University of Alberta

Distinguishing between the geomorphic and hydrometeorological controls recorded in clastic varved sediments

by

Scott Fraser Lamoureux ©

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"The land was low, barren and shapeless. Part of its interior was blanketed with ice. Its shoreline had neither the relief of a cliff nor a picturesque headland. There was only dull uninteresting slopes of sand and snow separating the frozen sea from the land ice....

Yet it aroused in us a deep sense of enthusiasm. A strip of tropical splendour could not have done more. The spring of man's passion is sprung by contrast, not by degree of glory."

-Dr. Frederick Cook, viewing the Sverdrup Islands after returning from the North Pole, June 14th, 1908

(from The Polar Passion by Farley Mowat, McClelland and Stewart, 1967)

Abstract

Varved sediments from Nicolay Lake, Cornwall Island, Nunavut were evaluated as a proxy hydroclimatic record. The seasonality of streamflow, sedimentology and ^{137}Cs and ^{210}Pb profiles support the varve interpretation. Temporal variability of lake and catchment controls that alter the accumulation of varves was investigated with annual isopach maps, to identify deposition changes related to shifting delta distributaries and slumps. Therefore, the resulting 493-year sediment yield record retains the range of past hydroclimatic conditions, especially large magnitude events.

Extreme deposition in 1951 and 1962 was related to the two largest recorded rainfalls at Isachsen. In each case, the timing of the rainfall agrees with timing of thick subannual rhythmites. Other extreme yields are interpreted as rainfall events, and a close correspondence was also observed between varves with (without) prominent subannual rhythmites and summers with (without) rainfall events exceeding ~13 mm total. Subannual rhythmites are produced when the rainfall followed the nival flood and where cool weather minimized soil storage of rain. Only four years of the weather record cannot be reconciled with the varves, likely due to localized rainfall or, in the case of 1965, a late season snow melt event.

The temporal pattern of rainfall yield events indicates that wet conditions coincided with the coldest periods of the "Little Ice Age" (LIA), as indicated by other temperature-sensitive proxy records. Increased sediment yield and rainfall frequency also agree with observations of cooler summers and increased frequencies of cold-wet synoptic types after 1962. Conversely, warmer years, particularly those indicated by ice core melt layer records, are recorded as periods of lower yield and infrequent rainfall. The timing of these cold-wet episodes is similar to several documented volcanic eruptions which have been previously used to explain LIA cooling. Sediment yield shows a general positive correlation with the ice core acidity record, suggesting that volcanism was an important climatic forcing during this period. The varve record indicates that a rainfall response was linked to large-scale synoptic changes that persisted for several years after eruptions rather than to an abrupt, short-lived temperature response.

Dedicated to Linda and Mackenzie

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CHAPTER 1. INTRODUCTION

1.1 Background

The potential for rapid and global climatic changes has resulted in an unprecedented effort by scientists to identify major climatic processes in order to evaluate- and ultimately predict- the climatic response to natural and human-induced changes to the atmosphere (Houghton *et al.*, 1996). Instrumental climate records are comparatively short (generally <100 years, Jones and Bradley, 1992), therefore, conventional observations provide only a limited perspective on past climate variability. Moreover, the majority of the instrumental climate record follows the commencement of important anthropogenic changes to atmospheric chemistry that began with the 19th century industrial revolution (Lamb, 1977). Given that many early weather records were from regions with early industrial activity and urbanization (Jones and Bradley, 1992; Karl *et al.*, 1993), our long term climate perspective is potentially compromised by local influences in the data and can not provide an indication of natural variability prior to large scale anthropogenic changes to the atmosphere and biosphere.

The field of paleoclimatology has developed in response to the need to identify natural climate variability and forcing mechanisms (Bradley, 1985). From this work has arisen a large number of proxy climate records from a wide range of climatic regions and with varying temporal resolutions. In particular, varved sediment records have recently been used to develop high resolution proxy climate records from a wide range of lake and marine environments (e.g. Zolitschka, 1992; Anderson, 1993; Desloges and Gilbert, 1994; Leavitt *et al.*, 1994; Bradley *et al.*, 1996; Hughen *et al.*, 1996; McQuoid and Hobson, 1997). A varve is a clearly defined sediment structure that represents deposition during one year. Originally, varves were described by De Geer (1912) to form in the proglacial environment. While varves are generally defined as strictly clastic, largely inorganic deposits, annual rhythms have been shown to exist in a variety of aquatic environments either partially or totally dominated by biological and geochemical (autochthonous) deposits (O'Sullivan, 1983). Once the presence of varves can be supported, an accurate down-core chronology can be established to reconstruct sedimentation rates or to date deposits on an annual basis, thereby providing a continuous high temporal resolution record for hundreds to thousands of years (O'Sullivan, 1983). Once an accurate varve chronology has been established, the rate of allochthonous and autochthonous accumulation can be established, thus providing an estimate of past hydrological activity from the catchment and/or lake biological productivity. Alternatively, the varve chronology can be used to date subfossil and geochemical proxies to provide less detailed (multi-year), but nonetheless, accurately dated proxy paleoenvironmental records (O'Sullivan, 1983; Bradley, 1985). Therefore, varved sediments provide the potential to develop high resolution proxy climate records that are more directly comparable with the temporal resolution of instrumental climate records than previous, low resolution sedimentary records with less certain dating.

One fundamental limitation of many varved records is a lack of clear understanding of how lake, catchment, and hydroclimatic processes interact to generate a sedimentary signal. Of particular importance, there is often no assessment of whether or not the processes involved consistently record a hydroclimatic signal over time. If the processes that control deposition vary, hydroclimatic interpretations from the sedimentary record may be misleading. Therefore, in order for interpretations of long varve records to substantively contribute to the larger scientific debate regarding global climate change, a systematic approach must be taken to evaluate these issues during the earliest stages of the sedimentary research. It is from this viewpoint that the current research is presented, as an evaluation of variability in the processes that control the formation of a varve record and, therefore, processes that can mimic hydroclimatic variations and lead to misinterpretations in the long sedimentary record.

1.2 Scope and Rationale

This dissertation aims to evaluate the potential for using varved sediments as a paleoclimatic proxy by investigating detailed sedimentology and pertinent lake, catchment and geomorphological process observations. Varved sediments from Nicolay Lake, Cornwall Island, Nunavut are the focus of this research. This site in the Canadian High

Arctic, was selected for study in order to reduce the complexity of hydrological and climatological controls found in more temperate varved environments, and to minimize the potential for catchment alterations due to human activities that could affect the sedimentary record. Nicolay Lake is subject to a short and well-defined period of hydrological activity during the summer, thereby limiting the influence on the sedimentary record to the spring and summer. Biological activity in the High Arctic lacustrine environment is also minimal, which essentially eliminates the role of autochthonous components in the sediment. Therefore, this site represents a conceptually and comparatively "simple" earth system in which to investigate a sedimentary record. A key difference between this study and previous investigations of varve proxy records in the High Arctic (e.g. Bradley *et al.*, 1996) is the deliberate absence of systematic, quantitative process observations (e.g. hydrological monitoring). The reason for this approach is two-fold: systematic process studies are inherently short term, therefore, any measure of variability in natural processes obtained from them is severely limited. Because the empirical process measurements from these studies are often viewed as authoritative, there is a tendency to interpret long proxy records as if the observed processes were effectively the same in the past. These short term process studies are valuable for identifying the specific processes that occur in the hydroclimatic and limnological systems. Clearly however, the potential exists that major sources of variability, which are important in the longer sedimentary record, simply do not occur during the period of observations. By investigating these processes using the longer sedimentary record, the effects of this short term bias can hopefully be minimized. Secondly, the physical and personnel resources required for prolonged process observations are prohibitive in most situations. If varved records are to be developed to address the climate change debate in a timely manner, there must be an efficient means of providing meaningful information with more limited resources.

Therefore, the scope of this research is to investigate the sedimentary record, first and foremost, as a proxy of lake and catchment process changes. Thematically, this procedure is as follows:

1) Identify the limnological and geomorphological controls on the formation of varved

sediments in Nicolay Lake. The emphasis is to identify the role played by sedimentary and catchment processes in the formation of discrete sedimentary structures and features, with the ultimate goal of identifying the potential for generating hydroclimatic proxy records exclusively from clastic sediments.

2) Identify the role of catchment processes in altering the long-term stationarity of the sedimentary record. Potentially, changes to sediment availability, the fluvial environment and geomorphic "memory" could all produce important effects in the sedimentary record that could be misinterpreted as evidence for hydroclimatic changes (e.g. Church and Ryder, 1972; Leonard, 1985; Lamoureux and Bradley, 1996).

3) Identify and remove the influence on sediment accumulation patterns of intra-lake depositional controls in order to produce a sediment accumulation chronology consistent with fluvial, catchment-sourced sediment yield. This procedure requires identifying: a) temporal variability in depositional patterns caused by sediment distributional processes; b) redistribution of sediment by within-lake processes, particularly slumping, and; c) controls that redirect the inflow of sediment into the lake, particularly on the delta, thereby altering the distribution of sediment in the lake.

4) Finally, identify what features of the varve record, if any, can be confidently related to specific hydroclimatic processes and suggest likely external forcing mechanisms for the observed changes.

1.3 Thesis outline and format

This research is presented as a group of four papers, each designed to stand alone. Methods and other pertinent site information are contained in each paper. Chapter 2 describes the lake and catchment environment, and the sedimentological evidence for varve formation. Holocene changes to the catchment environment are evaluated to assess their impact on varve formation and sediment availability. Chapter 3 describes the evidence from the varves for anomalous, intra-lake depositional processes, and develops a methodology to minimize their effects on the long term varve record of sediment accumulation rates.

Chapter 4 evaluates the major features of the varve record, identifies a rainfall-related mechanism for increased sediment yields and discusses the temporal variability of major rainfall events. Chapter 5 discusses the paleoclimatic implications of the synthetic rainfall record from Nicolay Lake by comparing this unique paleoprecipitation proxy with other paleotemperature records from the Arctic. Additionally, these results provide support for previous suggestions that volcanic activity was likely an important forcing mechanism for decadal- to century-scale climate change in the northern hemisphere. Chapter 6 summarizes the results of the research, and identifies key research questions for future work.

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CHAPTER 2: FORMATION OF CLASTIC VARVES AND RELATED ENVIRONMENTAL PROXIES IN MONOMICTIC NICOLAY LAKE, CORNWALL ISLAND, NUNAVUT

(For submission to *Canadian Journal of Earth Sciences*)

2.1 Introduction

Varved lake sediment records have been the focus of a wide range of recent research that has provided the first indications of the response of High Arctic landscapes to long term (>100 years) interannual variability in hydrological and climatological systems (Lamoureux and Bradley, 1996; Gajewski *et al.*, 1997; Smith, 1997). Due to the low biological productivity in many of these lakes, the main environmental record reported from varves, High Arctic and otherwise, has been that of annual sediment accumulation (e.g. Gilbert, 1975; Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Lamoureux and Bradley, 1996; Gajewski *et al.*, 1997; Leonard, 1997). However, there have been few investigations of the information that can potentially be derived from the sedimentary features contained within the varves (e.g. Gilbert, 1975; Smith, 1978; Desloges and Gilbert, 1994). Where detailed investigations of varve sedimentology from arctic lakes have been undertaken (Zolitschka, 1996; Gajewski *et al.*, 1997), sediment accumulation has been too low to resolve internal features of the varves, thereby limiting the hydroclimatic interpretations to a single measure of summer conditions. The limitations of this approach are revealed by the single quantitative study from the region, in which 29% ($r=0.54$, $p<0.01$) of the variance in the varve thickness record could be explained by summer temperature above the inversion level (Hardy *et al.*, 1996). Therefore, it remains poorly known what hydroclimatic information varve records contain and how long records can be used to increase our understanding of natural climate variability in the region.

Additionally, the effects of long term changes in sediment availability have not been addressed, which could result in misleading inferences about past changes to the hydroclimatic system (e.g. Leonard, 1985; Lamoureux and Bradley, 1996). Given the glacioisostatic emergence in the region (>100 m, Hodgson, 1991), catchments that supply sediment to varved lakes may have undergone important changes that altered sediment availability and yield (e.g. Church and Slaymaker, 1989) that could be misinterpreted as hydroclimatic changes. In order to confidently distinguish between geomorphic and hydroclimatic variability in the varve record, some understanding of the major catchment controls over sediment yield is required.

This paper provides a detailed evaluation of the laminated sedimentary record from Nicolay Lake, Cornwall Island (Figure 2.1, 2.2), to identify the geomorphic, limnological, and hydroclimatic processes that contribute to varve formation. Evidence from the sedimentary analysis and radiometric dating of recent sediments is used to support the hypothesis that the laminae in Nicolay Lake are varves. The varves in Nicolay Lake are thick by High Arctic standards and the use of thin sections permits the identification of subannual structures and other distinctive sedimentological features. Catchment and lake conditions that lead to the formation of varves are identified, and the Holocene evolution of the catchment is evaluated to identify important changes that have affected long term sediment yield. These results indicate that detailed sedimentological analyses from lakes with high accumulation rates can substantially extend the range of information available from clastic varved sediments, and show the importance of assessing the influence of catchment conditions on long term sediment availability.

2.2 Study Area

Nicolay Lake is a small, low elevation lake (2.5 m above sea level (asl), Table 2.1) separated from the coast by what appears to be a 50 m high arcuate moraine (Figure 2.2). The lake contains a single deep basin that is fed by a large river and several small streams

(Figure 2.3). Deposition from the river has produced a large delta on the south shore, which has prograded ca. 1 km and contains abandoned surfaces to 5 m asl. Similar deltaic features are widespread on Cornwall Island, suggesting that the sediment accumulation in the Nicolay delta is typical (Figure 2.4). The lake outlet is incised into a 5 m asl bench that continues 1.5 km to the coast, with remnant shorelines around the lakeshore visible to this elevation. Given the low elevation of Nicolay Lake, it is likely that the lake has only recently been separated from the sea, although an accurate isolation age is not available.

The river that constitutes the major source of water and sediment to Nicolay Lake drains a large, low relief catchment similar to others found on Cornwall Island and most of the other islands of the central and western High Arctic (Figure 2.2). Cornwall Island is underlain by the eroded Cornwall Arch, a northward striking anticline of marine and fluvial sedimentary rocks deposited in the Mesozoic Sverdrup Basin (Balkwill, 1983). Most of the catchment is underlain by the poorly consolidated Triassic Blaa Mountain Formation mudstones and Heiberg Formation sandstones, with more resistant Jurassic strata forming the eastern rim. Jurassic diabase intrusions are widespread in the Triassic sedimentary units, producing conspicuous dykes. Large sills and metamorphosed country rock form the isolated highlands found at Mount Nicolay and in the southwest part of the catchment (Figure 2.2). North-trending diabase dykes west and east of Nicolay Lake, together with considerable normal faulting on nearby Mount Nicolay, suggest that the uncommon depth of the lake may be structurally-controlled, although the subsurface structure is poorly known (Balkwill, 1983).

Catchment topography is composed of gentle ridges and wide, valley-bottom sandar. Deep ravines occur intermittently where rivers cut through ridges, separating the sandar and confining streams to narrow channels (Figure 2.2). Sediment cover is variable, but fine grained, erodible sediment is widespread. Radiocarbon dated marine shells indicate that postglacial submergence of the Nicolay River catchment reached at least 115 m asl in the early Holocene (8560±80 years BP, TO-5613), resulting in initial submergence of approximately 72% of the catchment. The complicated ridge and valley pattern in the modern catchment (Figure 2.2) would have generated a series of marine embayments throughout the interval of Holocene emergence (Hodgson, 1991). Similar embayments and lakes continue to characterize the modern coastline (Figure 2.4). During emergence, a veneer of marine sediments was draped on most slopes, with localized thicknesses of 1-20 m in valley bottoms (Lamoureux *et al.*, in prep.). Thick units of deltaic, marine, and fluvial sediments are extensive, particularly in the upper east fork (Figure 2.2), and have been substantially incised by rivers. Gravel and coarser materials are limited to igneous outcrops and to thin surface lags (Hodgson, 1982).

Hydroclimatic conditions on Cornwall Island are likely similar to those found elsewhere in the central and western islands where meteorological and hydrological observations are available. The severe High Arctic climate limits hydrological activity to the short summer melt season between June and August. At the nearby Isachsen weather station (Figure 2.1), mean daily summer temperatures average 2-4°C. Runoff on Cornwall Island is strongly nival and similar to that found throughout the central arctic islands (Woo, 1983). Peak discharge occurs during the initial 2-3 weeks of snow melt, and typically shows diurnal fluctuations that follow solar radiation variations (Woo, 1983; Lewkowicz and Wolfe, 1994; Hardy, 1996). Initial melt in the catchment is frequently ponded by snow-filled channels or by thick snow drifts which can significantly delay the formation of channelized flow (Woo and Sauriol, 1981). On Cornwall Island in 1995, meltwater in the lower catchment was prevented from reaching the lake for eleven days due to successive ponding in deep snow. In general, following peak nival discharge, river stage wanes for the remainder of the season as snowcover is depleted (Woo, 1983). Precipitation is minimal throughout the year, with snowfall concentrated during the early winter, and rainfall commonly occurring as low intensity events (<1 mm·day^{-1}). Occasionally, more intense rain can occur, and all High Arctic weather stations have recorded daily totals exceeding 15 mm. Intense rainfall can result in a rapid increase in discharge, although response to storms varies with changing soil moisture conditions and active layer depths (Woo and Young, 1997).

2.3 Methods

Fieldwork was carried out during the 1995, 1996 and 1997 seasons. All of the catchment and most of the surrounding terrain was traversed by foot, all-terrain vehicle, and snowmobile. Surficial mapping by Hodgson (1982) was confirmed during the field traverses and supplemented with the logging of sediment exposures and observations of hydrological processes. Sediment cores were recovered from Nicolay Lake during the late winters of 1995 and 1996 (Figure 2.3) using piston-percussion (Reasoner, 1993) and vibracoring methods (Smith, 1992). Cores obtained in 1996 froze while stored vertically, whereas the 1995 cores remained unfrozen. In the laboratory, the cores were split, photographed and logged. Subsamples were obtained for large-format thin sections and density, loss-on-ignition (LOI), and grain size determinations. Unfrozen sediment slabs for thin sectioning were separated with metal trays, dehydrated with acetone, and embedded under vacuum with a single application of Epo-thin™ epoxy resin (Lamoureux, 1994). For frozen subsamples, the cores were first cut into 1 cm thick parallel strips with a rock saw, and then cut to length with a knife, freeze-dried, and embedded with resin. Thin sections were prepared from the cured slabs using standard methods. Sedimentological descriptions and measurements were made with a low-power (12.5X) microscope under both plain and cross-polarized light using a calibrated eyepiece graticule. Density and LOI measurements were obtained following standard methods (Bengtsson and Enell, 1986). Down-core grain size distribution samples were wet sieved to 62.5 μm, dispersed in sodium hexametaphosphate and run in a Sedigraph 5000ET. Detailed grain size determinations were performed on ~1 mm thick samples using a Coulter laser scattering analyzer.

Sediment samples from core NL2 were separated for ^{137}Cs and ^{210}Pb determinations. Samples for ^{137}Cs were dried, packed into plastic vials and counted with a gamma spectrometer for a minimum of 75 000 seconds (~1 day). Unsupported ^{210}Pb levels were measured by alpha counting the daughter product ^{210}Po, using ^{210}Pb amounts from two deep samples as an estimate of supported lead production. ^{210}Pb ages were estimated using the constant rate of supply model (Appleby and Oldfield, 1978).

Water chemistry samples from lakes and streams were collected with a Kemmerer remote sampler and pre-cleaned Nalgene bottles respectively. Samples were vacuum filtered with 0.45 µm cellulose nitrate papers and alkalinity was determined in the field with a Hach digital titrator. Quantitative dissolved oxygen determinations were unsuccessful due to low temperatures, however, all samples from Nicolay Lake indicated the presence of oxygen[1]. Major ion chemistry was determined using a Dionex DX500 ion chromatography system using 20 mmol methanesulfonic acid and 1.7 mmol sodium carbonate-1.8 mmol sodium bicarbonate as eluents for cations and anions respectively.

2.4 Results

2.4.1 Physical limnology of Nicolay Lake

Field observations suggest that Nicolay Lake is a freshwater, cold monomictic lake. Water column measurements in the spring of 1995 indicated isothermal (2.4-2.7°C) conditions and a slight increase in solutes with depth (Table 2.2). Unlike many deep coastal lakes in the High Arctic there is no evidence of saline bottom waters trapped during glacioisostatic rebound (Hattersley-Smith *et al.*, 1970; Bradley *et al.*, 1996; Smith, 1997) in Nicolay Lake. The chemical composition of Nicolay Lake is similar to that of the catchment runoff (Table 2.2). Solute levels in Nicolay Lake, particularly Na^+ and SO_4^{2-}, were moderately higher than reported in lake DV09, a similar freshwater coastal lake on Devon Island (Gajewski *et al.*, 1997). However, it is interesting to note that the solute composition in DV09 was similar to that of the 1995 snowpack near Nicolay Lake and also

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[1] All samples produced an orange-brown flocculent after reaction with manganous sulfate and alkaline iodide-azide, indicating the presence of dissolved oxygen (Hach, 1992)

Cornice Lake, a headwater lake with a small catchment underlain entirely by diabase and with limited surficial sediments (Figure 2.2, Table 2.2). These differences highlight the importance of solute enrichment in river and lake water in the larger Nicolay Lake catchment by limited chemical weathering, probably by elution of salts and dissolution of carbonates from marine sediments, but provide no evidence for residual sea water in Nicolay Lake.

These results indicate that if Nicolay Lake was at one time meromictic, the saline water in the hypolimnion has been mixed and removed. The current isothermal conditions in the lake are preserved by cold inflowing water and pervasive lake ice (>75% in 1996 and 1997), which reduces solar warming and prevents wind mixing of deeper water in the centre of the lake. If the lake ice does break completely, this will generally occur after the major summer runoff season, so surface warming and thermal stratification are unlikely during the active sedimentation period.

2.4.2 Holocene stratigraphy

Two long sediment cores (NL20, 21, Figure 2.3) were recovered from Nicolay Lake to investigate the Holocene sedimentation record. Each core contains a similar sequence of basal diamicton interbedded with sandy rhythmites, overlain by massive mud, and capped by laminated mud (Figure 2.5). The diamicton occurs as two separate units, and is composed of rounded to subangular diabase, quartzite, and sandstone gravel, frequently in contact with each other, in a poorly sorted matrix. The lower diamicton is continuous across the bottoms of both cores, while the upper diamicton in NL21 is discontinuous. The sandy rhythmites that separate the diamictons have been deformed (Figure 2.5). Sandy rhythmites containing occasional clasts also overly the upper diamicton, and gradually grade into a thick unit of massive black mud. The mud appears structureless in both thin section and radiographs, and contains *Portlandia arctica* valves and abundant foraminifera throughout. Radiocarbon dates on shell samples from 260 and

560 cm dated 3500±50 (Beta-111707) and 9445±65 BP (AA-23582) respectively, indicating that the unit represents deposition through most of the Holocene (Figure 2.5). The transition from massive mud to the overlying laminae occurs between a depth of 160-220 cm. The laminae are composed of silt and clay couplets ranging from 1-10 mm in thickness, with occasional thin beds up to 80 mm thick. Molluscs are absent from the laminated sediments, and foraminifera are infrequent. Additionally, the laminated sediments of proximal core NL1 contain several discrete organic layers, containing *Brachythecium turgidum* and other terrestrial mosses (C. Lafarge-England, pers. comm. 1995).

The sequence of sediments in cores NL20 and NL21 represents the Holocene deglaciation of Cornwall Island, the subsequent transgression to marine limit, and the subsequent isolation of Nicolay Lake from the sea due to glacioisostatic emergence. Diamictons at the base of both cores are interpreted as till containing local lithologies. Previous investigation has revealed equivocal evidence for Late Wisconsinan glaciation of Cornwall Island (Hodgson, 1982), however, recent work demonstrates northward flow of ice across the island which incorporated shells ranging in age from 30-37 ka BP (Lamoureux *et al.*, in prep.). Rhythmites separating the two diamicton units indicate deposition in an ice-proximal embayment, with the discontinuous upper diamicton likely the product of ice rafting (Mackiewicz *et al.*, 1984; Powell, 1984; Lemmen, 1990). The sandy rhythmites and dropstones overlying the upper diamicton are the last evidence for deposition in a proximal glacial environment.

After c. 9.5 ka BP, ice left the Nicolay Lake basin and the sea inundated Cornwall Island to at least 115 m asl, as indicated by *Hiatella arctica* valves from marine silts at 106 m asl (8560±80 BP, TO-5613) located below prominent beaches. Thus, early in the Holocene, the area currently occupied by Nicolay Lake lay in a marine basin distal from fluvial sediment sources on the island. Marine muds were deposited in the proto-lake until at least 3.5 ka BP, while extensive fluvial and deltaic sediments were limited to littoral locations in the middle and upper catchment as postglacial emergence progressed.

The transition from massive to laminated sediments in Nicolay Lake is considered to be the product of sea level regression and overstepping by fluvial sedimentation. Benches at the outlet suggest that the Lake could have been isolated by c. 1 ka BP or later (Hodgson, 1991). At the same time, shallow marine embayments in the middle catchment would have become floodplains, resulting in a substantial increase in direct fluvial transport to the newly emerged lake. Previous Holocene fluvial, lacustrine, and marine fills in the catchment were also subject to incision by lowering base level, further increasing potential sediment transport into Nicolay Lake. Retelle (1986) noted a similar marine-lacustrine transition in the Beaufort Lakes, northeast Ellesmere Island, and suggested that fluvial sedimentation was responsible for the laminated sediments in the late-Holocene. Similar transitions from massive to laminated sediments have been observed in other High Arctic coastal lakes (Retelle and Marsella, 1994; Lamoureux and Bradley, 1996; Retelle and Lamoureux, in prep.). In contrast, Svendsen *et al.*(1989) report a seven-fold reduction in accumulation rates between the marine and lacustrine sediments in Linnédalen, Svalbard, primarily through reduced contributions from marine littoral processes. They note however, that fluvial sediment delivery from that catchment is comparatively minor. This situation differs substantially from Cornwall Island, which contains abundant evidence of modern and Holocene fluvial erosion and sediment redistribution (Hodgson, 1982). Therefore, it is likely that the recent laminated sediments in Nicolay Lake are the product of both increased direct sedimentation from the catchment and greater sediment trapping following isolation from the sea. Massive sediments were deposited prior to this period because sedimentation rates were not high enough to develop a visual rhythmicity or avoid bioturbation (O'Sullivan, 1983; Larsen and MacDonald, 1993).

2.4.3 Laminae sedimentology and stratigraphy

Clearly laminated sediments were recovered from all areas of the lake below 18 m depth (Figure 2.3). It is unknown what sedimentary structures, if any, occur at shallower locations. The laminae are similar in density, texture, and organic content (Figure 2.6) and generally show consistent distal fining and thinning (Chapter 3). The sediment composition is dominantly clastic and visual organic matter is uncommon except for thin layers of detrital moss in core NL1. Similarly, sediment extracts revealed sparse diatom concentrations in core NL1, and only individual valves were observed in the distal cores (I.R. Smith, pers. comm. 1996). In thin section, the laminae appear as millimetre-scale, normally graded units of sand, silt and clay separated by sharp, conformable contacts (Figure 2.7,2.8). The coarser basal sediments in each unit are composed dominantly of silt in all but the most proximal site (NL1, Figure 2.3). Grain-size analyses on ~1 mm thick sediment slices indicate that the texture of a typical unit in core NL3 varies from dominantly medium silt (mode 5.4ϕ) to fine clay (mode 9.0ϕ). The coarser sediments at the base of this lamina contain an admixture of grain sizes ranging from fine sand to fine clay while the upper sediments are dominated by fine clay (Figure 2.9). Frequently, units contain one or more graded rhythmites (Figure 2.7). The sediment that caps individual rhythmites is visually coarser than the overlying homogenous clay unit found in each major unit, indicating that the periods of quiescence between these deposits were shorter than was required for the fine clay caps to be deposited (Peach and Perrie, 1975). These rhythmites are more frequent in the cores closest to the delta (NL1, 2, 10) than in the distal sites.

Individual laminae are traceable between all of the cores and can be recognized on the basis of the pattern of laminae thicknesses and by internal structures (Gilbert, 1975; Smith, 1978; Sprowl, 1993; Lamoureux and Bradley, 1996; Zolitschka, 1996; Chapter 3). This correlation permitted the construction of a lake-wide stratigraphy of ~200 laminae, and >500 laminae in the western part of the lake. In most cases, the pattern of sediment accumulation is a simple distal thinning and fining radiating from a single distributary at the delta front. However, two other patterns are evident in the thicknesses of individual laminae. Of particular importance is a bifurcating pattern, where two trajectories of high accumulation occur on either side of proximal cores NL1 and NL2. This pattern is caused by the persistence of two major delta distributaries and has occurred sporadically during the last 100 laminae (Chapter 3). The second anomalous pattern involves thick localized accumulation in proximal core NL1. This pattern is associated with thick, massive sand mixed with coarse organic debris. The basal contact of these units is conformable and indicates that the underlying sediment was not eroded during deposition (c.f. Zolitschka, 1996). These deposits are attributed to low energy grain flows from the steep delta foreslope that produce a localized lobe of accumulation on the lake floor (Chapter 3).

In general, the uniform distribution of most laminae indicates that lake-wide deposition is dominated by low energy suspension settling (Smith, 1978; Smith and Ashley, 1985; Zolitschka, 1996). The graded structure of the laminae is consistent with the lack of thermal or chemical stratification in Nicolay Lake (Sturm, 1979) and the presence of clay and fine silt throughout the laminae indicates that the finest grains settle out throughout the period of active sedimentation. The wide distribution of silt and clay in the lake suggests that interflows or homopycnal flow are the major mechanisms for sediment dispersal (e.g. Lemmen *et al.*, 1988). Turbid inflowing water would be expected to generate density underflows in the lake (Gilbert, 1975; Smith *et al*, 1982; Smith and Ashley, 1985; Zolitschka, 1996). However, deposits associated with turbid underflows are sedimentologically distinct and limited to the most proximal site studied (NL1, Figure 2.3). Furthermore, major rhythmites within each lamina can be traced between cores, particularly in the shallower distal sites, indicating that sediment distribution during these events was not produced by underflows limited to the deep central basin (c.f. Gilbert, 1975).

One final sedimentary feature is evident in the thin sections. Isolated sand grains and thin (<0.1 mm) silt layers are frequent in the upper clays of the laminae (Figure 2.8). These subrounded quartz grains often exceed 100 μm diameter, and are conspicuous in size compared to the clay matrix. Similarly, the silt layers are typically discontinuous, and are composed of poorly sorted grains ranging from 10-80 μm diameter. These coarse inclusions are found at all core sites, although the sand grains are typically larger and more common at site NL14 and conversely less frequent and smaller in the eastern cores (Figure 2.3). Given the dichotomy between these grains and the fluvially-sourced, sorted silt and clay that constitutes the overall sediment matrix, these coarse, isolated deposits must have another origin. Possible mechanisms for the formation of these deposits are presented in the Discussion.

2.4.4 Radioisotope Geochronology

Given the consistent presence of laminae throughout the lake and the strong seasonality of river flow in the High Arctic, it is hypothesized that the laminae represent varves. The coarse sediment at the base of each lamina is likely related to deposition during the nival flood, while the fine clay that caps each unit is likely produced during late season runoff when sediment inflow is minimal and following the formation of complete ice cover in September. To test this hypothesis, samples were taken from core NL2 to determine whether profiles of ^{137}Cs and ^{210}Pb are consistent with laminae counts. The ^{137}Cs profile shows two major peaks that likely correspond to maximum fallout from nuclear bomb testing in 1963 and the Chernobyl accident in 1986 (Figure 2.10). Because the surface is missing from all of the cores studied (due to coring and transportation disturbances), the laminae cannot be counted back directly. Nonetheless, 23 laminae were counted between the two ^{137}Cs peaks, providing a qualitative agreement between the two chronologies. Based on these results, the sediment surface should represent accumulation in 1987, with 7 years lost.

The results based on ^{210}Pb ages, estimated with the constant rate of supply (CRS) model (Appleby and Oldfield, 1978), are also consistent with the varve interpretation. In general, there is no evidence for long term divergence of the laminae counts and the ^{210}Pb ages. However, between 9-13 cm depth, the two estimates diverge to produce a near constant c. 35 year difference below 15 cm (Figure 2.10). This difference is likely due to two factors: low levels of ^{210}Pb in the sediment and low accumulation rates for the two samples at 9 and 13 cm. The maximum ^{210}Pb concentration in Nicolay Lake is 0.055 $Bq \cdot g^{-1}$, and is similar to other measured values in the region (M.S.V. Douglas, pers. comm. 1997). Because of the ambient low levels of ^{210}Pb, minor reversals in the core profile occur at 9 and 13 cm. These same depths correspond to sections in NL2 with thin laminae, which could have resulted in the relatively high concentration of ^{210}Pb in the sediment and the decay reversals. The CRS age model is especially sensitive to changes in accumulation rates (Appleby and Oldfield, 1983), therefore, it is likely that the brief divergence in the laminae-^{210}Pb ages is an artifact of the lead dating and the noted reversals. Despite this complexity, the correspondence between the laminae counts, and both the ^{137}Cs and ^{210}Pb isotope profiles, support the hypothesis that the laminae in Nicolay Lake are likely varves.

2.5 Discussion

2.5.1 Controls over varve formation in Nicolay Lake

Nicolay Lake contains one of the few varved records from a nonglacial, freshwater lake in the Canadian Arctic (c.f. Coakley and Rust, 1968; Lemmen *et al.*,1988; Doran, 1993). The only other example is freshwater, isothermal lake DV09 on Devon Island (Gajewski *et al.*, 1997). Most documented varved lakes are either from the proglacial environment or are meromictic (Retelle and Marsella, 1994; Lamoureux and Bradley, 1996; Smith, 1997). Nicolay Lake differs from non-varved lakes in two respects: consistently high levels of sediment inflow, and a large effective depth. Unlike other sites in the High Arctic where varves have been reported, the lack of stratification and persistent ice cover do not appear to be controlling factors in this situation.

Consistently high accumulation rates from a fluvial source are considered critical for the formation of identifiable varve structures. High sediment accumulation rates permit the preservation of recognizable varve structures by separating the different seasonal components more clearly, and they also serve to minimize bioturbation (O'Sullivan, 1983). The mean varve thickness in Nicolay Lake is 2.92 mm, which is 2-10 times higher than annual accumulation rates reported from most arctic lakes, which are generally <1 mm (Lemmen *et al.*,1988; Svendsen *et al.*, 1989; Doran, 1993; Lamoureux and Bradley, 1996; Smith, submitted). The relatively small surface area of Nicolay Lake focuses sediment inputs from a large catchment into a small area, effectively increasing the accumulation rate (Table 2.1). In smaller catchments or where fluvial inputs are less pronounced, the dominant sedimentary signal may be from other sources like slope wash and gelifluction (Doran, 1993). In such cases, the annual rhythm of sediment deposition is inconsistent and compressed in the sediment record, and it may be further altered by biogenic or wind mixing and resuspension. Low sediment input may not be a limiting factor for varve formation in meromictic lakes, where deep sediments are protected from wave disturbances and anoxia prevents bioturbation of thin structures (O'Sullivan, 1983; Zolitschka, 1996). However, given that many of the lakes reported from the High Arctic do not have a consistent source of sediment, it is not surprising that varves are uncommon.

A second important factor in the formation of varves in Nicolay Lake is the large relative depth of the lake. Deep water has long been recognized as a major factor in the preservation of varves because it isolates the sediment from resuspension by wind and surface currents (O'Sullivan, 1983; Hilton, 1985; Larsen and MacDonald, 1993). However, in some cases where the sediment input is low and dominantly fine grained, deep water may prevent the settling of these sediments in a single season, preventing the formation of varves (Lemmen *et al.*, 1988). Observations at Nicolay Lake in the spring of 1995 indicated no measurable sediment in the water column prior to the spring melt, therefore, the depth of the lake does not appear to impede the settling of the finest sediments.

Other factors considered to prevent the formation of varved sediments in other arctic lakes do not apply to Nicolay Lake because of the high accumulation rates and relatively deep water. For example, it has been suggested that lake ice can limit the entry and dispersion of sediments, preventing the formation of rhythmites under the cover of ice or altogether. This possibility was used to explain the presence and absence of rhythmites in the littoral and profundal zones respectively of Stanwell Fletcher Lake, Somerset Island, Nunavut (Coakley and Rust, 1968), and by extension, to identify periods of varying ice cover related to climatic change (Doran, 1993). While ice cover may prevent sediment entry into lakes with minimal or early nival runoff (e.g. Doran, 1993), sediment deposition will not be prevented in more typical cases where stream and sediment inflows are prolonged (Woo, 1983). Moreover, monitoring studies indicate that turbid interflows expand over long distances under pervasive summer ice (Retelle and Child, 1996). Similarly, in 1996, turbid water was distributed throughout Nicolay Lake under extensive ice cover (>75%). Instead of inhibiting the formation of lake-wide sedimentation units, ice cover likely enhances preservation of the resulting deposits by minimising wind resuspension and disturbances, particularly in the centre of the lake (Hilton, 1985). Ice cover can also reduce wind-generated slumps (Larsen and MacDonald, 1993), which may explain the absence of slump deposits in the core record beyond the base of the delta foreslope (Chapter 3). Therefore, it is likely that other factors (i.e. low, inconsistent sediment influx) are more important constraints than ice cover in lakes without consistent varves.

Lakes containing varves are generally associated with stratified water columns (Sturm, 1979; O'Sullivan, 1983; Smith and Ashley, 1985; Larsen and MacDonald, 1993) and most of the known examples from the Canadian High Arctic are meromictic (Retelle and Marsella, 1994; Lamoureux and Bradley, 1996; Smith, 1997; Retelle and

Lamoureux, in prep.). Stratification of the water column promotes the formation of varves by encouraging interflows that permit suspension sorting and settling, and by isolating the hypolimnion from disturbances (Sturm, 1979; O'Sullivan, 1983; Smith and Ashley, 1985; Larsen and MacDonald, 1993). Seasonal or permanent stratification can also lead to an anoxic hypolimnion which minimises the bioturbation of thin sedimentary structures (e.g. O'Sullivan, 1983; Zolitschka, 1996). Although field measurements from an entire summer are not available from Nicolay Lake, there is no reason to assume that the isothermal, non-stratified state changes during the summer. Pervasive ice cover serves to minimise solar gains and sensible heat fluxes, and inflowing water temperatures rarely exceed 4°C (maximum 3.5°C, n=14). The unstratified water and a discontinuous influx of sediment correspond to Sturm's (1979) third case, which should produce a graded sediment unit for each major pulse of sediment inflow. Under these circumstances, identification of annual structures is dependent on the formation of a well-defined clay cap in the winter after the cessation of sediment inflow. The severe High Arctic climate assures that winter ice cover on Nicolay Lake is uninterrupted (c.f. Shaw *et al.*, 1978), permitting fine clay to settle to the bottom (c.f. Lemmen *et al.*, 1988). This distinctive clay cap permits recognition of annual structures in Nicolay Lake, regardless of the number of sediment pulses that enter the lake during the summer (Smith, 1978; Lambert and Hsü, 1979; Sturm, 1979; Gilbert and Shaw, 1981; Simola and Tolonen, 1981). Furthermore, these subannual rhythmites potentially contain a wealth of information regarding sediment transport events related to different catchment and hydroclimatic processes.

2.5.2 Catchment controls over varve formation

Of the factors that contribute to the formation of varves in Nicolay Lake, the high sediment influx is perhaps the most significant. Accumulation rates in High Arctic lakes are generally low (Doran, 1993; Zolitschka, 1996; Gajewski *et al.*, 1997), therefore, sediment yield in Nicolay Lake appears to be high compared with these other locations

(Chapter 4). In general, the High Arctic landscape is particularly conducive to sediment erosion and transport because vegetation is effectively absent (Edlund and Alt, 1989) and the bedrock is poorly lithified (e.g. Balkwill, 1983). Slope wash and gelifluction may be locally important, but long term measures suggest that these processes contribute limited amounts of sediment to lakes (Doran, 1993). The lack of vegetation is perhaps most important where erosion is concentrated, such as along channel banks. In these locations, the disturbance of permafrost and ground ice leads to mass wasting and erosion of soil materials (Lewkowicz, 1988; Woo and McCann, 1994). Gullying is also widespread and serves to transfer sediment to primary channels. All of these factors lead to relatively high sediment availability and yield which are further enhanced by the High Arctic hydrological regime (Woo and McCann, 1994). The semi-arid climate and strong seasonality of runoff produce an intense spring snowmelt and rapid response to intense rainfall (Cogley and McCann, 1976; Woo, 1983).

If high sediment supply has been an important factor in the the formation of varves in Nicolay Lake, the short length of record (c. 500 years) suggests that sedimentation rates have increased recently. Field evidence indicates that increased sediment availability has likely been a response to glacioisostatic base level lowering from early Holocene marine limit, which has driven the advance of a large sediment wave through the catchment. Additionally, the approximate synchroneity of the initiation of varve deposition and the isolation of the lake from the sea (c. <1000 BP) suggests that increased sediment trapping in the lake could have increased deposition rates.

Marine limit was established at c. 115 m asl on north-central Cornwall Island by at least 8.5 ka BP, possibly as early as 9.4 ka BP, inundating most of the Nicolay Lake catchment and forming two major marine embayments in the upper catchment (Figure 2.2). The embayment in the east fork was filled with a thick sequence of marine and deltaic sediments that prograded several kilometres to the north from the watershed boundary. During the early Holocene only a small fraction of the catchment remained above marine limit, limiting the area from which runoff and sediment could be derived (Figure 2.2). Therefore, it is possible that an active glaciofluvial environment developed during the last phase of deglaciation, resulting in the accumulation of a large amount of sediment near marine limit. However, field evidence for the retreat of ice on Cornwall Island and deposition of glaciofluvial sediments is generally sparse (Hodgson, 1982; Lamoureux *et al.*, in prep).

Postglacial emergence caused the abandonment of the upper embayment. The high elevation sediments were incised and eroded, resulting in a substantial transfer of sediment c. 2 km downstream to the next basin where new deltaic and marine sediments were deposited. This pattern of sediment storage and release continued through several iterations as relative sea level lowered to 9 m asl by late Holocene (Hodgson, 1991). Throughout this period (9.4 to 3.5 ka BP), Nicolay Lake was subject to limited distal sedimentation that produced the massive marine unit in the lake. Using the available radiocarbon dates to constrain accumulation during this period, the mean sedimentation rate for most of the Holocene was 0.5 $mm \cdot a^{-1}$, compared with the subsequent mean varve thickness of 2.9 mm. Therefore, the high sea level during the Holocene effectively prevented much of the sediment in the upper catchment from reaching the lake until recently.

The Holocene variation in sediment availability on Cornwall Island is similar to that observed in other catchments where external and internal controls have substantially altered sediment yield during long periods (Church and Slaymaker, 1989; Knox, 1989; Schumm, 1993). In this regard, the sequence of sediment yield from the Nicolay Lake catchment represents a variation of Church and Ryder's (1972) paraglacial sedimentation regime which is characterized by maximum yield following deglaciation. For Nicolay Lake, postglacial emergence of the coastline resulted in the progressive movement of sediment through downstream basins. Propagation of this sediment wave by base level-controlled degradation and aggradation has taken approximately 8000 years to reach Nicolay Lake. Delays of a similar magnitude have been observed in the major valleys of British Columbia in response to Late Wisconsinan deglacial sedimentation (Church and Slaymaker, 1989; Jordan and Slaymaker, 1991). In these cases, thick deglacial valley fills have become important sources of sediment, leading to a prolonged paraglacial relaxation (Church and Slaymaker, 1989). The Nicolay Lake catchment differs from these examples because the Holocene marine regression limited the fluvial and littoral environments to the upper and middle catchment. Therefore, rather than progressively exhausting the catchment of the paraglacial sediment, repeated storage and release cycles in upstream basins have spatially and temporally altered the paraglacial effect.

The progression of this paraglacial sediment wave has also contributed directly to the increase in accumulation rates in Nicolay Lake since c. 1 ka BP. Incision by the modern channel into the thick marine, deltaic and fluvial deposits is likely the dominant source of sediment available for transport. Qualitative evidence for the scavenging of channel bank sediments is apparent throughout the catchment and likely dominates the yield signal compared with slope wash and gelifluction (c.f. Doran, 1993). This situation is substantially different from other High Arctic lake catchments where sediment sources are not as clearly defined (Doran, 1993; Bradley *et al.*, 1996; Gajewski *et al.*, 1997). Therefore, the potential exists for paraglacial sediment availability effects like those found on Cornwall Island to be imprinted on other long sediment yield records, limiting their usefulness as proxy hydroclimatic records (Lamoureux and Bradley, 1996; Leonard, 1997). Application of low frequency bandpass filters to these records would serve to further increase the possibility of falsely interpreting a signal generated by varying sediment availability as a record of hydroclimatic change.

Finally, isolation of Nicolay Lake during the past 1000 years likely enhanced accumulation rates by increasing sediment trapping efficiency. Whether this was the critical factor in the formation of varves is unknown. Given the imprecise timing of the isolation and the change in sediment availability discussed above, the role of isolation can only be speculated upon. However, samples collected during high discharge in 1996 showed that the outflow contained only fine clay, so at the very least, Nicolay Lake is currently an effective trap for coarse sediments (silt and sand).

2.5.3 The paleoenvironmental record from subannual rhythmites

A large number of varve records from a range of environments have been used to measure interannual variations in sediment accumulation to reconstruct hydroclimatic conditions (e.g. Soutar and Crill, 1977; Leonard, 1985; Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Lamoureux and Bradley, 1996; Gajewski *et al.*, 1997; Leonard, 1997; Smith, 1997). The 500-year hydroclimatic record from Nicolay Lake is discussed elsewhere (Chapter 4), however, several features revealed by the detailed sedimentology could potentially provide new proxy environmental records and are discussed below.

The subannual rhythmites commonly found in the varves are potentially the most useful record in Nicolay Lake. Each of these units represents a distinct event of increased sediment inflow that could have lasted from hours to weeks (Gilbert, 1975; Østrem, 1975; Peach and Perrie, 1975; Smith, 1978; Lambert and Hsü, 1979; Gilbert and Shaw, 1981; Pickrill and Irwin, 1983; Smith and Ashley, 1985; Desloges and Gilbert, 1994; Retelle and Child, 1996). As in other varve records in which subannual units are discernible, the subannual record likely varies from proximal to distal sites (Smith, 1978). In proximal core NL1, many varves contain 15-40 subannual units that may represent diurnal variations in sediment delivery (Figure 2.11). Hydrological monitoring in the High Arctic has repeatedly shown that snow melt and river discharge respond to the diurnal cycle of solar insolation, which would thus be expected to generate variability in the delivery of sediment on a similar time scale (Woo, 1983; Lewkowicz and Wolfe, 1994; Hardy, 1996). The varve shown in Figure 2.11 reveals a sequence of subannual rhythmites consistent with the expected transport competence of a typical nival hydrograph (e.g. Woo, 1983). The rhythmites are initially thin with relatively fine basal units, indicative of the rising limb of the hydrograph. The rhythmites progressively thicken and become coarser, and then the pattern is reversed. Clearly, the interpretation of the rhythmites as diurnal features is speculative, and must be tested using field monitoring studies. However, given the known characteristics of the nival hydrograph and the likelihood of a rapid response to short term changes in sediment delivery in proximal sediments (Smith, 1978), the potential exists to identify diurnal rhythmites in a depositional environment like Nicolay Lake. Unfortunately, shifts in delta distributaries recorded in the accumulation record and complications arising from frequent turbidite deposition in the proximal core NL1 currently prevent a full evaluation of this ultra-high resolution record (Chapter 3). Nonetheless, the potential for similar records exists in varved lakes with high accumulation rates (i.e. proglacial lakes, Smith, 1978).

The subannual rhythmites in more distal sites are less frequent and likely represent the largest sediment delivery events associated with longer time scales (Smith, 1978). At these sites, the potential exists to identify events that substantially increased sediment delivery, primarily due to synoptic events (rainfall, snow melt) or large mass wasting events. Several researchers have identified sediment deposits likely related to large rainfall events (Gilbert, 1975; Østrem, 1975; Østrem and Olsen, 1987; Desloges and Gilbert, 1994; Leemann and Niessen, 1994) and glacier melt (Smith, 1997). In Nicolay Lake, prominent subannual rhythmites appear to record major rainfall events (>13 mm total), and exceptional sediment yields were likely generated by infrequent, intense summer rainfall (Chapter 4.). The potential for identification of subseasonal events in sedimentary records is clearly complicated by several factors, particularly subaqueous slumps, as well as differentiating the characteristics of deposits associated with different weather events (e.g. rainfall vs. snow melt). However, by selecting lakes that are more sensitive to specific catchment and limnological controls, and by systematically removing anomalous sedimentary signals produced by within-lake processes (Chapter 3), it is possible that varved sediments can provide substantially more information about the natural variability of hydroclimatic and geomorphic processes than is currently available.

2.5.4 Proxy ice cover information from the deposition of isolated eolian grains

The final sedimentological feature found in the Nicolay Lake varves that may constitute a useful environmental proxy is the isolated coarse grains and layers that occur within the clay units (Figure 2.8). Similar features have been documented in several other arctic lakes. For example, using thin sections, Retelle (1986) noted isolated sand grains and attributed them to eolian deposition. Doran (1993) also noted coarse sand and gravel deposits, and suggested that sediments washed onto the ice surface during the spring were subsequently randomly deposited from the drifting ice pan by surface drainage either at the ice edge or through strudel, small diameter holes that develop in the ice. Squyres *et al.*(1991) have documented the slow passage of clasts by melt through the permanent ice of the Antarctic Dry Valley lakes, leading to sporadic deposits of coarse sediment well beyond the shore. Similarly, the deposition of coarse sediment beyond the influence of fluvial transport has been attributed to the freeze-on of littoral sediments at the edge and base of an ice pan driven onshore by the wind. Subsequent drifting and melting of the pan could then deposit coarse sediments far from shore (O'Reilly, 1995; Smith, submitted).

The characteristics of the isolated grains in Nicolay Lake rule out several of these possible explanations and suggest an eolian source. The grains are too fine to have originated from the gravel beaches and it is unlikely that sand grains would be transported long distances by surface flow on the ice. In contrast, eolian deposits composed of organic matter, fines, sand, and even gravel have been noted from High Arctic locations (Teeri and Barrett, 1975; Lewkowicz and Young, 1991; Edlund and Woo, 1994). The primary source for eolian sediment on Nicolay Lake would be Mount Nicolay, located in the predominant upwind direction (Figure 2.2) (Hodgson, 1982). The mountain contains extensive outcrops of the weathered Heiberg Formation sandstone (Balkwill, 1983). In the late winter of both 1995 and 1996, the mountain was largely bare of snow and the snow on the lake ice showed visible concentrations of sediment in plumes aligned to prevailing northwest winds. Given the near-complete snow cover on most lowland slopes, it is reasonable to assume that the sediment on the lake originated from an exposed local source. Furthermore, the eolian sediments found in core NL14 and the other western cores are coarser than those found in the eastern cores. If long distance transport contributed significantly to the eolian deposits, it is unlikely that the eolian grains would show fining over the width of the lake (2 km), and therefore, it is likely that Mount Nicolay represents the main source for these sediments.

Once on the lake ice, the grains would be washed off into the water column by surface melt or by decay of the ice pan through melt and edge attrition (Heron and Woo, 1994). The wide distribution of the isolated grains in Nicolay Lake suggests a more widely available means than strudel for transferring sediment into the water. Alternatively, the grains could be deposited directly onto open water during summer storms. Either explanation suggests that the deposition of the grains would occur later in the melt season when ice cover would be reduced. In all cases, the grains appear in the upper, clay-rich part of the annual structure, which is consistent with late season deposition (Figure 2.8). Furthermore, the relatively late timing for deposition of the eolian grains suggests that grain deposition by melt-transport through persistent ice cover (Squyres *et al.*, 1991) is unlikely. If sediment was melting out of the base of the ice (Heron and Woo, 1994), there should be evidence for deposition of the sediments throughout the melt season.

Observations suggest that Nicolay Lake maintained substantial ice cover throughout the period 1995-7 (c.f. Doran *et al.*, 1996). For example, a plastic pipe dropped on the ice ~100 m from the pan edge in August, 1996, remained on the ice surface in the following year. This indicates that the ice pan did not substantially decrease in size prior to freeze-up. Moreover, observations in each spring indicated that the mean ice thickness was nearly constant (mean 2.4 m, s.d. 0.2 m for 18 holes). Given the persistence of the ice cover, the presence or absence of eolian grains could be used to estimate the extent of ice cover for a given year. Even though sand grains are found in multiple cores, the presence of these grains in the centre of the lake does not necessarily indicate the absence of ice. Drifting by a reduced ice cover could move the edge of the pan to sites throughout the lake. Despite these complexities, the importance of lake ice as an indicator of summer warmth (Palecki and Barry, 1986; Heron and Woo, 1994; Doran *et al.*, 1996) and as a limiting factor in biological activity (Smol, 1983) suggests that these deposits could provide useful paleoenvironmental information.

2.6 Conclusion

Detailed thin section observations and radioisotope chronologies strongly support the hypothesis that the sediments from Nicolay Lake are varved. The 1-80 mm thick laminae and thin beds are thick compared to those reported from other High Arctic lakes, and they also contain subannual rhythmites and distinct ice-rafted eolian deposits. Varves are produced in the monomictic lake by the combination of a strongly seasonal hydrological regime, high sediment influx, large relative depth of the lake, and pervasive lake ice cover. The Holocene development of the catchment has likely contributed to the current high sediment yield through the progressive glacioisostatic emergence of the island and downstream migration of a paraglacial sediment wave as the coastline regressed. Radiocarbon dates for the establishment of marine limit and the age of the first varves suggest an 8000 year delay between the onset of glacioisostatically induced base-level lowering and the arrival of the sediment wave in Nicolay Lake (c. 500 BP). This control over sediment availability has important implications for the interpretation of low frequency sediment yield records from catchments affected by glaciation, base level adjustments, or other major perturbations, and reinforces similar concerns raised by other researchers.

The clastic sedimentary record from Nicolay Lake appears to contain several possible paleoenvironmental records. Interannual sediment yield variations are likely indicative of variations in weather and discharge conditions, although the record may be influenced by several meteorological controls. Subannual rhythmites are of particular interest because they potentially record deposition on timescales of days to weeks. Proximal sediments contain structures suggestive of daily deposition, but field calibration is required to substantiate this possibility. Distal sites contain less frequent subannual rhythmites that likely represent major rainfall or snow melt events. Similarly, the variable presence of ice-rafted eolian grains in the varves is a potential record of both eolian activity and lake ice extent.

These results indicate that several paleoenvironmental indicators can be obtained from varved sediments, particularly from arctic and proglacial lakes with high accumulation rates. However, only through detailed sedimentological observations is it possible to systematically identify these proxies. Although similar varve records may provide important long term records of terrestrial environmental change, this potential remains unrealized in many published records.

Table 2.1. Morphometry of Nicolay Lake and catchment.

Nicolay Lake	
Elevation (m)	2.5
Surface area (km^2)	2.1
Length (km)	2.5
Width (km)	1.6
Maximum depth (m)	31
Relative depth (m)	6.0
Ratio of lake to basin area	0.023
Drainage basin	
Total area (km^2)	91.2
Maximum elevation (m)	240
Holocene marine limit (m)	115

Table 2.2. Chemical composition of Cornwall Island surface and lake waters from June, 1995 ($\mu eq \cdot l^{-1}$). Solute levels in Nicolay Lake (at 10, 20 and 28 m depth) are intermediate between those found in early season ponded snowmelt and free-flowing river conditions. All runoff is enriched in solutes compared with snowpack, suggesting some degree of chemical weathering. In contrast, Cornice Lake, in the upper catchment (Figure 2.2), contains solute levels similar to those measured in the snowpack (at 10 m depth). This headwater lake drains a terrain exclusively composed of diabase with minimal surficial sediment cover. The charge imbalance for the snowpack data is likely because alkalinity (HCO_3^-) was not measured.

	n	Li^+	Na^+	K^+	Mg^{2+}	Ca^{2+}	Cl^-	NO_3^-	SO_4^{2-}	HCO_3^-	ΣCation	ΣAnions
Snowpack	4	0.0	32.9	1.8	20.7	77.2	72.9	3.0	7.6	n.m.	132.7	83.6
Meadow melt	4	0.3	198.1	25.2	231.7	310.6	342.8	1.3	131.4	266.3	765.8	741.8
Ponded river	2	0.4	240.8	34.6	336.1	433.1	329.3	17.8	370.5	335.0	1045.1	1052.6
Free river	7	0.0	151.3	17.0	165.8	294.3	232.1	2.4	176.8	207.9	628.4	619.2
Nicolay Lake	3	0.0	216.5	16.0	191.0	382.4	328.9	7.2	331.5	120.0	805.9	787.5
Cornice Lake	1	0.0	32.1	3.5	37.5	103.4	47.3	0.9	133.0	70.0	176.6	251.2

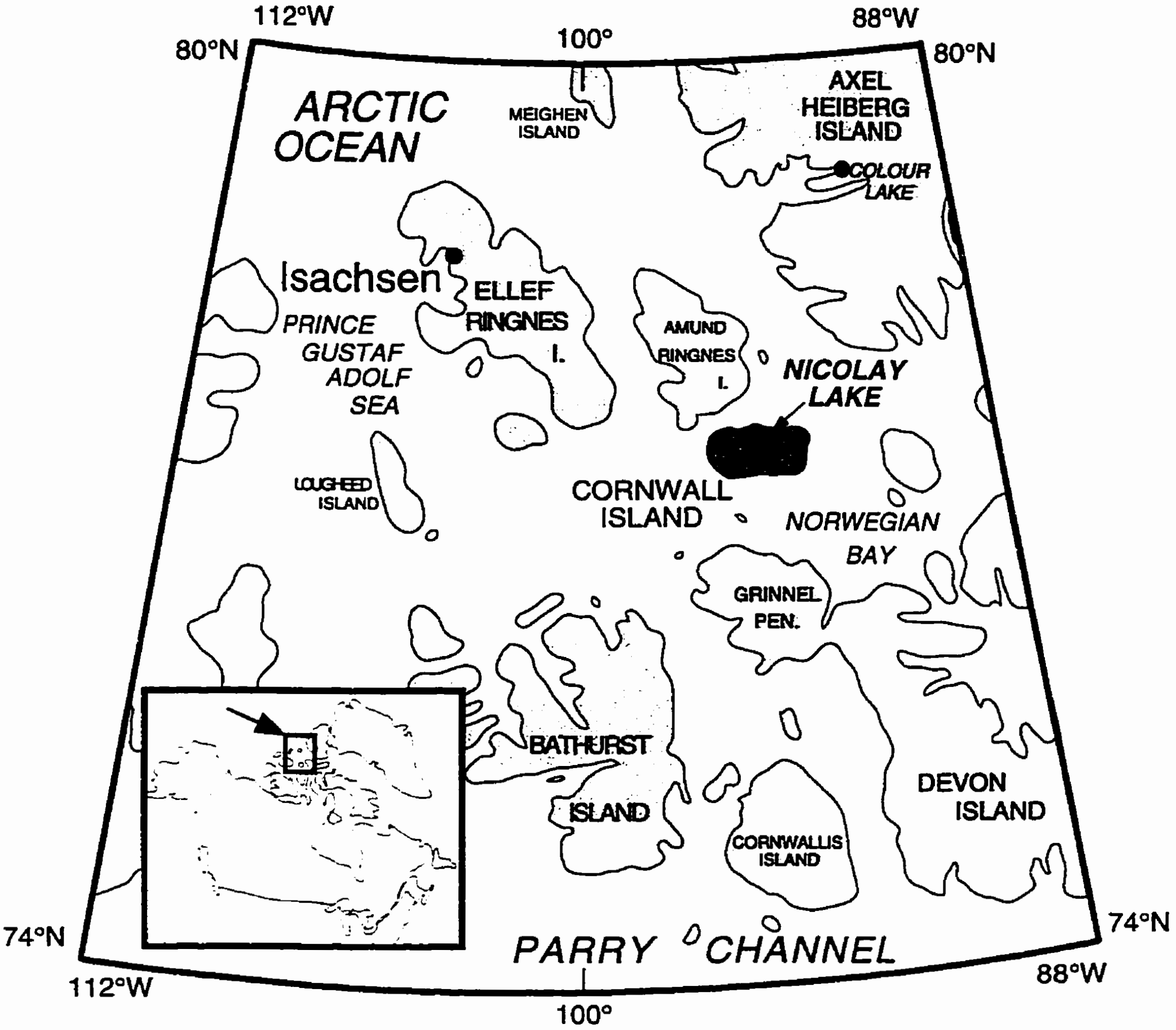

Figure 2.1. Map of the central Canadian High Arctic indicating the location of Cornwall Island.

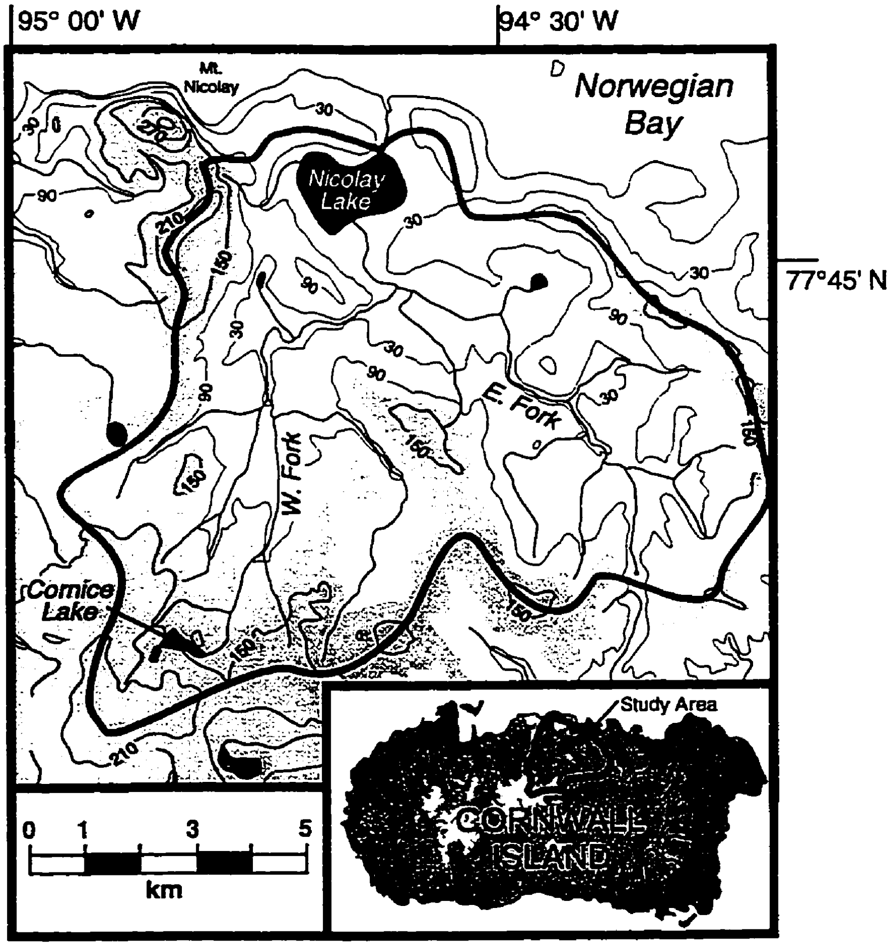

Figure 2.2. Map of the Nicolay Lake catchment. Contour interval is 90 metres. Areas above estimated Holocene marine limit (115 m asl) are shaded). Inset map shows the location of the catchment on Cornwall Island.

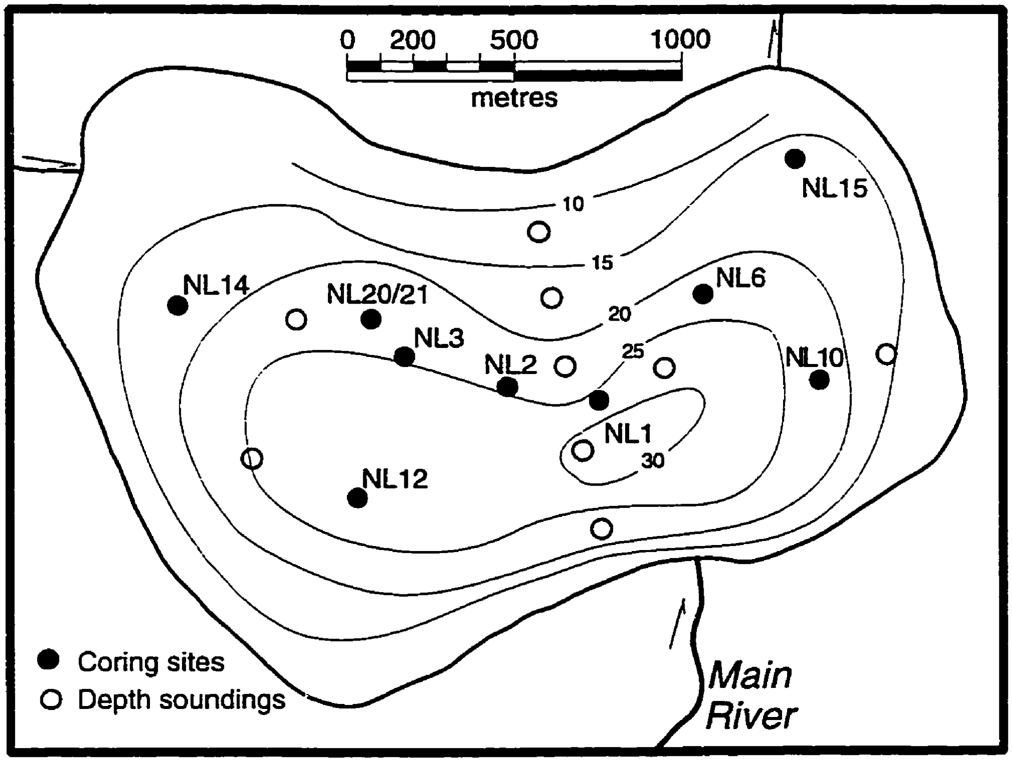

Figure 2.3. Coring sites in Nicolay Lake. Bathymetric contour interval is 5 m, and is based on the soundings and coring sites on the map. Cores NL20 and NL21 were retrieved using the virbracoring system (Smith, 1992) whereas the remaining cores were percussion cores (Reasoner, 1993).

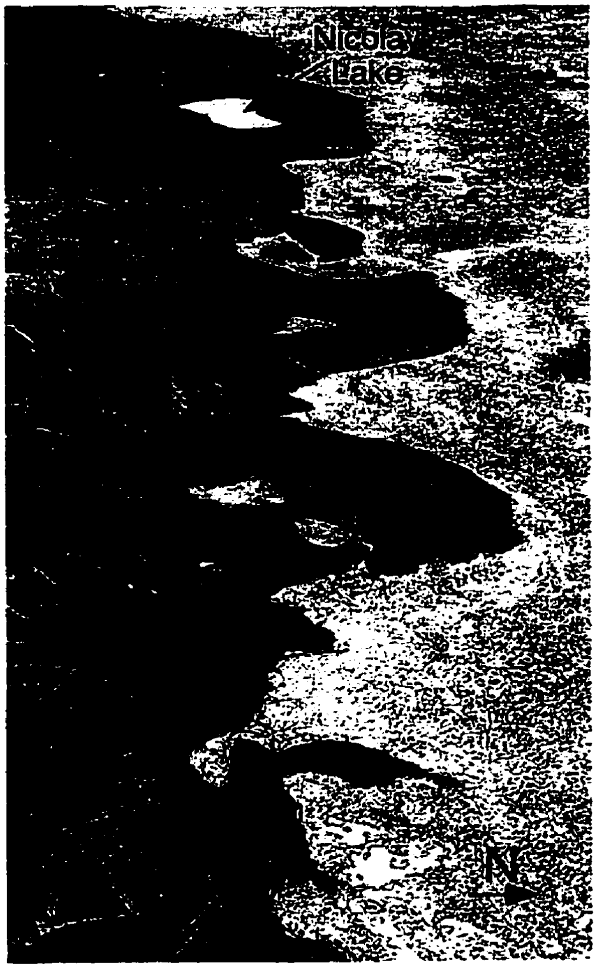

Figure 2.4. Oblique aerial photograph looking west along the north coast of Cornwall Island. Nicolay Lake (background) is one of several lakes separated from the coast by low ridges or by the progradation of deltas. Most of the foreground deltas drain catchments <25 km^2, indicating the high levels of sediment transport on the island. Photograph T440R-124, copyright Her Majesty the Queen in Right of Canada.

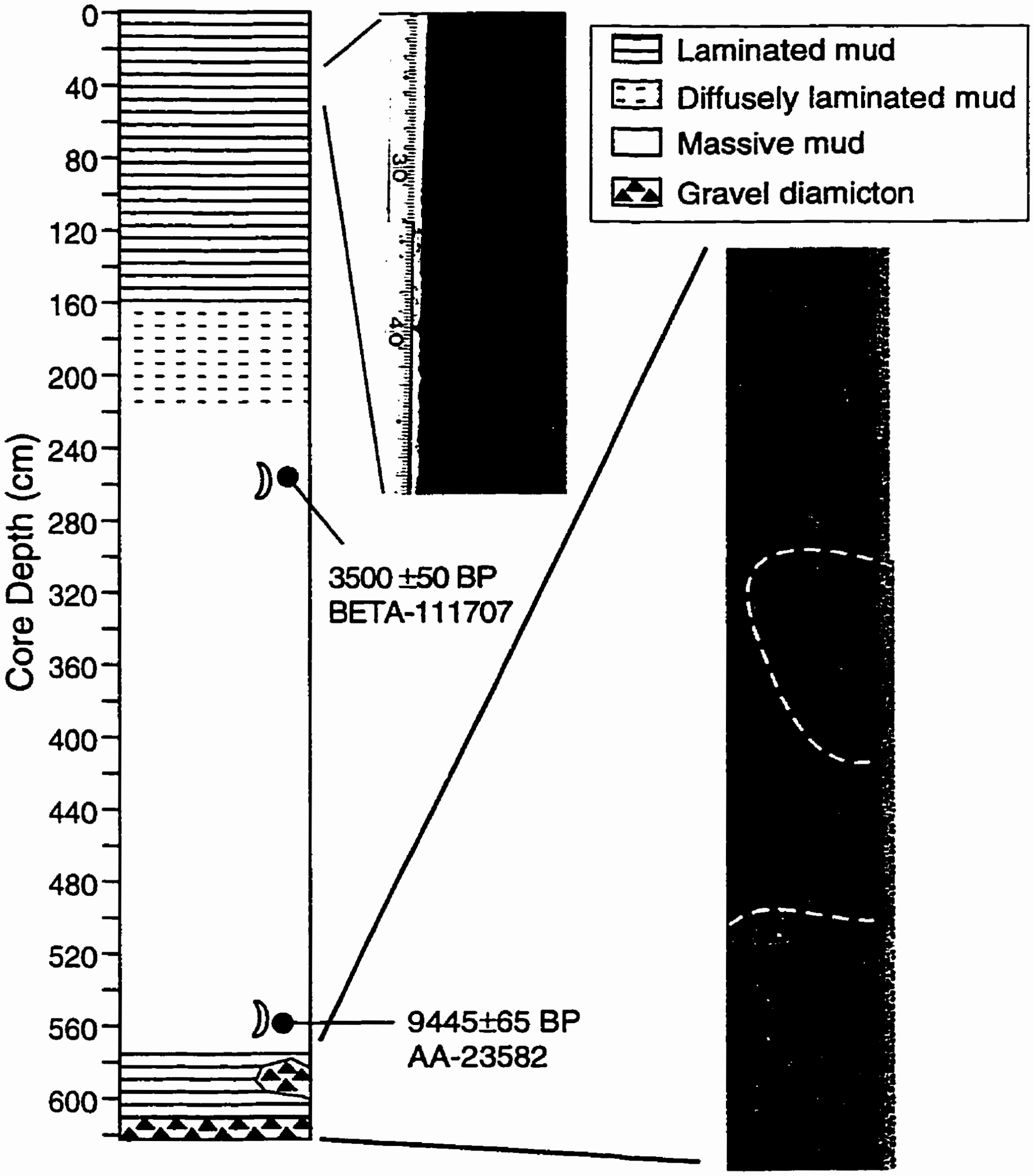

Figure 2.5. Composite stratigraphy from cores NL20 and NL21. The plotted radiocarbon dates suggest that the composite represents deposition through most of the Holocene.

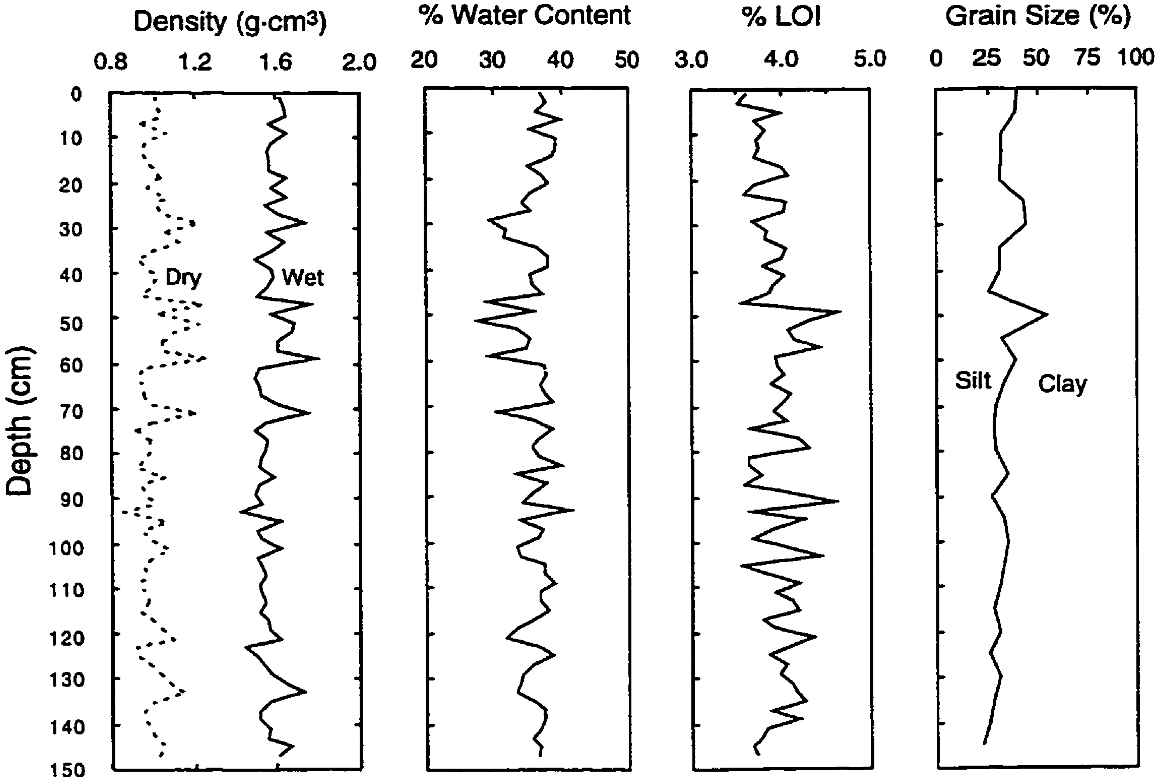

Figure 2.6. Down-core variations in density, water content, loss-on-ignition, and grain size from laminated core NL3. These parameters were typical of the laminated sediments in all of the distal cores from Nicolay Lake.

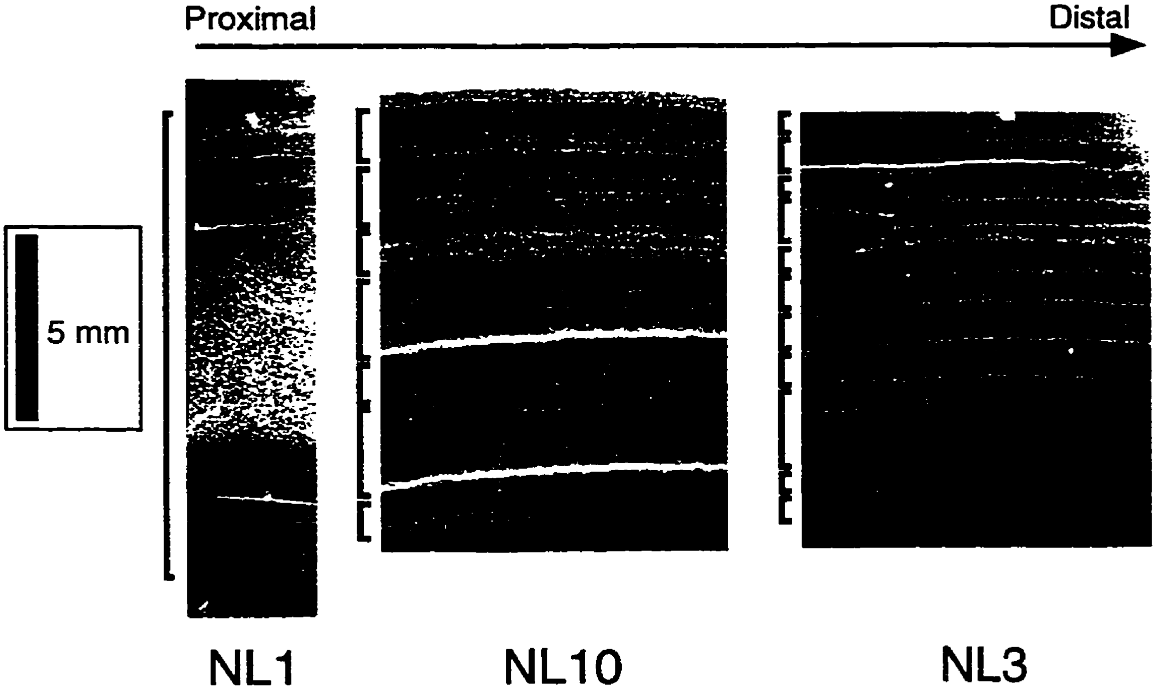

Figure 2.7. Photographs of laminae at proximal (NL1), intermediate (NL10), and distal (NL3) sites in Nicolay Lake. The extent of units interpreted as annual deposits (varves) are indicated for each core.

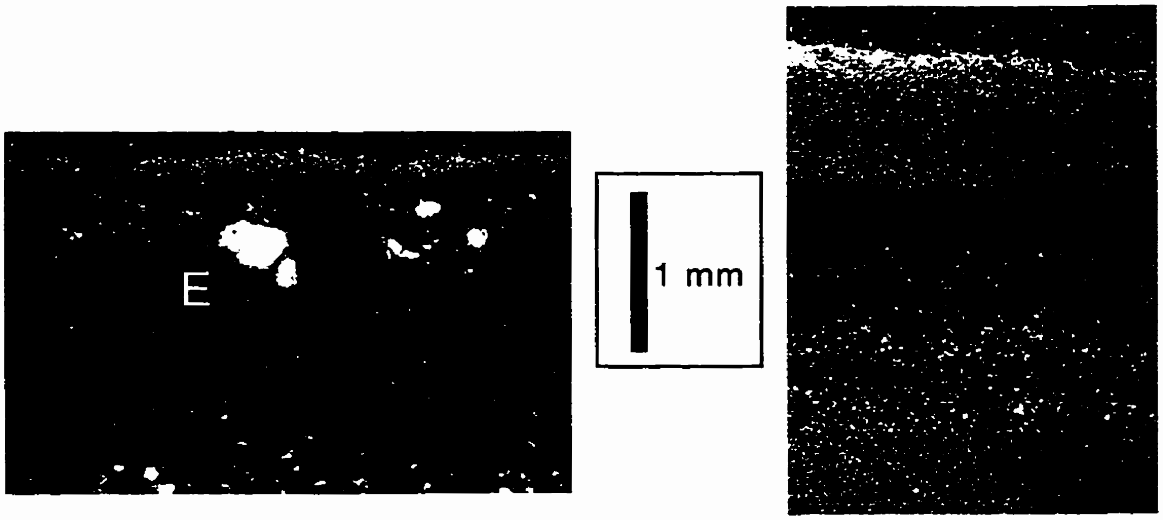

Figure 2.8. Microphotographs of individual laminae from core NL3. Both laminae contain a medium silt base that grades normally into a fine clay cap. Isolated sand and silt grains (white) are present in the upper clays of the left lamina, but appear absent from the other.

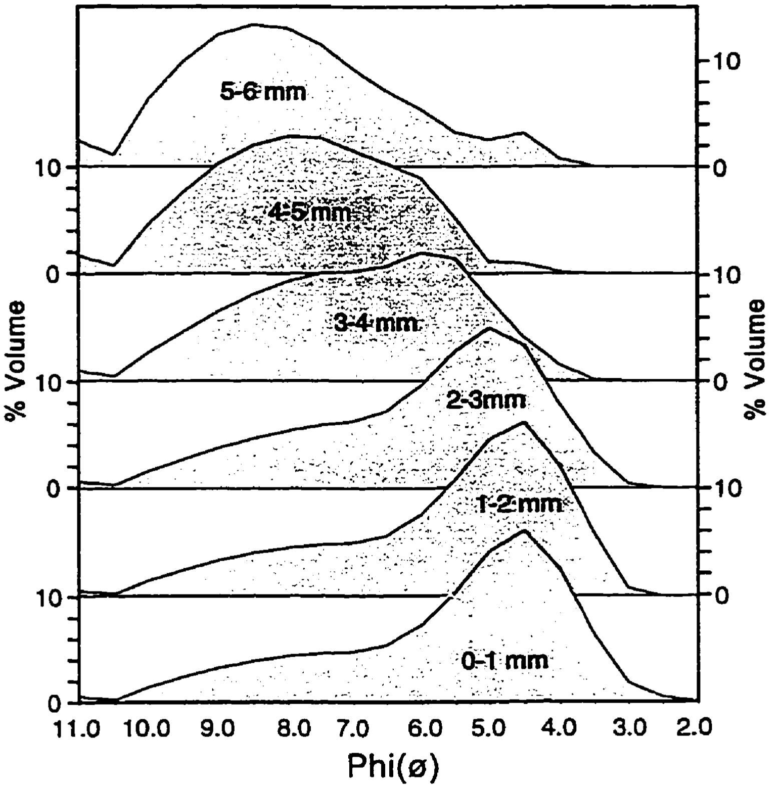

Figure 2.9. Grain-size distributions from a single lamina in core NL3. Indicated depths are from the base of the unit. The slight increase in % volume found at 11ϕ in each sample is an artifact of summing the finer grain-size classes.

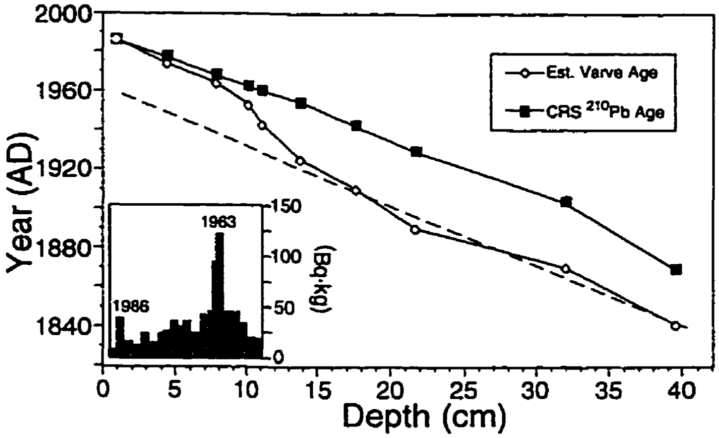

Figure 2.10. Isotope geochronology of the upper sediments in core NL2. Results from continuous ^{137}Cs determinations (inset) show a distinct 1963 bomb-test peak and a smaller 1986 Chernobyl peak. Modelled ^{210}Pb ages (CRS-constant rate of supply) show no evidence for long term divergence from estimated varve ages. The short term departure of the varve-lead ages at 8-14 cm depth is likely the product of ^{210}Pb concentration during a period of low accumulation rates. Following this interval, the lead ages show near-constant slope with varve ages (dashed line).

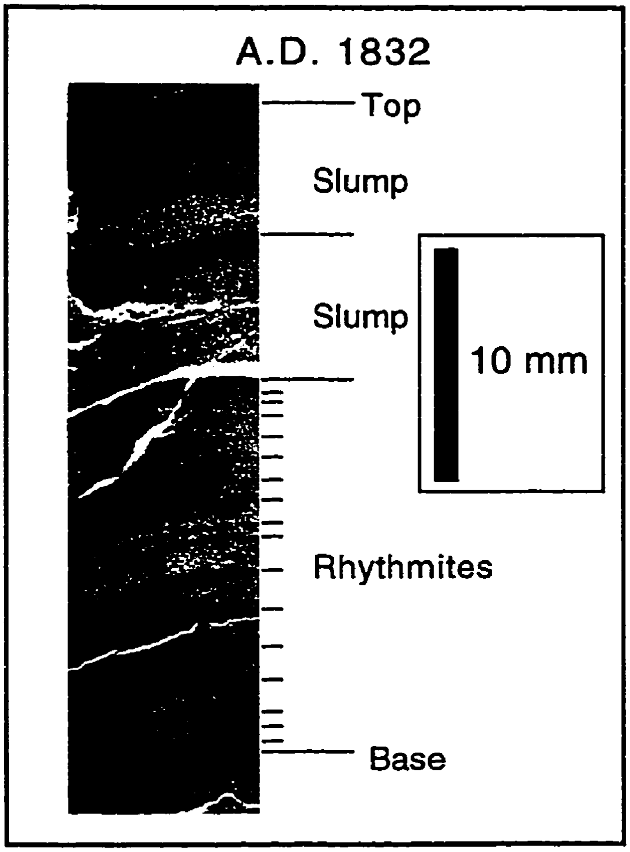

Figure 2.11. A varve from core NL1 containing subannual rhythmites suggestive of diurnal variations in sediment supply generated by diurnal range in solar receipts (e.g. Woo, 1983). The rhythmites initially coarsen and thicken upwards, followed by the reverse. The varve is capped by two sand-organic rich slump deposits common at this proximal site (Chapter 3).

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CHAPTER 3 SPATIAL AND INTERANNUAL VARIATIONS IN SEDIMENTATION PATTERNS RECORDED IN NONGLACIAL VARVED SEDIMENTS FROM THE CANADIAN HIGH ARCTIC[2]

3.1 Introduction

Varved sediment records have become accepted as important indicators of the natural variability of hydroclimatic processes in a wide range of environments. The measurement of annual sediment accumulation is the proxy record most frequently used to infer hydroclimatic information from varved clastic sequences because of a relatively simple relationship between weather conditions, river discharge, and sediment transport (e.g. Gilbert, 1975; Desloges and Gilbert, 1994; Leemann and Niessen, 1994; Hardy *et al.*, 1996; Lamoureux and Bradley, 1996; Leonard, 1997). Although this approach has been applied with apparent success, few researchers have attempted to measure the potential influence of local sedimentation controls on varve records, both systematic or stochastic, that constitute noise superimposed on the hydroclimatic signal. Because anomalous sediment deposition can directly alter accumulation-based hydroclimatic reconstructions, it is critical to identify and remove these sources of noise where possible.

Changes to lake-wide depositional patterns are commonly observed during field monitoring studies (Smith *et al.*, 1982; Retelle and Child, 1996) and in low resolution core studies (Dearing, 1983; Anderson, 1990; Foster *et al.*, 1990), but the consequence of these changes for the interpretation of core records has been largely ignored. Gilbert (1975) attributed differential varve accumulation in Lillooet Lake, British Columbia to the relative contribution from interflows and underflows. Although this study showed the spatial complexity of accumulation caused by primary deposition processes, it did not assess how patterns varied with time. Petterson *et al.* (1993) observed minimal differences between varve records from three cores separated by 20 m in Lake Kassjön, Sweden. However, their study, like other multi-core records (e.g. Lamoureux and

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[2] A version of this chapter has been accepted for publication in the Journal of Paleolimnology

Bradley, 1996), investigated localized inter-core reproducibility rather than lake-wide sedimentation patterns, thus precluding an assessment of how representative a single core is of overall, lake-wide sediment input. Furthermore, primary deposition patterns can be substantially altered as a result of reworking by wave action and subaqueous mass movements (Håkanson and Jansson, 1983). For example, sediment focussing in varved Fayetteville Green Lake, New York, was shown to cause irregular interannual variations in the ratio of accumulation in shallow to deep areas of the lake, suggesting that focusing is a stochastic process (Ludlam, 1984). Given these problems, considerable attention has been directed towards determining the influence of depositional heterogeneity on biostratigraphic and geochemical proxy reconstructions (e.g. Engstrom and Swain, 1986; Beaudoin and Reasoner, 1992; Anderson *et al.*, 1994). Despite these efforts, there is often no clear means of distinguishing between the record of hydroclimatic sediment input and noise contained in core records. Further, sporadic depositional anomalies that are masked by low resolution sampling may dominate higher resolution records where one or more individual anomalous measurements can lead to a misinterpretation of past conditions. Therefore, it is incumbent upon the researcher to determine whether the deposition processes in a lake are properly understood and stationary for the resolution of interest.

This study uses multiple varved cores to examine the spatial and interannual variability of sediment accumulation in a small basin to determine the consistency of deposition patterns and the effect anomalies would have on reconstructing and interpreting annual accumulation as a hydroclimatic proxy. Eight cores covering the past 197 years from Nicolay Lake, Cornwall Island, in the Canadian High Arctic, are used to document interannual accumulation patterns throughout the lake, recognize high and low frequency anomalies, and identify those coring sites which most accurately record catchment sediment input. The results of this work have important implications for varve-based hydroclimatic research and suggest a methodological framework for the identification and reduction of noise in sedimentological records.

3.2 Study Area

Nicolay Lake is located on the north-central coast of Cornwall Island at 2.5 m above sea level (asl) (Figure 3.1). This small (2.1 km^2), deep (31 m) freshwater lake develops weak thermal stratification during summer and a residual ice pan remains during all but the warmest summers, preventing wind mixing in the centre of the lake. Drainage into the lake is presently dominated by a single channel crossing a 1 km wide delta, fed by two confluent basins that drain a 81 km^2 unglaciated watershed. A small stream, draining a 10 km^2 catchment, enters the lake from the west but contributes little sediment. The main river occupies a wide valley bottom that contains fine-grained sandar separated by short ravines and sparsely vegetated ridges that rise to 150 m asl. Abundant unconsolidated sediment from Holocene raised marine deposits and poorly consolidated Mesozoic sedimentary rocks constitutes the primary source of fluvial sediment (Hodgson, 1982). The high sediment availability combined with a large catchment results in a strikingly higher sedimentation rate in Nicolay Lake compared with other nonglacial lakes reported in the High Arctic (Doran, 1993; Bradley *et al.*, 1996).

The severe High Arctic climate limits fluvial activity to the brief summer when mean daily temperatures average 2-4°C, compared with mean daily winter temperatures of -36°C. River flow is strongly nival and peaks during snowmelt in June and July. Initial snowmelt is temporarily ponded by snow drifts, limiting sediment transfer to the lake (e.g. Woo and Sauriol, 1981). Thereafter, the period of significant snowmelt commonly lasts only a few weeks, during which the majority of sediment is transported to the lake. During the remainder of the melt season, the river assumes a low stage with minimal sediment flux. Rainfall is comparatively low (32 mm mean annual rainfall at Isachsen, Figure 3.1), and frequently occurs as trace events associated with summer fog and low stratus. Intense summer rainfall can rapidly raise river stage and sediment transport capability, but is short lived and infrequent.

3.3 Methods

Using the ice pan as a coring platform, eight sediment cores were retrieved in the springs of 1995 and 1996 using both piston-percussion (Reasoner, 1993) and vibra-coring (Smith, 1992) techniques (Figure 3.1). Cores from 1995 were capped and transported unfrozen whereas the 1996 cores were left to freeze while standing vertically, then cut to length, and shipped frozen. All cores were subsampled for thin sections, and measurement of bulk density, loss-on-ignition (LOI), and particle size. Unfrozen sediment slabs, used for thin sections, were dehydrated with acetone and embedded with a single application of epoxy resin under vacuum (Lamoureux, 1994). Thin sections of frozen samples were obtained by cutting the core into lengthwise strips ~1cm thick with a rock saw. Parallel strips were then cut to length to provide overlapping coverage of the entire core and freeze-dried before being embedded with epoxy resin.

Sediment structures were described and measured in detail using a low-power (12.5X) microscope. Laminae count and thickness measurement methods were similar to those described by Lamoureux and Bradley (1996). Ice crystal casts from the frozen cores required viewing under polarized light to obtain measurements. The resulting series from each core were cross-correlated using sedimentary structures and prominent laminae to eliminate counting errors and establish a lake-wide chronology. In practice, counting inconsistencies observed between cores were minimal because of the thick couplets (<0.5%, c.f. Lamoureux and Bradley, 1996; Zolitschka, 1996).

3.4 Results

3.4.1 Sedimentology

The basal sediments from two 6.3m-long cores, obtained with the vibracorer, were comprised of a stony diamicton recording early Holocene deglaciation (overlying mollusc radiocarbon date: 9445±65 BP, AA-23582). Overlying the diamicton, sandy rhythmites contain frequent dropstones (5.6-6.0m depth), which are conformably overlain by 3.4 m of massive black, sulphidic mud containing mollusc fragments and abundant foraminifera. These muds grade into diffusely laminated sediments, which are overlain by 2 m of well laminated (varved) sediment. It is uncertain what caused the transition from massive to laminated sedimentation, but it is likely that sedimentation rates increased markedly following the filling of upstream sediment catchments and isolation of Nicolay Lake from the sea during glacioisostatic rebound.

Once oxidized, the laminated sediment appears as couplets of alternating light and dark gray laminae and thin beds between 0.5 and 80 mm thick (Figure 3.2). The sediment is composed of clayey silt (mean 8.6ϕ) with low organic content (LOI 4%) and uniform dry density ($1.4 g \cdot cm^{-3}$). In thin section, laminae appear as distinct couplets, composed of a light coloured silt layer that grades normally into a homogenous, red-brown clay layer (colour changes from the original light and dark gray are caused by dehydration and the embedding resin). The contact between clay laminae and overlying silt is sharp and conformable, and occasionally exhibits minor loading structures by the silt. The silt layers frequently contain rhythmic silty-clay sublaminae which are visually coarser than the capping clay laminae (Figure 3.2). Similar structures are observed throughout the laminae in each of the cores, although couplets at distal sites are thinner and show fewer sublaminae than those at proximal sites (Figure 3.3). In proximal cores (NL1 and 2, Figure 3.1), the laminae are coarser and are sporadically interrupted by thick (5-85 mm) units of massive sand and organic debris. The basal contacts of the sand units appear conformable, and suggest deposition by a low energy underflow, or turbidity current (Ashley and Smith, 1985; Zolitschka, 1996).

The presence of silt-clay couplets throughout the lake (Figure 3.3) implies that sediment is thoroughly dispersed as density plumes or by homopycnal flow of sediment-laden fluvial input. The sedimentary structures observed in Nicolay Lake are consistent with the ordering proposed by Smith (1978). Structures vary by location and reflect changes in the time-scale of sedimentation events. The central, proximal locations appear to record short-term, possibly diurnal events (order A, B), whereas distal sites display synoptic events within annual units (order B,C).

3.4.2 Radioisotope Chronology

Given the pronounced seasonality of sediment transport and deposition in Nicolay Lake, it is hypothesized that the silt-clay couplets represent varves. To test this hypothesis, profiles of ^{137}Cs and ^{210}Pb were determined from core NL2 (Figure 3.4). The ^{137}Cs profile shows a conspicuous peak corresponding with maximum bomb fallout in 1963. A less pronounced peak at the core surface likely corresponds to the 1986 accident at Chernobyl. Based on laminae counts, the two peaks appear to be 23 years apart, which is consistent with the proposed annual interpretation. Additionally, mean accumulation rates suggest that the estimated surface age from the ^{137}Cs (1987) is compatible with the loss of approximately 1 cm of sediment from the core during transport.

Results from the ^{210}Pb determinations are more difficult to interpret (Figure 3.4b). Although there is close correspondence between the ^{210}Pb CRS-modelled ages and the estimated varve ages in the upper 8 cm of core, the varve ages increase rapidly between 8-15 cm, resulting in a consistent ca. 35 year difference between the varve and lead ages at depths below 15 cm (Figure 3.4b). If subannual laminae were consistently being counted as varves, varve-lead ages should be expected to diverge with increasing depth. Similarly, erosional unconformities between 8-15 cm depth are unlikely to produce the observed difference between varve and lead ages in NL2 because each lamina can be cross-dated with the cores from different locations in the lake. The varve-lead age difference observed at 8-15 cm is likely an artifact of overall low levels of unsupported ^{210}Pb (maximum 0.033 $Bq \cdot g^{-1}$) and decay reversals associated with intermittent low sedimentation rates during the same interval. Low levels of ^{210}Pb have also been found in ponds at Isachsen (Figure 3.1, M.S.V. Douglas, pers. comm. 1997), suggesting that ^{210}Pb dating may be difficult to apply to clastic lake sediments in the region with highly variable deposition rates (Appleby and Oldfield, 1983). Overall though, the presence of clearly defined sediment couplets, the strong seasonality of sedimentation, and the correspondence of laminae counts to ^{137}Cs and ^{210}Pb determinations strongly support the hypothesis that the upper sediments in Nicolay Lake are varved.

3.4.3 Deposition Patterns

Recognition of individual couplets throughout Nicolay Lake permitted the construction of an accurate varve stratigraphy (Figure 3.3). Several core records were >500 years in length. However, for the purpose of this study, deposition patterns were investigated only where at least seven of the eight core records were available (Table 3.1). Therefore, patterns could be identified for the period 1778-1975 AD. All thickness measurement series are highly correlated, with the exception of that from core NL1 which is located near the base of the delta foreslope. The reduced intra-core correlation shown by NL1, and to a lesser extent by adjacent NL2, suggests that localized deposition by turbid underflows significantly influenced proximal accumulation, where thick sand units are common (Table 3.2, Figure 3.3). Although this appears to be an obvious source for the variance observed at proximal sites, mapping annual accumulation patterns reveals additional influences.

Three sedimentation patterns were observed during the 197 year record common to the cores. The dominant *normal* pattern records deposition from one or more closely-spaced distributaries in the central and eastern delta (Figure 3.5a, b). Sediment is dispersed throughout the lake with distal thinning and slightly higher accumulation in the eastern areas due to Coriolis effect (Ashley and Smith, 1985). Regardless of the *rate* of annual accumulation, this depositional pattern remains robust. Moreover, modest distal thinning is a key feature that differentiates the normal pattern of sediment input from the other patterns. To compare the degree of distal thinning with other deposition patterns, a simple index of proximal-distal deposition rates (PDI) was defined as the ratio of annual accumulation from cores NL1 (proximal) and NL14 (distal) respectively (Figure 3.1). For the normal pattern, the PDI values range from approximately 3 to 8 (Figure 3.5a, b). Although greater PDI values can occur during years with higher accumulation, the PDI still indicates a consistent distal thinning of accumulation (Smith *et al.,* 1982; Ashley and Smith, 1985; Zolitschka, 1996).

In contrast, a *bifurcating* pattern of sediment deposition commonly occurs during parts of the past century. This pattern is produced by the formation of a second major delta distributary and results in two distinct sediment trajectories emanating from opposite margins of the delta (Figure 3.5c, d). Unlike the normal pattern, bifurcating sedimentation is directed away from the centre of the lake. PDI values associated with this pattern are consistently between 0.5 and 1.1, indicating that the normal geometry of sediment dispersal breaks down and sedimentation at proximal sites NL1 and NL2 effectively becomes distal. The bifurcating pattern has important implications for varve-based, hydroclimatic reconstructions because cores from the deep, central part of Nicolay Lake are subject to yearly to decadal periods of anomalously low sedimentation produced entirely by geomorphic controls (c.f. Petterson *et al.*, 1993). For example, accumulation at proximal sites was substantially altered by the abrupt change to a bifurcating pattern between 1935 and 1957 (Figure 3.6). Sedimentation at site NL1 particularly decreased during this period while distal sites had no trend (Figure 3.6). This anomalous pattern reverted abruptly back to normal conditions in 1958. Interpretations of the Nicolay Lake accumulation record for the past century, the critical period of anthropogenic influence on the global environment, would be seriously biased if based solely on cores from the central, deepest zone of the lake.

The third sedimentation pattern observed in Nicolay Lake is sporadic and *localized*. This pattern shows anomalously high accumulation at the proximal site NL1, and to a lesser extent, at adjacent site NL2 (Figure 3.5e, f). Localized sedimentation results in a distortion of the normal distribution pattern, with PDI values ranging from approximately 10 to 91. It is associated with conformable deposition of thick sand units, likely by low energy, turbid underflows originating on the steep delta foreslope. In most years with localized sedimentation, thick proximal accumulations are contrasted by low distal accumulation, suggesting that turbidity flows fail to disperse significant quantities of fines to distal sites (Figure 3.5f). Although localized deposits are relatively thick, they are substantially different from sedimentation patterns in years that exhibit high accumulation with a normal deposition pattern (Figure 3.5b).

3.4.4 Principal Components Analysis

Because the impact of changes to the sedimentation pattern is felt most markedly in proximal locations, the best record of sediment input from the catchment will be found in distal parts of Nicolay Lake. Nonetheless, one cannot assume that distal records will be unaffected by those changes in sedimentation pattern. In order to determine which distal site provides the best sediment input signal, principal component analysis was used to identify the common variance between core records (Davis, 1986) in order to assess the appropriateness of choosing one or more sites as a representative record of lake-wide sedimentation. Since there are missing years from individual core series, analysis is performed for years with data common to all eight cores (Table 3.1).

The analysis reveals that 78% of the variance contained in all cores can be explained by the first component (Table 3.3). The component loading of each core is high (>0.856) for all cores except NL1 (Table 3.4). It is likely that the first component represents the normal deposition pattern described in the previous section. The high loading shown by most sites on the first component suggests that it may provide a useful proxy for lake-wide sedimentation. In contrast, the second component shows a high loading on NL1 and to a lesser degree on NL2 and NL10. Although the significance of the second component is debatable (λ_2=0.712), it may explain the variance attributable to the localized sedimentation pattern, pointing to the strong independent variance exhibited by sites NL1, NL2 and NL10 (Table 3.4). Many consider eigenvalues < 1.0 to be insignificant because an eigenvalue of 1.0 explains the same amount of variance as a single variable, and a smaller eigenvalue is of less value than an original variable (e.g. Davis, 1986). However, if a single site is the main source of variance for the second component, which is likely for the localized sedimentation pattern, then it is unlikely that the eigenvalue will exceed 1.0. For this reason, the second component is considered to record the presence of a localized sedimentation pattern and hence, it is accepted as a meaningful measure of localized record variance. Similar reasoning cannot be used to accept the third component, because several sites contribute to the eigenvalue (Table 3.4). However, it is interesting to note that the loadings for the third component are negative on the three western sites (NL3, 12, 14) and positive at all the others. Coriolis deflection of sedimentation to the eastern part of the lake may be one possible explanation for this loading pattern.

The loadings exhibited by sites NL2 and NL10 on the second component (localized deposition) are important because, unlike site NL1, the associated sediments are not distinctly coarser. Moreover, the negative loading of the second component on NL10 suggests that sediment is directed away from the site during years with localized deposition. Therefore, the principal component analysis distinguishes between fine-grained deposition by turbidity flows and lake-wide, fluvially-derived sedimentation. Without this analysis, differentiating between these sediment sources would be visually difficult to do. Fine grained deposition beyond the main turbidity deposit (as found at NL1) can be viewed as analogous to sediment focusing processes that have been widely described but remain poorly delimited in core stratigraphies (e.g. Davis and Ford, 1982). However, unlike previous lower resolution lake studies, the subtle influence of localized deposition in Nicolay Lake can be recognized with principal component analysis because of the accurate varve chronology and core network. This further reduces comparatively small sources of depositional noise in accumulation reconstructions.

When the dataset is re-analysed without sites NL1 and NL2, a single significant component explains 93% of the dataset variance (Table 3.3). The high loadings shown by all remaining sites indicate that this component provides an excellent proxy for lake-wide sedimentation (Table 3.4). Moreover, the uniformly large loading shown by each site suggests that a high degree of redundancy exists in the dataset and implies that a single distal site can be a suitable surrogate for the component, and hence, for lake-wide deposition. Based on individual site loadings, the most suitable sites are NL15 and NL3. In choosing site NL15 or NL3, only 5% of the overall variance is unexplained by the component, compared with 9% for site NL10 (Table 3.4). Although a new lake-wide depositional series can be constructed with component scores, individual missing years (particularly at the core surfaces, Table 3.2) would cumulatively create unacceptable series gaps.

Despite the selection of a distal core least affected by secondary components, this analysis cannot distinguish minor discrepancies that collectively result in approximately 5% unexplained variance. It is likely that some amount of this unexplained variance is due to minor sediment focussing processes and thickness measurement inconsistencies. Notwithstanding these limitations, the use of multiple sediment cores for identification of deposition patterns represents a substantial improvement over the use of short term field-based monitoring to assess the effect of differential deposition on long term reconstructions.

3.5 Discussion

The spatial and temporal record of sedimentation in Nicolay Lake reveals anomalies that must be removed if a meaningful record of catchment sediment input is to be obtained. Although these anomalies are specific to Nicolay Lake, they may be relevant to lake research elsewhere. Depositional heterogeneity in Nicolay Lake is the product of systematic geomorphic control and is measurable on annual to decadal time scales. This contrasts with previous studies where sediment deposition heterogeneity and focussing are relegated to stochastic processes that are not quantified for short intervals (Davis and Ford, 1982; Dearing, 1983; Ludlam, 1984; Anderson, 1990; Anderson *et al.*, 1994). The recognition that similar anomalies may exist in other lakes is critical for interpreting past sedimentation records. Moreover, biostratigraphic reconstructions dependent on fossil concentrations or accumulation rates would also be altered by conditions similar to those observed in Nicolay Lake.

In the proximal zone of Nicolay Lake, at site NL1, less than 45% of the variance can be explained by lake-wide, catchment-derived sedimentation (Table 3.4). Although much of the remaining variance can be attributed to turbidity deposits, removing this bias from the accumulation record is not straightforward. These results suggest that researchers cannot assume that a high quality paleoenvironmental record can be obtained from the deep, central parts of all lakes. Changing depositional patterns, and/or the redeposition of shallow sediments, could substantially complicate at-site accumulation and hydroclimatic inferences. Where redeposition is a dominant process, accumulation heterogeneity may be marked but low frequency trends still remain intact (Anderson *et al.*, 1994). Therefore, the role of depositional heterogeneity in each lake must be assessed individually for the level of detail required.

Anomalous turbidity deposits, like those found at site NL1, may be difficult to recognise near the deposit margin and could be easily overlooked. In Nicolay Lake, 5-10% of the total variance at sites NL2 and NL10 is explained by such turbidity sources (second component, Table 3.4). This compares with distal sites where deposition from the turbidity sources contributes <2% of the variance. Because these influences are often difficult to distinguish sedimentologically, combining sedimentation pattern and principal component analysis becomes a necessary methodology for identifying bias in sedimentary reconstructions.

In general, lake morphology plays an important role in controlling sediment deposition patterns (Håkanson and Jansson, 1983). Because of the small size of Nicolay Lake relative to the large river delta, distributary and sediment plume trajectory shifts are common and could affect the sedimentary record. However, incision, filling, and migration of delta distributaries due to changing flow conditions does not adequately explain the persistence of the bifurcated pattern. It is possible that distributary activations have only become discernible in the sedimentary record as the delta has prograded and widened, permitting dispersal trajectories to become progressively separated by greater distances. In this manner, widening of the delta may have permitted the development of a recognizable bifurcated pattern in Nicolay Lake only during the past century.

The effects of these depositional processes can likely be minimized, but not avoided, by careful selection of lakes for study. For example, cores retrieved from the distal zones of fiord-like lakes, with large length to width ratios, are less likely to be influenced by distributary shifts (Gilbert, 1975; Smith, 1978; Desloges and Gilbert, 1994; Leonard, 1997). However, long lakes often have more than one tributary, and distal sites can be subject to significant, multi-source sedimentation which may be an important consideration in distal sedimentation regimes (e.g. Leonard, 1985).

Lakes with low length to width ratios are more likely to be prone to these shifts, as shown in Nicolay Lake. Despite this need for caution, researchers are frequently forced to use lakes with less than ideal geometries. For instance, three years of sediment dispersal studies carried out at varved Lake C2, in the Canadian High Arctic -a lake and delta with dimensions similar to that at Nicolay Lake- suggested only minor variation in sediment dispersal (Retelle and Child, 1996). Despite the reassurance from this work, the interpretation of the 3300 year varve record from the lake did not rule out the important role that geomorphic considerations could have played in the low frequency sedimentation variability (Lamoureux and Bradley, 1996). Therefore, the systematic approach applied to Nicolay Lake permits identification and removal of the influence of geomorphic controls on sedimentation, and hence, provides more robust reconstructions. Other lower resolution lake studies utilizing multiple cores (Dearing, 1983; Beaudoin and Reasoner, 1992) reinforce the necessity of evaluating accumulation patterns and redeposition processes for paleoenvironmental reconstruction. This follows similar practices used to evaluate other high resolution proxy records such as ice cores (e.g. Fisher and Koerner, 1994).

Finally, recognition of localized turbidity deposits has an important implication for past fluvial sediment yield from the catchment. The widespread and proportional distribution of sedimentation (during years with 10-20 times the mean sedimentation rate) is distinct from localized sedimentation by turbidity currents (Figure 3.5b,f). This rules out a non-fluvial origin for high sediment deposition and suggests that processes exist within the catchment to generate high sediment yields. Although the processes involved are poorly understood, this study clearly distinguishes these high sedimentation events from turbidites, and suggests that they originated from events which are of hydroclimatic importance (c.f. Lamoureux and Bradley, 1996).

3.6 Conclusions

Analysis of varved sediment accumulation throughout Nicolay Lake has revealed significant annual to decadal scale anomalies that are potentially misleading in high resolution paleoenvironmental reconstructions. Turbidity currents in proximal locations are interpreted as an important source of localized interannual variance. Annual to decadal-scale deviations from the normal sedimentation pattern are also observed in the record during the past century and are attributed to persistent delta distributary shifts. The combination of sediment pattern and principal component analysis permits identification of major sedimentary biases and the selection of coring sites that contain the least bias.

The results from Nicolay Lake should caution researchers against simplistic attempts to derive hydroclimatic records from sediments deposited in dynamic lake environments. Although all geomorphic controls cannot be identified by the methods suggested, it is proposed that the investigation of changing depositional patterns in lakes should become a basic requirement for meaningful hydroclimatic reconstructions. Similarly, field studies intended to guide the interpretation of lake cores can be substantially supplemented by the investigation of temporal variations in sedimentation patterns throughout the lake.

The potential insights into past environmental processes available from lakes justify a cautious and systematic approach to interpreting the proxy data contained in sediment records. Methods used to identify anomalies in the Nicolay Lake record are relevant to future lake studies and suggest that important noise can be systematically removed, improving the potential for high resolution, hydroclimatic reconstructions.

Table 3.1. Calender-year extent of sediment cores used in this study. Gaps in individual cores are the result of cutting cores in the field (underlined) and sediment disturbances introduced during embedding.

	Year (AD)		
Core	Start	Finish	Gaps
NL1	1762	1985	1784-5, 1802, 1819-22, 1831-42, 1900, 1928
NL2	1808	1987	1820-3
NL3	1493	1975	
NL6	1778	1962	
NL10	1729	1988	1860, 1901-3
NL12	1473	1987	1959-68
NL14	1533	1981	1683, 1703, 1856
NL15	1700	1985	

Table 3.2. Intercore Pearson correlation coefficients (n=127). Note the low correlation between the proximal NL1 site and the other sites. The sample size (127) represents all instances where a thickness measurement was available from each core. The reduced sample size results from gaps in individual cores (Table 3.1).

	NL1	NL2	NL3	NL6	NL10	NL12	NL14	NL15
NL1	1							
NL2	0.715	1						
NL3	0.592	0.839	1					
NL6	0.493	0.766	0.747	1				
NL10	0.415	0.696	0.778	0.793	1			
NL12	0.531	0.833	0.964	0.700	0.755	1		
NL14	0.539	0.779	0.907	0.740	0.787	0.861	1	
NL15	0.555	0.822	0.861	0.794	0.908	0.838	0.855	1

Table 3.3. Principal components calculated for a) entire core set (127 years) and b) excluding cores NL1 and NL2 (176 years). All components with eigenvalues >0.25 are listed.

a)

Component	Eigenvalue (λ)	% Explained Variance	Cumulative Eigenvalue	Cum.% Explained Variance
1	6.271	78.389	6.271	78.389
2	0.712	8.904	6.983	87.293
3	0.405	5.060	7.388	92.353

b)

Component	Eigenvalue (λ)	% Explained Variance	Cumulative Eigenvalue	Cum.% Explained Variance
1	5.582	93.028	5.582	93.028

Table 3.4. Principal component loadings for each core location. The proportion of the variance in each core series explained by a given component is obtained by squaring the component loadings.

	All cores			Less NL1,2
Core	Component 1	Component 2	Component 3	Component 1
NL1	0.666	0.713	0.123	
NL2	0.911	0.227	0.020	
NL3	0.952	-0.020	-0.250	0.974
NL6	0.856	-0.135	0.382	0.954
NL10	0.875	-0.322	0.209	0.953
NL12	0.925	-0.055	-0.315	0.960
NL14	0.921	-0.095	-0.175	0.967
NL15	0.944	-0.136	0.085	0.980

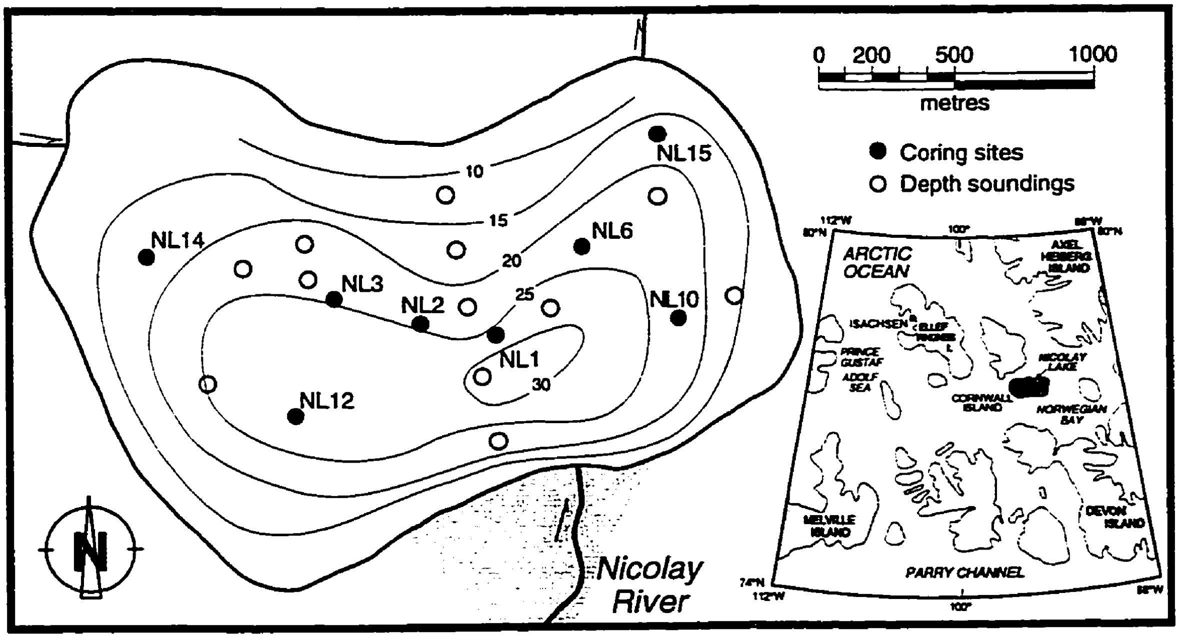

Figure 3.1. Bathymetric map of Nicolay Lake showing coring sites and extent of delta (shaded). Contours are in 5m intervals. Nicolay River is an unofficial name and the mapped location is based on 1950 aerial photographs. Inset map shows location of the lake and Cornwall Island in the central Canadian High Arctic.

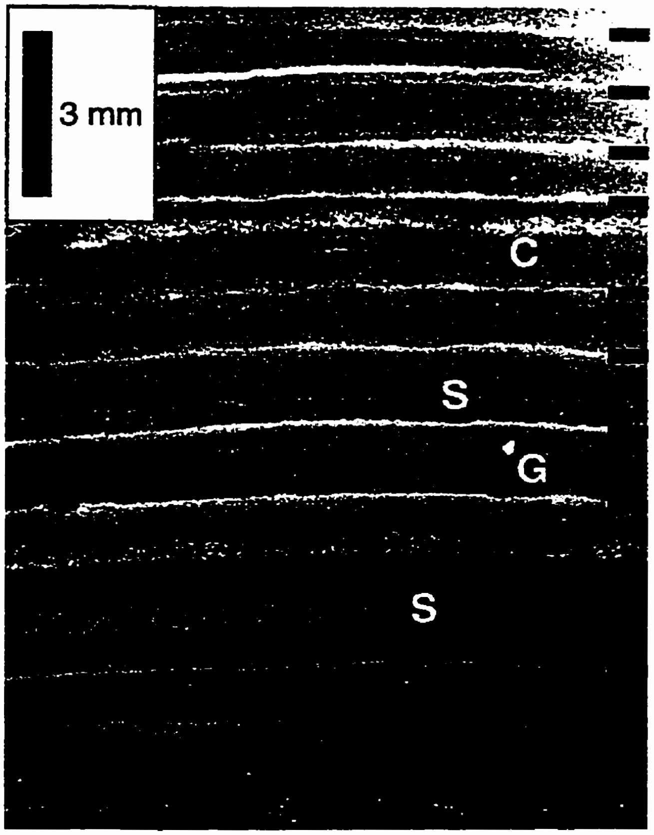

Figure 3.2. Photomicrograph of well-defined laminated sediments from percussion core NL3. The upper limit of each varve couplet is identified by the solid black line on the right edge. Common features found in the Nicolay Lake sediments include: one or more subannual laminae (S), individual sand grains (G), and a thin layer of coarse silt and sand in the upper varve (C).

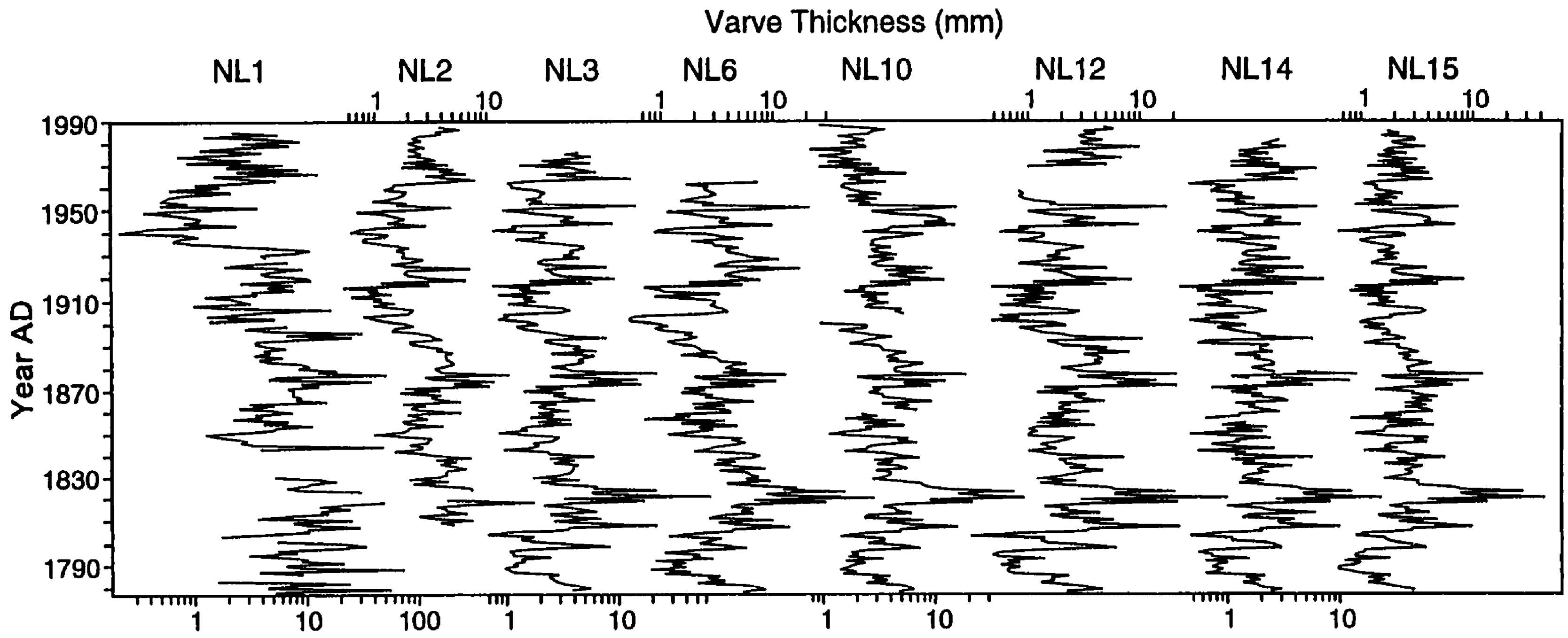

Figure 3.3. Interannual variation in varve thickness (mm) for each core in the study. Cores NL2-15 show strong similarity in the pattern and magnitude of interannual variability, indicating the similarity of the record throughout the lake. Core NL1, the most proximal core studied, contains numerous occurrences of high accumulation compared to the other cores. However, several major sediment influxes are apparent in all cores (i.e. three events ca. 1875 AD).

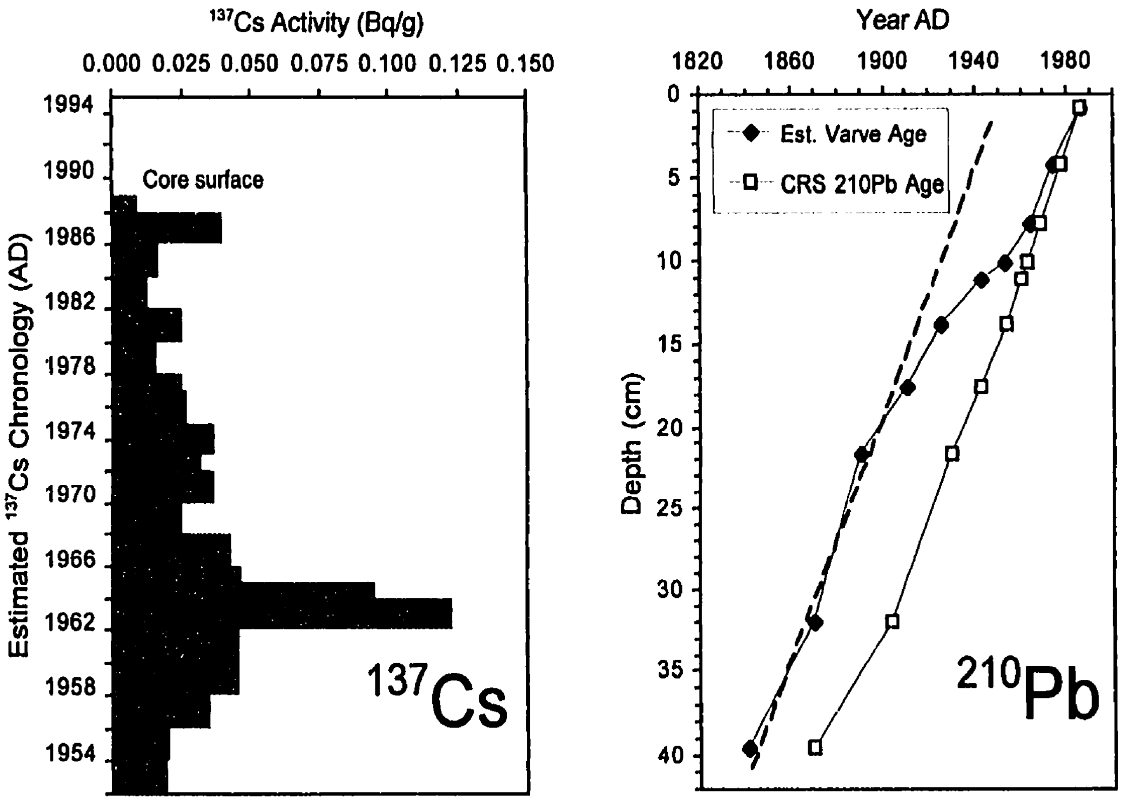

Figure 3.4. Profiles of (a) ^{137}Cs and (b) ^{210}Pb from unfrozen percussion core NL2. Dashed line on ^{210}Pb plot indicates approximate slope of the varve-^{210}Pb relationship and lack of divergence above 8cm and below 15cm.

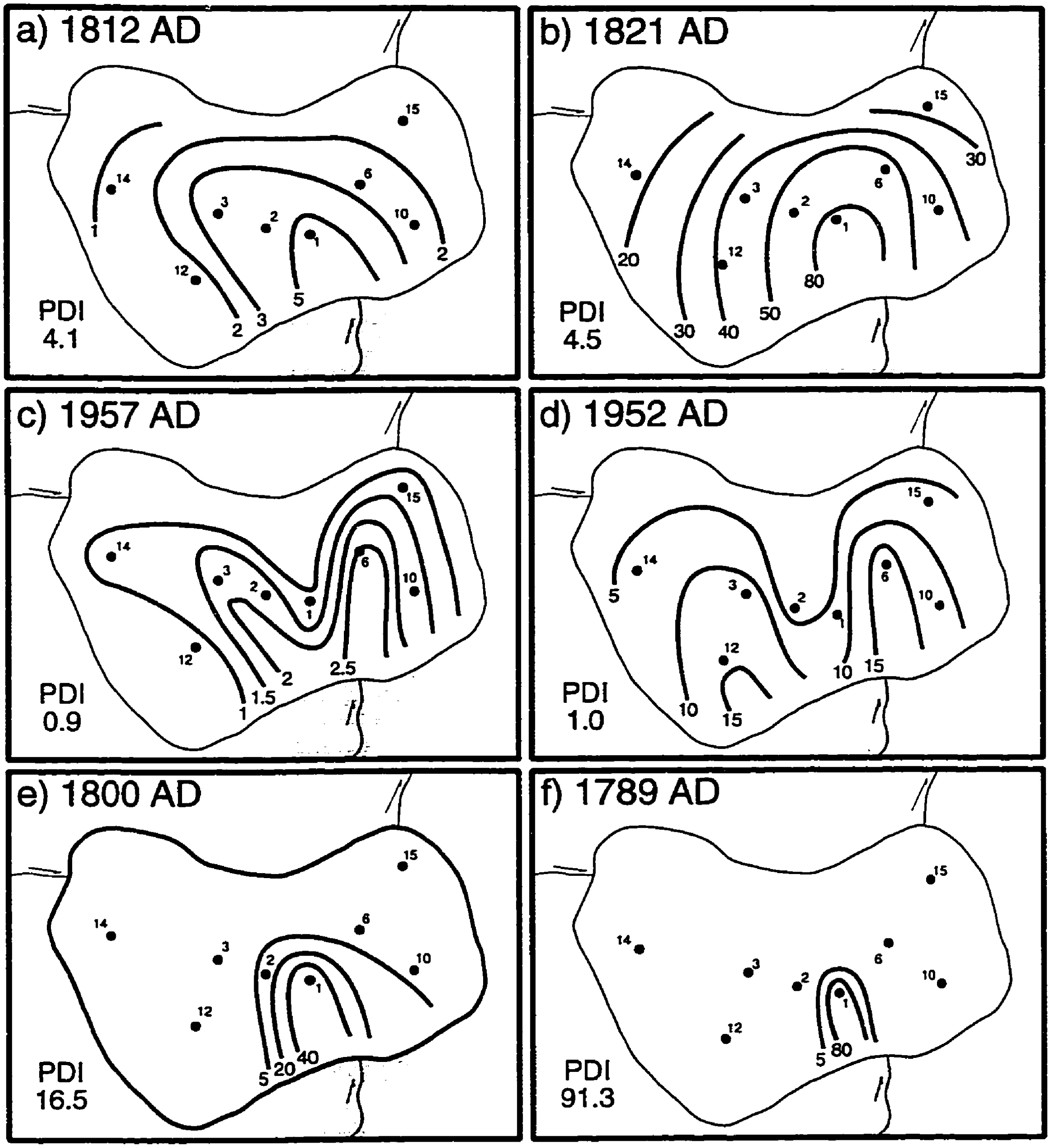

Figure 3.5. Examples of annual sediment accumulation in Nicolay Lake revealing normal (a,b), bifurcating (c,d), and localized (e,f) patterns. Contour intervals (mm) are irregular and vary on each map. Delta extent (shaded) and river distributary shown are from aerial photographs taken in 1950. Proximal-distal index (PDI) values are defined as the ratio of accumulation between cores NL1 and NL14 and are indicated for each year shown.

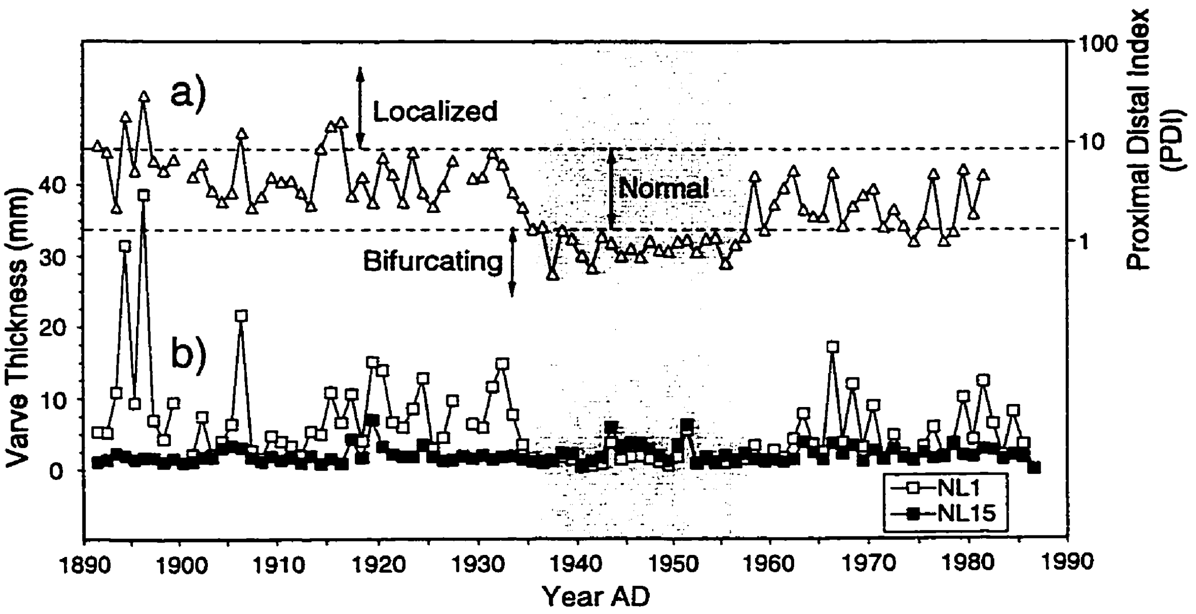

Figure 3.6. Temporal variations of the a) proximal distal index (PDI) during during the past century. Approximate PDI ranges are indicated for each deposition pattern. During the period of 1935-1957, PDI values abruptly shift to ~1.0, indicating the presence of a bifurcating sediment deposition pattern (shaded zone). Sporadic localized turbidite deposition occurs during years with PDI > 10. Varve thickness b) at proximal site NL1 and distal site NL15 show anomalous convergence and frequent reversal of deposition rates during the same period of bifurcating deposition.

3.7 References

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CHAPTER 4: FIVE CENTURIES OF INTERANNUAL SEDIMENT YIELD AND RAINFALL-INDUCED EROSION IN THE CENTRAL CANADIAN HIGH ARCTIC RECORDED IN LACUSTRINE VARVES

(For submission to *Water Resources Research*)

4.1 Introduction

Sediment yield is an important measure of the efficacy of different erosional and transport processes and an important means of identifying changing landscape and hydroclimatic conditions in a catchment (Walling and Webb, 1983; Kuhnle *et al.*, 1996). In the Canadian High Arctic (the islands located north of 75°N, Figure 4.1), few yield measurements are available to assess variability in hydrological processes, and to estimate the sensitivity of the High Arctic landscape to the hydroclimatic changes predicted by climate models (Woo and McCann, 1994; Kattenberg *et al.*, 1996). The scattered yield observations available vary considerably, in part due to terrain and catchment differences, and also because few are from the same years (Cogley, 1975; McLaren, 1981; Woo, 1983; Lewkowicz and Wolfe, 1994; Hardy, 1996). Moreover, multi-year monitoring programs have recorded large interannual variations in sediment yield and discharge (Woo, 1983; Lewkowicz and Wolfe, 1994; Hardy, 1996), making it difficult to assess which processes control short and long term variability (Woo and McCann, 1994). Given that establishing baseline yield conditions is critical to estimate and identify catchment responses to hydroclimatic change in the High Arctic (Woo and McCann, 1994), a method is needed to determine current and past yield variability. Varved lake sediments integrate the annual sediment yield from an entire catchment, and potentially can provide valuable long term records of interannual yield variability. Such records could be used to identify the important processes that control sediment delivery and the responses to hydroclimatic changes. In particular, investigations of varve-based sediment yield can substantially improve our understanding of the inter-annual variability of catchment yield processes (e.g. Zolitschka, 1998), compared to lake sediment reconstructions with temporal resolutions from decades to centuries (Dearing, 1983; Svendsen *et al.*, 1989; Foster *et al.*, 1990).

This paper reports the results of an investigation which uses the accumulation of varved sediments in Nicolay Lake, Cornwall Island, Nunavut, as a proxy record of long term sediment yield. The objectives of this study are: a) to determine whether varved sediments can provide an estimate of sediment yield comparable to conventional hydrological methods, b) to identify the major features of a long term (487 year) yield record, c) to provide an explanation for exceptional yields in some years, and d) to identify significant hydrometeorological controls over interannual yield variability. The physiography, climate, and hydrology of the Nicolay Lake catchment are similar to those of a large part of the central and western High Arctic Islands, therefore, these results provide an unprecedented and valuable perspective on the natural variability in catchment processes in a region largely unaffected by human activity.

4.2 Study Area

Nicolay Lake is a small (2.1 km^2), deep (31 m), freshwater lake located on the north-central coast of Cornwall Island at 2.5 m above sea level (asl) (Figure 4.1). The primary source of inflow is a river that drains a large (91 km^2), low (maximum relief of 240 m), and unglaciated catchment (Figure 4.2). Catchment slopes are sparsely vegetated and mantled with a veneer of marine and glacial sediments (Hodgson, 1982). Valley bottoms contain extensive, fine grained sandar with channels that are frequently incised into Holocene fluvial, lacustrine, and marine deposits. Poorly consolidated and fine grained Triassic sandstones and mudstones underlie most of the catchment, with several resistant Jurassic units forming the eastern rim (Balkwill, 1983). All of these formations are commonly exposed at the surface, and contribute to the large amount of sediment available for erosion. Diabase dykes intruded into the Triassic units are conspicuous as resistant outliers, and two large sills support isolated highlands that rise above ridges composed of the more recessive sedimentary formations. The surface cover and topography in the Nicolay Lake catchment are typical of the physiography found on Cornwall Island, although sediment availability appears to vary substantially between different basins. Hodgson (1982) investigated the surficial materials in the region, and noted that fluvial processes dominate the landscape. He observed that in several areas, raised deltas are continuous from high elevations (c. 115 m asl) down to modern sea level, indicating that the supply of fluvial sediment has been high during most of the Holocene. In the Nicolay Lake catchment, the migration of a paraglacial sediment wave (e.g. Church and Ryder, 1972) through successive topographic basins in the catchment during Holocene glacioisostatic rebound has likely increased sediment yield to Nicolay Lake during the past c. 500 years. The resulting increased sedimentation rates, together with the emergence and isolation of the lake, have likely been important factors in the formation of varves (Chapter 2).

Catchment discharge and sediment delivery are limited to the brief summer period during June-August. At the nearby Isachsen weather station, mean daily winter temperatures of -36°C preclude melting, compared to mean daily temperatures of 2-4°C during the summer (Environment Canada data). Stream flow is strongly nival, and is characterized by a brief period of high stage associated with peak melt energy during mid to late June (Woo, 1983). Initial melt is frequently ponded by dams formed by wind-drifted snowfall (Woo and Sauriol, 1981). These dams release at different times, resulting in a rapid increase in discharge for periods of twelve or more hours. Initial streamflow is prevented from entering the lake by its thick ice cover. Hence, the lake ice surface first floods until the ice is buoyantly raised, producing a narrow moat that permits the turbid water to enter the lake. Discharge wanes during the remainder of the summer as snow cover melts and the shallow active layer drains. Rainfall is normally low (32.4 mm mean at Isachsen) and commonly occurs as trace events lasting several days. Occasionally, however, intense rainfall occurs, leading to a rapid increase in stage and sediment transport (Cogley and McCann, 1976; Woo, 1983).

4.3 Methods

Deposition in Nicolay Lake was investigated using a network of eight sediment cores recovered during 1995 and 1996 using piston-percussion and vibracoring techniques (Figure 4.3) (Smith, 1992; Reasoner, 1993). The primary method for identifying annual sediment accumulation rates is measuring varve thickness. In order to obtain the best quality varve measurements, thin sections are generally required (Lamoureux and Bradley, 1996). The unfrozen cores (1995) were subsampled to produce overlapping slabs, which were then dehydrated with repeated applications of acetone, and embedded under vacuum with epoxy resin (Lamoureux, 1994). Frozen cores (1996) were cut with a rock saw, freeze-dried, and embedded under vacuum. Large format thin sections were made from the embedded slabs using standard methods. Cores were also sampled at regular depth intervals for measurement of dry bulk density, loss-on-ignition (LOI), and grain size distribution.

All cores contain an upper unit of well-laminated sediments 1.5-2.0 m thick. The bulk sediment is relatively uniform in dry density (1.4 $g{\cdot}cm^{-3}$), grain size distribution (8.6ϕ), and organic content (4% LOI). In thin section, the laminae are composed of couplets of light coloured silt grading normally into a homogenous, red-brown, clay cap. Individual couplets are separated by a sharp, conformable contact. Detailed sedimentological descriptions can be found elsewhere (Chapter 2). Due to the pronounced seasonality of sediment transport and deposition in the catchment, the couplets are hypothesized to represent varves, with the silt at the base of each varve deposited during summer runoff, and the fine clay cap produced by quiescent conditions during the fall/winter under ice cover. Profiles of ^{137}Cs and ^{210}Pb obtained from the surface sediments of core NL2 support the varve interpretation (Figure 4.4). The 1963 and 1986 ^{137}Cs peaks, representing maximum fallout from atmospheric bomb testing, and the accident at Chernobyl, respectively (Bollhofer *et al.*, 1994), are well defined in the core and separated by 23 couplets. Modeled ^{210}Pb ages are generally consistent with laminae counts, and there is no indication of long term divergence between the two age estimates (Figure 4.4). The brief divergence between the lead and laminae ages between 8-14 cm depth is likely produced by reversals in unsupported ^{210}Pb caused by lower deposition rates at that time (Appleby and Oldfield, 1983). However, the lack of long term divergence between the lead and laminae counts suggests that the age estimates are comparable. On the basis of the depositional seasonality, sedimentology and the radioisotope chronology, it is inferred that the laminae in Nicolay Lake are varves.

The thin sections were measured in detail with a low power microscope. Thickness measurements from each core were cross-dated using conspicuous marker layers and structures to identify and resolve discrepancies between cores (Lamoureux and Bradley, 1996). In practice, the thickness and clarity of the varves led to few counting errors between cores (<0.5%). Annual mass accumulation was calculated as the product of varve thickness and corresponding dry bulk density.

The lack of core information from the lake margins makes it difficult to estimate the total annual sediment loading to the lake, and hence, catchment sediment yield. Although deposition is likely minimal at shallow, distal locations, the delta foreslope is subject to high, unquantified accumulation rates. Therefore, any whole lake estimate would be most biased by assumptions about deposition rates around the delta. Annual whole lake sediment loading was conservatively estimated by multiplying the equal-weight average of accumulation at all eight core sites by the lake floor area below 15 m depth (where the cores were obtained, Figure 4.3). This measure of deposition likely underestimates actual catchment yield because: a) the cores used are primarily located in the distal region of the lake, reducing the lake-wide mean; and b) deposition is assumed to be negligible at depths shallower than 15 m where accumulation data are unavailable. The loss of sediment to outflow remains unknown, but is considered minimal based on several analyses of sediment concentration in lake outflow in 1996 (<2 $mg \cdot l^{-1}$). The bedload component is not included in the calculated yields because coarse sediments are restricted to the delta margin and are not represented in the sediment cores. Unlike other arctic environments (Woo and McCann, 1994), gravel transport is relatively rare in the catchment (Hodgson, 1982), and likely contributes a small fraction of the overall yield. Furthermore, dissolved loads are comparatively small due to the abundance of quartz and low levels of carbonate in the sediments and bedrock (Hodgson, 1982; Balkwill, 1983).

In order to make use of the long accumulation record obtained from cores in the west end of the lake (Figure 4.3), results from the all-core sedimentation average (197 years common to all cores) were regressed against the record from core NL3 (total length 487 years). This core was found to mimic lake wide deposition and to minimize the influence of localized turbidity currents in a detailed analysis of deposition patterns in the lake (Chapter 3). The high correlation between NL3 and estimated lake wide sediment load during the past 197 years (r^2=0.79, p<0.001) permits the use of this single core to estimate sediment yield for the entire 487 year record. The fine-grained sediment found in the cores means that the estimated sediment yield from the catchment is biased. However, given the lack of information available for the coarser fraction, the fine-grained sediment yield discussed in this paper is assumed to represent a minimum estimate of the total catchment yield.

4.4 Results

4.4.1 Representativeness of Sediment Yield Estimates

Estimated sediment yield from the Nicolay Lake catchment has shown a high degree of interannual variability, ranging from 21.8 to 1620.3 $t{\cdot}km^{-2}{\cdot}a^{-1}$ and with a mean of 109.8 $t{\cdot}km^{-2}{\cdot}a^{-1}$ (Figure 4.5). The interannual variability observed in the Nicolay Lake record is typical of that found by multi-year monitoring programs in the region (Cogley, 1975; Lewkowicz and Wolfe, 1994; Hardy, 1996). Absolute yields are relatively low in a global context (Walling and Webb, 1983) due to the severity of the High Arctic climate, which limits the active hydrological period. The results from Nicolay Lake are generally comparable with those from other unglaciated sites located in the central and western islands (Figure 4.1). This is particularly the case with sites that share similar catchment sediment cover and bedrock, such as those found on Bathurst Island (Table 4.1). In the only case where year-over-year comparisons are possible, Nicolay Lake and the Mecham River show comparable magnitudes during 1970 and 1971, although the Nicolay Lake estimates are consistently higher. This is likely due to more resistant carbonate bedrock in the Mecham River (Figure 4.1) catchment which reduces the availability of suspended sediment, a characteristic shared by other nearby catchments (Braun, 1997).

The 1974 yield to Nicolay Lake was six times less than estimated for the Consett Head River, 375 km to the southwest (McLaren, 1981). Both catchments share similar terrain, but, two factors suggest that the Consett Head yield estimate may be too high. The total sediment discharge was estimated using a rating curve derived for the nine day period of peak flow, during which 97% of the total sediment transport was estimated to occur, despite a lack of measurements. Given the possibility of hysteresis effects and sediment exhaustion during the late flood period, it is possible that the 1974 estimate is substantially too high (McLaren, 1981, p. 143-4). When the same rating curve was used to calculate sediment discharge in a similar catchment on Bathurst Island in 1976 (Snowbird Creek, Figure 4.1), the result was more than ten times the observed sediment yield (Wedel *et al.*, 1977). Because the 1974 yield estimate from the Consett Head River appears to be an order of magnitude higher than other regional estimates, the actual yield from this site is probably closer to the estimate obtained from Nicolay Lake for the same year (Table 4.1). Therefore, in general, comparisons with published data from the central and western islands suggest that sediment yield estimates from Nicolay Lake are representative of the region.

4.4.2 Characteristics of the Long Sediment Yield Record

Sediment yield recorded in Nicolay Lake exhibits a small, but statistically insignificant increase between 1500 and 1987 AD. Superimposed on this trend are periods of higher and lower yield that persist for 10-40 years. Many of these periods with overall higher yield begin with a year of extreme yield. A single factor ANOVA test shows that there are significant differences between each 50-year period ($p<0.001$, 486 d.f.), although most periods exhibit statistically similar variance. Notable exceptions occur for the 1801-1850 and 1651-1700 AD periods, where significant ($p<0.05$) differences in the variance were noted (Table 4.3). Both periods contain several years with exceptional yields that increase the variance markedly.

An alternative measure of yield variability reveals important differences between periods with similar means and standard deviations. Mean sensitivity, as defined by Fritts (1976):

$$ms_x = \frac{1}{n-1} \sum_{t=1}^{t=n-1} \left| \frac{2\,(x_{t+1} - x_t)}{(x_{t+1} + x_t)} \right| \qquad (1)$$

measures the mean interannual variance of the data set, and ranges from 0 in data with minimal variability to +2 in data with large interannual variations (Fritts, 1976). The interannual variance in the Nicolay Lake yield record closely covaries with mean sedimentation for each 50-year period (excluding 1551-1600 AD, $r^2=0.769$, $p<0.01$), indicating that periods with increased sedimentation are characterized by higher interannual variability. The only exception to this pattern was during 1551-1600 AD, where yield was below the long term mean, but had higher interannual variability than any other period (Figure 4.5). The low standard deviation for this period indicates that the interannual departures from the mean yield were relatively small, but frequent. This behavior contrasts with 1901-1950, which had a similar mean yield and standard deviation to 1551-1600, but lower interannual variability.

Overall, the dominant features of the Nicolay Lake yield record are the extreme events, several of which exceed the long term (487-year) mean by an order of magnitude (Figure 4.5). Periods containing one or more extreme yield years tend to have higher measures of mean, variance, and interannual variability, although the latter can be high in the absence of extreme yields (e.g. 1551-1600). Therefore, this simple analysis shows that a high degree of interannual variance is common in the entire yield record, and further, that any attempt to reduce the data to multi-year averages will only tend to mask the different signals in the data.

4.4.3 Magnitude and Frequency of Extreme Yield Events

The occurrence and magnitude of extreme yielding years constitutes an important component of the Nicolay Lake yield record. Sporadic, thick deposits in other varve records have been considered to result from both hydrometeorologic (e.g. rainfall events ((Østrem and Olsen, 1987)) and non-climatic processes (e.g. subaqueous slumping (Hardy *et al.*, 1996)). In the case of Nicolay Lake, however, analysis of annual deposition patterns clearly differentiates localized, slump-related deposits from lake-wide deposits presumably composed of catchment-sourced sediments (Figure 4.6). This process permits the removal of these anomalous localized deposits from the accumulation record (Chapter

3). However, given the importance of the extreme yielding years to long term yield and to the statistics from individual 50-year periods, it is important to identify the size and recurrence characteristics of these events to evaluate their importance to catchment yield.

A probability estimation approach was followed to provide a measure of yield magnitude recurrence. This method is commonly used in risk analysis for estimation of flood quantiles (Bobée *et al.*, 1993). Quantiles are estimates of the size of an event for a given return period (i.e. 100-year recurrence), and permit evaluation of the magnitude of particular events within a probabilistic framework estimated from the dataset. Generally, the technique involves fitting an asymmetric probability distribution to the data to estimate the recurrence of extreme events with low probabilities. However, despite the wide application of these techniques in hydrology, there is little agreement as to which probability distributions are most appropriate for use in risk assessment. Moreover, the distributions are not based on any specific physical processes, but rather, are used because they provide a good fit to the data (Bobée et al, 1993). Despite these conceptual limitations, probability estimation techniques provide a useful framework for investigating the properties of extreme events in data sets (e.g. Katz and Brown, 1992), particularly in the Nicolay Lake yield record.

Seven probability distributions (normal, two and three-parameter lognormal, gamma, and Pearson and logPearson type-III) were fitted to the varve yield data set using maximum likelihood parameter estimates, and a generalized extreme value (GEV) model was applied using probability-weighted moments (Hosking *et al.*, 1985). The yield data are highly skewed (γ=6.64) and in general, the best fit was obtained with the three parameter distributions. Using Filliben's (1975) probability plot coefficient test, the GEV distribution provided the best fit to the data (r=0.991, p<0.01 (Chowdhury *et al.*, 1991)). The GEV model takes on an EVII form

$$F(y) = \exp\left\{-\left[1-\kappa\left((y/\alpha)-\xi\right)\right]^{1/\kappa}\right\} \qquad \kappa \neq 0 \qquad (2)$$

with a lower limit and a positively skewed tail, which is consistent with the data set. In this cumulative distribution function, α is the scale parameter, ξ is the location parameter, and κ is the shape parameter (Hosking *et al.*, 1985). Using the GEV model, parameters were estimated from the 487 year record, quantiles were calculated, and the number of quantile exceedences was determined for each 50-year period (Table 4.4).

Extreme yielding years control the mean yield for most periods and also significantly contribute to the total yield. For example, three years during the 1801-1850 period exceed the 100-year quantile estimates, increasing overall yield during a period with persistently higher yield. This contrasts with the high mean yield during 1651-1700, which had only a single 100-year quantile exceedence. Instead, higher mean yield during this period resulted from increased occurrences of moderate yields; nearly 1 year in 7 exceeded the long term 25-year quantile from 1651-1700 compared to approximately 1 year in 16 during the period 1851-1900, even though both periods have similar mean yields (Table 4.4). Additionally, several periods with low mean yield did not contain any exceedences of the long term 25-year quantile, particularly 1501-1550, when no year exceeded the long term 10-year quantile. Thus, each 50-year period exhibits different occurrence of high magnitude components, a feature of the data that is difficult to identify solely from conventional measures of mean and standard deviation.

It is evident that the occurrence of large magnitude events was irregular. The five years in which yields that exceeded the 100-year quantile occurred during the 17th and 19th centuries (Table 4.4). These periods were also characterized by increased frequencies of 25 and 50-year quantile exceedences. Only through the quantile estimation procedure is this temporal distribution of extreme yields apparent, particularly given the large numbers of outliers that are estimated to range between 5 and 25-year recurrences (Figure 4.5).

Finally, the quantile estimation procedure provides an alternative measure of the long term mean that explicitly includes the bias introduced by the extreme yields. Therefore, the estimated 2-year recurrence yield (81.6 $t{\cdot}km^{-2}{\cdot}a^{-1}$) is substantially lower than the first moment (109.8 $t{\cdot}km^{-2}{\cdot}a^{-1}$), and provides a more probable measure of mean (modal) yield from the Nicolay Lake catchment (Katz and Brown, 1992).

4.4.4 Mechanism for Extreme Sediment Yields

Several processes could potentially produce the extreme yields observed in the Nicolay Lake record. However, comparison with the weather record from Isachsen (Figure 4.1) strongly suggests that infrequent, heavy summer rainfall was responsible for exceptional yields in 1951 and 1962. Summer rainfall is low in the High Arctic (Table 4.2), although on occasion heavy rainfall has been observed which produces substantial erosion (Thomas and Thompson, 1962; Adams, 1966; Cook, 1967; Cogley and McCann, 1976; Hodgson, 1977). Church (1988) suggested that large rainfall events in arctic catchments could generate yields substantially larger than snowmelt alone. This conclusion is supported by studies that have documented exceptionally high suspended sediment loads in response to major storms (e.g. Cogley and McCann, 1976; Woo and McCann, 1994). Similarly, varve studies have also documented thick deposits attributed to major rain events (e.g. Gilbert, 1975; Østrem, 1975; Østrem and Olsen, 1987; Desloges and Gilbert, 1994).

During arctic rainfall events, sediment erosion occurs by wash on poorly vegetated slopes, gullying, and localized earthflows, but is dominated by the erosion of channel banks and remobilization of floodplain sediments during high river stage (Wilkinson and Bunting, 1975; Cogley and McCann, 1976; Hodgson, 1977; Church, 1988; Woo and McCann, 1994). Rainfall of modest intensity appears to have a more limited effect on sediment yield. Cook (1967) noted that sediment mobilization near Resolute (Figure 4.1) was minimal during events of less than 7.8 mm·day^{-1}. This may be related to the storage of rain in the active layer or to evaporation, both of which tend to reduce the runoff ratio of a given event (Woo, 1983). Depending on vegetation and soil moisture conditions, High Arctic runoff ratios can vary widely. However, poorly vegetated catchments (like Nicolay Lake's) generally have a greater response to rainfall (Woo and Young, 1997). Discharge produced by summer rainfall is not limited by factors that alter runoff during the early nival flood (i.e. snow dams, ponding). Furthermore, there is also an increased availability of thawed channel and slope sediments to erode later in the summer.

Comparison between the Nicolay Lake sediment yield and the Isachsen weather record indicates that exceptional deposition in 1951 and 1962 is likely related to the two largest rainfall events on record. In 1951, a four-day event (37.5 mm total) occurred near the end of the summer (mid-August, Figure 4.7a). The structure of the 1951 varve (408.2 t·km^{-2}) shows a thick rhythmite just prior to the deposition of winter clay at the end of the season. Based on the temperature record, it is likely that the two rhythmites found at the base of the 1951 varve were related to two major phases of snow melt prior to the rainfall. The 1962 varve structure (377.0 t·km^{-2}) appears to have been produced by the opposite sequence of weather conditions. A 3-day rainfall event (23.5 mm total) occurred early in the season as a rain-on-snow event (Church, 1988), several days after melting temperatures began (Figure 4.7b). The thick rhythmite related to this rainfall event occurs at the base of the 1962 varve, while subsequent nival melt and warm temperatures likely produced the overlying sediment unit. The size and sequence of rhythmites within each varve (1951 and 1962) are consistent with the weather events recorded at Isachsen, supporting the inference that major rainfall was responsible for exceptional sediment yields in those years.

Observations by the author during a period of heavy rainfall on Cornwall Island in 1996 provide an analog for the conditions that produced the extreme yields of 1951 and 1962. Between July 13-16, nival flow was waning and snow cover in the catchment was estimated at <20%. The river channel above Nicolay Lake was gravel-armored, the fine grained sediment having been removed by the large nival flood (Figure 4.8a). Thereafter, eight days of rain (totalling an estimated 30-50 mm) increased river stage by >0.5 m and caused extensive floodplain inundation and localized earth flows. Modern and relict floodplain sediments, together with channel bank erosion, were likely the most important sources of sediment transported during the event (Figure 4.2). Following the rainfall, the magnitude of sediment transport by the river was clearly indicated by the large amount of sand that filled the river bed (Figure 4.8b). Attempts to recover the 1996 lake sediments were unfortunately unsuccessful; however, it is likely that the yield from 1996 was at least similar to the 1951 and 1962 yields.

4.4.5 Sedimentation Arising from Smaller Rainfall Events

Given the rainfall interpretation for extreme yields in 1951 and 1962, it is important to identify the yield response to a wider range of rainfall conditions. In particular, smaller subannual rhythmites like those used to recognize the 1951 and 1962 rainfall episodes are commonly found in other varves, and are produced by a shift from a low to high energy sedimentation regime. Although several geomorphic processes could produce increased sediment transport (e.g. mass wasting), it is also quite likely that the observed sedimentary transitions could be the result of higher discharge and increased transport competence. The size of these smaller subannual rhythmites in Nicolay Lake (>1000 t each) suggests that the most likely explanation for these deposits is a hydrometeorological process that affected the entire catchment rather than localized erosive events. Therefore, it is possible that either rainfall or increased snow melt could be responsible for the subannual rhythmites found throughout the varve record.

To assess the possible relationship between weather conditions and the deposition of multiple sediment units, the presence or absence of these units was compared with the weather record from Isachsen for the period 1948-78. Rainfall events were identified and totals calculated from periods when measurable rainfall was observed on one or more successive days. Events with less than 7.8 mm total were removed because it is unlikely that these events would have significantly increased river stage or sediment transport (e.g. Cook, 1967). The rainfall events that remained were compared to the varve record for each year in the weather record. Subannual rhythmites were identified from the thin sections from all distal cores (excluding NL1, Figure 4.3) and only the structures present in each core were used for comparison with the rainfall record.

Multi-day events that could substantially increase discharge (e.g. >7.8 mm·day^{-1}, Cook, 1967) are frequent, occurring in 68% of the years. Comparison of the varves to the Isachsen weather record reveals that subannual rhythmites were present (or absent) in summers with (without) multi-day rainfall events exceeding 7.8 mm in 17 of the 31 years (Table 4.5). Further, in eleven of the years when a direct relationship between rainfall and subannual sedimentation events could not be initially established, relatively simple mechanisms can be invoked to explain the discrepancy. In five of these cases, the rainfall probably occurred during the snowmelt period, when it is doubtful that sedimentation generated by either process could be separated. In five other cases, the major rainfall occurred after prolonged warm periods (with 140-340 melting-degree days (MDD)). These years were warmer than average (mean 158 MDD total at Isachsen) and would likely have resulted in substantial evaporation and drier soil conditions (Woo, 1983; Lewkowicz and Wolfe, 1994; Woo and Young, 1997). Studies from several High Arctic catchments indicate that the runoff generated by rainfall can be significantly reduced by the storage of rainfall in a relatively dry active layer (Woo and McCann, 1994; Woo and Young, 1997). Therefore, warm summer temperatures during these five years likely minimised the discharge and sediment transport generated by major rainfall events, preventing the deposition of identifiable rhythmites in the varve record (Table 4.5).

Only the subannual unit in the 1965 varve appears to be the result of a major, late season snow melt event (Table 4.5). Temperatures during the early summer of 1965 were consistently colder than normal, and likely generated a small nival flood and preserved much of the winter snowcover. An abrupt warming in early August could have resulted in a secondary river discharge peak (Hardy, 1996) and produced the rhythmite in the varve. Similar late-season warm periods are common in the Isachsen record. However, 1965 was the only year in which such a period was preceded by consistently cold temperatures in the early summer.

Finally, three varves from the early 1950s can not be reconciled with the weather record using the same criteria. In both 1954 and 1955, several recorded rainfall events are not visible in the varves, whereas, the otherwise unremarkable weather in 1950 appears to have produced a subannual sediment unit in Nicolay Lake (Table 4.5). The observed differences could be due to localized precipitation at either site (e.g. Thomas and Thompson, 1962; Cogley and McCann, 1976). However, there is little evidence for localized effects associated with major events in the remaining 28 years examined. This suggests that rainfall events that generated an identifiable sedimentary response were region-wide features, and that the distance of Nicolay Lake from the weather station has not limited identification of the majority of significant regional rainfall events. Alternatively, the sediment chronology may be incorrect during the early 1950s, a time where a discrepancy was noted between varve and ^{210}Pb ages (Figure 4.4). However, if the chronology was inaccurate, it would be difficult to explain the match between the major rainfall event and varve in 1951. Moreover, the low accumulation rates during the 1950s are reasonable explanation for the ^{210}Pb dating problems during this period (Appleby and Oldfield, 1983). Assuming that the chronology is correct, the absence of an explanation for these three years indicates that localized rainfall or other processes influence the record, albeit to a limited degree.

The subannual rhythmites in the recent varve record support the interpretation that the two largest rain storms recorded at Isachsen produced exceptional sediment yields, and that smaller rhythmites were likely related to major, multi-day rainfall events. This record is complicated by variations in the catchment response to rainfall due to soil moisture conditions (Woo and Young, 1997). Only 3 years out of the 31 year record (9.7%) cannot be explained by the timing of major rainfall or by soil storage attenuation of rainfall. Based on the 1948-78 varve and weather records, three major rainfall-sediment deposition scenarios can be recognized. In the simplest case, major rainfall events generate increased sediment transport and the deposition of a rhythmite. The Nicolay Lake record indicates that these conditions occur when total rainfall exceeds approximately 13 mm and when soil conditions allow minimal potential storage (Figure 4.9). In the second scenario, prolonged warm weather can lead to relatively dry soil conditions and the subsequent attenuation of the rainfall signal, typically after ~75 MDD (Figure 4.9). However, there is evidence that even following periods of exceptional warmth (~200 MDD), large rainfall events (>30 mm) can exceed the soil water storage capacity and produce a sedimentary response (Figure 4.9). Finally, rainfall that occurs during peak snow melt is unlikely to generate a sedimentary signal that is distinguishable from the snow melt signal. Under these conditions, only heavy rainfall (>20 mm) can increase discharge and sediment transport sufficiently to create an exceptionally thick sediment unit (i.e. 1962).

These results suggest that extreme yields and subannual structures in the longer varve record prior to 1948 were also generated by major rainfall events. However, it is difficult to distinguish the subannual rhythmites consistently throughout the entire 487-year record. Variations in thin section thickness can either enhance or conceal minor sedimentary structures, which leads to the selection of different major subannual structures on each thin section. Therefore, although the interpretation of major rhythmites is consistent on a given thin section, as is the case for the recent record discussed above, the same cannot be confidently assumed of the rest of the record. Notwithstanding this limitation, the recent record can be used as an indication of the frequency of rainfall for the entire record (see Discussion). While it is likely that other factors- both known (snow melt in 1965) and unknown (i.e. in 1950)- produced some of the subannual units, these processes are comparatively minor during recent times. This interpretation allows identification of the long term contribution of summer rainfall to sediment yield in this region of the High Arctic and changes in the magnitude and frequency of rainfall in response to known temperature variations (see Discussion).

4.4.6 Alternative Extreme Yield Mechanisms

Hydroclimatic factors other than heavy rainfall cannot adequately explain the exceptional yields in the recent Nicolay Lake record. For instance, high temperatures that lead to increased snowmelt rates might possibly generate high discharge and sediment transport. Hardy (1996) showed that sediment yield from the Lake C2 catchment, Ellesmere Island (Figure 4.1), varied by an order of magnitude between 1991 and 1992 in response to a small mean temperature difference (1.1°C). A quantitative relationship derived for the catchment indicated an exponential rise in suspended sediment discharge in response to increasing summer temperatures (Hardy *et al.*, 1996). High temperatures in 1956 at nearby Alert also coincided with high yield (9.5 standard deviations above the mean) in Lake C2 (Hardy *et al.*, 1996). Both of these observations suggest that the potential exists for an exaggerated sediment yield in response to higher temperatures. However, several factors limit the transport capacity of meltwater. Early season discharge can be substantially hindered by snow-filled channels and ponded by thick snow drifts. Additionally, sediment entrainment can be reduced (or enhanced) by runoff in snow-walled channels (Woo and Sauriol, 1981). Observations on Cornwall Island during the initial two weeks of streamflow in 1995 showed that extensive ponding and damming, particularly in ravines (Figure 4.2), slowed the formation of channelized flow. Furthermore, when high temperatures are more common (primarily July and early August) reduced snowpack limits potential meltwater formation, and hence, sediment transport. Only during years when snow melt is delayed by persistent low temperatures is there likely to be sufficient snow to generate a secondary discharge peak (e.g. 1965, previous section, see also Hardy (1996)).

Mass wasting events could also explain the exceptional yields in Nicolay Lake. Retrogressive thaw slumps and skin flows are common features in some arctic regions (e.g. Lewkowicz, 1988), however, the sediment derived from these highly localized processes is unlikely to contribute appreciably to the short term sediment yield from a large catchment. For instance, the thick unit in 1951 attributed to rainfall contains an estimated 18 000 t of sediment *lake-wide*. Assuming a soil bulk density of 1.50 g·cm^{-3} (Miller and Donahue, p. 58) and an active layer thickness of 50 cm (Hodgson, 1982), this event would require removal and transport of approximately 24 000 m^2 of sediment during a single season. No surface detachment scars of this scale were observed in the catchment. Moreover, it is likely that a slump of this size would contribute sediment over a number of years rather than during a single summer. Thus, the slump would have to be even larger to produce the observed yield in a given year. Observations made by the author during rainfall in 1996 and by Hodgson (1977) indicate that large numbers of small earth flows are mobilized during saturated soil conditions resulting from heavy rainfall. However, most of these flows remained largely in place following the rainfall, and were eroded and transported in subsequent years. Therefore, it is more likely that mass wasting processes are only partially responsible for the increased yield during major rainfall events.

4.5 Discussion

4.5.1 Long-term sediment yield from varved sediments versus hydrological monitoring

Sediment yields from Nicolay Lake and other sites in the central and western High Arctic are generally higher than those from small, nonglacial catchments in the eastern islands. Multi-year studies at Lake C2 (LC2) and Hot Weather Creek (HWC) on Ellesmere

Island suggest low, but highly variable yields (Figure 4.1, Table 4.1). This is particularly the case with the LC2 catchment on the north coast of Ellesmere Island, despite steep slopes and high relief in the catchment (Hardy, 1996), and a higher mean snowfall than in areas to the south (Table 4.2). In this case, a more limited melt season, resistant bedrock, and the paucity of surficial sediment play an important role in limiting sediment transport. At HWC, the terrain and bedrock are more similar to conditions found in the central and western High Arctic, however, reduced snowfall (see Eureka, Table 4.2) and increased valley-bottom vegetation reduce discharge peaks and sediment entrainment (Lewkowicz and Wolfe, 1994). These limited data reveal the importance of localized hydroclimatic and catchment controls on yield in nonglacial High Arctic streams. In contrast, yields from the glaciated Schei River and Nicolay Lake were similar in 1973 (Table 4.1), even though discharge produced by glacier melt and the increased availability of glacial sediments (Schei River) would be expected to substantially increase seasonal sediment transport compared with nonglacial catchments (Nicolay Lake) (Lawson, 1993). However, because of the different hydrological regimes in each catchment and the small amount of comparable data, this yield similarity is potentially misleading.

The broad similarity between the varve-estimated sediment yields from Nicolay Lake and other monitored sites suggests that the Nicolay Lake data provide a long term record of annual sediment yield indicative of conditions in the western and central High Arctic islands. Perhaps more important however, the highly variable yield record from Nicolay Lake indicates that mean conditions are difficult to establish without many years of data (Woo and McCann, 1994). Given the length of the varve yield record, it is interesting to consider how representative of average conditions previous yield estimates from High Arctic catchments may have been. While the goal of these studies may not have been to provide an definitive measure of sediment yield, published values can be viewed as authoritative, given the sparsity of yield data from the region.

To evaluate the extent to which short term monitoring projects can provide an accurate estimate of mean and extreme sediment yield conditions, a Monte Carlo simulation was performed using the GEV model developed from the 487 year Nicolay Lake record. A total of 10 000 runs, simulating hypothetical three and ten year river monitoring projects on the river supplying Nicolay Lake, was carried out to estimate the probability of obtaining a) a reasonable approximation of mean sediment yield (±10%), b) a close estimate of the long term 100-year quantile value (90% of Q_{100}), and c) close estimates of both during the monitoring program. Results indicate that the probabilities of obtaining any of these benchmarks are low for a three year project, which are long by High Arctic standards, and only marginally improved by extending the project length to ten years (Table 4.6). Even with ten years of monitoring, the probability of obtaining a close estimate of long term mean sediment yield is only slightly better than 1 in 4. Finally, the simulations suggest that it is extremely unlikely that monitoring for ten years or less will produce reliable estimates of both mean conditions and the magnitude of a 100-year event.

While this test does not directly evaluate previous High Arctic sediment yield estimates, these results are indicative of the limitations inherent in relatively short (<10 years) observational records (Woo and McCann, 1994). Given the low probabilities, it appears unlikely that any of the published High Arctic yield estimates are representative of mean catchment conditions. The high interannual variability observed in these studies likely represents only a small fraction of the long term range of sediment yield and hydrological states. Moreover, the difficulty in establishing mean yield and the inherent variability from these basins makes assessment of changing hydroclimatic conditions based on sediment yield measurements unreliable (Woo and McCann, 1994), especially if future research is also based on short term monitoring projects. Despite the inherent limitations of yield estimates from previous hydrological monitoring projects, they remain an important area of research that can provide a greater understanding of short term hydroclimatic processes and responses (i.e. Woo, 1983; Hardy, 1996).

4.5.2 Rainfall and the paleoclimatic record contained in varved sediments

Rainfall has played a substantial role in influencing overall sediment yield during the past five centuries on Cornwall Island. In total, fifteen events greater than or equal to the 1951/62 events are recorded. These events, representing 3% of the entire record, contribute 15.6% of the total long term sediment yield. Similarly, the 1951 and 1962 events together represent 5% of the record and 17.3% of the yield during the past 50 years. Therefore, the impact of extreme rainfall during the instrumental period is comparable to the last 500 years. The role played by less intense rainfall is difficult to quantify due to problems related to consistently interpreting the subannual rhythmites in the long record. However, when the inferred rainfall component (rhythmites) is removed from the Nicolay yield record for 1948-1978, the mean yield is reduced by 40%, and the yield record contains 59% less variance. For this same period, rainfall events are likely responsible for all but two of the yields exceeding the 5-year quantile, and thus, contribute substantially to the overall data skewness. Therefore, although it cannot be shown directly that a similar rainfall component applies to the entire long record, data from Nicolay Lake indicate the important influence of major rainfall events on sediment yield in this environment.

If differences in past interannual yield behaviour can be largely explained by the occurrence of major rainfall events, then the temporal variations in these sedimentary units suggest that synoptic conditions conducive to major rainfall events have probably varied as well. Heavy rainfall (25 -year quantile) was most frequent during the 17th and 19th centuries (Table 4.4). These periods have been identified as the coldest periods of the past 400 years in the Canadian High Arctic (Alt *et al.*, 1985), and throughout the arctic (Overpeck *et al.*, 1997). World-wide, colder conditions during these times are referred to as the Little Ice Age (LIA) (Grove, 1988; Jones and Bradley, 1992).

Hydrologic process models that assume runoff is largely limited to snow melt, and hence, temperature, would predict reduced discharge intensity and sediment yield during colder periods of the LIA (e.g. Hardy, 1996). However, the Nicolay Lake record shows the very opposite, indicating an increase in the frequency and magnitude of rainfall during the LIA, and generally higher yields as well (Figure 4.5). Therefore, the Nicolay record suggests that colder conditions produced greater sediment yield in this environment. Although these results appear counter-intuitive, the climatology of the High Arctic shows that the synoptic type responsible for the most rainfall at Isachsen also brings the coldest mean summer temperatures (Bradley and England, 1979). Under these conditions, high pressure to the southwest generates westerly flow over the western High Arctic and permits cyclonic activity to reach the region. Recent records indicate that after 1963 and through the

1970s, High Arctic summer temperatures decreased markedly, and cold-wet synoptic types became more frequent (Bradley and England, 1978, 1979). At the same time, sediment yield at Nicolay Lake also increased (Figure 4.5), suggesting a general relationship between higher yields, cooler temperatures, and more frequent cold-wet synoptic types. Therefore, it is hypothesized that the 17th and 19th centuries were also characterized by increased occurrences of cold-wet synoptic types. These conditions would be conducive to higher instances of rainfall and cooler temperatures, producing both increased mean erosion and sporadic events of extreme deposition. In contrast, reduced sediment yield and yield variability during the 16th and early 20th centuries suggest that these periods were characterized by warm, relatively dry synoptic types. If correct, the Nicolay varve record becomes especially important as an indicator of hydroclimatic variations in the High Arctic during the LIA, because the varves provide additional climatic information (precipitation proxy) not apparent in other temperature sensitive records (e.g. Lamoureux and Bradley, 1996; Overpeck *et al.*, 1997). By combining proxy records with dissimilar hydroclimatic responses, the potential exists to identify the short and long term synoptic controls over natural hydroclimatic variability.

Finally, this study demonstrates that similar varve records are unlikely to provide a robust record of a single hydroclimatic variable. In the case of Nicolay Lake, rainfall appears to be responsible for moderate and extreme events, however, the influence of other climatic variables on interannual yield variability (e.g. temperature, spring snowpack) remains poorly understood. Given the limited ability of other lake studies to quantitatively explain yield variance with climatic variables (e.g. Leemann and Niessen, 1994; Hardy *et al.*, 1996), it is quite reasonable to assume that much of the interannual variance is produced by several factors, including some that are non-climatic. Despite these limitations, this study has shown that the potential exists to identify weather-induced sedimentary events which could prove to be an important means of distinguishing the changing role played by different climatic variables, including synoptic types that integrate temperature and precipitation (Bradley and England, 1979; Alt, 1987). Ultimately, this will lead to improved paleoclimatic information from sedimentary records and a clearer understanding of the response of hydrological processes and catchments to natural climatic variability.

Table 4.1. Sediment yields reported from High Arctic catchments compared with estimated yield from Nicolay Lake for the same year. Data from Hot Weather Creek and Lake C2 are included to provide comparison with other published yields, however, the Nicolay Lake record does not extend after 1987. Note the high interannual variability evident at multi-year sites.

Location	Year	Sediment Yield ($t\ km^{-2}a^{-1}$)	Nicolay Lake Yield ($t\ km^{-2}a^{-1}$)	Source
Mecham River, Cornwallis Island	1970	22.1	174.5	Cogley, 1975
	1971	12.7	71.7	Cogley, 1975
Schei River, Ellesmere Island	1973	150.0	177.6	Cogley, 1975
Consett Head River, Melville Island	1974	605.0	109.0	McLaren, 1981
Snowbird Creek, Bathurst Island	1976	25.6	49.9	Wedel *et al.* 1977
Whitebear Creek, Bathurst Island	1976	22.8	49.9	Wedel *et al.* 1977
Hot Weather Creek, Ellesmere Island	1990	51.9[1]	N/A	Lewkowicz and Wolfe, 1994
	1991	1.9[1]	N/A	Lewkowicz and Wolfe, 1994
Lake C2, Ellesmere Island	1991	1.4	N/A	Hardy, 1996
	1992	12.4	N/A	Hardy, 1996

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[1] Value is maximum sediment yield predicted at the site.

Table 4.2. Thirty year precipitation normals (1961-1990) from Canadian Atmospheric Environment Service weather stations in the High Arctic (locations can be found in Figure 4.1). Isachsen normals are based on 1949-1978 data.

	Mean Annual Precipitation (mm equivalent)	Mean Annual Snowfall (cm)	Mean Annual Rainfall (mm)
Alert	154.2	164.9	14.4
Eureka	68.0	53.3	22.4
Isachsen	110.2	79.4	32.4
Mould Bay	104.8	92.9	27.5
Resolute	139.6	97.3	50.4

Table 4.3. Matrix of results from f-test of variance between 50-year periods. Data were normalized with a log-transformation. Matrix values indicate the likelihood that the variance between two periods is different. Results indicating $p<0.10$ are underlined and $p<0.01$ are in bold type. These results indicate the significant difference in variance shown by 1651-1700 and 1801-1850 compared to other periods. Additionally, these same periods show highly significant ($p<0.01$) differences in variance compared to 1501-1550. These results indicate the importance of extreme events in these records: the presence (1651-1700 and 1801-1850) or absence (1501-1550) of extreme yields produces markedly different statistical properties.

Period	Variance	n	1951-1987	1901-1950	1851-1900	1801-1850	1751-1800	1701-1750	1651-1700	1601-1650	1551-1600	1501-1550
1951-1987	0.352	37	0.500									
1901-1950	0.329	50	0.407	0.500								
1851-1900	0.326	50	0.398	0.490	0.500							
1801-1850	0.572	50	0.063	0.027	0.025	0.500						
1751-1800	0.338	50	0.441	0.462	0.452	0.033	0.500					
1701-1750	0.399	50	0.348	0.248	0.240	0.104	0.279	0.500				
1651-1700	0.519	50	0.110	0.055	0.053	0.366	0.067	0.179	0.500			
1601-1650	0.297	50	0.284	0.359	0.368	0.011	0.324	0.149	0.026	0.500		
1551-1600	0.361	50	0.474	0.372	0.362	0.053	0.408	0.362	0.102	0.246	0.500	
1501-1550	0.259	50	0.154	0.200	0.207	**0.003**	0.174	0.064	**0.008**	0.315	0.121	0.500

Table 4.4. Annual sediment yield exceedences for Nicolay Lake, based on 487-year record GEV quantiles. Periods containing 100-year or greater events are shaded.

		Year AD									
Quantile Estimate (years)	Sediment Yield ($t{\cdot}km^2{\cdot}a^{-1}$)	1951-1987	1901-1950	1851-1900	1801-1850	1751-1800	1701-1750	1651-1700	1601-1650	1551-1600	1501-1550
25	292.4	3	-	3	4	1	3	7	2	-	-
50	390.9	1	-	3	4	1	1	2	1	-	-
100	518.9	-	-	1	3	-	-	1	1	-	-
200	685.4	-	-	-	1	-	-	-	-	-	-
500	985.5	-	-	-	1	-	-	-	-	-	-
1000	1293.7	-	-	-	1	-	-	-	-	-	-

Table 4.5. Comparison of summer weather conditions at Isachsen with the presence or absence of subannual sediment units in Nicolay Lake. Note that the Isachsen station was closed during the spring of 1978.

Year	Rainfall (mm)	Heavy Rain (>7.5mm)	MDD season/Before rain event		Subannual Laminae	Comments/Explanation
1948	38.3	Yes	150	25	No	Abundant low intensity rainfall
1949	10.8	No	210	200	No	Dry year
1950	12.1	No	148	120	Yes	?
1951	55.0	Yes *	250	250	Yes	Major rainfall event
1952	16.7	Yes	210	145	No	Rainfall follows very warm period
1953	73.4	Yes	75	20	Yes	
1954	83.4	Yes(several)	220	100	No	?, Last major event freezing rain
1955	28.1	Yes	100	55	No	?
1956	28.2	Yes	130	30	No	Rain during nival melt period
1957	38.0	Yes	300	250	No	Follows exceptional warmth, last rain freezing
1958	31.9	Yes	348	75/340	No	First rain nival, second after exceptional warmth
1959	5.8	No	260	-	No	Dry year
1960	30.7	Yes	250	100	No	Abundant low intensity rainfall
1961	47.1	Yes	110	30	Yes	Nival rainfall
1962	31.5	Yes*	300	<5	Yes	Major nival rainfall event
1963	53.8	Yes	200	20/160	Yes	First rain with nival melt, later rainfall prolonged
1964	15.9	No	80	20	No	Rainfall with nival melt

*-These years contain the two largest single day's rainfall in the Isachsen record. #- A regional rainfall event of >15 mm is recorded in many weather station and camp records. Underlined years: a reasonable explanation for the presence/absence of a rainfall-sedimentary unit can be made. **Bold** years: the rainfall-sedimentary record is not reconcilable.

Table 4.5. continued

Year	Rainfall (mm)	Heavy Rain (>7.5mm)	MDD season	Before rain event	Subannual Laminae	Comments/Explanation
1965	17.6	No	120	120	Yes	Late snowmelt with relatively high temperatures
1966	38.5	Yes	240	160	No	Rainfall follows warm temperatures in August
1967	39.6	Yes	100	48	Yes	Nival rainfall
1968	13.7	No	190	160	No	Dry year
1969	46.6	Yes	115	40/75	Yes	Prolonged wet period in August
1970	31.9	Yes	150	10/145	No	First with nival, second follows most MDD
1971	23.2	No	250	240	No	Rain follows a very warm summer
1972	9.2	No	80	-	No	Dry year
1973	49.8	Yes	180	75/180	Yes	First rainfall with nival melt?
1974	21.1	Yes	150	25	No	Nival rainfall
1975	46.1	Yes	120	40	No	Nival rainfall
1976	26.7	No	130	10/110	No	First with nival,second rain after warm period
1977	12.3	No	225	5	No	Dry year
1978	n/a	Yes#	n/a	n/a	Yes	Major regional rainfall event indicated at other sites

*-These years contain the two largest single day's rainfall in the Isachsen record. #- A regional rainfall event of >15 mm is recorded in many weather station and camp records. Underlined years: a reasonable explanation for the presence/absence of a rainfall-sedimentary unit can be made. **Bold** years: the rainfall-sedimentary record is not reconcilable.

Table 4.6. Monte Carlo estimated probabilities of obtaining approximate values of long term a) mean sediment yield, b) 100-year quantile (Q_{100}), and, c) both a) and b) from short term hydrological monitoring projects. Results are based on occurrences of the stated criteria during 10 000 simulations. Simulated sediment yields were calculated using the 487-year GEV parameters determined from the Nicolay Lake varve record.

Criteria:	Probability, P(x)	
	3-year	10-year
±10% of long term mean sediment yield	0.176	0.292
Projects with one year > 90% of Q_{100}	0.038	0.129
Projects containing both of the above criteria	0.000	0.006

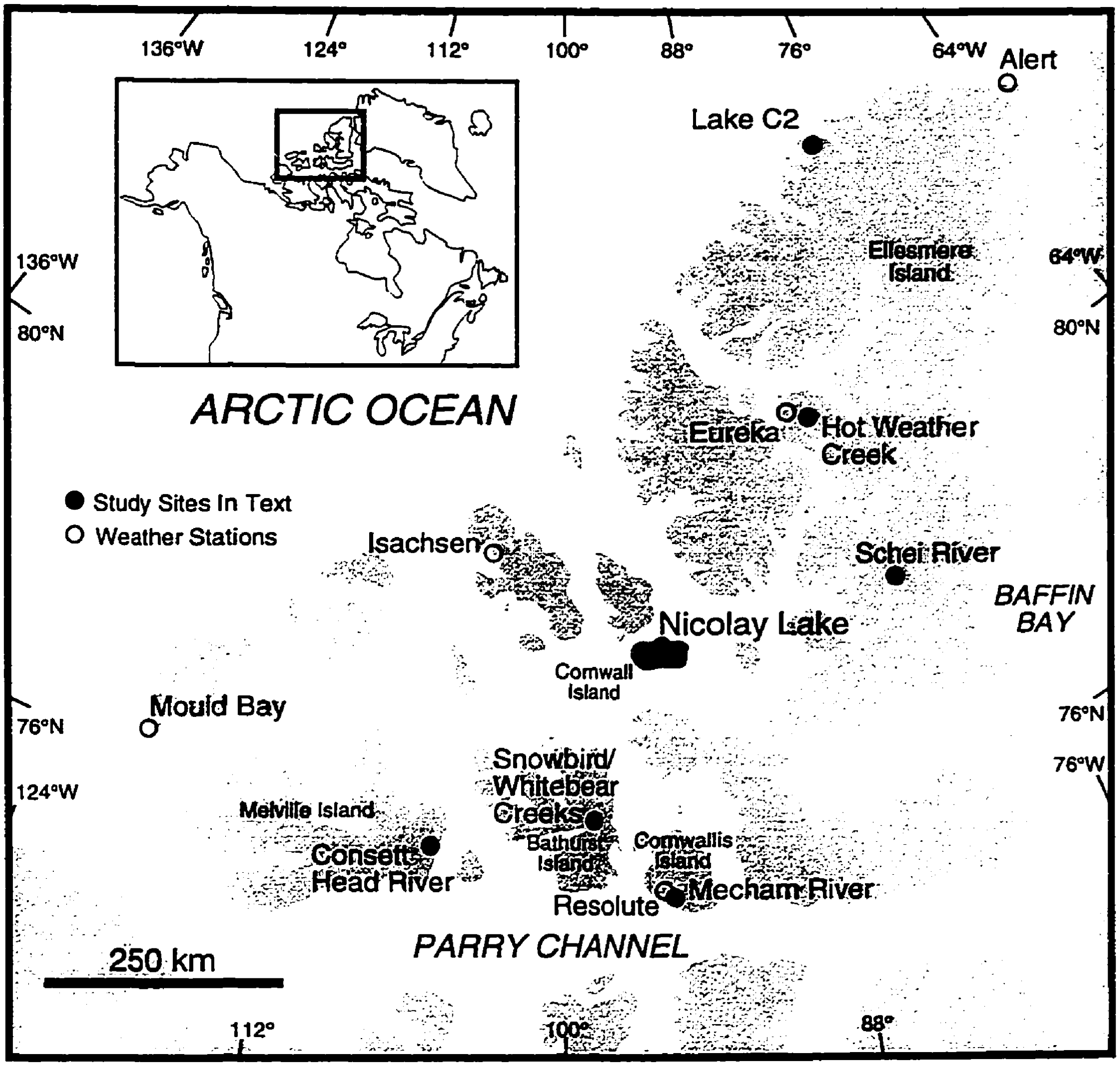

Figure 4.1. Locations of sites in the Canadian High Arctic referred to in the text. Generally, the High Arctic is considered to be the region north of Parry Channel.

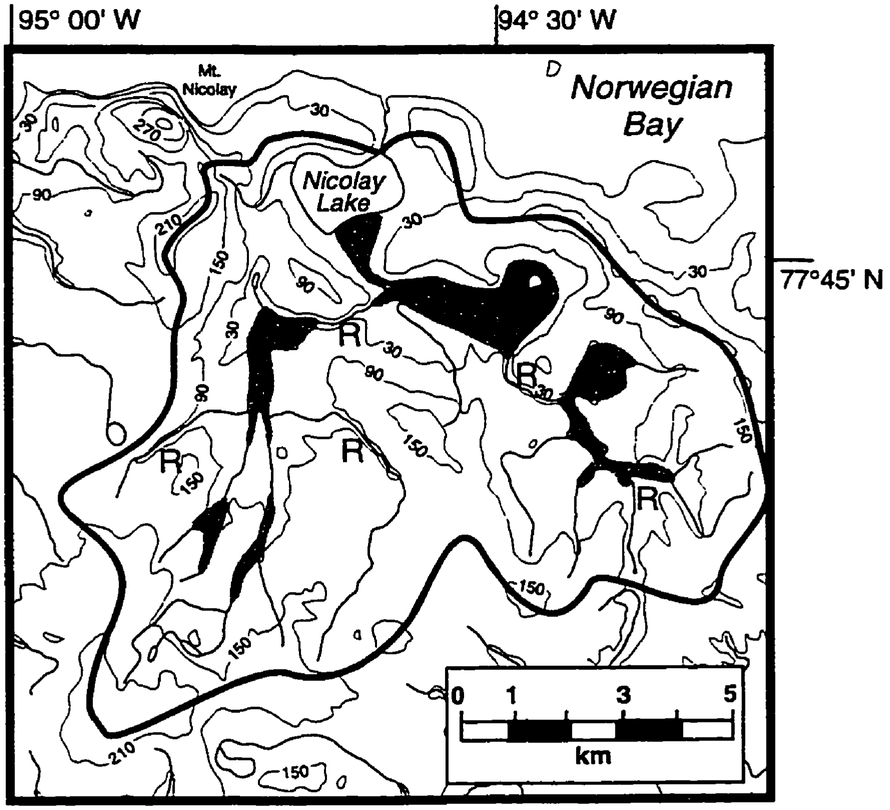

Figure 4.2. Map of the Nicolay Lake catchment on north-central Cornwall Island. Areas in the catchment containing significant modern and inactive floodplain sediments that are actively eroding are shaded. These areas are likely sources for much of the catchment yield. Major ravines (indicated as: R) link different floodplains, and are areas that commonly contain snow drifts and deep snow which pond early season meltwater. Contour interval is 90 metres.

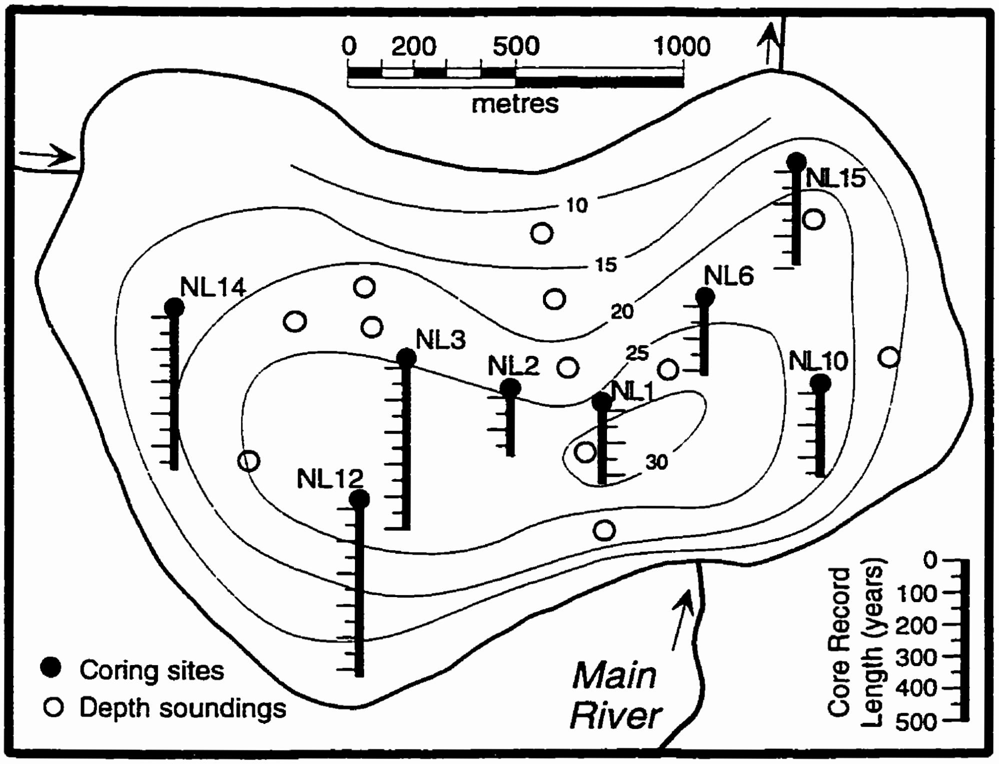

Figure 4.3. Bathymetric map of Nicolay Lake indicating the locations of cores used to estimate catchment sediment yield. Note that the three cores in the western lake contain longer records due to overall lower deposition rates.

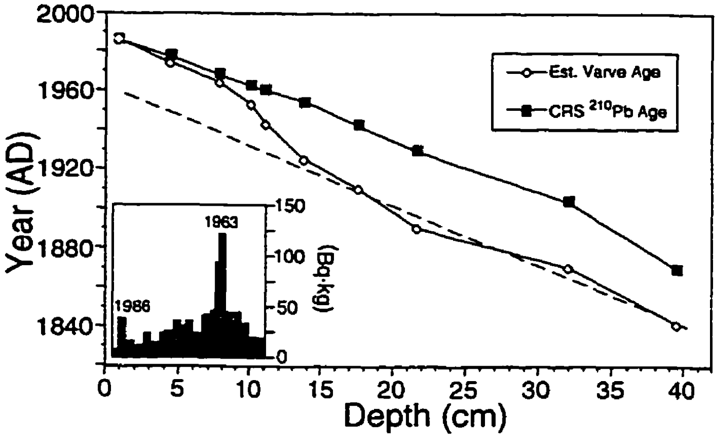

Figure 4.4. Isotope geochronology of the upper sediments in core NL2. Results from continuous ^{137}Cs determinations (inset) show a distinct 1963 bomb-test peak and a smaller 1986 Chernobyl peak. Modelled ^{210}Pb ages (CRS-constant rate of supply) show no evidence for long term divergence from estimated varve ages. The short term departure of the varve-lead ages at 8-14 cm depth is likely the product of ^{210}Pb concentration during a period of low accumulation rates. Following this interval, the lead ages show near-constant slope with varve ages (dashed line).

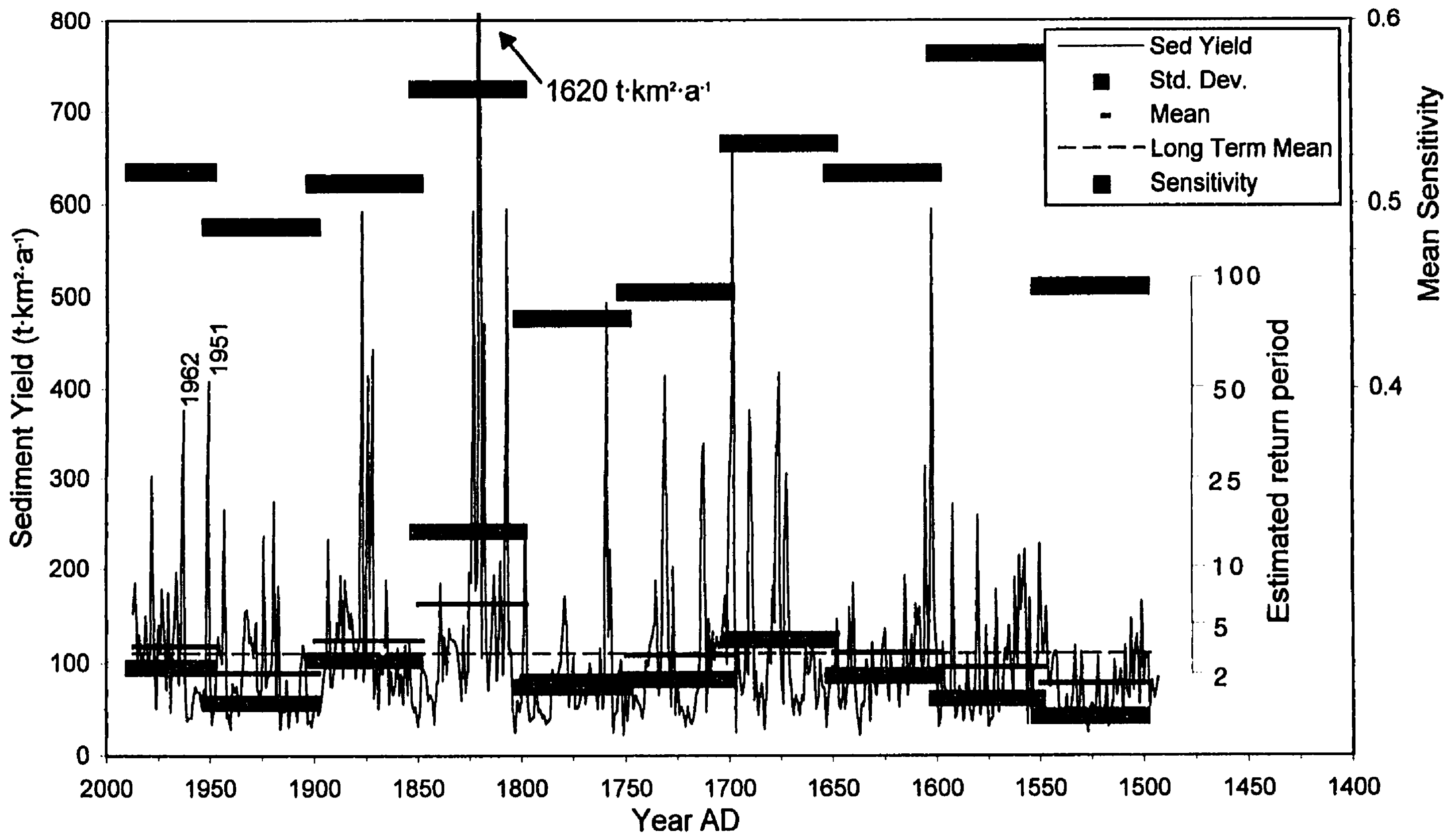

Figure 4.5. Long term sediment yield reconstructed from Nicolay Lake. Long term and 50-year means, standard deviation, and mean sensitivity (interannual variance) are indicated. Estimated GEV-PWM quantiles are indicated on the right inset ordinate scale.

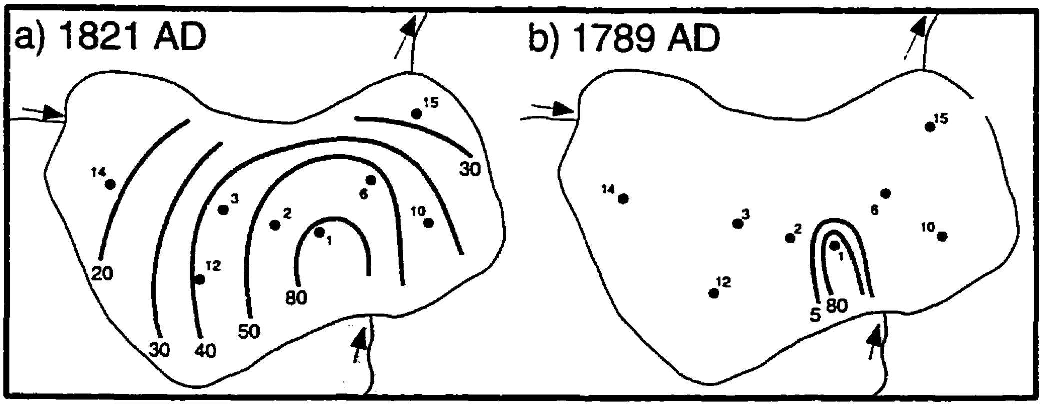

Figure 4.6. Sediment isopach maps showing the two end members for recognized sedimentation patterns in Nicolay Lake. Predicted proximal-distal thinning occurred in most years (a) and likely indicates catchment-sourced sediment from that year's runoff. In contrast, the localized deposition in 1789 (b) likely records a subaqueous slump and hence, is not indicative of catchment yield or hydroclimatic conditions. By analysing annual patterns, the effects of these anomalous deposits were removed from the sediment yield record (Chapter 3).

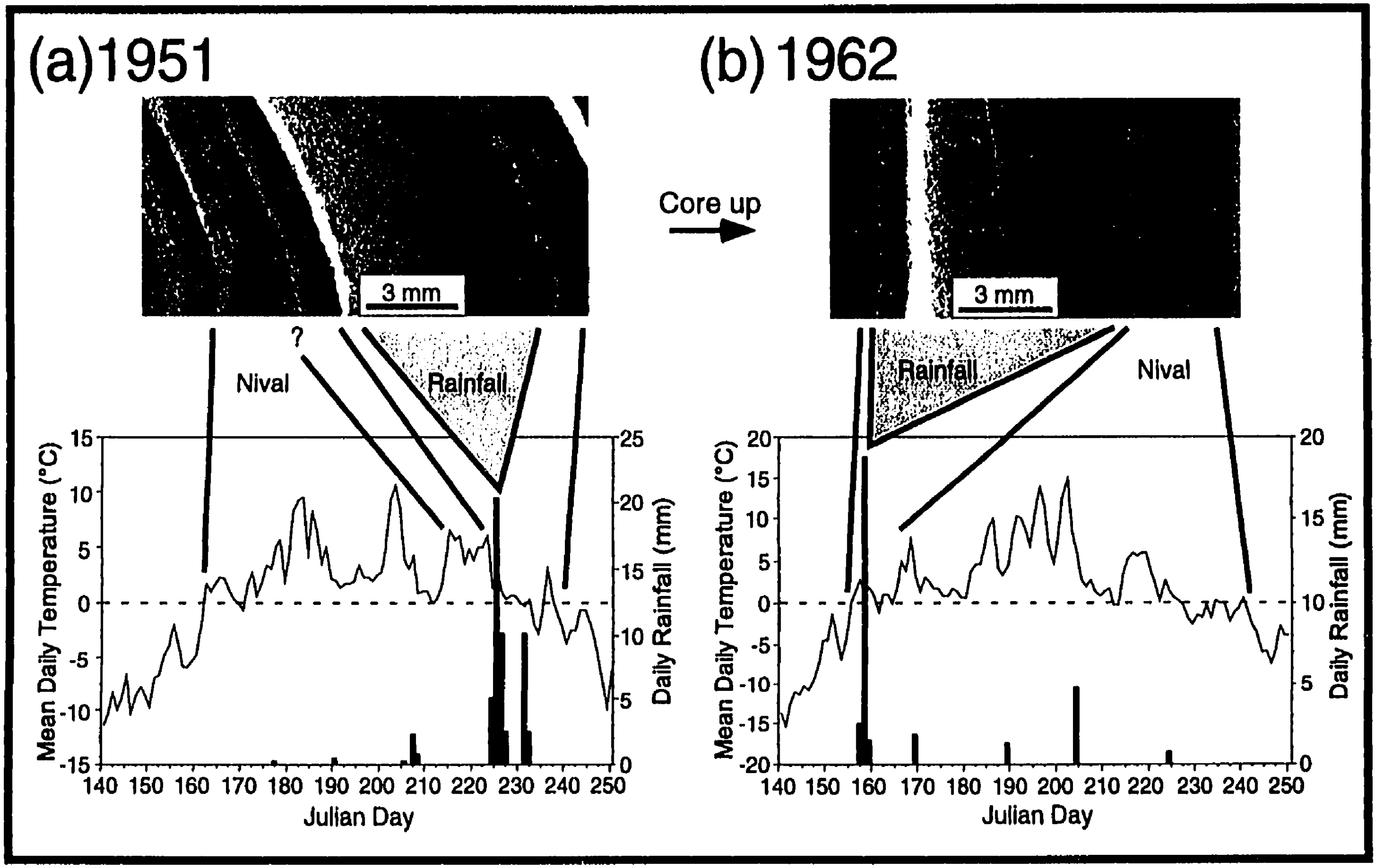

Figure 4.7. Comparison of Isachsen weather data and sedimentary structures from (a) 1951 and (b) 1962. Periods dominated by snowmelt are indicated, as are the deposits considered related to the major rainfall events on Julian Day 226 (1951) and 158 (1962).

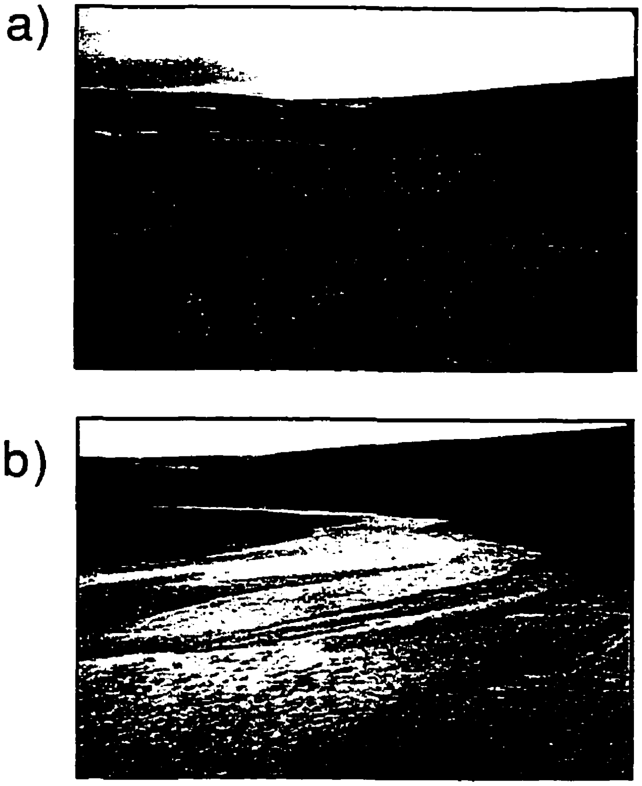

Figure 4.8. Photographs of the main catchment river 1 km above Nicolay Lake showing changes produced by a major rainfall event in 1996. On July 16 (a), channel material is dominantly gravel and sparse vegetation covers the adjacent floodplain (foreground). After eight days of rainfall (b), the channel is filled with sand, and several bars are also apparent in the thalweg. The floodplain in the foreground is covered with sand, completely covering the vegetation.

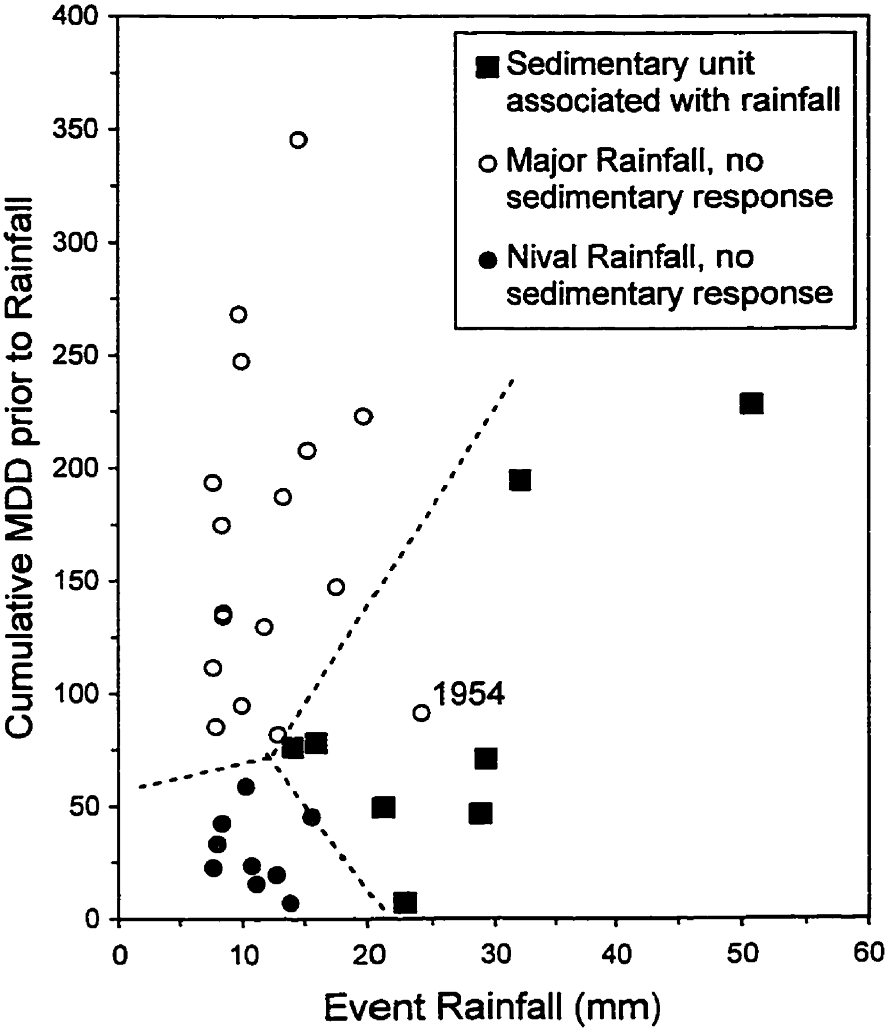

Figure 4.9. Relationship between the sedimentary response in Nicolay Lake to rainfall events (multi-day) exceeding 7.8 mm total and melting degree days (MDD) prior to the rainfall event. All weather data is from the Isachsen station (1948-1977). Subannual deposits are associated with large (>13 mm total) storms. However, when substantial MDD (>150) occurred prior to the rain, soil water storage prevented a recognizable deposit. Early season rainfall was likely obscured by nival snowmelt, with exception of intense events. A major event in 1954 (24 mm total) does not appear to have produced a distinguishable sedimentary unit (see text).

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CHAPTER 5: INCREASED RAINFALL FREQUENCY DURING THE LITTLE ICE AGE RECORDED BY VARVED LAKE SEDIMENTS IN THE CANADIAN HIGH ARCTIC

(For submission to *Nature)*

5.1 Introduction

Much of the debate regarding future climate change is centered on temperature predictions (Houghton *et al.*, 1996) and most paleoclimatic researchers have focused on temperature reconstructions from proxy records. This is particularly the case in polar regions where ice cores (e.g. Hammer *et al.*, 1980, Fisher and Koerner, 1994) and lake sediments (Lamoureux and Bradley, 1996; Hardy and Bradley, 1997; Overpeck *et al.*, 1997) are generally the only possible high resolution proxy records. Results from these studies have improved our understanding of recent climatic variations and possible forcings, but only address one dimension of climatic variability. In the Canadian High Arctic (the area north of 75°N), ice cores and varved sediments have clearly indicated that colder conditions were widespread during the period 1600-1900 AD (Overpeck *et al.*, 1997) but, as for many other areas, little is known about precipitation changes during this period. This paper presents the first proxy record of summer rainfall conditions from the region and indicates that cold, wet synoptic conditions were more frequent during the LIA.

5.2 Methods and Interpretations

To reconstruct past rainfall events, a network of eight sediment cores from Nicolay Lake, Cornwall Island, Nunavut (77°46'N, 94°45'W) was used to identify a lake-wide varve accumulation record and estimate annual catchment sediment yield. Anomalously thick deposits related to subaqueous turbidites were identified and distinguished from varves deposited in years with exceptionally high sediment yield (Chapter 3). The short hydrological season at this site generates a well-defined seasonal rhythmicity in the sediments and ^{137}Cs and ^{210}Pb determinations from recent sediments support the interpretation that the rhythmites are varved[3] (Chapter 3). The final varve record was constructed by cross-dating the eight cores, thereby eliminating counting errors and providing a consistent record of interannual fine-grained sediment yield (Lamoureux and Bradley, 1996; Zolitschka, 1996; Chapter 3). Although the error for the varve chronology cannot be directly estimated, counting errors related to thin structures or minor sediment disturbances (Lamoureux and Bradley, 1996; Zolitschka, 1996) are rare in the Nicolay varves. Therefore, the chronology is estimated to be accurate to within 5% or better (Chapter 3).

One or more subannual rhythmites frequently occur within the varve structures (Chapter 2). These subannual units record an abrupt increase in sediment delivery to the lake and relate to events of duration ranging from hours to weeks, depending on the location in the lake (see similar examples in: Gilbert, 1975; Smith, 1978; Desloges and Gilbert, 1994; Leemann and Niessen, 1994). The record used for this study was taken from a distal location in the relatively small lake, so it is likely that the subannual rhythmites represent sediment delivery related to synoptic events (Smith, 1978; Chapter 2). Comparison with the weather record from Isachsen, located 200 km to the west, indicates that the two thickest subannual rhythmites deposited during the past 40 years coincide with the two largest daily rainfall events[4]. Similarly, the presence or absence of subannual

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[3] Divergence occurs between the estimated varve and constant rate of supply ^{210}Pb ages for a short section of the record. This discrepancy is believed to be the result of minor reversals in unsupported ^{210}Pb resulting from low sediment accumulation rates in this section of the core (Chapter 3). The lack of long term divergence between the varve and lead ages, together with the ^{137}Cs profile, sedimentology, and pronounced seasonality of runoff, support the hypothesis that the laminae are varves.

[4] The sequence of the subannual rhythmites in 1951 and 1962 further supports the interpretation that these units are related to major rainfall. Rainfall in 1951 was late in the summer and the thick sediment unit occurs at the top of the 1951 varve. Conversely, the major rainfall in 1962 was during the initial snowmelt and the thick rhythmite associated with this event occurs at the base of the 1962 varve (Chapter 4).

rhythmites corresponds to the occurrence (or absence) of major rainfall events (>13 mm total) in all but four years of the 1948-1977 weather record[5]. Therefore, it is hypothesised that the majority of the subannual rhythmites represent a runoff and sediment delivery response to major rainfall events in this semi-arid environment. These rainfall events generate above-average sediment yields due to the high sediment availability in the catchment and the sparsity of protective vegetation (Edlund and Alt, 1989; Woo and McCann, 1994; Chapter 4). Periods of increased yield lasting 10-30 years generally follow extreme yielding years (Figure 5.1). These major events likely increased subsequent sediment availability and transport by temporary channel storage and the transfer of sediment to main channels by earthflows and gullying (Hodgson, 1977; Woo and McCann, 1994).

5.3 Paleoclimatic Interpretation

The periods in the varve record that suggest the occurrence of frequent rainfall show a close correspondence to cold periods indicated by paleotemperature records from the High Arctic. Most notably, the persistently highest sediment yield of the 493-year record occurs during the 19th century, which coincides with the coldest interval of the LIA throughout the arctic (d'Arrigo & Jacoby, 1993; Overpeck *et al.*, 1997). Increased occurrences of rainfall between 1670-1760 also correspond to more localized colder conditions in the arctic (Overpeck *et al.*, 1997), and the increased incidence of heavy rainfall between 1550-1610 occurs at a time of cool conditions and more positive mass balance in the Devon Island ice

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[5] Four years in the 30-year weather record cannot be reconciled with the presence or absence of subannual rhythmites in the varves. In 1950, major rainfall was not recorded at Isachsen but the varve record shows a subannual rhythmite. In contrast, major rainfall in 1954 and 1955 does not appear to have produced discernible sedimentary units in the Nicolay record. Only in 1965 does a subannual rhythmite appear to be related to a late summer snowmelt event during an otherwise cold summer (Chapter 4).

core (Alt, 1985; Fisher and Koerner, 1994; Overpeck *et al.*, 1997). Furthermore, a marked increase in yield after 1962 coincides with colder summers in the Canadian High Arctic, more frequent positive mass balance on ice caps, and increased frequency of cold, wet synoptic types in the region[6] (Bradley and England, 1978, 1979). Increased sediment yield and more frequent major rainfall events after the 1960s appear unremarkable compared to other periods during the LIA. In contrast, rainfall frequency is lower during periods of warmer conditions that characterized the early 1500s and 1900s, and the last half of the 1700s (D'Arrigo & Jacoby, 1993; Overpeck *et al.*, 1997). Years with a higher proportion of melt layers in the Agassiz ice core (Fisher and Koerner, 1994), that record higher temperatures also correspond to periods of lower sediment yield and infrequent rainfall, especially between 1850-1960 (Figure 5.1). When circum-arctic temperatures appear to have peaked from 1935-1960 (Overpeck *et al.*, 1997), the varves from Nicolay Lake reveal lower yield coincident with infrequent rainfall.

5.4 Regional Climatic Forcing: Volcanic Aerosol Loading

Overpeck *et al.* (1997) suggested that most of the observed cooling during the LIA appears to relate to major peaks in sulfate loading in the GISP2 ice core (Zielinski, 1995). Volcanism has been frequently proposed as a possible forcing mechanism for the colder weather of the LIA (Lamb, 1970; Grove, 1988; Bradley and Jones, 1992). Studies of the climatic response to major eruptions have generally shown an abrupt, but short-lived effect on hemispheric temperatures (Kelly and Sear, 1984; Sear *et al.*, 1987; Bradley, 1988). Nonetheless, results from these studies are complicated by competing ENSO effects on temperature (Mass and Portman, 1989), and by the different location and season for each eruption (Sear *et al.*, 1987). However, significant temperature decreases seem to occur between 1-12 months after a major eruption and can last for up to three years (Kelly and Sear, 1984; Sear *et al.*, 1987; Bradley, 1988). Moreover, some proxy climate records

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[6] Cold-wet synoptic types are relatively infrequent in the instrumental weather record, however, they are considered to be the conditions that produce the largest proportion of major rainfall events in the region (Bradley and England, 1979).

suggest that the effects can be longer lived (LaMarche and Hirschboeck, 1984; Scuderi, 1990; Crowley *et al.*, 1997; Dawson *et al.*, 1997) and the potential for longer term climate changes in response to repeated eruptions is indicated by a negative correlation of volcanic and temperature proxies during the past five centuries (Hammer *et al.*, 1980; Wigley, 1991; Jones and Bradley, 1992).

The sediment yield record from Nicolay Lake shows a close correspondence between more frequent rainfall and increased volcanic aerosol loading to the atmosphere. Above-average acidity is apparent in the Crête ice core record through most of the last five centuries (Hammer *et al.*, 1980), with the exception of the late 1700s, and the mid-1800s and 1900s (Figure 5.1). The periods of lower acidity coincide with increased melt on the Agassiz Ice Cap (Fisher and Koerner, 1994) and reduced sediment yield and frequency of rainfall-induced sedimentation in the varve record. Lower yields during the early 1500s occur at a time of variable aerosol conditions in the Crête record, although the GISP2 and GRIP records suggest that this period was characterized by frequent smaller volcanic eruptions (Zielinski, 1995; Clausen *et al.*, 1997). In several cases, periods with frequent rainfall begin within 2-5 years of major eruptions (Figure 5.1). Figure 5.2 shows sediment yield in the years following the 1601(unknown source) and 1815 Tambora eruptions. In both cases, there is no immediate response, however, several major rainfall events occur in the decade following the eruptions. Recently, increased sediment yield and rainfall recorded in the Nicolay Lake varves coincide with a decrease in High Arctic temperatures and increased frequencies of cold, wet synoptic types following the 1963 Mount Agung eruption (Bradley and England, 1978,1979). Collectively, these results suggest a decadal-scale change in atmospheric conditions following major eruptions that leads to increased occurrences of major rainfall in the High Arctic. In contrast, the effects of some large eruptions appear to be absent in the varve record, particularly the 1784 Laki event (Hammer *et al.*, 1980; Clausen *et al.*, 1997). However, the Laki event is considered to be over represented in the Greenland cores (Hammer *et al.*, 1980; Zielinski, 1995; Clausen *et* *al.*, 1997) and other proxy records suggest that the late 1700s were relatively warm (Overpeck *et al.*, 1997), possibly due to increased solar irradiance (Lean, 1991; Lean *et al.*, 1995). Therefore, volcanic loading from Laki may have been offset by solar gains, reducing the frequency of the synoptic conditions required for increased rainfall. Similar conditions may have prevailed during the early 1900s when aerosol loading by several large volcanic eruptions (Lamb, 1970; Robock and Free, 1995) was coincident with the highest insolation of the past 400 years (Lean, 1991; Lean *et al.*, 1995).

These results suggest that volcanic activity and the rainfall events recorded in Nicolay Lake are linked by increased instances of storm penetration into the Canadian Arctic Islands during cold periods. Increased meridional flow and the deepening of longwaves in the polar front over North America could explain increased moisture flux to the Beaufort Sea and cyclogenesis in the Arctic Basin (Serreze, 1995). North American tree ring records suggest such a synoptic pattern may have been more frequent during colder periods of the LIA (Lough and Fritts, 1987). Wavelet analysis of the Nicolay Lake sediment yield record provides supporting evidence for a synoptic link between volcanic activity and rainfall occurrence. The 55-70 year spectral signal in the 1800s and the weaker c.120 year signal between 1650-1900 (Figure 5.3) are intriguing given the similar approximate cyclicities apparent in the volcanic sulfate record from the GISP2 record (Zielinski, 1995). The major 55-70 year spectral signal in the 1800s is associated with the highest sediment yields of the entire record, suggesting the correlation between volcanic forcing and varve accumulation was stronger at this time than at any other during the past 500 years. Additionally, sediment yield in the early 1800s shows strong periodicity in the 2-3 and 10-12 year bands (Figure 5.3) which coincides with the episode of high yield and increased rainfall during the early 1800s (Figure 5.1). Several possible mechanisms might explain the higher frequency components, including the quasibiennial oscillation of the stratosphere (QBO, Holton and Tan, 1982), ENSO activity (Rasmusson and Carpenter, 1982), and the 11-year irradiance cycle (Lean, 1991), signals that are most apparent in low- and mid-latitude climate records (Graham, 1995; Lean *et al.*, 1995). Because these periodicities are dominant in the early 1800s when major rainfall was most frequent, it is possible that the spectral signal indicates an increased influence of southern synoptic systems in the Canadian High Arctic.

5.5 Conclusions

The sediment record from Nicolay Lake indicates an increased incidence of major summer rainfall during the coldest periods of the LIA, suggesting that these periods were characterized by cold, wet synoptic systems (Bradley and England, 1979). These results also provide additional support for the possible forcing of summer climate in this region by volcanic activity (Overpeck *et al.*, 1997). Changes observed in weather records during the past thirty years (Bradley and England, 1979) and the Nicolay Lake varves both confirm that climate change in the High Arctic is not strictly limited to temperature. Therefore, climate models that predict modest summer temperature changes in the High Arctic (e.g. Kattenberg *et al.*, 1996) must also address potentially important precipitation changes as well in order to evaluate possible future climate in the arctic.

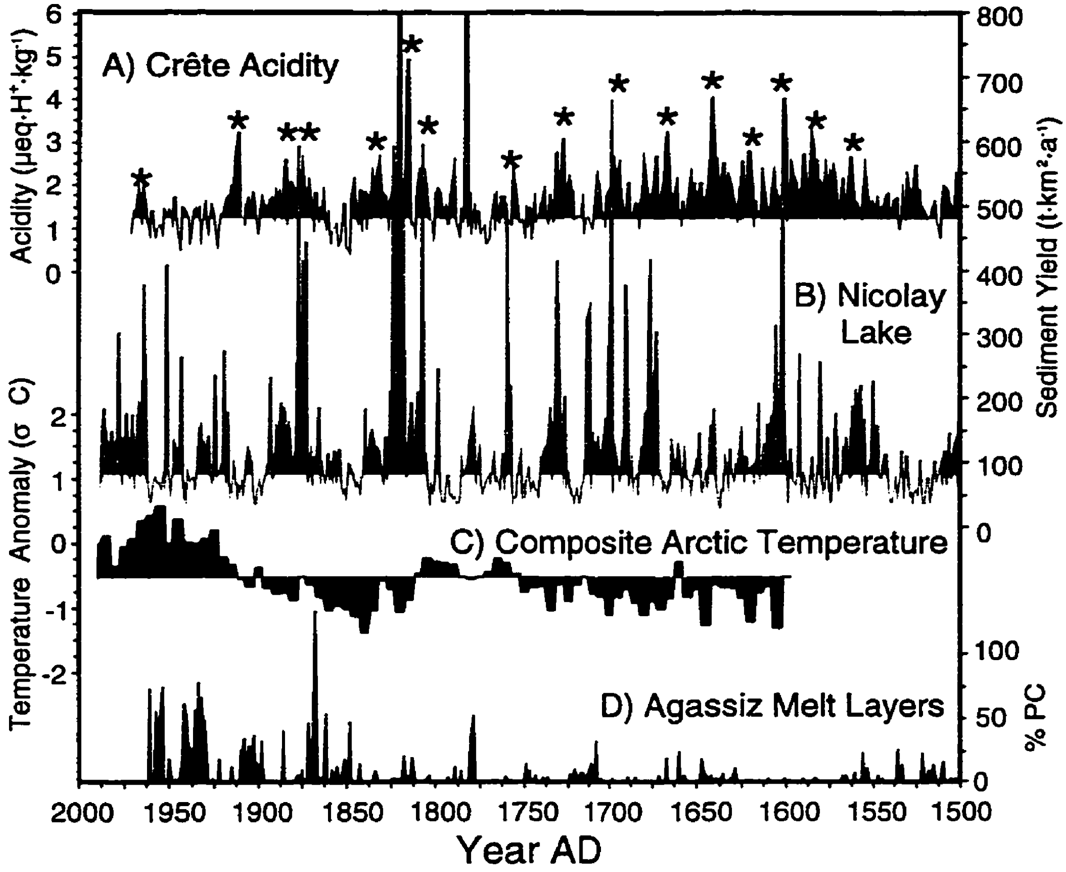

Figure 5.1. The A) Crête ice core volcanic acidity record (Hammer *et al.*, 1980) compared to variations in major arctic climate proxies during the past 500 years: B) sediment yield estimated from Nicolay Lake varves (Chapter 4); C) composite circum-arctic summer temperatures from ice core, tree ring, varve, and marine sediment records (Overpeck *et al.*, 1997); and, D) Agassiz ice cap, Ellesmere Island, percentage annual melt layers (Fisher and Koerner, 1994). All records have annual resolution, except C), which has 5-year resolution. Shading baselines in the first three records represent: A) mean background acidity, B) 2-year reccurence (modal) sediment yield, and C) 1600-1980 mean temperature anomaly. Stars above major volcanic acidity peaks indicate eruptions followed by one or more extreme sediment yields at Nicolay Lake within 2-5 years.

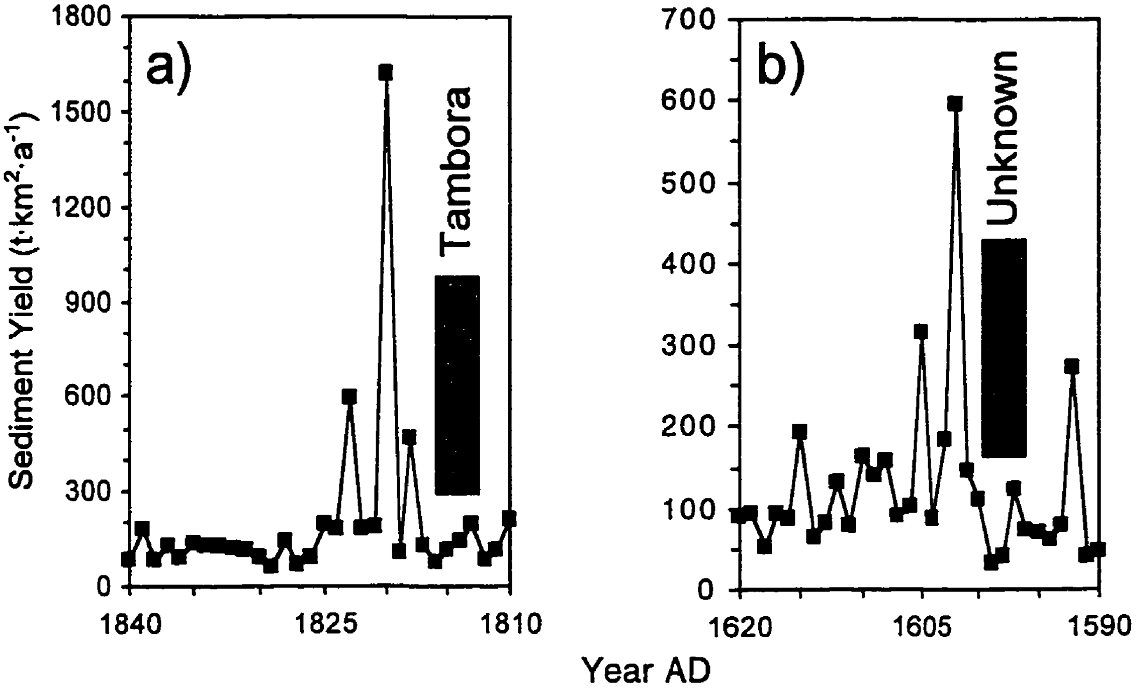

Figure 5.2. The temporal relation between two major historical volcanic eruptions recorded globally, compared with rainfall-induced, extreme sediment yields at Nicolay Lake. The 1815 eruption of Tambora, Indonesia (a) has been considered the reason that the 1816, "year without a summer" occurred throughout much of the northern hemisphere (Grove, 1988). In comparison, a major eruption in 1600-01 (source unknown) has been identified in most northern hemisphere ice core records (Robock and Free, 1995). Other major eruptions with similar responses in Nicolay Lake are indicated in Figure 5.1.

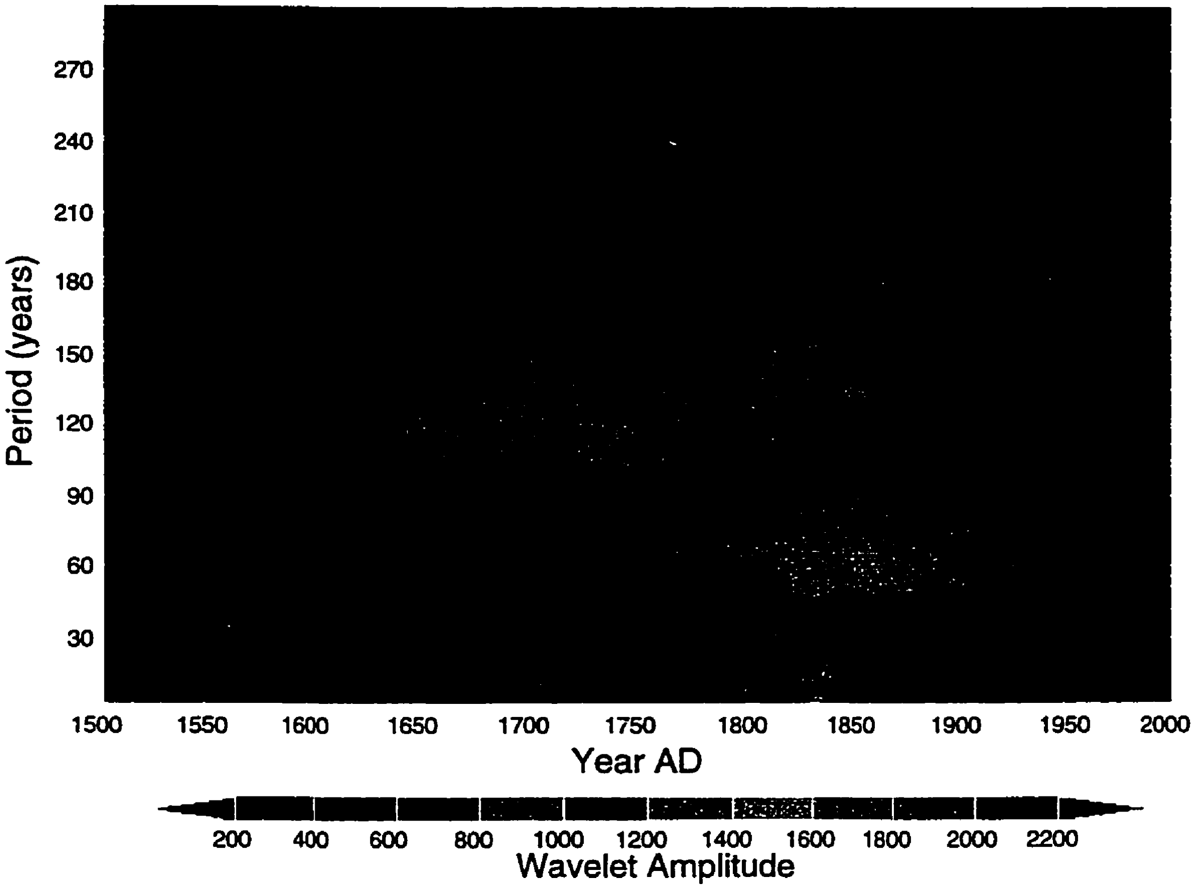

Figure 5.3. Time-frequency plot of wavelet amplitude for the Nicolay Lake sediment yield record. Note the high frequency peaks in the early 1800s (2-3 and 10-13 years).

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CHAPTER 6. CONCLUSIONS

6.1 General Conclusions

Results from this study have indicated that the sediment yield signal from varved sediments contains both systematic noise caused by geomorphic controls and an important hydroclimatic signal produced by individual weather events. These conclusions have important implications for reconstructing past environments using varved sediments, and the methods used in this work have general applicability to other environments where varves are found.

Geomorphic controls that alter the accumulation of clastic sediment at a given point in the lake can be classified into three major categories: catchment controls on sediment availability; changing configuration of the fluvial-lacustrine interface; and intra-lake sediment redistribution (e.g. turbidites). In Chapters 2 and 3, each of these three controls were identified and last two removed from the long term varve sediment yield record. The role of changing sediment availability was shown to be an important factor in the presence or absence of varves in the lake, due to the resulting changes in sediment accumulation rates. Deglacial sediments appear to have become an important paraglacial sediment source for Nicolay Lake during the past five hundred years as a result of Holocene glacioisostatic emergence of the catchment and the development of a direct fluvial connection to the lake (Chapter 2). Clearly, similar conditions could occur in other High Arctic catchments, although this factor has not been considered in previous studies.

Within the varve record, systematic anomalies in the annual sediment accumulation patterns were identified using a combination of isopach mapping and statistical analysis (Chapter 3). These methods clearly identified the anomalous deposits produced by turbidites and changes to the location of sediment inflow from the delta, both of which have important consequences for the reconstruction of sediment accumulation. By selecting core records on which these influences are minimized, a robust record of fluvially-sourced sediment accumulation was created for subsequent evaluation of the hydroclimatic signal.

This made it possible to distinguish years in which high sediment accumulation was produced by exceptional catchment sediment yield from years characterized by localized, thick deposits generated by turbidites. The identification of high yield years was critical to creating a record of major rainfall events, the first record of its kind from the arctic and elsewhere.

Further analysis revealed the strong influence of individual, short-lived rainfall events on interannual sediment yield variance. This result is significant because it shows how carefully sedimentary records must be interpreted. Clearly, lake sediments contain a record of both short term (hours to days) and long term (seasonal, interannual) events. Distinguishing the processes that control specific sedimentary deposits is therefore not a straightforward problem, with the potential for the misinterpretation of short term deposits as representative of longer periods of accumulation, and vice versa. It is clear from Nicolay Lake that a varve may provide evidence for both short and long term processes in a manner similar to or opposite of what might be assumed. In many cases, the largest sediment yields were generated by storms lasting less than a few days, while summers dominated by nival runoff often had substantially smaller yields. The High Arctic hydrological literature emphases the role of nival snow melt, and rarely considers the impact of rainfall on sediment transport. However, these results clearly show the importance of rainfall in this environment, and suggest that it is critical for future varve studies to try to identify the yield signal generated by a *variety* of processes.

The rainfall signal from Nicolay Lake provides a unique and new paleoclimatic record that complements existing proxy temperature records. For the first time, the potential exists to evaluate the response of synoptic conditions to possible climatic forcings. Although generating new proxy climate records is often used as a justification of paleoclimatic research, often, the resulting records simply reproduce the variability known from other records. In this study, the result is both broadly (and in detail) supportive of other temperature proxies, and provides an entirely new perspective on climate variability. Further research directed at identifying new climatic proxies will substantially further our understanding of the full range of natural climatic variability and permit a better understanding of possible future climate.

6.2 Future Research

Three areas of future research have developed from this work which could lead to substantial progress in developing more reliable paleoclimatic records from varved sediments. This research has identified the potential for hydroclimatic information from subannual rhythmites. However, a primary limitation in using these structures to reconstruct events is that observations are at best qualitative, and consistently interpreting and classifying structures is difficult. Discriminating between events lasting days, weeks, and the entire runoff season remains highly subjective. One approach to this problem is to quantify the sedimentary textural information contained in each lamina, and to combine this information with numerical sedimentation models to estimate the period of deposition for each rhythmite. Further, these methods could be used to distinguish between specific depositional processes, particularly underflows and interflows, in order to identify the hydrological context of each sedimentary unit. Progress with this problem will require the development of "microsedimentological" methods to quantify grain size textural changes. Promising methods might include: calibrated image analysis of thin sections or radiographs, geochemical proxies of sediment texture (e.g. trace metal content, lithology), flume modeling, analysis of deposits produced in controlled laboratory conditions, dedicated field monitoring studies of sediment dispersal and deposition, and numerical simulations of sedimentary processes and deposition.

Long term variation in sediment availability remains a difficult factor to account for in varve records. While progress has been made in this area of fluvial geomorphology, most studies have documented changing sediment availability at low temporal resolutions. Therefore, to assess the consequence of geomorphic preconditioning in varve records, research must be directed at determining the controls that affect the high frequency (annual to decadal) sediment yield signal. Potentially, the sedimentary record may contain quantifiable evidence of these effects. Lithological, geochemical and isotopic proxies could prove useful in determining the relative contribution of different sediment sources and their temporal variability. Coupled with detailed catchment surveys and process studies, this approach could lead to substantial progress in this problem.

Finally, the eolian sand grains identified in Nicolay Lake could provide a useful, independent paleoclimatic proxy record. Further work is required to substantiate the eolian hypothesis for the origin of these grains and how they are transported to deep-water sediments. In particular, calibration with late-season satellite imagery of lake ice cover may provide an indication of the relationship between the spatial distribution of eolian deposits and ice extent. Additionally, sedimentary fossil records could be used to further examine the relationship between aquatic productivity, lake ice cover, and eolian deposits.

6.3 Final comments

The most serious limitation to the interpretation of varved sediments as a proxy record of hydroclimatic conditions is the lack of detailed process work to accompany the sedimentological investigations. However, detailed sedimentological work provides an important impetus and direction for process studies. Armed with a knowledge of the key characteristics of the sedimentary deposits, process investigations can be focused on resolving important questions, and hence, lead to a substantial improvement in our understanding of these processes in the past. In this manner, sedimentary records will continue to contribute to the larger science and debate regarding the nature and future of global environmental change.

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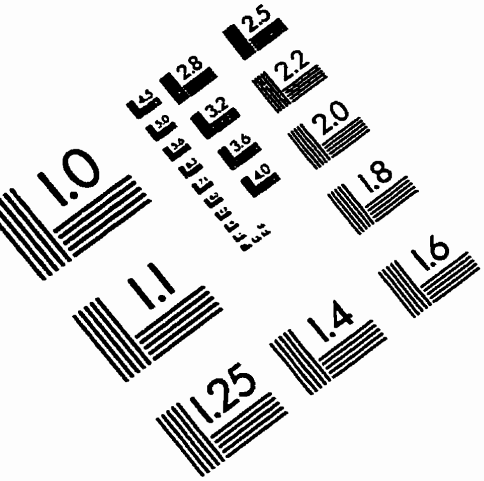

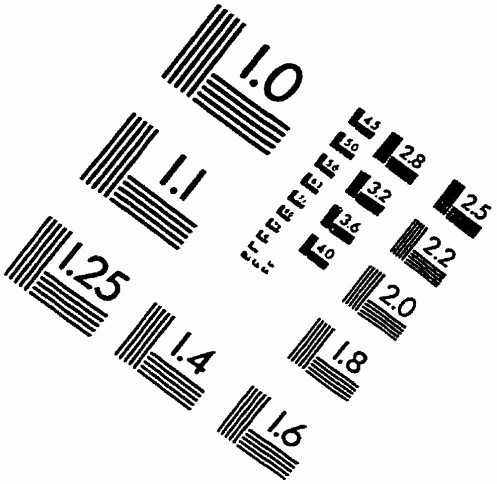

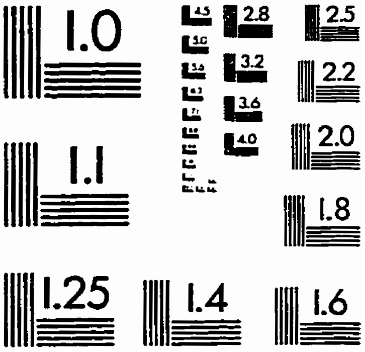

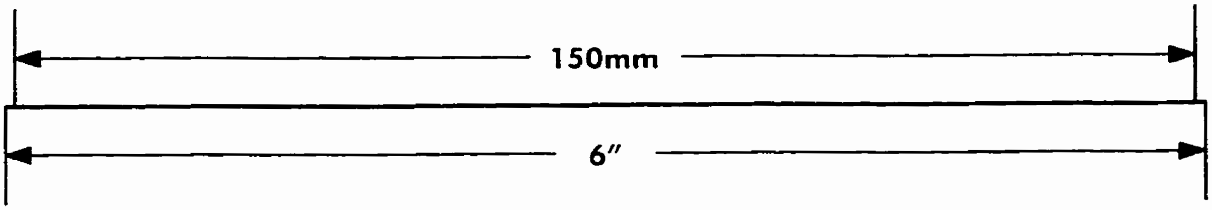

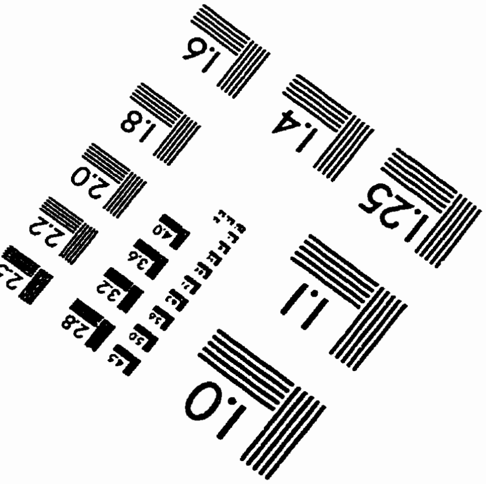

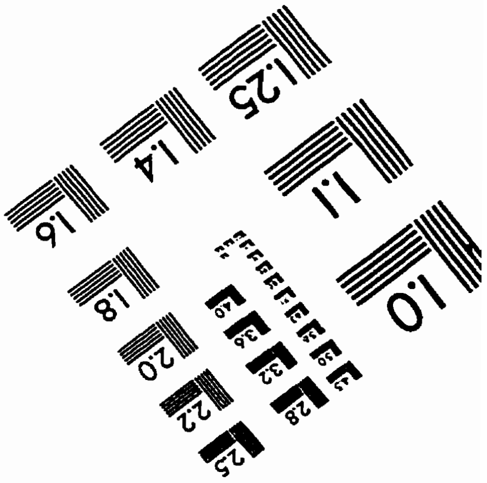

APPLIED IMAGE, Inc
1653 East Main Street
Rochester, NY 14609 USA
Phone: 716/482-0300
Fax: 716/288-5989

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