of the core ca. 9640 ±380 B.P. Accumulation rates in terms of the depth of sediment in the lake in the pre 2400 B.P. period compared to the post 2400 B.P. period are remarkably low when it is considered that it is proposed that Kha Lake did not come in to existence until 2350 B.P. and that filtering of the material did not start until this time. This indicates that either the basal date on the sediments cored in Kha Lake does not indicate the date of formation of the lake, that some depositional environment has always existed at the Kha Lake site (i.e. the fan that now constrains Kha Lake may have extended across the valley impounding the lake and subsequently been eroded on more than one occasion during the Holocene), or that Klept Lake has never functioned as a very good sedimentary trap. Whatever the reason, it can be concluded that in comparison to the other lakes in the watershed Klept Lake is not a very sensitive site, exhibiting a relatively complacent record, lowest variance, with input from local slopes dominant.

The sediments of Kokwaskey Lake (Figures 5.3 and 5.7) seem to provide a particularly sensitive record of changes in sedimentation, with consistent departures from the mean recorded in different cores. In general the late Holocene is characterised by high sedimentation rates with two notable increases in the last 3000 years, the peak at 15 cm and one just before 2400 B.P., with minor excursions around 4900 B.P. Minima in the mid to early
Holocene (centred ca. 6800 years ago) are especially conspicuous. The lower part of the record is characterised by relatively high rates of sedimentation.

Sedimentation rates for Kwoiek Lake (Figures 5.4 and 5.8; Table 5.1) are the most variable. Rates peaked before 12 255 ±770 yrs B.P. and have been high from 5035 ±1875 yrs B.P. to the present, with two major peaks, one just prior to 2400 years ago and the other after 1240 ±245 yrs B.P.

Figure 5.9 presents summary plots of the temporal trends in sedimentation rates for each of the lakes in a downstream sequence. The vertical axis is standardised in terms of depth to better illustrate fluctuations in the absolute rates of sedimentation. The greatest rates of sedimentation are observed in Kha and Kokwaskey Lakes. From the depths of accumulation shown on Figure 5.9 it can be seen that absolute rates of sedimentation have decreased from Kha to Klept to Kwoiek Lake. Kokwaskey has a second major source from Chochiwa glacier and the Haynon Lake chain, complicating interpretation of its signal. This down-system decrease evident from Kha to Kwoiek Lake would suggest a dampened response to Neoglacial forcing, which is consistent with the expected pattern of sedimentation from the paraglacial model as outlined in section 1.3.

In order to assess the degree of variability through time for each lake the sedimentation indices must be defined and compared for similar time periods. The average value, the reference, will vary depending on the time period selected i.e. will be different for the last 2400 years as compared to that for the full Holocene Epoch. Because the record for Kha Lake encompasses only the last 2400 years, the mean sedimentation rate for the last 2400 years was determined for each core and comparable sedimentation indices computed. The results are presented in Table 5.1. Over the full Holocene Epoch the degree
Figure 5.9  Downstream attenuation of absolute rates of sedimentation and variability (Standard depth scale, different time variate)

a) Kha Lake  b) Klept Lake  c) Kokwaskey Lake  d) Kwoiek Lake
of variability in the sedimentation records of Kokwaskey and Kwoiek lakes is greater than that for Kha and Klept lakes. This study has documented that there have been marked changes in sedimentation from the early to latter parts of Holocene which are not represented in the Kha lake deposits because they only encompasses the post 2400 B.P. period. Klept Lake has already been described as relatively complacent. Hence it is difficult to evaluate any attenuation of variability over the full postglacial period. For the post 2400 B.P. period if the record for Klept Lake is ignored there would seem to be a general decrease in variability downsystem.

Although there is general agreement between the records in the lakes in terms of highs and lows in the sedimentation rates i.e. lower values in the earlier part of the Holocene, higher in the latter, there are important differences in the details of the records. One example is the markedly different patterns in sedimentation ca. 6000 B.P. in Klept and Kokwaskey Lakes. The above discussion has focused on the total sediment influx. As demonstrated in Chapter 4, distinct sediment fractions are being introduced into the lakes, not all of which are derived from the headwater glaciers. Thus if these records are to be used as a proxy of Neoglacial activity within the catchment it is important to establish the glacial-derived component. The next section isolates and interprets fluctuations in the glacial sediment signal through time.

5.2 Changes in the glacial sediment signal through time

As identified in section 4.2 three distinct sediment populations are being introduced into the lakes. The coarsest fraction is either of colluvial or indeterminate origin (see SEM results, section 4.3), while it is suggested that the intermediate and fine fractions are the glacial sediment of interest in this study. The graphical separation procedures outlined in section 4.2
were used to identify the relative proportions of each textural fraction for each sample of those cores that were studied intensively for changes in sedimentation rates. The temporal variability of the "intermediate" and "fine" fractions combined, as % composition of each sample, is presented in Figure 5.10.

When the proportions of the fine and intermediate fractions are used to weight the sedimentation index to derive a new index of the variability of rates of glacial sediment influx, through time, more interesting trends emerge (see Figure 5.11). In Figure 5.11 the vertical axis has been transformed from a depth to a temporal scale based on calculations of the influx of organic material. If, as outlined in sections 4.1 and 5.1, it is assumed that the influx of organic material has remained relatively constant through time, then an expected rate of organic influx can be defined per unit time using the tephra horizons and radiocarbon dates. This average organic influx rate can be used to define units of similar temporal duration i.e. to partition the core into units of similar organic content which, given the assumptions outlined above, were deposited in a given period of time. If combined with information on changing bulk density of the sediments this methodology can be used to document changes in the influx of clastic sediment through time at a given temporal resolution. The time periods chosen in this set of analyses were 10 years for Kha Lake, and 50 years for Klept, Kokwaskey and Kwoiek Lakes, consistent with the temporal resolution of the analyses (i.e. 1 cm in each of the cores). During preliminary analysis of the organic matter content data it was noted that organic matter influx rates change dramatically in the earlier part of the Holocene, undoubtedly as a consequence of changes in terrestrial vegetation (see Chapter 6). This suggests that the rates of organic influx should not encompass this period
Figure 5.10 Variations in proportions of glacial derived fractions with depth

a) Kha Lake  b) Klept Lake  c) Kokwaskey Lake  d) Kwoiek Lake

% Intermediate & fine fraction

-2350 ±110

9640 ±380

2400 -

-2400 -

-4900 ±325 -

-3 M

6800 - - /- -

-11 485 ±185'

-1240 ±245-•-

-2400- -

4900 ±325-

2400 -

-5035 ±1875-

12 255 ±770
Figure 5.11 Temporal variability in glacial-derived sediment. Note the standard temporal scale on the ordinate. The variate is a relative scale that should only be compared down-core, not between lakes (see discussion in section 4.1).

a) Kha Lake  b) Klept Lake  c) Kokwaskey Lake  d) Kwoiek Lake

--- Composite

--- Kha Lake  --- Klept Lake  --- Kokwaskey Lake  --- Kwoiek Lake
and therefore should not be defined as an average for the entire postglacial period. Ideally they would be defined for the early/mid Holocene period to the present. The average values used in the construction of Figure 5.11 are based on different periods for each of the lakes depending on the dates available. An average value is defined for the only dated period in Kha Lake to 2350 B.P., for the sediments down to Mazama tephra in Klept and Kokwaskey Lakes, and to Bridge River tephra for Kwoiek Lake. This relatively short period was chosen for Kwoiek Lake because of the large error bars associated with the radiocarbon dates in this lake. These values are used to develop a chronology back to approximately 10,000 B.P. (based on information on pollen spectra presented in Chapter 6 indicating relative stability in the catchment's vegetation by this time). The magnitude of possible errors associated with the chronology are considered further below. Sedimentation rates per unit time were then calculated from the influx of clastic material for these "standard" time intervals. A 21-point running mean (see section 5.1) was placed through the data to better illustrate the low frequency changes in sedimentation regime that are of interest in this study.

From the records displayed in Figure 5.11 it would appear that the rates of glacial sediment influx in all lakes are fairly constant until ca. 7000 B.P. At that time sedimentation rates in Kokwaskey and Klept Lakes show a gradual increase. In Klept Lake this is followed by a minor, well defined peak of ca 1000 years duration, approximately 6000 to 5000 B.P. Rates in all three lower lakes show a pronounced increase ca 4000 to 3000 B.P., peaking ca 3500 years B.P. in Klept Lake, 3000 B.P. in Kokwaskey Lake and 2900 B.P. in Kwoiek Lake. A second major increase is evident in the last 1000 years. The chronology of these later events can be seen best in the higher resolution record of Kha Lake. The high sedimentation rates of the earlier 3000 - 2000 year event
would seem to have fallen to lower levels by 1500 years B.P., starting to rise almost immediately, reaching a maximum ca 300 - 250 years ago.

The synchronicity of events recorded in each of the lakes is best seen in the final plot in Figure 5.11 where the trends for the individual lakes are superimposed. Attention should be directed to the relative magnitude of fluctuations down the individual cores not between cores (see explanation in section 5.1). Although there is good general correspondence between the records from the four lakes it is apparent that differences do exist in the details of the chronologies of the individual records. For example the timing of the mid Neoglacial phase which peaks ca 3500 years B.P. in Klept Lake, 3000 B.P. in Kokwaskey Lake and 2900 B.P. in Kwoiek Lake. The question is raised as to whether these are real and reflect an attenuation of the Neoglacial signal down system or whether they are an artefact of the way the chronology has been derived for the records presented in Figure 5.11. It is possible to estimate potential errors in the organic matter influx rate chronology using dates that have not been used to define the original average influx rates i.e. to predict where the "independent" dated horizon would be expected to be found in the core and to compare this with its actual stratigraphic position. The most reliable chronological horizons are the tephra deposits. The radiocarbon dates obtained in the upper portions of the cores in this study have very large error bars (see Table AII.1) and were not used. The Bridge River tephra was not used in the definition of average organic influx rates in either Klept or Kokwaksey Lakes, so it is possible to use its position to estimate the order of magnitude of likely errors. The position of Bridge River tephra in Klept Lake is predicted to occur four sedimentation units above where it actually occurs i.e. an error of 200 years, suggesting that events in the upper portion of this record may be
dated of the order of 200 years too old. In Kokwaskey Lake the Bridge River
tephra is two units below its actual position i.e. events may be dated of the
order 100 years too young. This indicates that the confidence that can be
ascribed to the chronology presented in Figure 5.11 is of the order ± 200
years, at least for the latter part of the Holocene. This suggests that there
may well be some attenuation of the Neoglacial sediment signal as the
differences in the lake chronologies, for example for the Neoglacial phase
cia. 3500 to 2900 B.P., are greater than 200 years, although the difference in
timing may not be as pronounced as indicated in Figure 5.11.

When the glacial sediments trends are compared with those of total
sedimentation rates (Figure 5.9) i.e. all sources combined, a number of
important differences are evident (see for example the high sedimentation
rates ca 170 cm depth in Kokwaskey in Figure 5.9 not evident ca 5000 B.P. in
5.11). It is proposed that the trends in Figure 5.11 provide a proxy record
of Neoglacial activity over the Holocene Epoch.

Some of the finer material is undoubtedly derived from episodic mass
wasting. However, textural data on the surficial materials derived from
plutonic rocks of the Coast Mountains (see Clague, 1989; Figure 1.10) and of
the Stein River watershed (Ryder personal communication) indicate a
predominance of sandy material with a low proportion of fines. The important
point is that the mass wasting events, at least as evidenced by the coarsest
fraction, are not occurring at a basin-wide scale, whereas there is a
coherent sedimentary signal apparently imparted by glacial activity in the
watershed's headwaters. Thus some confidence can be assumed in interpreting
the fine-lake sediment record as a palaeo-record of glacial sediment supply.
However, it is important to stress that the samples analysed in detail were
deliberately chosen not to reflect localised inputs of colluvial material.
Therefore the sampling strategy deliberately selects against this fraction and any interpretations of the colluvial signal through time should be considered accordingly. The temporal variability of colluvial activity at the drainage basin scale as recorded by lake sediments is worthy of further study.

This section has demonstrated that the signal in Kha lake is dominated by glacial sediment, evidenced by the close correspondence of total and fine-fraction sedimentation rates (compare Figure 5.9 with 5.11). Kha Lake provides a high resolution sedimentation record for the last 2400 years, with peaks in sedimentation rates in the period post 2350 +110 and in the recent period. The record in Klept Lake is smoothed considerably when the colluvially derived material is removed, with three peaks 6000 - 5000 B.P., 4000 - 3000 B.P. and the period post 2000 B.P evident. In Kokwaskey Lake there are two fine sediment peaks one ca. 3000 years B.P. and the other in the last 750 years. In Kwoiek Lake there are two similar peaks in glacial-derived sediment, one slightly later than in Kokwaskey, centred on 2900 B.P. and the last 1000 years, which seems to be of slightly lesser magnitude but longer duration. The implications of these fluctuations in terms of a record of Neoglacial activity in the Coast Mountains of southern British Columbia are considered further in Chapter 6.

It is interesting to compare the results from the detailed analysis of the glacial sediment signal with the lithostratigraphies of the cores to see whether certain facies are associated with periods of greater Neoglacial activity (compare Figure 5.11 with cores logs in Appendix I). There would appear to be no single facies that is consistently associated with periods of greater Neoglacial activity. In Kha Lake periods of greater glacial sediment supply are broadly associated with laminated silt
deposits. In Klept Lake variations in the sediment lithostratigraphy is more a function of inputs of coarse material from colluvial sources, however, periods of greater glacial sediment influx are associated with massive silts, while other periods with more massive sands. In Kokwaksey Lake the uppermost varved sediments correspond to the increased sediment supply associated with the Little Ice Age. Periods of lower glacial sediment input are associated with coarser facies. In Kwoiek Lake the most recent period of increased glacial sediment influx is associated with laminated silts, while earlier phases of Neoglacial activity correspond to facies of massive silt. It can be concluded that although phases of Neoglacial activity are broadly correlated with variations in the texture of the deposits in each of the lakes, the core lithostratigraphies cannot be interpreted directly as a proxy of Neoglacial activity. Thus the detailed analyses of the sediment sources and lake sediment deposits conducted in this study are a necessary prerequisite in identifying phases of Neoglacial activity from the lake-sediment record.

5.3 Characteristics of temporal variability

The above discussion has focused on the smoothed general trends in the sedimentation data through time. Church (1980) discusses temporal variability in environmental data in the framework of "trend", "persistence" and "intermittency". Trend includes cyclic and quasi-cyclic behaviour through time and is concerned with the general patterns documented above. Persistence occurs when a particular value of a sequence constrains adjacent values. This is usually the result of continuity or storage constraints in physical systems and may be studied via correlograms or by investigating the Markovian properties of the event sequence (Yevjevich, 1972). Intermittency refers to the (non-serial)
tendency for like values to be grouped in a sequence, and is of value in considering the time distribution of extreme events. Given the damping of the Kwoiek Creek system because of the lakes, and the prescreening of the data for any apparently anomalous high magnitude events of local origin, the issue of intermittency is not considered further.

The degree of persistence in each of the records indicates the dominant temporal scales of "history" in sedimentation records. Autocorrelation or serial correlation describes the linear dependence among successive values of a series that are a given lag apart. In order to analyse persistence in a record it is necessary to separate the random and non-random elements of a time series (Matalas, 1963). Trend must be eliminated from the non-random component before studying the oscillatory behaviour of the time series.

Analyses for persistence were conducted on the raw glacial-derived sedimentation data defined for constant time units outlined above (10 years for Kha Lake, 50 years for the other three lakes) using the organic influx data (i.e. the raw data which make up Figure 5.11). Trend was removed from these data by subtracting a 21-point running mean and the residuals analysed for different levels of serial correlation. Figure 5.12 presents the data on the serial correlation coefficients for the core in each of the lakes that was studied in detail. The upper line on each graph in Figure 5.12 represents the serial correlation coefficients calculated, and the lower line the expected values if the process is a simple Markovian process (see further discussion below). If a time series is randomly distributed once trend has been removed the serial correlation coefficients between values for all orders will be zero.

Two features of the plots are of particular interest. The first is the
Figure 5.12 Serial correlation coefficients for the data. The upper line in each diagram indicates the values obtained for successive correlation values, the lower line the expected values if the sequence is random (see text for explanation).

a) Kha Lake

\begin{align*}
\text{Correlation coefficient} & \quad 0.35 \\
& \quad 0.30 \\
& \quad 0.25 \\
& \quad 0.20 \\
& \quad 0.15 \\
& \quad 0.10 \\
& \quad 0.05 \\
& \quad 0.00 \\
\end{align*}

\begin{align*}
\text{Time} & \quad 0 \\
& \quad 400 \\
& \quad 800 \\
\end{align*}

b) Klept Lake

\begin{align*}
\text{Correlation coefficient} & \quad 0.40 \\
& \quad 0.35 \\
& \quad 0.30 \\
& \quad 0.25 \\
& \quad 0.20 \\
& \quad 0.15 \\
& \quad 0.10 \\
& \quad 0.05 \\
& \quad 0.00 \\
\end{align*}

\begin{align*}
\text{Time} & \quad 400 \\
& \quad 800 \\
\end{align*}

c) Kokwaskey Lake

d) Kwoiek Lake

\begin{align*}
\text{Correlation coefficient} & \quad 0.4 \\
& \quad 0.3 \\
& \quad 0.2 \\
& \quad 0.1 \\
& \quad 0.0 \\
\end{align*}

\begin{align*}
\text{Time} & \quad 400 \\
& \quad 800 \\
\end{align*}
statistically significant first order serial correlation in all of the lakes i.e. the $r_1$ values for adjacent sedimentation rates (KHA $r_1=0.35$, $n=410$; KLP $r_1=0.42$, $n=220$; KOK $r_1=0.44$, $n=410$; KWK $r_1=0.36$, $n=198$; all significant at $a=0.01$). This indicates strong history in the sedimentation system at the timescale of the sampling interval of the analyses. The first and second serial correlation coefficients (representing 50 and 100 years of sedimentation) are statistically significant in Kwoiek, Kokwaskey and Klept Lakes, while the first 15 coefficients (representing 150 years of sedimentation) are significant in Kha Lake ($a=0.01$).

The second feature of interest is the deviations of the serial correlation coefficients in all 4 lakes from those expected from a simple Markovian process. If a sequence of values is non-randomly distributed in time, then each value repeats some of the information of the previous value, which in this study is what is simulated by the simple first-order Markovian process i.e. the first order coefficient is successively multiplied for increasingly higher orders to generate an "expected" serial correlation coefficient that is due solely to the first order serial correlation in the data. These values are displayed graphically as the lower line on each of the graphs. Speculatively it could be suggested that the deviations represent true persistence in the data and these separations have physical significance in terms of glacial-driven sedimentation processes, for which a temporal scale can be defined. For example they may be related to storage effects within the glacial-sediment system affecting sediment supply and release of material into the fluvial system. The data for Klept and Kokwaksey Lakes exhibit a very close correspondence to the first order Markovian decay, indicating only first order persistence in the data i.e. a "history" of the order 50 years. For
Kwoiek Lake if the second order correlation coefficient is also incorporated into the model (see the dashed line) a much better fit is obtained, suggesting history over timescales of the of 100 years. Speculatively, these fluctuations may be interpreted in terms of relaxation times of sediment stores within the sediment cascade related to Neoglacial events. They may relate to the time for the sediment stores to attain stability in the proglacial environment, for example stabilization of moraines, of the order 100-150 years. Conversely the data may indicate changes in the organic flux and relate to the stability of the terrestrial ecosystem, although the pollen data presented in the next chapter demonstrate that at the watershed scale the terrestrial vegetation would appear to have been relatively stable over the Holocene Epoch.

5.4 Summary

The data presented in this chapter indicate that there is a coherent, sensitive and continuous record of glacial sediment supply in the clastic component of the down-valley lakes in the Kwoiek Creek watershed. Isolation of the glacial sediment signal through direct sediment source identification and description of sedimentation patterns which are present throughout the Kwoiek Creek watershed provides a basis for partitioning the glacially derived portion of the record. When knowledge of the source is combined with a consideration of rates of sediment influx, a record of glacial activity emerges.

In general the correspondence between lakes is strong when the finest size fraction is considered in conjunction with sedimentation rates, with virtually all the changes which appear in one lake appearing in cores spanning the same time periods from other lakes. The sedimentary signal is not one of simple selective deposition away from the source. The degree of
continuity in the system has varied through time, and it is proposed, is
dependent on the degree of glacial forcing. For example, the earliest peak
in glacial-derived sediment in Klept Lake ca 6000-5000 B.P. is not
recorded in any detail in the Kokwaksey and Kwoiek lakes, whereas the two
subsequent phases of Neoglacial activity, which regional evidence suggests
were of a greater magnitude (see Chapter 6 for full discussion) are
pronounced in all of the lakes. It is proposed that variability in glacial
sediment supply in the Kwoiek Creek watershed is dominated by events of
Neoglacial and Glacial order, superimposed on which are the much shorter
term events e.g. mass wasting evident in the raw sedimentation data, that
were removed from the data in this study. The chronology of the proposed
Neoglacial fluctuations is considered in greater detail in Chapter 6.
CHAPTER 6 REGIONAL CORRELATION

Independent evaluation of the chronology of Neoglacial activity presented in Figure 5.11 for consistency with regional palaeoenvironmental conditions is problematic. Any discussion is restricted because of the incompleteness of many of the records obtained from other sites in southern British Columbia and ambiguities in their interpretation. Furthermore, regional comparisons have inherent problems given the macro-scale nature of the controls on climate change which modify mean mid-latitude circulation patterns, which in turn can yield very different synoptic scale climatic responses within a "region" (see discussion by Yarnel, 1982). However, despite these problems it is important to compare the records of major climatic fluctuations over the Holocene Epoch, in southern B.C. and at the study site, in order to assess the consistency of the chronology inferred from the lake sediment record. This chapter presents proxy climatic data, pollen, macrofossils, glacial chronologies and tree line studies, from the Coast Mountains of British Columbia and elsewhere in the Pacific Northwest, for comparison. The locations of all sites are shown on Figure 6.1. The structure of the chapter is chronological. The first section is concerned with the pattern of regional deglaciation and the implications of the basal dates obtained in this study, the second with palaeobotanical and palaeogeomorphological evidence for postglacial environmental change, and the third section is a consideration of the implications of the lake-sediment data derived in this thesis for Holocene glacial chronologies in southern British Columbia and the nature of the framework for future research in glacierized alpine watersheds.

6.1 Deglaciation

Studies to date have shown that the Cordilleran Ice Sheet reached its maximum extent in southern British Columbia approximately 14 000 to 14 500
Figure 6.1 Locations of previous palaeoenvironmental reconstructions in southern British Columbia discussed in text. The ecotone boundary between coastal and interior systems is shown as a dashed line. Kwoiek Creek shown as a large circle.


Deglaciation sites indicated by open square: 1. Chilliwack River valley.
years B.P. (see references in Armstrong, 1981; Clague, 1981, 1989; Ryder & Clague, 1989). Deglaciation was in progress by 13 500 years B.P. and the ice sheet wasted rapidly (Clague, 1981). The regional pattern of deglaciation was complex, but in general, the peripheral glaciated areas and highlands became ice free first. Active glaciers are thought to have remained longest in some mountain valleys, but probably coexisted with remnants of dead ice in the valleys and plateaus of the B.C. interior. By about 9 500 - 10 000 years B.P. the glaciers in the region were no more extensive than they are today (Fulton, 1971; Clague, 1981).

Deglaciation dates derived from basal dates on bogs and lake sediments in the southern Coast Mountains are presented in Table 6.1. Some of these dates have been questioned as being anomalously old due to old-carbon effects. The basal radiocarbon dates obtained in this study (Table 6.2) suggest that extensive areas of the mountains of southern B.C. were ice free prior to 11 500 yrs B.P. The significance of the dates from the Kwoiek Creek watershed is that they are from the floor of a mid-elevation mountain valley, downstream from contemporary alpine glaciers. As such they provide information on the status of valley glaciers within the Cordilleran system. The two oldest dates are from the two lowest lakes in the valley, 12 255±770 yrs B.P. (S-3010) (Kwoiek, elevation 835 m) and 11 485±185 yrs B.P. (S-2935) (Kokwaskey, elevation 1050 m). Taking the most conservative estimate of deglaciation (date less 2 standard deviations) these dates indicate that the middle and lower portions of the catchment were ice free and vegetation was established prior to 11 000 years B.P. with sedimentation occurring in the lower lakes from this time on. The dates are younger with elevation, suggesting an upvalley sequence of deglaciation (Table 6.2). However, they are not consistently taken from the same relative stratigraphic position in
<table>
<thead>
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<th>Author</th>
<th>Site</th>
<th>Date</th>
</tr>
</thead>
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<tr>
<td>Hebda (1982)</td>
<td>Finney Lake</td>
<td>13 170 ±870 (Hebda pers. comm)</td>
</tr>
<tr>
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<td>Marion Lake (305 m)</td>
<td>12 350 ±190 (I-5950)</td>
</tr>
<tr>
<td></td>
<td>Surprise Lake (540 m)</td>
<td>11 230 ±230 (I-5816)</td>
</tr>
<tr>
<td>Saunders et al (1987)</td>
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</tr>
<tr>
<td></td>
<td>Tamihi Slide (310 m) (Fraser Lowland piedmont lobe)</td>
<td>11 200 ±90 (GSC 4041)</td>
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<td>11 000 ±170 (I-5346)</td>
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<td>Squeah Lake (205 m)</td>
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<td></td>
<td>11 140 ±260 (I-6058)</td>
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<td>9 810 ±160 (S-1570)</td>
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<tr>
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<td>Tiedemann glacier (825 m)</td>
<td>9 510 ±150 (GSC-939)</td>
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<tr>
<td>9 640 +380</td>
<td>10 400</td>
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* Maximum and minimum dates are computed based on two standard deviations
the lake sediments for significance to be attached to this i.e. they are from different depths above the glacial/postglacial sediment contact (see section 3.4, and core logs in Appendix I).

These results are consistent with those presented by Mathewes et al (1972) and Mathewes & Rouse (1975) for Pinecrest and Squeah lakes to the south, in the Fraser canyon near Yale. Mathewes et al's dates (11 000 ±170 yrs B.P. (I-5346), 11 140 ±260 yrs B.P. (I-6058) and 11 430 ±150 yrs B.P. (I-6057) were obtained at an elevation of approximately 205 m a.s.l. The dates from the present study are at higher elevations and closer to the contemporary alpine glacial limit. Hence at the position of the lakes, the last ice advance and subsequent retreat must have occurred prior to this time, indicating that deglaciation was more widespread within the mountain system and that it may have been progressing at a faster rate earlier than was conventionally thought.

These dates have important implications for the modelling of regional deglaciation in the southern portion of the province, specifically the nature of the retreat/disintegration of the Cordilleran ice sheet in mountain valleys. For example, the COHMAP (Cooperative Holocene Mapping project) (1988) simulations have boundary conditions for 12 ka which include a full Cordilleran ice sheet and for 9 ka extensive areas of ice in the Coast Mountains. New evidence for the influence of earlier and more rapid deglaciation should be carefully evaluated in such simulations.

6.2 Holocene Epoch: Palynological records

In general pollen records provide a more complete record of long term changes in climate in the Pacific Northwest than do glacial records. Although vegetation is probably less sensitive to short-term climatic fluctuations than are glaciers, vegetation records provide a continuous, although somewhat
smoothed proxy record of change.

Several sites in coastal and interior in southern British Columbia, have yielded informative, reasonably well dated palynological records, with supporting evidence from plant macrofossils, molluscs and sediment stratigraphy. All of the study sites lie within the maximum Cordilleran ice limit, and none is older than 12 500 yrs. The records are reviewed in detail by Mathewes (1984) and Ritchie (1987). The locations of the previous studies conducted within the coastal ecotone are shown in Figure 6.1.

A consistent feature throughout the Pacific Northwest is the high frequency (up to 90% of total pollen) of diploxylon Pinus pollen between ca. 12 000 and 10 000 years B.P., indicating a forest, or parkland forest, dominated by lodgepole pine (Barnosky, 1984). These early records are difficult to interpret in terms of a climatic signal given that macroclimatic effects are complicated by species migration, natural succession of plant communities, and soil development.

Between 10 500 yr B.P. and 10 000 yr B.P. a dramatic change is apparent in many pollen diagrams from south coastal British Columbia with an abrupt increase in Pseudotsuga menziesii and Alnus spp. (Mathewes, 1973; Mathewes & Rouse, 1975). This increase is interpreted as reflecting a transition from cool, moist conditions which prevailed during deglaciation to a dry, warm climate. The evidence for this in the vicinity of the Kwoiek Creek watershed is particularly strong at Pinecrest and Squeah Lakes (see location on Figure 6.1), with Douglas-fir, grasses, bracken fir and spikemoss reaching peak frequencies at ca. 8620±135 B.P. (Mathewes & Rouse, 1975).

Palynological indications of increasing wetness on the coast in the latter part of the Holocene Epoch begin before 5000 yr B.P. Increasing frequencies of western hemlock and cedar type pollen (probably Thuja) ca. 6800 yr B.P.
(Mazama tephra) have been reported extensively in coastal regions of the Pacific Northwest (see for example, Mathewes, 1973; Hansen & Easterbrook, 1974; Mathewes & Rouse, 1975; Leopold et al. 1982; Heusser, 1983). Palaeoclimatic reconstructions using numerical transfer-functions, however, do not indicate late Holocene cooling or an increase in wetness (Mathewes & Heusser, 1981), rather more or less consistent conditions over the last 6000 years, illustrating problems with the sensitivity of palynological data in coastal southern British Columbia.

6.2.1 Palynology: Kwoiek Creek watershed

Pollen results of a core from one site, in Kwoiek Lake (KWK C.15), are presented to outline the history of postglacial vegetation in the Kwoiek Creek watershed. This provides a basis for comparison with the history determined from the physical characteristics of the lake sediments and for comparison with regional pollen signals. Lake deposits were chosen in this study because preservation of pollen is generally better than in peats (Faegri and Iversen, 1964). Furthermore previous attempts to core bogs in the headwaters of the Kwoiek Creek watershed have found only thin accumulations of peat (Ryder, personal communication).

Laboratory preparation followed a standard procedure. Samples of known mass and volume were boiled in 5% KOH, screened, treated in HF and acetolysis solution, and stained with safranine. Lycopodium tablets were added to each sample in a concentration that produced about 1 trace spore to 4 fossil grains, in order to calculate pollen concentrations. Pollen residues were mounted in flotex resin and examined at magnifications of 400 and 1000x (oil immersion). Approximately 250 terrestrial grains were tallied for each sample. This is a lower number than usually tallied because of the low pollen concentrations within the sediments. The samples were selected after the
chronology for the core had been determined, to provide regular temporal coverage hence they do not have a constant spacing. Pollen identifications were based on the reference collections of Dr. G.E. Rouse (Departments of Botany and Geology, University of British Columbia) and published atlases and keys (for example, Bassett et al., 1978; Moore & Webb, 1978). Grains that could not be identified from these sources were tallied as unknown; grains that were broken or hidden, or that had deteriorated beyond recognition were recorded as indeterminate. Because these numbers are small they are combined. The category *Pseudotsuga* may incorporate some *Larix* as the two are difficult to differentiate. Differentiation of haploxylon pine (*Pinus albicaulis*) from diploxyon pine (*Pinus contorta* or *Pinus ponderosa*) pollen was attempted based on the ornamentation of the grains; haploxylon pines have warts on the leptoma, whereas the diploxyon pines have no ornamentation in that area (Ting, 1965). However, many of the grains, particularly in the lower portion of the record, are broken, consequently the presence or absence of such features is not clear, and the two are combined. The pollen grains of *Abies* and *Picea* were not identified to the species level because the size range method outlined by Hansen (1947) is problematic (Mathewes, 1973). Cupressaceae pollen was separated into *Chamaecyparis* and *Juniperus* with the aid of reference slides. Given the variability in sedimentation rates (documented in Chapter 5) absolute pollen concentrations, are not very meaningful unless they can be determined with confidence for known periods of time (Faegri & Iversen, 1964), so individual palynomorphs are presented as a percentage of total pollen. The results are presented in Figure 6.2. The solid shading on the plots represent the actual percentages, the lines the percentages x 10, so they are more clear for those species not so abundant. Present day vegetation patterns for the watershed are summarised in section
Figure 6.2 Pollen diagram for Kwoiek Lake
Much attention has been directed to the zonation of pollen diagrams (Birks & Birks, 1980). Given the vastly differing pollen productivity and dispersal mechanisms of different plants, standard grouping techniques, for example principal components analysis, are inappropriate. Because the primary objective of this study was to interpret the pollen record in the context of its regional consistency, zonation of the pollen diagram was undertaken visually to enable easier comparison with literature data where similar visual zonation has been used.

Kwoiek Lake is not as sensitive as the Pinecrest and Squeah sites, (Mathewes & Rouse) mentioned above, which are located in the climatically transitional zone of the Fraser Canyon, where the vegetation is moisture stressed and very sensitive to changes in effective precipitation. However, the overall pattern evident in the Kwoiek Lake pollen diagram is consistent with the Pinecrest and Squeah Lake records (the closest previous study). Emphasis is directed primarily to the conifer and angiosperm pollen as a record of watershed-scale changes in vegetation.

The basal zone is characterised by initial high percentages (maximum 64%) of Pinus (probably Pinus contorta). At this time Picea and Tsuga Mertensiana relatively are high (indicating a "coastal site"; Barnosky, 1984). Alnus constitutes approximately 20% of the pollen, although this is its lowest value for the postglacial period. Little else is present in Zone I. At the base of zone II initially low absolute pollen concentrations rise and there is a transition in the vegetation composition, with increases in Abies, Pseudotsuga, Alnus and Betula. This is entirely consistent with other palynological studies in the area, and indicates a successional transition to more shade-tolerant conifers and the hypsithermal assemblage. At the same
time pollen of *Myrica, Gramineae* and *Pteridium* exhibit an increase. There are no marked mid-Holocene transitions indicative of the end of the Hypsithermal interval evident in other studies in the region. The transition from Zone II to Zone III is associated with a gradual decrease in *Pseudotsuga*, an increase in *Tsuga heterophylla* and most markedly an increase in *Thuja chamaecyparis*. *Corylus* appears at this time (consistent with patterns documented by Mathewes, 1973; Mathewes & Rouse, 1975; King 1980). The rise of *Thuja* and a decrease in Douglas Fir at this time may be indicative of increased wetness. Alternatively it may reflect a decreased frequency of fire (Mathewes & Rouse, 1975), which in turn may be related to wetness. Zone III is characterised by relatively stable levels of *Pinus, Picea, Abies, Pseudotsuga, Thuja* and *Alnus*. The increase in *Alnus, Betula* and *Rosaceae*, at the expense of the conifers, at the very top of the cores undoubtedly indicate the effect of anthropogenic disturbance in the catchment.

Throughout the core many conifers, for example *Pinus* (after the initial colonisation of other conifers), *Tsuga mertensiana, Pseudotsuga* etc, are complacent and give only a general indication of climate change. Although the lower reaches of the catchment are xeric, the contributing area to the lakes extends over an extensive area where the species have a wide altitudinal range and the conifers are thus not sensitive indicators of climatic change. However, the most important feature of the pollen diagram in the context of the thesis is that the changes that it does show are consistent with the regional patterns documented in the literature, indicating that the Kwoiek Creek watershed functioned like other sites in the southern Coast Mountains.

6.3 Holocene Epoch: Glacial chronologies

Although the record of Holocene glacier fluctuations in the Coast Mountains is fragmentary, recent studies have documented a consistent regional picture
in terms of timing of events, despite important differences in the relative magnitudes of events between sites. The radiocarbon dates from these studies are reported in Table 6.3 and the sites are located in Figure 6.1. The dates are from Neoglacial lateral moraines, and sites upvalley from Neoglacial end moraines, where in some places in situ sheared tree stumps provide dates for glacial overriding (Ryder & Thomson, 1986). The dates are broadly categorised into three Neoglacial phases.

Over the past twenty years several authors have proposed that significant glacier expansion occurred in various parts of the Canadian Cordillera between 6 and 9 ka B.P. (see for example, Beget, 1983; and Osborn & Luckman, 1988 for a review of the Canadian Cordillera). Luckman and Osborn (1979) have discussed significant problems associated with the dating control of these studies. In addition, theoretical climatic reconstructions for example, Kutzbach & Guetter (1982), COHMAP (1988), and pollen data indicate that the early Holocene Epoch was quite unfavourable for the accumulation of glacier ice. No convincing evidence for such advances is reported for the southern Coast Mountains.

A phase of glacier expansion about 6000-5000 C-14 years BP is indicated by dates from glacially overridden growth-position tree stumps in Garibaldi Park and from roots on a nunatak on Mount Breakenridge (see dates in Table 6.3; sites originally described by Mathews, 1951). Glacier transported wood fragments of similar age from a small glacier 6 km southeast of Bridge Glacier (5500 ±70 years B.P., Blake, 1983) and Garibaldi Park (6170 ±150 years B.P.) may have been derived from trees overridden by this advance. Older transported wood fragments from the same areas can be interpreted only in terms of a relatively high tree line. No end moraines are associated with this advance probably because its terminal positions were overridden during
Table 6.3 Glacier chronologies for Coast Mountains broadly categorised by date

<table>
<thead>
<tr>
<th>Location</th>
<th>Lat &amp; Long (N) &amp; (W)</th>
<th>C-14 Date (yr B.P.)</th>
<th>Lab no.</th>
<th>Elevation (m a.s.l.)</th>
<th>Reference</th>
</tr>
</thead>
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<tr>
<td>Early Neoglacial expansion</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>I. Overridden in situ stumps</td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mt Garibaldi</td>
<td>49°52' 122°59'</td>
<td>5260+200</td>
<td>Y-140</td>
<td>1860</td>
<td>Stuiver et al (1960)</td>
</tr>
<tr>
<td>Sentinel Glacier</td>
<td>49°54' 122°59'</td>
<td>5300+70</td>
<td>GSC-2027</td>
<td>1510</td>
<td>Lowdon &amp; Blake (1975)</td>
</tr>
<tr>
<td>Mt Breakenridge</td>
<td>49°44' 121°57'</td>
<td>5950+140</td>
<td>GSC-760</td>
<td>2134</td>
<td>Lowdon &amp; Blake (1968)</td>
</tr>
<tr>
<td>II. Glacially transported wood fragments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sentinel Glacier</td>
<td>49°53' 122°59'</td>
<td>6170+150</td>
<td>GSC-1477</td>
<td>1670</td>
<td>Lowdon &amp; Blake (1973)</td>
</tr>
<tr>
<td>Sphinx Glacier</td>
<td>49°55' 122°58'</td>
<td>7640+80</td>
<td>GSC-1993</td>
<td>1650</td>
<td>Lowdon &amp; Blake (1975)</td>
</tr>
<tr>
<td>Mid Neoglacial expansion</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>I. Moraine bog/ Peat litter</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Tiedemann Glacier</td>
<td>51°21' 124°56'</td>
<td>2250+130</td>
<td>GSC-948</td>
<td>825</td>
<td>Fulton (1971)</td>
</tr>
<tr>
<td>Tiedemann Glacier</td>
<td>51°21' 124°56'</td>
<td>2940+130</td>
<td>GSC-938</td>
<td>825</td>
<td>Fulton (1971)</td>
</tr>
<tr>
<td>Gilbert Glacier</td>
<td>50°53' 124°11'</td>
<td>2040+40</td>
<td>S-1572</td>
<td>1450</td>
<td>Ryder &amp; Thomson (1986)</td>
</tr>
<tr>
<td>II. Overridden/ Transported wood</td>
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<td></td>
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<tr>
<td>Tiedemann Glacier</td>
<td>51°19' 124°58'</td>
<td>3345+115</td>
<td>S-1470</td>
<td>980</td>
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Table 6.3 (cont.)

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<th>Location</th>
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<th>Latitude</th>
<th>Age (Years)</th>
<th>Sample Code</th>
<th>Authors and Year</th>
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<td>3415±70</td>
<td>S-1462</td>
<td>1460</td>
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<tr>
<td>Tide Lake</td>
<td>56°16' 130°03'</td>
<td>2730±170</td>
<td>GSC-1372</td>
<td>650</td>
<td>Lowdon &amp; Blake (1973)</td>
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<tr>
<td>Jacobsen Glacier</td>
<td>52°03' 126°04'</td>
<td>2470±50</td>
<td>GSC-4155</td>
<td>1370</td>
<td>Desloges &amp; Ryder (in press)</td>
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</table>

**Late Neoglacial (Little Ice Age)**

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<th>Location</th>
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<th>Age (Years)</th>
<th>Sample Code</th>
<th>Authors and Year</th>
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<td>Klinaklini Glacier</td>
<td>51°19' 125°49'</td>
<td>400±45</td>
<td>S-1566</td>
<td>530</td>
<td>Ryder &amp; Thomson (1986)</td>
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<td>(Tree root from palaeosol)</td>
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<tr>
<td>Klinaklini Glacier</td>
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<td>900±40</td>
<td>S-1567</td>
<td>400</td>
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<td>(Tree stump in growth position)</td>
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<tr>
<td>Franklin Glacier</td>
<td>51°16' 125°26'</td>
<td>835±45</td>
<td>S-1568</td>
<td>1170</td>
<td>Ryder &amp; Thomson (1986)</td>
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<td>(Tree root from palaeosol)</td>
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<tr>
<td>Bridge Glacier</td>
<td>50°49' 123°34'</td>
<td>680±50</td>
<td>S-1463</td>
<td>1750</td>
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<td>(Log close to growth position)</td>
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<td>455±65</td>
<td>S-2297</td>
<td>670</td>
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<tr>
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<td>625±140</td>
<td>S-2298</td>
<td>670</td>
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<td>S-2296</td>
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<tr>
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<td>Longitude</td>
<td>Age (± Error)</td>
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<td>1110±70</td>
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<td>785±70</td>
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<td>126°22'</td>
<td>460±50</td>
<td>GSC-4030</td>
<td>533 Desloges &amp; Ryder (in press)</td>
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<td>Ape Lake</td>
<td>52°05'</td>
<td>126°10'</td>
<td>770±60</td>
<td>GSC-4028</td>
<td>1395 Desloges &amp; Ryder (in press)</td>
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<td>Jacobsen Glacier</td>
<td>52°04'</td>
<td>126°08'</td>
<td>400±60</td>
<td>S-2979</td>
<td>1495 Desloges &amp; Ryder (in press)</td>
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<td>(Palaeosol)</td>
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<td>Borealis Glacier</td>
<td>50°10'</td>
<td>126°07'</td>
<td>20±60</td>
<td>GSC-4163</td>
<td>1418 Desloges &amp; Ryder (in press)</td>
</tr>
</tbody>
</table>

Laboratories:
S - Saskatchewan Research Council
GSC - Geological Survey of Canada
Y - Yale
WAT - Waterloo
late Neoglacial time. This episode is referred to by Ryder and Thomson (1986) as the "Garibaldi phase", a phase rather than an advance because there is no apparent subsequent episode of contraction. This expansion may well correspond to the transition from warm and dry conditions of the early to mid Holocene, commonly called the xerothermic interval and documented in the pollen records (section 6.2.1), to the cooler moister conditions of the late Holocene. The Garibaldi phase can be correlated with the Dome Peak expansion (South Cascade glacier, Miller 1969) and possibly the Gamma Peaks advance at Glacier Peak (Beget, 1984) in the northern Cascade Mountains of Washington state. In the Canadian Cordillera the mid-Holocene Epoch transition to cooler, wetter conditions appears to be time-transgressive, approximately 6000 years B.P. in the Coast Mountains and 3000-4000 years B.P. in the Rockies (Osborn & Luckman, 1988).

Evidence of a mid-Neoglacial phase, the Tiedemann advance, in the western British Columbia, ca. 3300 to 1900 years B.P. comes from Tiedemann and Gilbert glaciers in the southern Coast Mountains; Jacobsen Glacier, Bella Coola; and from Tide Lake in the northern Coast Mountains (Ryder & Thomson, 1986; Ryder, 1987; Desloges & Ryder, in press). Tiedemann Glacier was more extensive than during the Little Ice Age for about two millennia, from 3345 to 1300 years B.P., with a maximum at about 2300 years B.P. An advance of the Gilbert glacier commenced before 2200 years B.P. and culminated ca. 1900 years B.P., when its size approximated its late Neoglacial extent. Middle Neoglacial advances have been well defined both north and south of the study area. For example, in the St. Elias Mountains (Denton & Karlen, 1977), and on Mount Rainier (Crandell & Miller, 1964) mid-Neoglacial moraines lie just beyond those of the late Neoglacial.

A late Neoglacial advance is common to all glacierized mountains although
its time span is variable (Table 6.3). Reliable dates from overridden growth-position tree remains indicate that in the Coast Mountains, the late Neoglacial advance commenced before 900 B.P. and expansion continued until it reached its maxima. Multiple and overridden moraines indicate that minor fluctuations in ice positions probably occurred close to the time of the maximum (Ryder & Thomson, 1986; Ryder, 1987). Dates obtained from dendrochronology and lichenometry indicate that most glaciers in the Canadian Cordillera began to recede from maximum Little Ice Age positions at various times during the eighteenth, nineteenth and twentieth centuries (Ryder, 1989). Rates of recession have decreased markedly in the last few decades and some glaciers have advanced (Osborn & Luckman, 1988).

In summary, Neoglacial advances within the Coast Mountains began by 6 ka BP and glaciers were more extensive over most of the last 4 ka than earlier during the Holocene. The recent climatic amelioration (i.e. since the late Neoglacial maximum) has had a greater cumulative effect than any previous climate fluctuation over the Holocene Epoch (Ryder, 1987). The Holocene trends are summarised diagrammatically in Figure 6.3 with similarly highly schematic trends from the palaeobotanical records.

6.4 Significance of results from Kwoiek Creek watershed

The chronology of glacial activity presented in this study is entirely consistent with those reviewed in this chapter (see Figure 6.3). There is no evidence in the sedimentary records of any of the lakes for an early Holocene phase of glacial activity. Sedimentation rates in the early postglacial are high but the characteristics of the sediments indicate material of indeterminate origin, probably derived from young Fraser Glaciation deposits, not the alpine glaciers at the head of the Kwoiek Creek watershed (see SEM results in section 4.3.3). This is the period of paraglacial sedimentation
Figure 6.3 Schematic representation of Holocene Epoch glacial and pollen signals

Composite glacial chronology (Ryder & Thomson, 1986)

Climatic trends from palaeobotanical data (Mathewes, 1984)

Chronology from lake sediment record, Kwoiek Creek

Fluctuations in influx of glacial derived sediment: a proxy Neoglacial chronology
documented by Church & Ryder (1972). It is difficult to assign a precise date to the end of this period but data from Kwoiek and Kokwaskey Lakes (Figure 5.9) indicate a decrease in sedimentation rates soon after deglaciation to much lower rates, probably within a period of a 1000-2000 years. The exact chronology is difficult to resolve because of a lack of dateable material in the lower portions of the cores and the inappropriateness of extending the assumptions of constant influx of organic material to this time to derive a chronology.

Changes in the sedimentation regime of the lakes are evident ca. 6800 B.P. (Figure 5.11), postdating Mazama tephra deposition. These changes are most prominent in Klept and Kokwaskey Lakes. There is, however, no evidence of increased deposition of glacially derived sediments in Kwoiek Lake at this time. It is possible that this mid-Holocene "phase" of glacial activity increased glacial sediment supply, which was strongly filtered down-system.

The two most recent episodes of Neoglacial activity, documented in the literature are evident in all of the lake sediment records. The first is centred ca 3500 B.P. in Klept Lake, 3000 B.P. in Kokwaskey Lake and 2800 B.P. in Kwoiek Lake. The second occurs in the last 750 years (postdating 1240 ±245 B.P.), with greatest sedimentation rates approximately 400 years ago documented for Kha Lake. In terms of relative activity (i.e. strength of sedimentary response) these two events would seem to be comparable in magnitude, and are much stronger than any other events over the postglacial period. However, the most recent episode appears to be of longer duration. The high resolution Kha Lake record indicates that within each of these Neoglacial periods there are fluctuations in sediment supply to the fluvial system (see Figure 5.11) which may reflect periods of advance, stillstands and subsequent advance. For example, for the most recent Neoglacial phase
there is a peak in sedimentation ca 400 years B.P. and a second rise within the last 100 years. When compared with regional data it may be speculated that the 400 B.P. peak corresponds to the period just before maximum Little Ice Age conditions, and that in the last century to the maximum rates of glacial recession. This would suggest that Neoglacial driven sediment yield is at a maximum just after the Neoglacial peak and during the subsequent phase of retreat, consistent with the notions of paraglacial sedimentation.

The major advantage of the lake sediment approach as used in this study is that it provides a continuous record, enabling a consideration of both the magnitude and frequency of postglacial changes at a site. At no site within the Coast Mountains is there terrestrial evidence for all three Neoglacial phases evident in the lake sediment record for the Kwoiek Creek watershed. In fact there are only two or three sites with evidence for the two most recent Neoglacial phases because the most recent Little Ice Age advance was generally more extensive than earlier events and therefore destroyed all evidence of their occurrence. Furthermore the lake sediment record may be easier to date than the terrestrial record. This is particularly true in an environment such as the Kwoiek Creek watershed where the lakes of interest are below tree-line and consequently there were frequent incorporations of organic material in the lake sediments which can be dated, thereby providing a chronology against which to interpret changes.

The implications of both the methodology and the substantive findings for southern British Columbia are considered further in the final chapter.
CHAPTER 7  SUMMARY & CONCLUSIONS

This research project has sought to make two basic contributions. First to develop a methodology to interpret changes in the Holocene Epoch palaeo-sediment system over timescales $10^2$-$10^3$ years, which makes explicit the link between sediment sources and lake-sediment sinks. This permits a more critical interpretation of the lake sedimentary record, such that changes in the contribution of glacial sediment through time can be identified with confidence. This provides a level of understanding that goes beyond previous descriptive studies that solely document changing characteristics in the sediment sink through time. Second to provide a continuous record of palaeoenvironmental conditions, specifically glacial activity, for the southern Coast Mountains of British Columbia.

7.1 The methodology

The alpine sediment system is proposed as a framework for studying alpine sediment transfers through time. Previous studies have documented that the dominant controls over Holocene proglacial sediment transport rates over timescales $10^2$-$10^3$ years relate to glacial and Neoglacial activity. Sediment availability and supply together with meltwater stream capacity are the controlling factors. Superimposed on these factors are the effects of episodic mass wasting and high magnitude hydrological events. Previous attempts to model the lake-sedimentary response have been largely restricted to the immediate proglacial environment. This study extends that work downvalley to lakes with lower sedimentation rates and presents a methodology to separate the glacial sediment signal from colluvial sediment transfers. This is achieved through sediment source-sink matching at the drainage basin scale by documenting the synchroneity
of trends down-system in successive lakes, i.e. attenuation of the glacial signal.

It is demonstrated that the organic matter content of the sediments exhibits a strong inverse relation with sedimentation rates and can be used to infer rates of influx through time, and thus to provide a chronology for changes in sedimentation regime. Textural analysis of the sediments indicates that grain-size distributions are polymodal. Graphical partitioning of log-probability grain size plots was used to separate three constituent populations which are related to specific sediment sources.

Surface texture analysis using the Scanning Electron Microscope (SEM) was used as a way of identifying the source of the coarse and intermediate lake sediment populations. A statistical approach was developed in which 30 grains from replicate known samples were characterised for 34 surface textures and objectively classified as to source using a Euclidean difference statistic. Those characteristics that have discriminating value were identified and were used to discriminate the source of material of unknown origin. Colluvial derived sediments, glacial derived sediments and deposits derived from the older surficial materials of Fraser Glaciation were differentiated. Analyses of known sedimentary environments indicated that surface textures are established largely during the weathering phase of the sediment's history and not greatly altered or destroyed during subsequent transport. Although the generality of the differentiating characteristics remains to be determined for other environments, the methodology is appropriate for use in a wide range of sediment routing studies.

Mineralogical analysis of the fine silt fraction was less successful. No
clear distinction could be made between colluvial and recent glacial deposits although the older surficial materials exhibit a clear signal. The similar trends in the temporal variability of the finest fraction throughout the drainage basin are used as evidence that the finest fraction represents the glacial signal of interest derived from the catchment's headwaters. When the proportions of the fine and intermediate fractions are used to weight sedimentation rates, an index of the influx of glacial sediment in each of the lakes through time results. The record is smoothed with resolution of the order 50 years. The degree of variance and absolute rates of sedimentation decrease downsystem as would be expected. Analyses of the sedimentation time series indicate persistence in the record of the order 100-150 years which is speculated to represent the relaxation time of sedimentary stores within the watershed. The absence of strongly weathered material in the recent sediments of each of the lakes indicates little contemporary reworking and deposition of older Fraser Glaciation deposits. Rather, material that is being moved in the fluvial system is derived from contemporary glacial and colluvial sources.

Thus the sedimentary signal in the lakes of the Kwoiek Creek watershed is not simply one of selective deposition away from the source, but of differential input of sediment from distinct sources and through distinct transfer pathways. It is concluded that downvalley lake sediments do provide a sensitive and continuous record of changes in glacial driven sedimentation rates, provided the sediment from different sources is identified.

7.2 Palaeoenvironmental reconstructions

The basal dates obtained in this study suggest that extensive areas of the mountains of southern B.C. were ice-free prior to 11 500 B.P. The
oldest dates obtained are from the two lowest lakes in the watershed, 12 255 ±770 yrs B.P. (S-3010) (Kwoiek, elevation 835 m) and 11 485 ±185 yrs B.P. (S-2935) (Kokwaskey, elevation 1050 m). Taking the most conservative estimate of deglaciation (date less 2 standard deviations) these dates indicate that the middle and lower portions of the catchment were ice free prior to 11 115 years B.P. and that sedimentation has occurred in the lower lakes from this time.

From the records it would appear that the rates of glacial sediment influx in Klept, Kokwaskey and Kwoiek Lakes are low and fairly constant until ca. 7000 B.P, providing no evidence for early Holocene glacial activity. Approximately 7000 B.P., sedimentation rates in Kokwaskey and Kwoiek Lakes show a gradual increase, while in Klept Lake a minor, well defined peak of ca 1000 years duration occurs 6000 to 5000 B.P. indicating greater glacial sediment supply and a phase of renewed glacial activity, the Garibaldi Phase. Glacially driven sedimentation rates in all three lower lakes show a pronounced increase ca 4000 B.P., peaking ca. 3500 to 2900 years B.P. in the different lakes. This phase can be correlated with the regional Tiedemann Neoglacial advance. There is a third major peak in the last 750 years, correlated with the Little Ice Age. The chronology of the two latter events can be seen best in the high resolution record of Kha Lake. The high sedimentation rates of the earlier 3000 - 2000 year event would seem to have fallen to lower levels by 1500 years B.P., starting to rise again about 750 year B.P., reaching a maximum ca. 400 years B.P. and again in the last 100 years. There is consistency in the timing of the events in each of the lakes, lending support to both the argument that they represent Neoglacial activity, and to the use of the organic influx calculations as a basis for deriving a chronology of
changes.

The primary advantage of lake-sediment records is their continuity, and as demonstrated in this study, their apparent sensitivity to Neoglacial forcing. At no sites within the Coast Mountains is there terrestrial evidence for all three Neoglacial phases and at only one or two sites is there evidence for more than one event, because the recent Little Ice Age has destroyed evidence of virtually all earlier Neoglacial activity. In general, because of lower rates of sedimentation, it is easier to obtain full Holocene Epoch sediment records from downvalley rather than from proglacial lakes. The temporal resolution of these downvalley records is not as great as those of proglacial sediments, but events which lasted of the order of $10^2$ years can be resolved, and such resolution is appropriate for interpreting changes at timescales of the order $10^3$ years. Furthermore because such lakes are below treeline there are more frequent inclusions of organic material which make the records easier to date, thereby providing a chronology against which to interpret changes.

Wider application of this lake-sediment approach would permit questions relating to the synchronicity/diachronicity of palaeoenvironmental change to be addressed, which will lead ultimately to a greater understanding of the mechanisms and nature of the forcing function, namely climatic change.
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Ideally, a facies is a distinct sediment deposit that forms under certain conditions of sedimentation, reflecting a particular process or environment (Reading, 1978). The Kwoiek Creek lake sediments are classified on the basis of sedimentary structures, lithostratigraphy, sedimentary properties and grain size analyses as outlined in section 3.5. This is an adaptation of the scheme developed by Eyles et al. (1983) and utilised by Schmok (1986) in a similar context. The objective is the systematic documentation of the sedimentary sequences based on visual appraisal to allow prescreening and removal of deposits that are not representative of changes in sedimentation patterns throughout the lakes. For representation purposes the sediments are categorised into six major sedimentary units: laminated and massive silts, laminated and massive fine sands, rhythmites, and laminated blue-grey clays, with inclusions of organic matter, ash and larger particles (stones) recorded separately. The more detailed characteristics of each of the deposits are discussed in Chapter 4. Only the composite core log is presented for each site (see Chapter 3 for explanation of coring strategy).
Core: Kha 1

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 2

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 2 (cont.)

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 3

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 4

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 5

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kha 6

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Klept 1

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Sedimentary units

- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Klept 3

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Klept 4

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Klept 6

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kokwaskey 1

Sedimentary units

- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kokwaskey 2

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kokwaskey (cont.)

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 3

Depth in cm

Sedimentary units
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 4

Depth in cm

1 2 3 4

Sedimentary units
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwotek 5

- 0-10 cm: Sedimentary units
- 10-20 cm: Organic matter
- 20-30 cm: Fine sand
- 30-40 cm: Fine sand/silts
- 40-50 cm: Laminated silts
- 50-60 cm: Laminated sands
- 60-70 cm: Laminated blue-grey clays
- 70-80 cm: Organic matter & silts
- 80-90 cm: Ash
- 90-100 cm: Stones
Core: Kwolek 8

Sedimentary units
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 10

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 11

Sedimentary units
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 12

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays

Depth in cm

0
10
20
30
40
50
60
70
80
90
Core Kwoiek 13

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 14

Sedimentary units:
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays
Core: Kwolek 15

Sedimentary units
- Organic matter
- Fine sand
- Fine sand/silts
- Silts
- Laminated silts
- Laminated sands
- Ash
- Organic matter & silts
- Stones
- Laminated blue-grey clays

Depth in cm

1
2
3
4
APPENDIX II  CHRONOLOGY

I.1 Radiocarbon chronology

Organic material submitted for radiocarbon dating was extracted from cores in the lab, cleaned of mineral material and immediately sealed. The samples were then sent to the Saskatchewan Research Council Radiocarbon Laboratory where routine preparation procedures were followed which involved presorting to remove visible rootlets, treatment with sodium hydroxide to remove the soluble organic fractions, and treatment with HCl to remove the sodium hydroxide and any carbonates due to leaching. The dates obtained are presented in Table AII.1. The materials that have been dated were identified as specifically as possible (Table AII.1). With the exception of the basal sample from Kokwaskey (S-2935) they are remnants of terrestrial flora: cones, needles and pieces of wood. It is assumed that no post-depositional mixing or contamination of the organic material occurred, and so all dates are interpreted as maxima for the units in which they are enclosed, although they may provide minimum dates for events within the watershed, for example deglaciation. Discussion of the significance of the dates is incorporated within the body of the thesis.

II.2 Tephra Identification

In a number of cores two distinct tephra layers were observed: the lower at approximately 2/3 depth in the cores, a finer grained and a white-yellow colour (10 YR 7/3); the upper, approximately 1/4 depth, much coarser and grey (10 YR 7/1). It was important to establish the identity of these tephras in order to be able to use them as time-stratigraphic markers in conjunction with radiocarbon dates to provide a chronology of sedimentation events.
Table AII.1  Radiocarbon dates obtained in the study. Stratigraphic positions and core logs in Appendix I

<table>
<thead>
<tr>
<th>Date</th>
<th>Max</th>
<th>Min</th>
<th>Sample ID</th>
<th>Site location</th>
<th>Material dated</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 255 ±770</td>
<td>13 795</td>
<td>10 715</td>
<td>S - 3010</td>
<td>Kwoiek lake</td>
<td>Engelmann Spruce cones &amp; needles</td>
</tr>
<tr>
<td>5 035 ±1875</td>
<td>8 785</td>
<td>1 285</td>
<td>S - 2970</td>
<td>Kwoiek lake</td>
<td>Wood</td>
</tr>
<tr>
<td>1 240 ± 245</td>
<td>1 730</td>
<td>750</td>
<td>S - 2987</td>
<td>Kwoiek lake</td>
<td>Wood</td>
</tr>
<tr>
<td>11 485 ±185</td>
<td>11 855</td>
<td>11 115</td>
<td>S - 2935</td>
<td>Kokwaskey</td>
<td>Granular algal material</td>
</tr>
<tr>
<td>4 900 ±325</td>
<td>5 550</td>
<td>4 350</td>
<td>S - 2988</td>
<td>Kokwaskey</td>
<td>Wood</td>
</tr>
<tr>
<td>9 640 ±380</td>
<td>10 400</td>
<td>8 880</td>
<td>S - 3011</td>
<td>Klept</td>
<td>Cones &amp; needles</td>
</tr>
<tr>
<td>1 380 ±390</td>
<td>2 160</td>
<td>600</td>
<td>S - 2989</td>
<td>Klept</td>
<td>Wood</td>
</tr>
<tr>
<td>2 350 ±110</td>
<td>2 570</td>
<td>2 130</td>
<td>S - 2936</td>
<td>Kha</td>
<td>Wood</td>
</tr>
</tbody>
</table>

* Calculations based on ± two standard deviations
Three Holocene volcanic eruptions distributed tephra over south-western British Columbia: Mazama (6800 BP) (Bacon, 1983), Mt. St. Helens Yn (3400 BP) (Mullineaux, 1975) and Bridge River (2400 BP) (Mathewes & Westgate, 1980). The mapped extent of fall-out plumes suggests that Mazama and Bridge River tephras are present in the Kwoiek Creek watershed. Hence the primary effort was directed towards differentiating these two tephras, although careful comparisons were made against literature values for other tephras to ensure that no erroneous identifications were made.

Many techniques have been proposed for the identification and differentiation of tephras: optical methods involving the determination of the refractive index of glass (e.g. Wilcox, 1965); bulk chemical analysis (e.g. Westgate and Gorton, 1981); and, chemical analysis of the glass (e.g. X-ray emission; emission spectrographs; neutron activation analysis; electron microprobe; thermomagnetic properties; X-ray fluorescence). Electron microprobe analysis of glass encased titano-magnetites is usually the preferred method because it can be conducted on single shards of glass and thus minimises problems of contamination. However, it is unsuited for the differentiation of Mazama and Bridge River tephras because their compositional fields of titano-magnetites are similar (King et al., 1982; Beaudoin and King, 1986).

In a study of the Pacific Northwest tephras Cormie & Nelson (1983) conclude that X-ray fluorescence (XRF) analysis of bulk glass separates provides a reliable method for rapidly identifying and differentiating between Mazama, Mount St. Helens Yn and Bridge River tephras. They found that the <62 μm size-fraction was chemically very similar to the glass separates. In addition, in areas where only the Mazama, St Helens Yn and Bridge River tephras occur they found that it is possible to simplify the
procedure even further. The chemical treatments (with HCl and NaOCl to remove organic stains, metal oxides and carbonates) can be omitted for clean samples as they have little effect on the concentrations of Y, Zr and Nb which are different in these three tephras (Cormie, 1981). The Mazama tephra can be distinguished by its high Zr concentration, from direct analysis of the <62 µm. The potassium concentration in Mount St. Helens Yn is characteristically low and may be useful for distinguishing this tephra from Bridge River. However, problems with potassium due to contamination and weathering effects may be greater.

II.2.1 Methodology in this study

X-ray fluorescence analysis of both minor and major element concentrations was used in this study in conjunction with microscope observations of shard morphology to identify and differentiate the tephras.

The tephras were tentatively identified on the basis of features observed in freshly split cores and by distinctive properties discernible from standard petrographic techniques, including colour, texture, glass shard habit, and phenocryst assemblages.

Photomicrographs (Figure AII.1) show the distinct nature of the glass shards. The lower tephra has glass shards which are commonly thin, bubble-wall fragments. The upper deposit has typically chunky shards and displays lineated gas vesicules. These morphologies are very similar to those documented by Reasoner and Healy (1986) for Mazama and Bridge River tephra, respectively, deposited in Mary Lake in the Canadian Rockies.

In all cases the samples were dry sieved through a 62 µm sieve and the smaller size fraction was collected for analysis. The rationale for this
Figure AII.2 Photomicrographs of glass shards of Bridge River and Mazama tephra (shards approximately 150 μm in length)

a) Bridge River tephra

b) Mazama tephra
stems from the findings of Cormie and Nelson (1983), who state that by removing the larger fraction most of the phenocrysts are also removed, which are the major contaminants. It is assumed that the < 62 μm fraction is composed primarily of glass. In this study this was confirmed by viewing the samples < 62 μm fraction analyzed under an optical microscope.

X-ray fluorescence analysis of a series of standards, samples of known origin and unknown tephras were analyzed for major (Fe, Mn, Ti, Ca, Ca, K, Si, Al, Mg oxides) and minor (Nb, Zr, Y, Sr, Rb, Pb, Zn, Cu, Ni, Co, Cb, Mn, Ti, V, Cr, Ba) element concentrations using a Philips PW 1400 XRF machine, in the Department of Oceanography, The University of British Columbia. The raw data were used to calculate means and standard deviations for each element concentration for the known tephras. These are reported with the values from Cormie & Nelson's study in Table AII.2.

Following Cormie & Nelson (1983) a simple statistical measure of difference, the "A statistic", was computed to determine whether the relative concentrations of the elements were sufficiently different from tephra to tephra to differentiate the samples. Such identification requires that the differences between the averaged concentrations for the different tephras be large compared to the variability of one tephra between sites:

\[ A_{e,i,j} = \frac{|\bar{x}_{e,i} - \bar{x}_{e,j}|}{2(S_{e,i} + S_{e,j})} \]

where \( \bar{x}_{e,i} \) and \( \bar{x}_{e,j} \) are the average relative concentrations of element \( e \) for tephras \( i \) and \( j \)

\( S_{e,i} \) and \( S_{e,j} \) are the corresponding standard deviations

The \( A \) coefficient serves to identify those elements that most usefully characterise the tephra. For any element, if \( A > 1 \) then individual samples from 2 tephras can be correctly identified with a probability > 95% using.
Table AII.2  Element concentrations for Mazama and Bridge River tephra

<table>
<thead>
<tr>
<th>Element</th>
<th>Mazama</th>
<th></th>
<th>Bridge River</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{x}$</td>
<td>S.D.</td>
<td>$\bar{x}$</td>
<td>S.D.</td>
</tr>
<tr>
<td>Majors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Si</td>
<td>67.93</td>
<td>1.15</td>
<td>67.64</td>
<td>2.36</td>
</tr>
<tr>
<td>Al</td>
<td>14.33</td>
<td>0.18</td>
<td>14.70</td>
<td>0.18</td>
</tr>
<tr>
<td>Ti</td>
<td>0.53(0.25)</td>
<td>0.04(0.03)</td>
<td>0.56(0.20)</td>
<td>0.07(0.03)</td>
</tr>
<tr>
<td>Fe</td>
<td>2.89(1.28)</td>
<td>0.47(0.24)</td>
<td>3.01(1.17)</td>
<td>0.65(0.23)</td>
</tr>
<tr>
<td>Ca</td>
<td>2.20(1.39)</td>
<td>0.37(0.71)</td>
<td>2.29(1.52)</td>
<td>0.03(0.75)</td>
</tr>
<tr>
<td>Mg</td>
<td>0.88</td>
<td>0.32</td>
<td>0.98</td>
<td>0.33</td>
</tr>
<tr>
<td>K</td>
<td>2.68(2.16)</td>
<td>0.28(0.56)</td>
<td>2.54(2.51)</td>
<td>0.24(0.62)</td>
</tr>
<tr>
<td>Na</td>
<td>4.57</td>
<td>0.24</td>
<td>4.21</td>
<td>0.74</td>
</tr>
<tr>
<td>Mn</td>
<td>0.06</td>
<td>0.02</td>
<td>0.07</td>
<td>0.007</td>
</tr>
<tr>
<td>P</td>
<td>0.11</td>
<td>0.01</td>
<td>0.17</td>
<td>0.014</td>
</tr>
<tr>
<td>S</td>
<td>Not adequately calibrated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minors</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>822.20</td>
<td>135.70</td>
<td>803.05</td>
<td>85.77</td>
</tr>
<tr>
<td>Co</td>
<td>8.70</td>
<td>3.62</td>
<td>8.80</td>
<td>4.95</td>
</tr>
<tr>
<td>Cr</td>
<td>20.27</td>
<td>7.74</td>
<td>36.15</td>
<td>30.19</td>
</tr>
<tr>
<td>Cu</td>
<td>36.88</td>
<td>5.49</td>
<td>29.58</td>
<td>9.92</td>
</tr>
<tr>
<td>Mn</td>
<td>542.18</td>
<td>64.82</td>
<td>639.80</td>
<td>182.29</td>
</tr>
<tr>
<td>Na</td>
<td>4.18</td>
<td>0.40</td>
<td>3.66</td>
<td>0.89</td>
</tr>
<tr>
<td>Nb</td>
<td>7.58(12)</td>
<td>1.04(3)</td>
<td>10.10(16)</td>
<td>0.42(4)</td>
</tr>
<tr>
<td>Ni</td>
<td>14.00</td>
<td>4.18</td>
<td>7.00</td>
<td>7.21</td>
</tr>
<tr>
<td>P</td>
<td>50.60</td>
<td>55.70</td>
<td>19.05</td>
<td>3.04</td>
</tr>
<tr>
<td>Pb</td>
<td>50.60(50)</td>
<td>5.04(6)</td>
<td>42.60(45)</td>
<td>0.71(5)</td>
</tr>
<tr>
<td>Rb</td>
<td>336.63(260)</td>
<td>59.67(19)</td>
<td>349.00(290)</td>
<td>33.09(27)</td>
</tr>
<tr>
<td>Sr</td>
<td>47.23</td>
<td>14.56</td>
<td>65.50</td>
<td>16.40</td>
</tr>
<tr>
<td>V</td>
<td>25.13(21)</td>
<td>1.63(4)</td>
<td>18.30(13)</td>
<td>0.71(4)</td>
</tr>
<tr>
<td>Zn</td>
<td>59.05</td>
<td>7.31</td>
<td>82.35</td>
<td>28.35</td>
</tr>
<tr>
<td>Zr</td>
<td>217.75(219)</td>
<td>17.92(18)</td>
<td>160.45(136)</td>
<td>9.83(17)</td>
</tr>
</tbody>
</table>

1 oxide %
2 concentrations ppm
$\bar{x}$ mean
S.D. one standard deviation
values in brackets are those reported by Cormie & Nelson (1983)
that element alone. The A coefficient requires that the elemental
concentrations be normally distributed. This was verified by Cormie
(1981). The A-coefficients for the known samples run in this investigation
are reported in Table AII.3. Zirconium (Zr) was found to be a useful dis-
riminator, as was Yttrium (Y).

The A statistic can be adapted, to an I statistic (Cormie & Nelson,
1983), so that an unknown sample be identified, by quantitative comparison
with the known tephras:

\[
I_{e,i,j} = \frac{|x_{e,i} - \bar{x}_{e,j}|}{2(S_{e,j})}
\]  

(AII.2)

where \(x_{e,i}\) is the concentration of element e in the sample i

\(\bar{x}_{e,j}\) is the average concentration of element e in the known tephra j

\(S_{e,j}\) is the standard deviation of element e for tephra j

An I value \(\leq 1\) indicates a sample (i) should be classified as reference
tephra (j), a value \(> 1\) indicates that the two are dissimilar. For each
sample the I values are scanned element by element rather than combining
the different elements into a single identification statistic, because the
concentrations of certain elements can be extremely sensitive to low
levels of contamination and weathering effects. Abnormal I values indicate
that the samples should undergo additional treatments. Such information
may not be apparent in a combined statistic.

Examples of the results of the I-statistics for data collected in this
study, and identifications based on these are presented in Table AII.4.
These results are consistent with the preliminary identifications of the
tephra units as Bridge River and Mazama tephra within the cores. In all
cases the lower deposit was identified as Mazama and the upper as Bridge
River, with no evidence of reworking and multiple deposition at any site.
### Table AII.3 The A statistic for comparison of Mazama and Bridge River tephra

<table>
<thead>
<tr>
<th>Element</th>
<th>&quot;A&quot; statistic</th>
<th>Mazama/B.R.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.004</td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>0.51</td>
<td></td>
</tr>
<tr>
<td>Ti</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Fe</td>
<td>0.05</td>
<td></td>
</tr>
<tr>
<td>Ca</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Mg</td>
<td>0.08</td>
<td></td>
</tr>
<tr>
<td>K</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>1.25</td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>0.04</td>
<td></td>
</tr>
<tr>
<td>Co</td>
<td>0.005</td>
<td></td>
</tr>
<tr>
<td>Cr</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>Cu</td>
<td>0.24</td>
<td></td>
</tr>
<tr>
<td>Mn</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Na</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>0.86</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>Pb</td>
<td>0.26</td>
<td></td>
</tr>
<tr>
<td>Rb</td>
<td>0.70</td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>0.007</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>0.30</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>1.46</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>0.32</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>1.03</td>
<td></td>
</tr>
</tbody>
</table>

Values >1.00 indicate the elements which are most useful in discriminating between Mazama and Bridge River tephra.
Table AII.4  Examples of I-statistics for "unknown samples"

<table>
<thead>
<tr>
<th></th>
<th>C8</th>
<th>C9</th>
<th>C10</th>
<th>C11</th>
<th>C15</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>For Mazama</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al</td>
<td>1.38</td>
<td>0.25</td>
<td>1.08</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>P</td>
<td>2.50</td>
<td>1.00</td>
<td>3.50</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>1.36</td>
<td>0.13</td>
<td>0.18</td>
<td>1.87</td>
<td>0.63</td>
</tr>
<tr>
<td>Y</td>
<td>1.94</td>
<td>0.60</td>
<td>0.70</td>
<td>2.16</td>
<td>0.30</td>
</tr>
<tr>
<td>Zr</td>
<td>1.41</td>
<td>0.29</td>
<td>0.05</td>
<td>1.72</td>
<td>0.28</td>
</tr>
</tbody>
</table>

|        |      |      |      |      |      |
| **For Bridge River** |      |      |      |      |      |
| Al     | 0.36 | 0.77 | 0.44 | 1.14 |
| P      | 0.35 | 1.43 | 0.36 | 1.79 |
| Nb     | 0.35 | 3.33 | 3.45 | 0.83 | 1.43 |
| Y      | 0.35 | 6.20 | 6.41 | 0.14 | 5.49 |
| Zr     | 0.35 | 2.38 | 3.01 | 0.22 | 3.43 |

<table>
<thead>
<tr>
<th></th>
<th>B.R.</th>
<th>M*</th>
<th>M</th>
<th>B.R.</th>
<th>M</th>
</tr>
</thead>
</table>

* some ambiguity with Al and P, yet other elements show strong discrimination
II.3 **Dated anthropogenic effects**

In all the lakes changes in the sediments of some of the cores for the most recent period is evident. The uppermost 2-8 cm of core are characterised by coarser, laminated deposits indicating localised inputs of coarser sediment. This is believed to be a consequence of accelerated erosion within the catchment, primarily as a consequence of logging road construction. This change in the record can be used to provide a datum within the surface sediments and was used to establish the fact that the rhythmites in the upper portion of the Kokwaskey Lake sediments are annual deposits i.e. varves. Information on the logging history, specifically the date of road construction adjacent to each lake, was provided by B.C. Forest Products (Fletcher Challenge) and is reported in Table AII.5. These are assumed to date the obvious recent change in the records.
Table AII.5  Date of logging road construction past each lake

<table>
<thead>
<tr>
<th>Lake</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kwoiek</td>
<td>1971</td>
</tr>
<tr>
<td>Kokwaskey</td>
<td>1974</td>
</tr>
<tr>
<td>John George</td>
<td>1977</td>
</tr>
<tr>
<td>Klept</td>
<td>1977</td>
</tr>
<tr>
<td>Kha</td>
<td>1979</td>
</tr>
</tbody>
</table>
APPENDIX III Examples of cumulative grain size curves

**SEDIMENTATION ANALYSIS: Size Distribution Plot**

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range Low Limit</td>
<td>0.001 mm</td>
</tr>
<tr>
<td>Range High Limit</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Weight</td>
<td>37.4 g</td>
</tr>
</tbody>
</table>

**Histogram Data**

<table>
<thead>
<tr>
<th>Percentile Finer</th>
<th>Value (phi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5%</td>
<td>+8.00 phi</td>
</tr>
<tr>
<td>10%</td>
<td>+8.55 phi</td>
</tr>
<tr>
<td>25%</td>
<td>+9.00 phi</td>
</tr>
<tr>
<td>50%</td>
<td>+9.50 phi</td>
</tr>
<tr>
<td>75%</td>
<td>+9.84 phi</td>
</tr>
<tr>
<td>90%</td>
<td>+10.00 phi</td>
</tr>
</tbody>
</table>

**Cumulative Distribution**

<table>
<thead>
<tr>
<th>Fraction Remaining by Weight</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>0.001</td>
</tr>
<tr>
<td>0.8</td>
<td>0.002</td>
</tr>
<tr>
<td>0.7</td>
<td>0.003</td>
</tr>
<tr>
<td>0.6</td>
<td>0.004</td>
</tr>
<tr>
<td>0.5</td>
<td>0.005</td>
</tr>
<tr>
<td>0.4</td>
<td>0.006</td>
</tr>
<tr>
<td>0.3</td>
<td>0.007</td>
</tr>
<tr>
<td>0.2</td>
<td>0.008</td>
</tr>
<tr>
<td>0.1</td>
<td>0.009</td>
</tr>
</tbody>
</table>

**Graph**

- Sand
- Silt
- Clay

**Dominant Size**

- 0.004 mm
- 0.1 mm

**Recessive Size**

- 0.254 mm
- 0.5 mm

**Mean**

- +7.30 phi

**Median**

- +7.30 phi

**Variance**

- 1.92 phi

**St. Dev.**

- +1.42 phi

**Kurtosis**

- +1.41 phi

**Skew**

- -1.27 phi

**Moments**

- +1.24 phi

**Percentage Finer**

- 5%: +8.00 phi
- 10%: +8.55 phi
- 25%: +9.00 phi
- 50%: +9.50 phi
- 75%: +9.84 phi
- 90%: +10.00 phi
SEDIMENTATION ANALYSIS Size Distribution Plot

Range: Lower Limit = .004 mm. +6.00 phi.  
Upper Limit = .354 mm. +1.50 phi.

Weight of given interval = 18.3 g.

- Dominant sieve = .004 mm. +6.00 phi.
- Recessive sieve = .354 mm. +1.50 phi.
- Mean Moment = +6.46 phi.
- Graphic = +6.22 phi.
- Median = +7.08 phi
- Variance = 2.08 phi
- St. Dev. Moment = +1.90 phi.
- Shear Moment = -1.02 phi.
- Kurtosis Moment = 2.94
- Graphic = 1.87

Percentile Finer
- D.95 = +7.99 phi.
- D.90 = +7.98 phi.
- D.80 = +6.91 phi.
- D.50 = +4.18 phi.
- D.40 = +2.64 phi.
- D.30 = +2.30 phi.

SEDIMENTATION ANALYSIS Size Distribution Plot

Range: Lower Limit = .001 mm. +9.50 phi.  
Upper Limit = .008 mm. +3.50 phi.

Weight of given interval = 17.4 g.

- Dominant sieve = .008 mm. +9.50 phi.
- Recessive sieve = .001 mm. +3.50 phi.
- Mean Moment = +7.30 phi.
- Graphic = +7.27 phi.
- Median = +7.25 phi.
- Variance = 1.81 phi
- St. Dev. Moment = +1.80 phi.
- Shear Moment = +1.12
- Kurtosis Moment = 3.91
- Graphic = 1.91

Percentile Finer
- D.95 = +1.05 phi.
- D.90 = +1.15 phi.
- D.80 = +1.75 phi.
- D.50 = +0.75 phi.
- D.40 = +0.41 phi.
- D.30 = +0.88 phi.
- D.20 = +5.57 phi.
SEDIMENTATION ANALYSIS: Size Distribution Plot

KOK 240

Range: Lower Limit = 0.001 mm, +10.00 phi.
Upper Limit = 0.354 mm, +1.50 phi.

Volume of given interval = 10.1 g.

- Dominant sieve = 0.004 mm, +8.00 phi.
- Recessive sieve = 0.250 mm, +2.00 phi.
- Mean Moment = +6.32 phi.
- Median = +7.99 phi.
- Variance = 3.14 phi.
- St. Dev. Moment = +1.77 phi.
- Skew Moment = -0.85
- Kurtosis Moment = 2.82
- Graphic = +0.84

- Percentile Finer
  D16 = +6.19 phi.
  D50 = +7.60 phi.
  D90 = +7.82 phi.
  D95 = +8.00 phi.

Sieve Size

(pg)

SEDIMENTATION ANALYSIS: Size Distribution Plot

KOK 310

Range: Lower Limit = 0.001 mm, +10.50 phi.
Upper Limit = 2.828 mm, -1.50 phi.

Volume of given interval = 84.8 g.

- Dominant sieve = 0.004 mm, +8.00 phi.
- Recessive sieve = 0.022 mm, +5.50 phi.
- Mean Moment = +2.62 phi.
- Median = +2.85 phi.
- Variance = 2.84 phi.
- St. Dev. Moment = +1.82 phi.
- Skew Moment = -0.01 phi.
- Kurtosis Moment = 1.05
- Graphic = +1.01

- Percentile Finer
  D16 = +5.97 phi.
  D50 = +5.91 phi.
  D90 = +5.26 phi.
  D95 = 5.05 phi.

Sieve Size

(pg)