HOLOCENE GLACIER FLUCTUATIONS IN GARIBALDI PROVINCIAL PARK, SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA

by

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M.Sc. (Geography, Geology, Mineralogy), University Freiburg, 2001

THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

In the
Department
of
Earth Sciences

SIMON FRASER UNIVERSITY

Spring 2006

APPROVAL

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Degree: Doctor of Philosophy

Title of Thesis: Holocene glacier fluctuations in Garibaldi Provincial Park, southern Coast Mountains, British Columbia

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ABSTRACT

Glacier fluctuations of the last 10,000 years have been reconstructed in Garibaldi Provincial Park in the southern Coast Mountains, British Columbia, from historical documents, dendrochronologic and lichenometric dating of moraines, and radiocarbon dating of fossil wood in glacier forefields. Six major periods of glacier advance are recognized: 7700-7300, 6400-5100, 4300, 4100-2900, 1600-1100 ^{14}C years BP, and the last millennium. Evidence for each of these six periods was found in the forefield of Sphinx Glacier, the only glacier in western North America with so complete a record. Evidence for each period, except the 4300 ^{14}C years BP event, was found at two or more sites, showing the regional significance of the advances. The data demonstrate that the Little Ice Age in Garibaldi Park began as early as AD 1000. The earliest maximum was achieved in the 12th century, followed by recession until sometime in the 14th century. Several glaciers advanced into forests in the 14th century, culminating with the construction of moraines in the late 17th, early 18th, 19th, and early 20th centuries. Helm Glacier provides a near complete record of fluctuations since the 14th century. Glaciers receded between the 1930s and 1960s at average annual rates of about 30 m. Between the 1960s and 1980s, glaciers advanced up to 300 m, but since then they have receded at annual rates of 5-10 m. Ice cover has decreased by about 240 km^2 since the Little Ice Age maximum, with most of this loss occurring after the 1920s. Some small glaciers in the park have already vanished, and more are likely to disappear if the current trend continues. The record from Garibaldi Park is broadly synchronous with records of glaciers throughout the world, suggesting a global forcing mechanism. Hemispheric temperature change can explain glacier behaviour during the last millennium. The Garibaldi record shows a relation to reconstructed Holocene sunspot activity, suggesting that changes in solar activity probably play an important role in global climate change.

Keywords: glacier fluctuations, dendrochronology, Holocene, Little Ice Age, Garibaldi Provincial Park, southern Coast Mountains, British Columbia

To my parents

Civilization exists by geological consent - subject to change without notice. (William Durant)

ACKNOWLEDGEMENTS

I sincerely thank the many people who have helped me during my time at Simon Fraser University. First and foremost, I thank my senior supervisor, Dr. John J. Clague, for his support in all aspects of this research. I thank the staff of the Department of Earth Sciences and Office of Graduate Studies. The support and friendship of my friends and fellow graduate students in the Quaternary Geoscience Research Centre, especially Jon, John, Lauren, Michelle, Tracy, Kenna, Berto, Brian, Greg, and Tom, are greatly appreciated. My supervisory committee members, Drs. Gerald Osborn, Dan Smith, and Rolf W. Mathewes, provided advice and constructive criticism. I thank the external and internal examiners, Drs. Brian H. Luckman and Lionel Jackson, respectively, for their interest in this work and their helpful comments.

This work would not have been possible without the permission of B.C. Parks; I particularly thank Chris Platz for his support and flexibility. The Rangers in Garibaldi Park – Katy, Ed, Brad, Jenny, James, and Scott – helped me get to some of my study sites. I also thank the pilots of Glacier Air Tours and Whistler Air for transporting me to Snowcap Lakes and Stave Glacier, and Berto, Jon, John, Jerry, Vanessa, Chanone, Kenna, and Brian for assistance in the field.

Many others have helped me with my research. Dr. Gerald Osborn shared unpublished radiocarbon ages from several glaciers in Garibaldi Park and provided entertainment during fieldwork. British Columbia Archives allowed me to access the original glass negatives of the first geodetic survey of the park by A.J. Campbell in 1928-

1929. Michael Feller, President of the British Columbia Mountaineering Club, made available the club's collection of historical photos of Garibaldi Park. I thank Dr. Brian Menounos for producing the digital elevation model of the park, which he freely shared with me, and Dr. Sami Solanki for sharing his Holocene sunspot reconstructions. Finally, support and encouragement from Drs. Brian H. Luckman, Greg C. Wiles, Lori Daniels, Olga Solomina, and Kurt Nicolussi are acknowledged.

Financial support was provided by the Natural Sciences and Engineering Research Council of Canada through Research Grants to Dr. Clague, and by the Geological Society of America through a Research Grant to me. I was partially supported by Graduate Fellowships and the President's Ph.D. Research Stipend from Simon Fraser University.

I want to extend my sincerest thanks to my family and friends for their unflinching moral support and encouragement. Last but not least, I want to thank my parents for their moral and financial support and their encouragement, which has allowed me to get where I am today.

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CHAPTER 1
INTRODUCTION

The 1990s was the warmest decade of the last century and probably the warmest of the last millennium in the Northern Hemisphere (Mann *et al.*, 1998). Most climate scientists agree that this recent warming is anomalous, but the cause of the warming and the effect of humans on climate are debated. Our understanding of Earth's climate and the role that humans play in modifying it can be improved by studying the behaviour of climate over long periods, ranging from centuries to millennia (Bradley and Jones, 1993; Mayewksi *et al.*, 2004; Moberg *et al.*, 2005). Many biological and physical systems are sensitive to even minor changes in climate, and their careful study provides a long-term perspective on climate change and its causes.

Temperate alpine glaciers are sensitive to changes in climate and have been used to reconstruct past climate both on long timescales (e.g., Denton and Karlén, 1973) and short ones (e.g., Oerlemans, 2005). Previous research indicates that glaciers in the western Canadian Cordillera and adjacent areas responded rapidly to historical climate change (Burbank, 1982; Luckman *et al.*, 1987; Harper, 1993; McCarthy and Smith, 1994; McCabe and Fountain, 1995; Bitz and Battisti, 1999; Kovanen, 2003; Lewis and Smith, 2004a). Their deposits and landforms archive information on climate change in western Canada throughout the Holocene and especially the last millennium (Ryder and Thomson, 1986; Luckman *et al.*, 1993; Luckman, 2000; Luckman and Villalba, 2001).

Background

Our current understanding of Holocene glacier fluctuations is based largely on terrestrial evidence, but the terrestrial record is biased because most Northern Hemisphere glaciers were most extensive in the later part of the Little Ice Age (AD 1600-1900) and evidence of earlier Holocene advances was largely destroyed or obscured by these late advances. Major glacier recession in recent decades, however, has revealed new evidence of pre-Little Ice Age glacier activity in many glacier forefields around the world and has thus provided a much better understanding of Holocene glacier history (reviews by Ryder and Thomson, 1986; Luckman *et al.*, 1993; Nicolussi and Patzelt, 2000; Hormes *et al.*, 2001; Glasser *et al.*, 2004; Holzhauser *et al.*, 2005).

Most studies of Holocene glacier fluctuations in western Canada have been conducted in the Rocky Mountains (Luckman *et al.*, 1993; Luckman, 1995, 1996, 2000, in press; Osborn *et al.*, 2001; Wood and Smith, 2004). Only a few studies from the Coast Mountains had been published when I began my research in British Columbia in 2001 (Ryder and Thomson, 1986; Smith and Laroque, 1996; Smith and Desloges, 2000). However, much progress has been made over the last four years, with many papers documenting Holocene glacier fluctuations in the southern Coast Mountains and on Vancouver Island (Larocque and Smith, 2003; Laxton *et al.*, 2003; Smith, 2003; Lewis and Smith, 2004a, 2005; Menounos *et al.*, 2004; Reyes and Clague, 2004; Haspel *et al.*, 2005; Jackson and Smith, 2005; Smith *et al.*, 2005; Reyes *et al.*, 2006).

One area of western Canada that has received considerable attention over the past 70 years is Garibaldi Provincial Park, about 70 km north of Vancouver (Taylor, 1936, 1937; Mathews, 1951; Mokievsky-Zubok and Stanley, 1976; Ricker, 1979; Ricker *et al.*, 1983). Even so, the Holocene history of the park's glaciers was known only in the broadest sense prior to this study.

Research Objectives

The main objective of this research was to reconstruct glacier fluctuations in Garibaldi Provincial Park over three different time periods: (1) the Holocene prior to the Little Ice Age; (2) the last millennium (Little Ice Age); and (3) the 20th century. The forefields of 18 glaciers in the park were investigated, and a regional chronology was developed by dating advances at several sites. Radiocarbon dating of fossil wood, dendrochronologic and lichenometric dating of moraines, and acquisition of historical documents were the main methods of investigation. The accuracy of reconstructed glacier margins and the temporal resolution of advances differ according to the dating methods that were used and are greatest for the 20th century. The record from Garibaldi Park was compared to records of glacier fluctuations elsewhere in western Canada and, to a lesser extent, mountain areas in Europe and South America in order to address the issue of climate forcing.

My research in Garibaldi Park is underpinned by my interest in global commonalities in glacier behaviour. Glaciers throughout the world have retreated in recent decades, and global glacier fluctuations during the last millennium appear to have been similar. Based on an extensive literature review and research in both the Southern and Northern hemispheres, I am of the opinion that there are more similarities than differences in the timing of global glacier fluctuations in the Holocene. My long-term goal, thus, is to develop a global picture of glacier behaviour on decadal to millennial timescales to better understand climate change and climate forcing. In this thesis, I compare my observations on glacier fluctuations in Garibaldi Park to local climate and glacier mass balance data and to dendrochronologically reconstructed regional climate. The comparisons show that the Garibaldi Park record can be explained by regional climate forcings. However, my priority was to compare the Garibaldi record with hemispheric and global data to show that there are many broader commonalities and that Holocene glacier fluctuations in Garibaldi Park can be explained by global forcing mechanisms.

Thesis Overview

The thesis comprises five main chapters. Chapter 2 summarizes methods that have been used to reconstruct paleoenvironmental and paleoclimatic change in western Canada. It also summarizes results of previous research. An important conclusion of this chapter is that more confidence can be placed in studies that use multiple types of evidence than in studies that rely on only one type. The manuscript was published in 2004 (Koch *et al.*, 2004a). My co-authors contributed critical reviews and some data.

Chapter 3 describes limitations in the use of tree rings to date landforms. Published glacier-related dendrochronology research in the western Cordillera of the Americas is summarized and evaluated. I show that, even though the dendrochronological method has been widely applied, improvements are still possible. These improvements are illustrated using results gathered through a detailed study in Garibaldi Park. Dr. Clague assisted with writing this chapter.

Chapter 4 describes glacier behaviour in Garibaldi Park in the 20th century based on study of aerial photographs, historical ground photographs, and photographs that I took during flights over the park in 2002 and 2003 and during fieldwork between 2002 and 2004. Glaciers in the park were inventoried and their present-day and Little Ice Age maximum extents were mapped on a digital elevation model. The digital elevation model used in this study was provided by Dr. Brian Menounos (University of Northern British Columbia). Dr. Clague assisted with writing this chapter.

Chapter 5 examines glacier fluctuations in Garibaldi Park during the past millennium. Detrital and *in situ* wood samples, including branches, logs, snags, and stumps, are present in all nine glacier forefields that were studied in detail, providing a well constrained record of the Little Ice Age history of the glaciers. Lichen and living trees were used to date stabilization and abandonment of moraines at the end of the Little Ice Age. This chapter builds on previous work by Mathews (1951). Several unpublished radiocarbon ages were provided by Dr. Gerald Osborn (University of Calgary). Dr. Clague assisted with writing this chapter.

Chapter 6 considers Holocene glacier fluctuations in Garibaldi Park prior to the Little Ice Age. Radiocarbon ages on detrital and *in situ* stumps and snags in several glacier forefields provide evidence for five major advance periods prior to the Little Ice Age. Several unpublished radiocarbon ages were provided by Dr. Osborn. Dr. Clague assisted with writing this chapter.

Chapter 7 summarizes the main results, significance, and limitations of the research. It also makes recommendations for future work.

CHAPTER 2
ENVIRONMENTAL CHANGE IN GARIBALDI PROVINCIAL PARK, SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA[1]

Abstract

We reconstructed Holocene environments in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia, by examining a diverse set of proxy paleoenvironmental records, including tree rings, lake sediments, glacial landforms, and photographs. This integrated study, in combination with previous research in adjacent areas, provides a more detailed picture of past climate, vegetation, and glacier extent in Garibaldi Park than has heretofore been available. The data suggest recurrent, complex, and successively more extensive glacier advances during the last half of the Holocene, followed by dramatic warming, snow and ice loss, and a rise in treeline in the twentieth century. The multi-proxy approach used in this study is broadly applicable to other mountain areas. It yields more reliable and robust paleoenvironmental reconstructions than approaches based on only one or two types of data.

Keywords: paleoenvironment, glacier fluctuations, treeline, lake sediments, Holocene, Garibaldi Provincial Park, southern Coast Mountains

[1] The following chapter has been published as: Koch, J, Menounos, B. Clague, J.J., and Osborn, G., 2004. Environmental change in Garibaldi Provincial Park, southern Coast Mountains. *Geoscience Canada*, 31: 127-135; reprinted with permission of the Geological Association of Canada.

Introduction

The Kyoto Accord and recent droughts on the Canadian Prairies have heightened public interest in climate change. In many areas of the Northern Hemisphere, the 1990s were the warmest decade of the last century and, possibly, the last 1000 years (Fig. 2.1; Mann *et al.*, 1998). Most climate scientists agree that this recent warming is anomalous, but debate continues about its source. Part of the difficulty in establishing the cause of warming on such short timescales is that Earth's climate system is complex, strongly non-linear, and behaves in ways that are poorly understood. One way to improve our understanding of Earth's climate is to study its behaviour over long periods, ranging from centuries to millennia or more (Bradley and Jones, 1993).

Many biological and physical systems are sensitive to changes in temperature, precipitation, and other climate variables. Their careful study may provide a long-term perspective on climate change and its causes. Confidence in such proxies as faithful recorders of past climate is increased when a common climate signal can be obtained from several independent sources (Mann, 2002).

Alpine and subalpine environments are particularly sensitive to climate change. Many ecological and geomorphic processes in high mountains are influenced by changes in precipitation and temperature (Ryder, 1998; Luckman and Kavanagh, 2000). We use a multi-proxy approach to reconstruct past precipitation and temperature in Garibaldi Provincial Park in the southern Coast Mountains north of Vancouver over the past several millennia. Garibaldi Park is an ideal location for this research because 60% of the area is above treeline, 21% is covered by snow and glacier ice, and its climate is controlled by both maritime and continental air masses. In addition, Garibaldi Park is near a major urban centre and is one of the most visited provincial parks in British Columbia.

In this paper, we briefly discuss previous paleoenvironmental research in the mountains of western Canada and present some of our findings from Garibaldi Park. The objectives of the paper are to (1) illustrate the main methods used in Holocene alpine paleoenvironmental research in the Cordillera of western Canada, (2) show the power of multidisciplinary research in elucidating past environments, and (3) summarize the history of late Holocene environmental change in the park.

Our research is partly driven by the premise that a better understanding of past climate change is important for forecasting future impacts of a warming climate. As glaciers in the southern Coast Mountains recede and, in some cases, disappear, the timing and magnitude of runoff may change significantly, affecting fish populations, power generation, and water supply. The disappearance of glaciers may also impact tourism, as they are a major attraction for outdoor enthusiasts. Furthermore, changes in treeline can adversely impact some plants and wildlife that depend on open parkland.

Climate Change Research in Western Canada

Researchers have used historical climate and observational data in conjunction with proxy climate records to reconstruct decadal- to centennial-scale fluctuations in climate over the last millennium (Fig. 2.1). The period that has received the most attention is the Little Ice Age, which began about AD 1200 and ended about AD 1900 (Grove, 2001; Luckman, 2004). Global surface air temperatures during the Little Ice Age may have averaged about 1º C lower than today, but fluctuated markedly over decadal and centennial timescales (Bradley and Jones, 1993). Most glaciers were more extensive during the Little Ice Age than at present. Those in the Canadian Rockies, for example, achieved their maximum extent of the last 10,000 years in the seventeenth to nineteenth centuries (Luckman, 2000).

Much of the research on Holocene glacier and climate fluctuations in western Canada has been done in the southern Canadian Rocky Mountains (see Luckman, 2000, for references). A variety of methods have been used to identify and date former glacier margins in the Rockies, including geomorphic analysis, stratigraphic and sedimentological observations, radiocarbon dating of fossil plants in glacial sediments, dendrochronology, and lichenometry. Changes in tree growth at high elevations and changes in sediment delivery to proglacial lakes have also been used to infer climate and glacier fluctuations during the Holocene (Leonard, 1997; Luckman, 2000).

Other mountain ranges in western Canada have been studied in far less detail than the Rockies, and much of that work has been done in the British Columbia Coast Mountains (e.g., Mathews, 1951; Brink, 1959; Ryder and Thomson, 1986; Ryder, 1987; Desloges and Ryder, 1990; Smith and Laroque, 1996; Smith and Desloges, 2000; Gedalof *et al.*, 2002; Larocque and Smith, 2003; Clague *et al.*, 2004). Most of these studies, however, utilize only one or two types of paleoenvironmental proxy data to detail past climate change. In this article, we use documentary, geomorphic, sedimentological, and biological evidence to more fully document paleoenvironmental change in one area of the Coast Mountains over the past several millennia.

Study Area

Garibaldi Provincial Park is located in the southern Coast Mountains, about 70 km north of Vancouver, British Columbia (Fig. 2.2). It is one of the first provincial parks established in the province, having been given park status in 1927 after several years of lobbying by recreational and environmental enthusiasts. There are over 150 glaciers in

Garibaldi Park, including two icefields larger than 10 km^2 (Garibaldi Neve and Mamquam Icefield). Several peaks are more than 2500 m in elevation. Mount Garibaldi (2678 m asl) is only 20 km from tidewater at the head of Howe Sound.

The landscape of Garibaldi Park has been strongly shaped by Quaternary continental and alpine glaciation. Mount Garibaldi is a Quaternary volcano, and its present form is the product of an explosive eruption at the end of the last glaciation, about 13,000 years ago. At that time, the western half of the volcano erupted onto glacier ice filling nearby Cheakamus and Squamish valleys, and subsequently collapsed when the ice melted (Mathews, 1952).

The southwestern part of the park is strongly influenced by maritime air masses, but climate becomes increasing continental to the north and east. Average annual precipitation at Squamish, at the head of Howe Sound, is 2370 mm, but it declines to 1230 mm at Whistler, 60 km to the north. Overall, the climate is humid and cool, with very wet winters and dry summers. Annual precipitation ranges from 1000 to more than 3000 mm (water equivalent). More than 75% of the precipitation falls as snow between October and March.

Vegetation in Garibaldi Park is altitudinally zoned. A forest dominated by mountain hemlock and subalpine fir covers most areas between 1000 m and 1700 m asl (Brooke *et al.*, 1970). At the upper limit of this zone, continuous forest gives way to parkland comprising islands of small, commonly stunted trees and subalpine meadows (Brooke *et al.*, 1970).

Paleoenvironmental Proxies

Instrumental records, photographs, and documents are the most reliable sources of information on past vegetation, ice cover, and climate in mountains. Photographs and maps are available for Garibaldi Park, but only for the last 90 years. Few climate data exist for the park, and climate data from adjacent areas only reach back to the late 19th century. Thus other means must be used to assess environmental change. Fortunately, Garibaldi Park contains many natural climate archives. One example is the park's forests. The widths and densities of annual rings in trees are partly controlled by climate, specifically temperature, precipitation, and snow cover. Furthermore, since tree rings can be resolved to the year, they afford opportunities to date glacier advances, for example where trees have been overridden by a glacier. Times of glacier advance and retreat can be less precisely determined by radiocarbon dating *in situ* and detrital wood in glacier forefields or glacial deposits, and by measuring lichens and soils on moraines and other glacial landforms (Luckman, 1998a; Larocque and Smith, 2003). Proglacial lake sediments are another valuable climate proxy. Many proglacial lakes experience higher sedimentation during times of more extensive ice cover or rapid glacier retreat (Leonard, 1986a, 1997; Menounos, 2002). Sediments in many proglacial lakes are varved (annually laminated) and thus offer the same temporal resolution as trees for paleoenvironmental studies. They also may provide a continuous record of environmental change, unlike moraines and other glacial landforms, and that record may extend much farther back in time than living trees. A disadvantage of lake sediment records is that sedimentation in lakes can be influenced by factors that are not related to glacier fluctuations, for example landslides and floods. In addition, lags may exist between the production of sediment under glaciers and its delivery to lakes.

Glacier Fluctuations

Glaciers in western North America advance or retreat in response to changes in winter accumulation and synoptic conditions during summer (e.g., Burbank, 1982; Bitz and Battisti, 1999; Moore and Demuth, 2001). The net mass balance of Sentinel Glacier in Garibaldi Park, for example, is positively correlated with winter precipitation ($r^2 = 0.70$) and negatively correlated ($r^2 = -0.32$) with summer temperature (Bitz and Battisti, 1999). Inter-annual to inter-decadal changes in winter accumulation in western North America are influenced by large-scale, ocean-atmospheric processes, including the El Niño-Southern Oscillation (ENSO) (Shabbar and Khandekar, 1996; Shabbar *et al.*, 1997), and the Pacific Decadal Oscillation (PDO), an index of inter-annual to inter-decadal North Pacific sea surface temperature anomalies (Mantua and Hare, 2002). PDO and ENSO exert their strongest control in the mountains of western North America during winter (Mantua and Hare, 2002).

Glaciers that have a persistent positive net mass balance will adjust their areas, lengths, and thickness to accommodate the increased mass. They typically leave moraines and trimlines, delimiting their former extents long after they have receded. Conspicuous moraines and trimlines in Garibaldi Park delineate the maximum recent cover of ice during the Little Ice Age (Figs. 2.2 and 2.3).

The time of the Little Ice Age maximum in Garibaldi Park may differ from glacier to glacier by as much as decades due to differences in glacier response times, but Figures 2.2 and 2.3 give a sense of the amount of ice loss in the park since the most extensive advance of the Little Ice Age in the early eighteenth century. At least 630 km^2 (33%) of the park was covered by ice in the early eighteenth century. Ice cover in 1996 was 390 km^2, a loss of 38% in less than 300 years (Koch *et al.*, 2003a). Moraines dating to the late nineteenth century are very close to Little Ice Age maximum ice limits, thus most of the ice loss has happened in the last 150 years. In fact, much of the thinning and retreat dates to the last 80 years (Fig. 2.3) and occurred during two intervals, one between about 1930 and 1960 and another starting in the late 1970s and continuing to the present. The two retreat phases were separated by a stillstand or minor readvance of many glaciers in the late 1960s and early 1970s (Fig. 2.3). Glaciers in other parts of the Canadian Cordillera have fluctuated in a similar manner to those in Garibaldi Park since the late nineteenth century (e.g., Osborn and Luckman, 1988; Luckman, 2000).

Ages of glacier advances can be estimated by dating plant remains in lateral and terminal moraines, or by determining the age of trees or lichens growing on the moraines (Figs. 2.4 and 2.5; Luckman, 2000). Changes in tree growth may reveal the duration of an advance, as both react to the same forcing (Luckman, 2000). Cooler climate leads to glacier advance and, commonly, to narrow rings in temperature-sensitive trees (Luckman, 1996, 1998a). Some tree species, for example mountain hemlock (Peterson and Peterson, 2001), may also put on narrow rings during years when the snowpack is thick and lingers late into the summer.

The oldest tree on a moraine provides a minimum estimate for the time of moraine stabilization (Fig. 2.4; Lawrence, 1946). The tree ages need to be adjusted to account for the time between moraine stabilization and seedling germination ("ecesis"; McCarthy and Luckman, 1993; Winchester and Harrison, 2000). Photographic records and field studies indicate that the ecesis interval in Garibaldi Park is generally less than 20 years, but in some situations can be as long as 70 years (Chapter 3).

The age of a glacial advance can also be estimated by dating living trees damaged during the advance, dead trees in growth position overridden by the glacier *(in situ* stumps), and detrital wood within moraines or lying on the surface in the glacier forefield (Fig. 2.5; Luckman, 1998a, and references therein). The most valuable ages are those derived from *in situ* trees, especially if the rings can be cross-dated into living chronologies to obtain the year when the tree was damaged or killed. Detrital wood and damaged and dead trees in growth position are present in the forefields of glaciers in Garibaldi Park, allowing us to acquire a more complete Holocene glacier record than has been possible in other parts of the Coast Mountains to date. Radiocarbon dating of these materials has revealed advances around 6000 and 3000 years ago and during the last 500 years (Fig. 2.6; Koch *et al.*, 2004b). Evidence for these events is provided by *in situ* stumps and detrital wood from several glaciers in Garibaldi Park. Other, more poorly constrained advances occurred about 8000, 4500, and 1500 years ago. The 8000- and 4500-year advances are inferred from detrital wood in the forefields of two glaciers in the park. Evidence for the 1500-year-old event has been found at only one glacier in the park, but has been documented elsewhere in the southern Coast Mountains (Reyes *et al.*, 2004, 2006).

Late Little Ice Age moraines in Garibaldi Park have been dated more precisely by lichenometry and dendrochronology. Most glaciers achieved their maximum Little Ice Age extent in the late seventeenth or early eighteenth century (Koch *et al.*, 2004b).

Tree Growth and Climate

Alpine environments are ideal sites for dendroclimatic studies. Trees near treeline produce annual rings that vary in width and density in response to changing environmental conditions. Temperature and precipitation are the principal environmental factors affecting tree growth near treeline (Fritts, 1976; Schweingruber, 1996). Subalpine coniferous trees are particularly useful for reconstructing climate over the last millennium because they respond to changes in temperature and precipitation, yet can live for hundreds of years. Subalpine fir and mountain hemlock, for example, can attain ages of about 300 and 900 years, respectively.

Previous studies have shown that ring-width chronologies of these species correlate positively with summer temperature and the PDO, and correlate negatively with winter precipitation, spring snowpack depth, and glacier mass balance (Lewis, 2001; Peterson and Peterson, 2001; Gedalof *et al.*, 2002; Peterson *et al.*, 2002). Mountain hemlock ring-width chronologies can also be correlated over much of the Pacific Northwest, including Garibaldi Park (Gedalof and Smith, 2001a), which allows us to apply them in our study.

Lake Sediments

Sediments in many lakes consist of distinctive annual couplets, termed varves. Varves yield valuable hydroclimatic information that cannot be obtained from other paleoenvironmental datasets. Flood events and seasonal hydrology, for example, can be inferred from detailed sedimentological analysis of varves (Menounos, 2002). The lower, coarser-grained portion of a varve is deposited during late spring and early summer snowmelt. Other coarse layers may record severe rain-on-snow storms in the watershed, typically in summer or fall (Fig. 2.7). The basal, coarse layer of a varve is commonly overlain by micro-laminated silt and clay, reflecting variable streamflow during summer. These sediments, in turn, are capped by clay deposited during winter when inflow to the lake is lowest and the lake is ice-covered.

Reconstructing hydroclimatic events from lake sediments is complicated by changes in sediment supply (Desloges and Gilbert, 1995), which result, for example, from fluctuations in glaciers (Leonard, 1997) or summer temperature (Leonard, 1986a) on decadal and centennial timescales. Acquisition of varved sediment records from several lakes in a region, as has been done in Garibaldi Park, can reveal the common hydrologic signals contained in the records.

We have obtained and analyzed cores of varved sediments from Cheakamus, Green, and Glacier lakes (Fig. 2.2). Some of the conclusions that we have drawn from these records are: (1) varve thickness is most highly correlated with the intensity of the annual flood during the period of streamflow monitoring; (2) varve thickness correlates with inter-annual changes in air temperature prior to the period of rapid glacier recession in the early twentieth century; and (3) temporal patterns of sedimentation are consistent with published records of glacial activity in the Canadian Cordillera and with our moraine chronologies based on tree rings and lichens. The lake sediment records suggest that ice cover was more extensive than present ca. 3000 to 2500 years ago and between AD 1700 and 1920.

Treeline Fluctuations

Changes in treeline provide important insights into past climate. Treeline is a dynamic boundary reflecting a balance between environmental conditions favouring and limiting tree growth (Arno and Hammerly, 1984). Temperature and the depth and duration of snowpack determine the location of treeline. Trees do not germinate successfully where the mean temperature of the warmest month is less than ca. 10° C (Arno and Hammerly, 1984). Thick snowpacks and late-lying snow also determine vegetation distribution in the subalpine zone, as snow inhibits the successful germination of trees (Arno and Hammerly, 1984). Differences in aspect and local topography result in a variable vegetation cover near treeline, with islands of trees separated by meadows, an ecotone referred to as parkland. For this reason, the term "treeline" represents a transitional zone rather than an exact altitudinal line (Holtmeier, 1985).

Previous studies have shown that alpine treeline fluctuated throughout the Holocene, at all timescales and in all mountain ranges around the world (Rochefort *et al.*, 1994; Kullman, 1995). Treeline was lowest during the final phase of the Little Ice Age in the nineteenth century. Since then, treeline has advanced upslope, reaching heights not attained for several centuries or even millennia (Kullman, 2001). Recent studies indicate that treeline is more sensitive to small changes in climate than previously thought and that paleo-treeline identification may prove to be a useful tool for reconstructing past climate (Kullman, 1998). The Pacific Northwest shows great potential in this regard (Woodward *et al.*, 1995; Rochefort and Peterson, 1996).

Treeline in Garibaldi Park has not been disturbed by humans, and apparently has not been affected, at least over the last several hundred years, by large forest fires (Cashman, 2004) or insect outbreaks. Therefore, recent shifts in treeline can be attributed to changes in climate. We have determined the position of treeline at a few locations in Garibaldi Park in the twentieth century from photographic records dating back to the 1910s (Fig. 2.8). We have also sampled trees in areas with long photographic records to establish germination dates and growth rates (Koch *et al.*, 2003b). Similar studies in the Canadian Rocky Mountains have provided important information on climate change (Luckman and Kavanagh, 2000) and for use in land management

(Rhemtulla *et al.*, 2002). Preliminary findings from our study indicate that treeline in some parts of Garibaldi Park has risen about 40 m over the last 100 years and that many alpine meadows have been invaded by trees over this period (Koch *et al.*, 2003b).

Conclusions

The climate of western Canada has fluctuated considerably since the last ice sheet disappeared from the region about 11,000 years ago. On the longest timescale, we see progressive cooling over the Holocene. Cooling was accompanied by successively more extensive advances of glaciers and was driven by a progressive decrease in summer solar insolation in the Northern Hemisphere (Luckman, 1993, 2000).

Long-term changes in solar insolation, however, cannot explain the shorter, decadal-scale changes in climate inferred from the geologic and historical records, including those of the last century. Most of these shorter-term climate changes are driven by complex, as yet poorly understood, linked ocean-atmosphere effects (Clark *et al.*, 2002), by short-term changes in the total output of radiation from the Sun (Lean, 2002), by volcanism (Angell and Korshover, 1985), or by some combination of these factors (Paul and Schulz, 2002). Environmental changes since the end of the Little Ice Age, however, suggest that the climate of the twentieth century was unusual in the context of the Holocene. The changes include average global surface warming of about 1º C (Bradley and Jones, 1993), recession of some glaciers from their most advanced positions of the last 10,000 years to positions they likely have not seen in the last 8000 years (Koch *et al.*, 2004b), and concurrent upward migration of treeline from its lowest Holocene level to a level most likely not reached in the last 7000 years (Kullman, 2001). If this trend continues into the future, we may pass through a threshold from the present climate regime into a new, different one, with unexpected consequences for all of us.

Figures

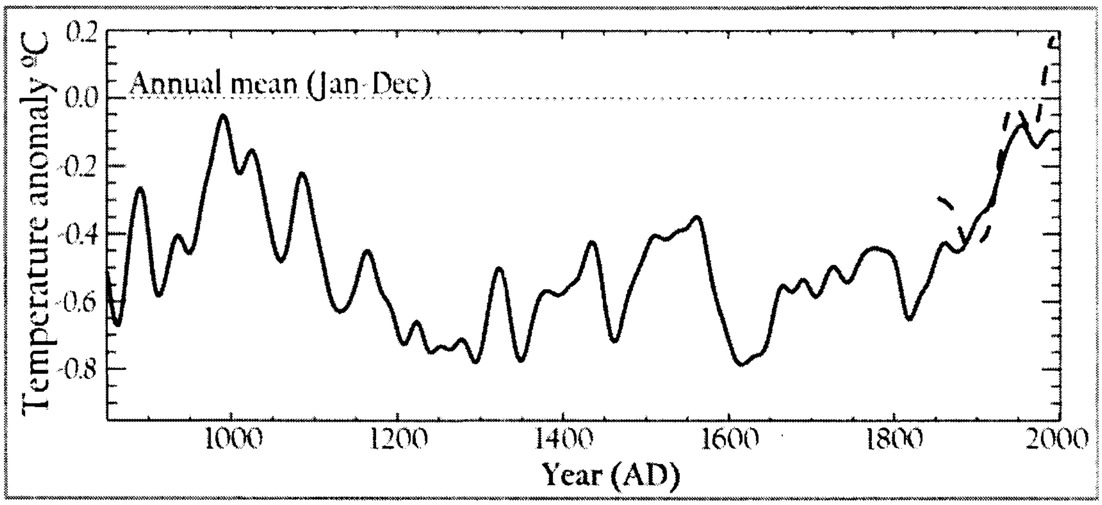

Figure 2.1 Inferred changes in average annual temperature in the Northern Hemisphere over the last 1100 years based on tree-ring records. The reference line is the mean annual temperature for the period 1961-1990, averaged over land areas north of 20° N. The dashed line is the observed temperature record since the mid-19[th] century. Based on Esper *et al.* (2002), modified by Briffa and Osborn (2002).

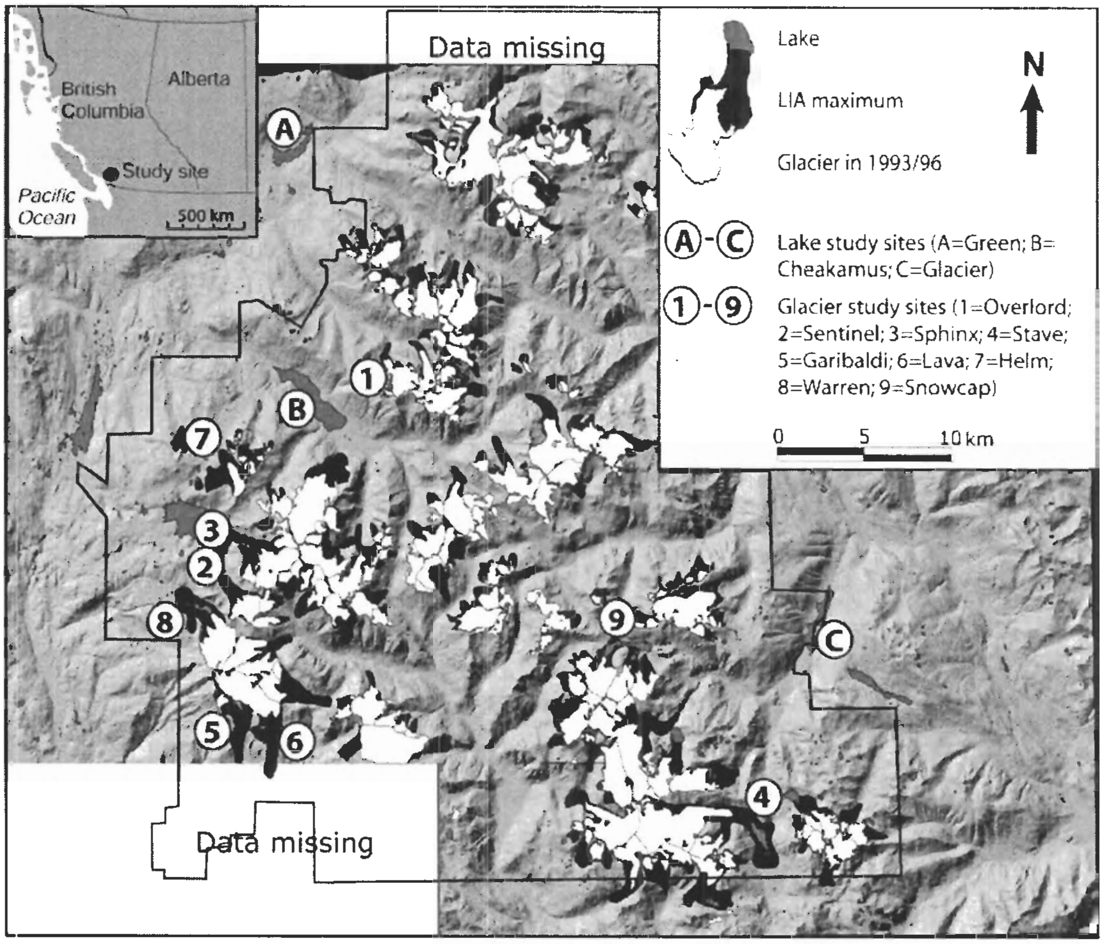

Figure 2.2 Digital elevation model of Garibaldi Park and surrounding area. Study sites are labelled A-C and 1-9, the former being lake coring sites. Ice cover is shown at present (white areas) and at the maximum of the Little Ice Age (black areas).

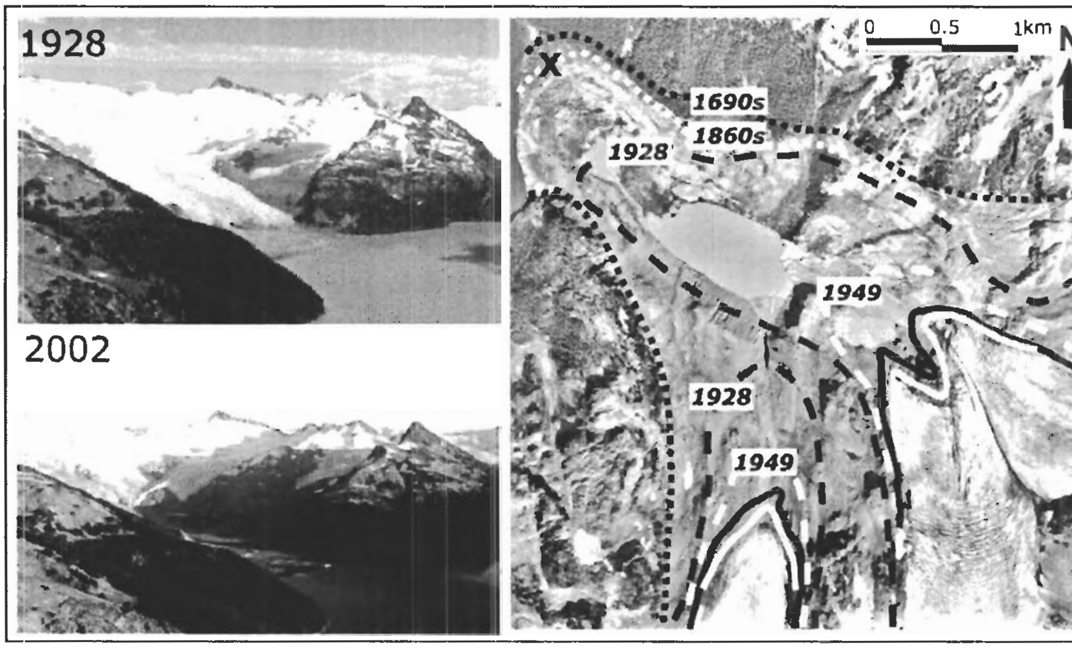

Figure 2.3 Historic recession of Sphinx Glacier. Photographs taken in the summers of 1928 (top left; B.C. Archives I-64740; reprinted with permission of the British Columbia Archives) and 2002 (bottom left). Some Little Ice Age moraines, dated by dendrochronology and lichenometry, and positions of the glacier snout since the late 1920s are indicated on the airphoto at the right (B.C. airphoto 30BCB93041-147; reprinted with permission of the Province of British Columbia). The glacier receded throughout the twentieth century, with a minor readvance between 1969 (white solid line) and 1973 (black solid line). The location of Figure 2.4 is indicated by "X".

Figure 2.4 Moraine crest in the forefield of Sphinx Glacier. Trees were cored to obtain a minimum date for construction of the moraine. The location of the photo is shown in Figure 2.3. View is to the southwest; the present-day glacier snout is about 2 km to the left.

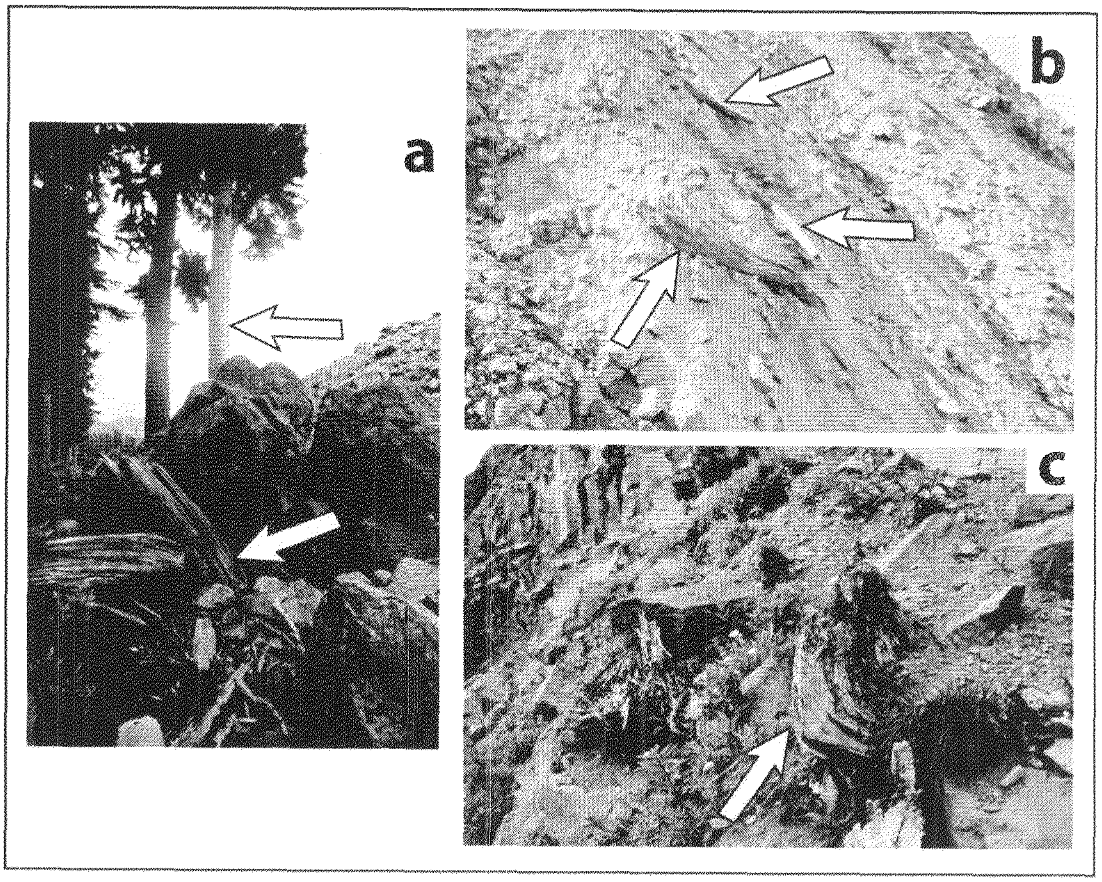

Figure 2.5 Examples of damaged and killed trees in the forefields of glaciers in Garibaldi Park. (a) Damaged tree (arrow in background) and killed tree (arrow in foreground) on the distal side of the outermost moraine of Warren Glacier. This moraine dates to AD 1705. (b) Detrital wood (arrowed) at Sentinel Glacier. The wood yielded a radiocarbon age of 6040 ± 60 ^{14}C years BP (Beta-186508). (c) Tree stumps in growth position in front of Sphinx Glacier. The trees were killed by the glacier 580 ± 70 ^{14}C years BP (Beta-186512). Glacier flow was right to left in (a) and (c), and left to right in (b).

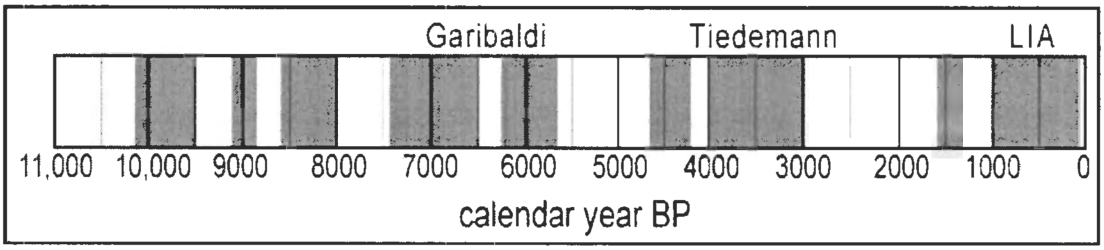

Figure 2.6 Glacier advances (vertical gray bars) in Garibaldi Park inferred from radiocarbon and moraine ages (Koch *et al.*, 2004b). Moraines were dated by dendrochronology, lichenometry, and, where possible, both methods. *In situ* stumps (e.g., Fig. 2.5c) and detrital wood (e.g., Fig. 2.5b) were radiocarbon dated. All advances have been identified in at least two glacier forefields, except the 1500-year-old event. "Tiedemann" and "Garibaldi" are names applied to previously established glacier advances in the southern Coast Mountains (Ryder and Thomson, 1986; Ryder, 1989).

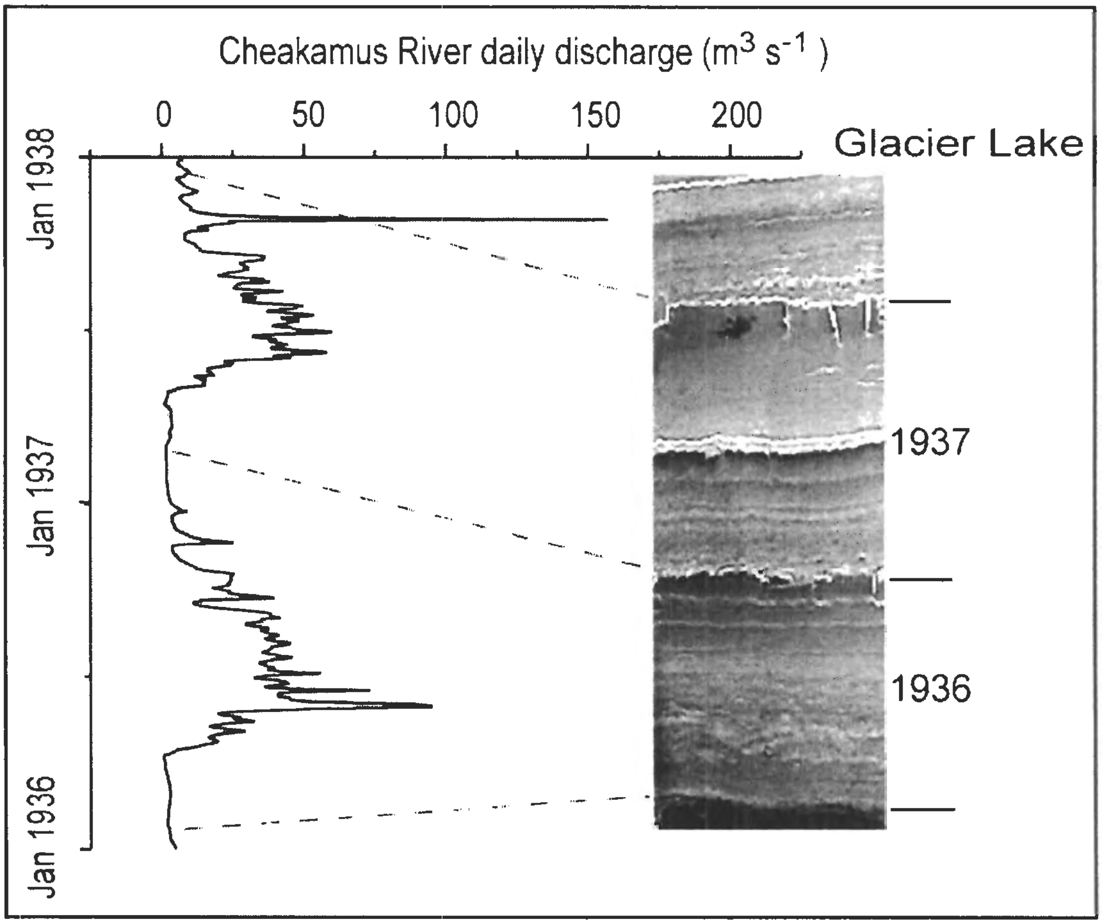

Figure 2.7 Portion of a core of varved lake sediments recovered from Glacier Lake, showing the relationship between couplet thickness and stream inflow (approximated from the nearby Cheakamus River streamflow record). Each couplet comprises a thick layer of silt deposited during summer and a thin layer of clay deposited during fall and winter. Varve thickness is related primarily to the magnitude of the annual flood and, over longer time scales, to changes in ice cover in the basin.

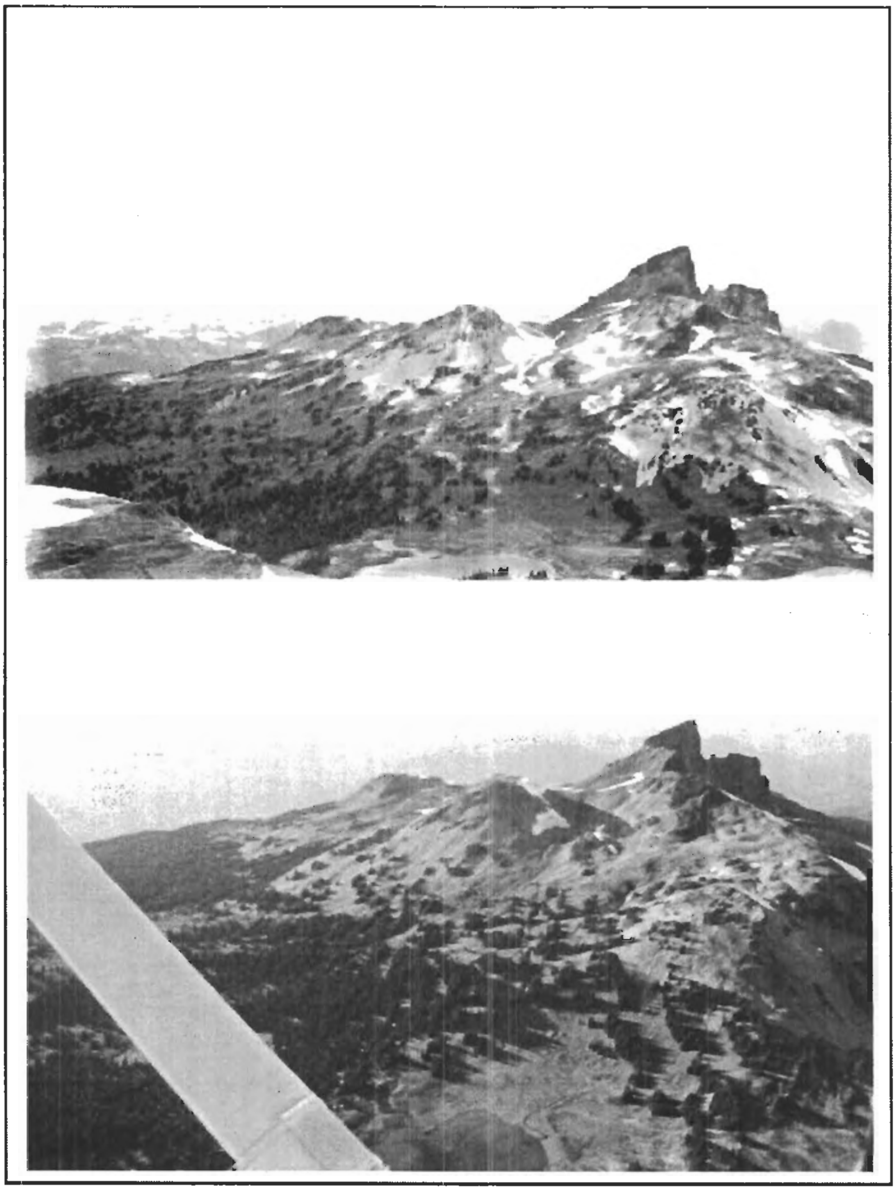

Figure 2.8 Photographs of the area west of Garibaldi Lake, taken in the summers of 1928 (top; B.C. Archives I-64739; reprinted with permission of the British Columbia Archives) and 2002 (bottom). Over this 74-year period, trees have invaded Black Tusk Meadows (left centre) and treeline has risen (left of Black Tusk).

CHAPTER 3
ACCURACY OF DATING LANDFORMS WITH TREE RINGS

Abstract

Dating of late Holocene landforms below treeline in high mountains commonly is done using dendrochronology. Four factors can reduce the accuracy of ages obtained by dendrochronology: (1) locating the oldest living tree on a surface; (2) the method of counting the rings; (3) the age-height correction factor; and (4) ecesis, which is the time it takes trees to successfully germinate on a bare surface. A review of published studies from the western Cordillera of the Americas shows that some of these issues have not been fully addressed. Research in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia shows that the accuracy of tree-ring ages can be improved if (1) crossdating and chronology construction, rather than simple ring counts, are done; (2) individual age-height correction factors are applied; and (3) site-specific ecesis estimates are made. Researchers should report their methods in more detail and provide uncertainties in their age estimates that take into account age-height and ecesis corrections.

Keywords: dendrochronology, age-height correction, ecesis, moraines, western North America, Garibaldi Provincial Park, British Columbia

Introduction

Accurate dating of late Holocene landforms and processes is important in a wide range of studies, including paleoenvironmental reconstruction, hazard assessment, and process geomorphology. Accurate dating of glacier fluctuations, for example, enables correlation of events over large areas. Precise chronologies are important for assessing risks posed by landslides, floods, snow avalanches, and other hazardous processes, and for better understanding a variety of other geomorphic processes, for example dune and river channel migration.

In many areas photographs and written records are not available prior to the early twentieth century, thus other, less direct methods must be used to date landforms. The methods that are most commonly used to date late Holocene landforms are radiocarbon dating, lichenometry, and dendrochronology. The first two methods are not addressed in this paper, as other researchers have discussed the limitations involved in their use (e.g., Jochimsen, 1973; Innes, 1985; Arnold, 1995; McCarthy, 1999). This paper focuses on dendrochronology, a widely used dating technique that has its own unique set of limitations (Shroder, 1980; Luckman, 1986, 1998a; McCarthy *et al.*, 1991; McCarthy and Luckman, 1993; Palik and Pregitzer, 1995; Wiles *et al.*, 1996; Villalba and Veblen, 1997).

Four conditions must be met to successfully date a surface using tree rings. First, the rings must form annually. This condition is met in most of the world due to seasonal changes in the metabolism of trees. Second, live or dead trees of the first-generation forest must be present on the surface (Matthews, 1992). If this condition is not met, dendrochronology will underestimate the age of the surface. First-generation forest commonly can be recognized by the absence of old, large, fallen trees on the forest floor or by differences in species composition. Third, the dated trees must have colonized the surface shortly after it formed. Factors such as fire, seed crop, and unfavourable climate can delay colonization, leading to an apparent surface age that is too young. Fourth, the oldest living tree must be sampled, which is often difficult on surfaces covered by dense forest. If dating is done with increment cores, the cores must include the pith. If any of these conditions is not met, the ages that are obtained will be inaccurate.

Dendrochronology generally yields minimum ages because (1) trees begin to grow some time after the surface formed or stabilized (ecesis; McCarthy and Luckman, 1993), and (2) many tree-ring dates do not include a correction for the time the tree grew to sampling height (age-height correction). Trees directly date an event only if they were tilted, scarred, or killed by that event. Several methods have been proposed to estimate ecesis and to make age-height corrections, but problems remain.

I reviewed relevant information from 54 studies that used dendrochronology to date landforms in the western Cordillera of the Americas (Fig. 3.1; Table 3.1). Furthermore, I completed a targeted study of the factors discussed above in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia (Fig. 3.2). The southwest part of the park is strongly influenced by Pacific maritime air masses, but climate becomes increasingly continental to the north and east. Average annual precipitation at Squamish, at the head of Howe Sound, is 2370 mm, but it declines to 1230 mm at Whistler, 60 km to the north. It, therefore, is an ideal area to evaluate limitations of generalized methods of tree-ring dating. Based on this analysis, I highlight problems in tree-ring dating and propose protocols for reducing errors.

Tree-ring Dating

The number of rings of the oldest tree on any given surface is a minimum age for that surface. Many tree species, however, produce false rings or no rings during some years. False rings form when a tree stops photosynthesizing due to early frost or other disturbances but then resumes growth in the same year. False rings can be distinguished from true rings under a microscope. Missing rings result from suppression of tree growth. A tree may be unable to add cells to its perimeter over its full length from crown to root. The lower the tree is sampled, the more likely the sample will contain missing rings. Furthermore, cores extracted from trees should include the pith. If the pith is missed, the missing rings must be added to the ring counts (Villalba and Veblen, 1997).

Replicating data by taking two cores from each tree increases the likelihood of detecting missing and false rings, but it does not eliminate the problem. Heikkinen (1984) estimated that as many as several tens of rings may be missing from the trees he sampled, but few other authors have commented on the problem. Samples were crossdated (Stokes and Smiley, 1968) in only two of the 54 studies (Villalba *et al.*, 1990; Koch and Kilian 2005). Without crossdating in the latter study, moraine ages would have been underestimated due to missing rings or overestimated due to false rings.

At least two cores were taken from each tree sampled in Garibaldi Park. If the pith was not recovered, additional samples were taken until a sample contained the pith. Living-tree chronologies were constructed for all sampled trees at each study site in the park. The chronologies were checked and verified by the International Tree-Ring Data Bank (ITRDB) software program COFECHA (Holmes, 1983) and crossdated (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32).

Without crossdating, the ages of some moraines would have been overestimated by up to 11 years and others would have underestimated by up to 9 years.

Age-height Correction

A correction must be made for rings that are missed when coring above ground level. Several methods are used to make this correction, but each has limitations and may result in errors of up to 30 years (Wong and Lertzman, 2001). Most authors of papers considered in this study made age-height corrections, but they provided little information on the methods they used (Table 3.1). Some authors applied age-height-corrections from other published studies in areas with different climates or for other tree species, which may result in error. Sampling heights range from 10 cm to 130 cm above the ground. The error may be small 10 cm above the ground, but can become significant farther up the stem (McCarthy *et al.*, 1991). In rare circumstances, trees produce adventitious root systems and the root collar is below ground level. Errors of up to several decades are possible in such situations (DesRochers and Gagnon, 1997).

An average age-height correction, based on the mean rate of growth to sampling height of all seedlings sampled, was applied in most of the reviewed studies. The growth rate to sampling height may be similar for all trees at a sampling site where there is little relief and similar mircoclimate (Vasiliauskas and Chen, 2002), but an average correction factor can introduce errors of up to several decades for sites with considerable relief and spatially variable climate (Villalba and Veblen, 1997; Winchester and Harrison, 2000; Koch and Kilian, 2005). A correction factor based on rings near the pith is more appropriate for such sites (Winchester and Harrison, 2000; Koch and Kilian, 2005). This correction assumes that wide rings near the pith are associated with fast vertical growth and narrow rings near the pith are associated with slow vertical growth, thus ring width and stem height are positively correlated (Tranquillini, 1979; Körner, 1999). However, studies near treeline in the Canadian Rocky Mountains and the European Alps have shown that the two can be negatively correlated or not related at all (Paulsen *et al.*, 2000; Kavanagh and Wilson, 2002).

In Garibaldi Park, trees were sampled as close to the ground as possible (10-50 cm) to reduce age-height errors. Correction factors, established by sampling several seedlings at ground level at each site, range from 0.37 to 5.27 cm/year (Table 3.2).

Increment growth is positively correlated with vertical growth in Garibaldi Park. For example, two trees on the same moraine in the forefield of Sphinx Glacier both have 115 rings (Fig. 3.3). One of the trees is about 18 m high (b in Fig. 3.3) and has an average vertical growth rate of 1.57 cm/year; the other is 5 m high (a in Fig. 3.3) and has an average vertical growth rate of 0.43 cm/year. The taller tree has an average annual increment growth rate of 2.61 mm, and the smaller tree 1.01 mm. Accordingly, the taller tree has wider rings at the pith (an average of 2.74 mm/year for the first 10 rings) than the smaller tree (an average of 0.98 mm/year for the first 10 rings). Use of the same average correction factor for both trees would overestimate the age of the taller tree and underestimate the age of the smaller tree. The error would increase with coring height and could reach several decades for cores taken 50 cm above the ground.

The rate of vertical growth in Garibaldi Park differs markedly with elevation and climate (Fig. 3.4; Table 3.2). It is similar only where environmental conditions are about the same, for example at Overlord Glacier (1600 m asl; 2.03 cm/year) and Helm Glacier (1750 m asl; 1.98 cm/year). Three examples show that vertical growth is affected by differences in (1) elevation in the forefield of the same glacier (Overlord Glacier; Fig. 3.4),

(2) climate in the forefields of different glaciers (Lava and Overlord glaciers), and (3) snow depth at similar elevation in the same forefield (Sphinx Glacier). The elevation range of the Overlord Glacier forefield is about 300 m. Vertical growth rates of seedlings were determined at 1375, 1600, and 1675 m asl in the forefield. Average annual growth is 3.62 cm at the lowest site, 2.03 cm at the middle site, and 1.67 cm at the highest site where snow is deeper and climate colder. Seedlings at similar elevation at Lava Glacier (1400 m asl) and Overlord Glacier (1375 m asl) grow at annual average rates of 1.66 cm and 3.62 cm, respectively. Climate at Lava Glacier is maritime and the snowpack is thick. In contrast, climate at Overlord Glacier is more continental and the snowpack is thinner. Average vertical growth of seedlings on Sphinx Glacier moraine crests is 2.46 cm/year. It is only 2.06 cm/year, however, in the flat part of the forefield. The moraine crests are snow-free much earlier in the summer than the adjacent forefield (Fig. 3.5).

Ecesis Estimates

Sigafoos and Hendricks (1969) argued that ecesis estimates must be site- and species-specific because germination times differ considerably with geology, topography, and microclimate. Their findings have been verified by many researchers (McCarthy and Luckman, 1993; Winchester and Harrison, 2000, Koch and Kilian, 2005). Other factors contribute to variability in ecesis, for example availability of seed crop and climate change over time (Luckman, 1988a).

Most researchers correct for ecesis (Table 3.1), but commonly by using previously established estimates from the region (Smith *et al.*, 1995; Luckman, 1995; Wiles *et al.*, 1999, 2002, 2003; Larocque and Smith, 2003). Average ecesis values are commonly used, but methods and results are generally not fully reported in published studies.

Two methods are commonly used to estimate ecesis: (1) analysis of aerial photographs or historic ground photographs; and (2) establishment of the age of trees on a surface of known age. In the former case, ice margins are mapped on successive aerial photographs, and living trees are sampled at sites deglaciated at known times (McCarthy and Luckman, 1993; Wiles and Calkin, 1994; Winchester and Harrison, 2000). In the latter case, ecesis is estimated from the age of the oldest tree growing on a surface of known age (Lewis and Smith, 2004a). Alternatively, if an event damaged or killed trees, it can be precisely dated and ecesis can be established by coring the oldest trees that recolonized the surface (Luckman, 1988a, 1996; Koch and Kilian, 2005). Seedlings and saplings on young surfaces are cut at ground level to make the ring count. Mature trees on older surfaces must be cored above ground level, requiring an age-height correction.

Ecesis values in Garibaldi Park were obtained by analyzing aerial and ground photographs, and, where possible, by studying surfaces of known age. Ecesis was estimated at each forefield and, in some cases, at several sites in each forefield (Table 3.3). When several sites were investigated in an individual glacier forefield, sites with varying conditions were chosen to represent favourable growth conditions (e.g., wet patches, fine substratum) and unfavourable conditions (e.g., coarse substratum). Data presented by Mathews (1951), Fraser (1970), Ricker (1979), and Ricker and Tupper (1979) indicate that ecesis in Garibaldi Park differs strongly with elevation and climate.

The best estimates of ecesis in Garibaldi Park come from two glacier forefields where trees were damaged, killed, and tilted during glacier advances, and thus can be accurately dated. Construction of the outermost moraine of Warren Glacier and the second-to-outermost moraine of Overlord Glacier damaged and killed trees. Living trees were sampled on these moraines. The damaged tree at Warren Glacier is still alive, and killed trees at both glaciers were crossdated into living tree-ring chronologies The Warren Glacier moraine dates to AD 1705 and the Overlord Glacier moraine to AD 1702 (Koch *et al.*, 2004a). Only seven trees have germinated on the crest of the Warren Glacier moraine, and the oldest yielded a count of 286 rings in 2004. Thus, ecesis is eleven years. The oldest tree sampled on the Overlord Glacier moraine yielded 294 rings in 2002, which indicates an ecesis of six years. In the latter case, the moraine supports a dense forest, thus the oldest tree may not have been sampled. In both cases, the oldest tree sampled is similar in age to the next four or six younger trees. At Overlord Glacier the six oldest trees differ in age by only nine years, and at Warren Glacier the four oldest trees differ by ten years. I thus conclude that the sampled trees are the oldest on the Overlord moraine and that they germinated shortly after the moraine stabilized.

Ecesis was independently estimated in both forefields using aerial photographs. At Warren Glacier, a seedling with 26 rings in 2002 grew at a site that was under ice in AD 1949, which establishes a maximum value of ecesis of 27 years. At Overlord Glacier, a seedling with 36 rings grew at a site that was under ice in AD 1929; ecesis there is less than 37 years. The sample site at Warren Glacier is at about the same elevation as the dated moraine, but the site at Overlord Glacier is 175 m higher than the dated moraine. The much higher ecesis estimates in the forefields than on the adjacent moraines is probably due to differences in snow cover. The moraines are covered by snow for a much shorter time than the forefields (Fig. 3.5). The higher elevation of the forefield sites at Overlord Glacier may also be a factor in delaying germination, although the sites are well below treeline.

Ecesis values in Garibaldi Park range from 13 years at Stave Glacier, which is the lowest of the study sites (1100 m asl) to 49 years at Helm Glacier, the highest study site (1750 m asl) (Fig. 3.6). Nearly identical values were obtained at Sphinx and Sentinel glaciers (26 and 25 years respectively), which are at the same elevation and have similar snow cover and geology. Ecesis at 1400 and 1600 m asl at Lava Glacier is similar (34 and 38 years, respectively), but the former value is much larger than the value obtained at about the same elevation (1375 m asl) at Overlord Glacier (25 years). Ecesis at 1500 m asl at Sphinx and Sentinel glaciers is less than it is 100 m lower at Lava Glacier (25 and 26 years vs. 34 years). The most likely causes of these differences are elevation and local climate. The data plotted in Figure 3.6 indicate that there is a strong positive relation between elevation and ecesis. Differences in snow cover related to the strong northeasterly climate gradient across Garibaldi Park may partly explain the differences in ecesis, especially for sites at similar elevations. This supposition is supported by ecesis values determined at five forefields between 1550 and 1675 m asl located along a northeasterly transect (Table 3.4). Ecesis is shortest at sites with a maritime climate (high precipitation, cool temperatures), and longest at sites with continental climate (low precipitation, cold temperatures). Ecesis is similar at very maritime (very high precipitation, cool temperature) and intermediate (sufficient precipitation, cold temperatures) sites. Ecesis estimates between 1375 and 1500 m asl at glacier forefields generally corroborate these findings. Thus, successful germination and survival of seedlings is inhibited at sites with low precipitation, which is likely caused by the lack of sufficient insolating snowcover in winter and more common drought conditions in late summer. Ecesis is short at sites where drought conditions are rare and snowcover is sufficient for insolation of seedlings during winter.

Worst-case Scenario

Here, I present a worst-case scenario that illustrates the maximum total error that may result from using generalized dendrochronological methods to estimate the age of landforms (Table 3.5). The outermost moraine of Warren Glacier, which has been calendar-dated to AD 1705, provides a control for comparison. Living trees on the moraine were cored as close to the ground as possible and also 50 cm above the ground. Dates were determined from cores extracted at 50 cm height to illustrate problems arising from not taking into account vertical growth. Two cores at 50 cm height from the oldest tree suggest that the tree is 272 years old. Vertical growth to 50 cm above the ground in the Warren Glacier forefield ranges from 20 to 23 years (Table 3.2); an average value of 21 years is added to the age of the oldest tree. Ecesis at this site ranges from 16 to 29 years (Table 3.3); the average value of 22 years is added. Summing the two corrections yields an apparent age for the moraine of AD 1687, which is 18 years too old. An even more inaccurate result is obtained if regional averages based on all values from Garibaldi Park are used. A regional vertical growth correction of 22 years and a regional average ecesis value of 28 years yield an apparent age of AD 1680, which is an overestimate of 25 years.

By crossdating all cores from the moraine, I was able to show that the cores included four false rings. The oldest tree has very wide rings near the pith, suggesting that it grew to coring height in only 14 years (Table 3.2). Furthermore, an ecesis value of only 11 years is assumed for the oldest tree (Table 3.3), which germinated on a favourable seedbed and was sheltered from katabatic winds by a large boulder. Niederfriniger-Schlag and Erschbamer (2000) have shown the importance of large boulders in glacier forefields for tree germination. The age of the moraine, based on these site-specific data, is AD 1709, which is close to the true age of the moraine.

Conclusions

Researchers realized more than a half-century ago that dendrochronology offers more precise and accurate dating of surfaces than any other method except direct observation (Lawrence, 1946). The method has since been widely applied (Table 3.1). However, improvements in dendrochronological methods are possible. First, I recommend using a more rigorous method than simply counting rings. Crossdating and chronology building eliminate possible dating errors of about ten years. Second, a local age-height correction factor, based on the width of pith rings, should be applied in lieu of one based on an average growth rate or a regional value. Average local or regional age-height corrections are appropriate only in areas with little relief and spatially uniform climate. Third, ecesis values should take into account elevation, aspect, snow depth, and other relevant environmental factors. Average local or regional ecesis values are appropriate only in areas with small environmental differences.

These methodological improvements will increase the accuracy of dendrochronology and help in efforts to compare events on regional, hemispheric, and global scales (Luckman and Villalba, 2001). Otherwise, these efforts may be compromised by apparent differences that are the result of the inherent inaccuracies in the method. Comparison of datasets would be facilitated if researchers would more fully report the methods they use, report results as estimates, and round results off to the nearest decade to indicate generally unavoidable errors in the methods.

Figures

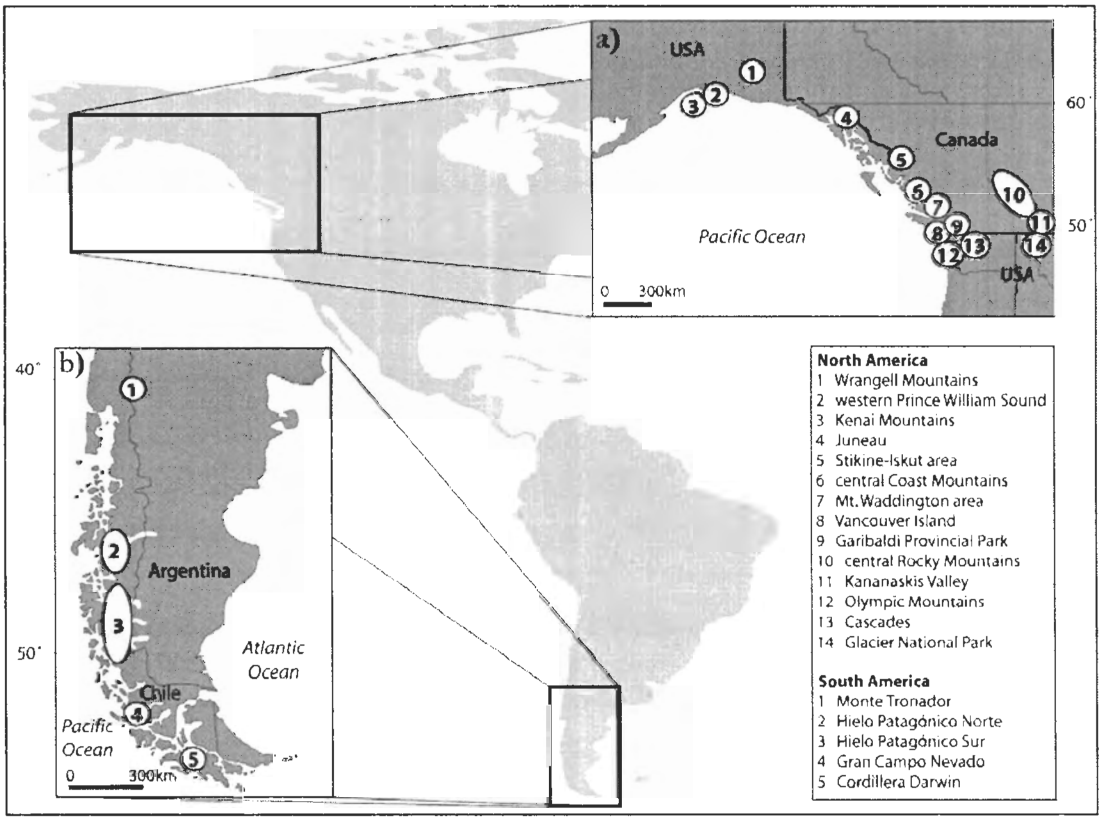

Figure 3.1 Locations of sites cited in the paper (see also Table 3.1).

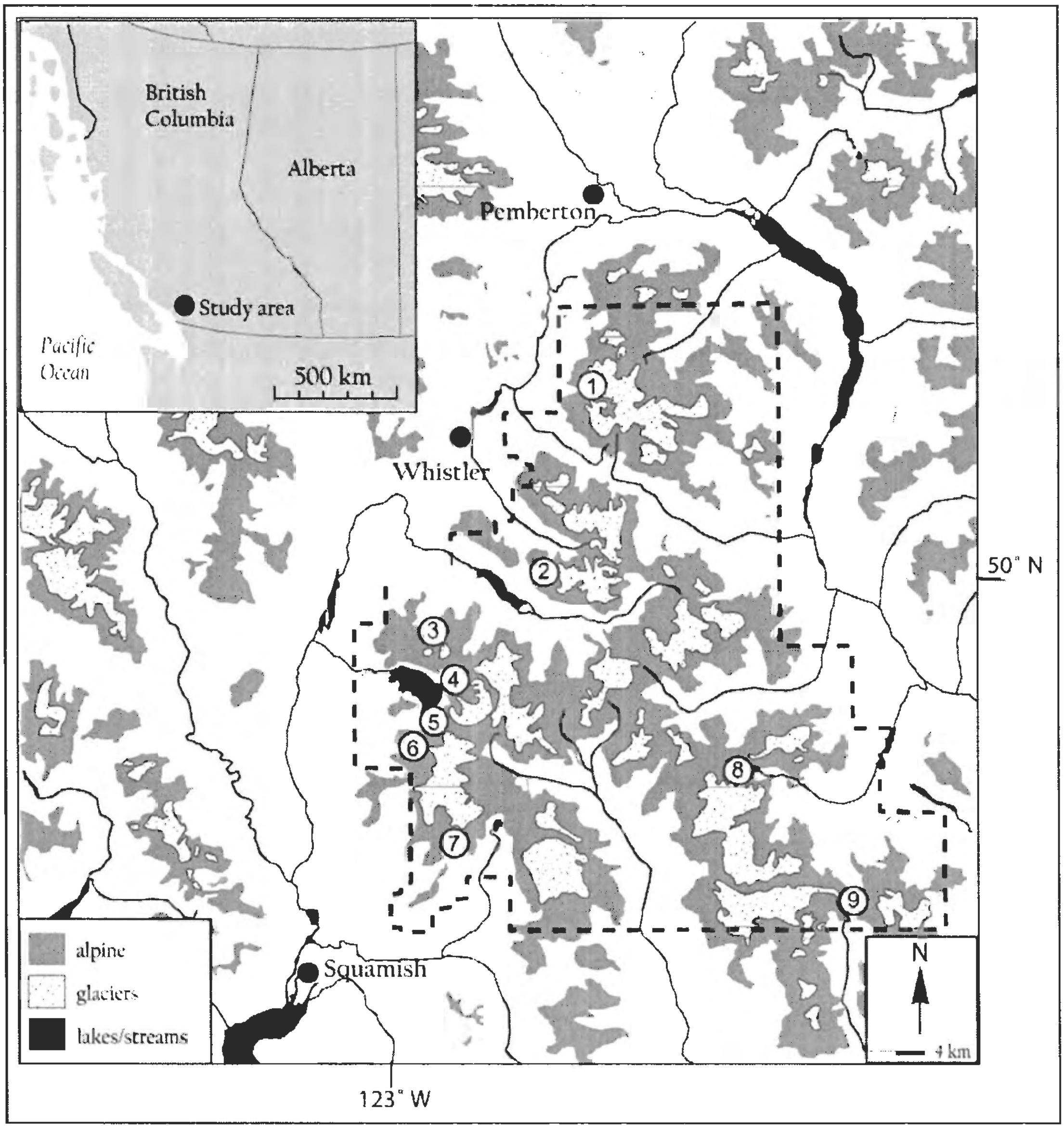

Figure 3.2 Map of Garibaldi Provincial Park, showing locations of study glaciers (1, Wedgemount Glacier; 2, Overlord Glacier; 3, Helm Glacier; 4, Sphinx Glacier; 5, Sentinel Glacier; 6, Warren Glacier; 7, Garibaldi/Lava glaciers; 8, Snowcap Lakes; 9, Stave Glacier).

Figure 3.3 Trees on the crest of a Sphinx Glacier moraine. Trees (a) and (b) have the same number of rings but differ in height and circumference. View is to the southwest; the glacier snout is 3 km to the left.

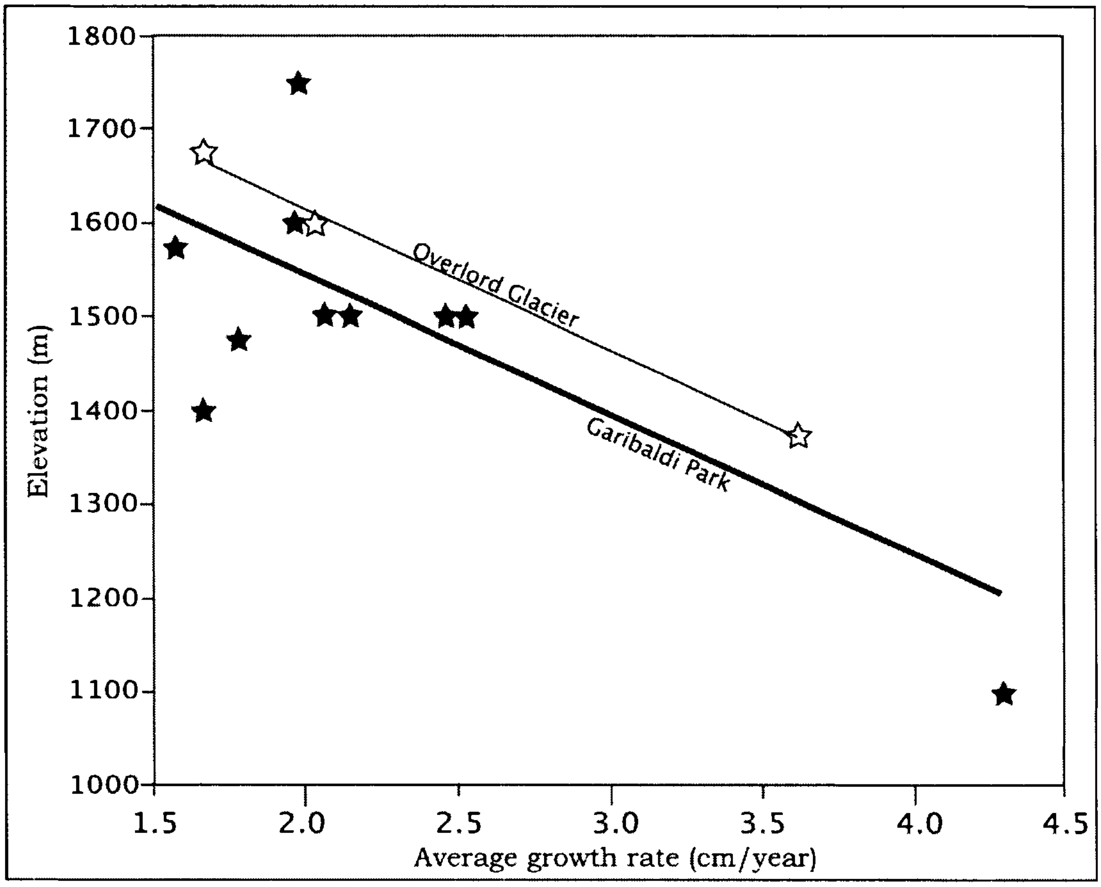

Figure 3.4 Relation between average growth rate and elevation in Garibaldi Provincial Park (full stars and thick trend line) and for Overlord Glacier alone (outlined stars and thin trend line).

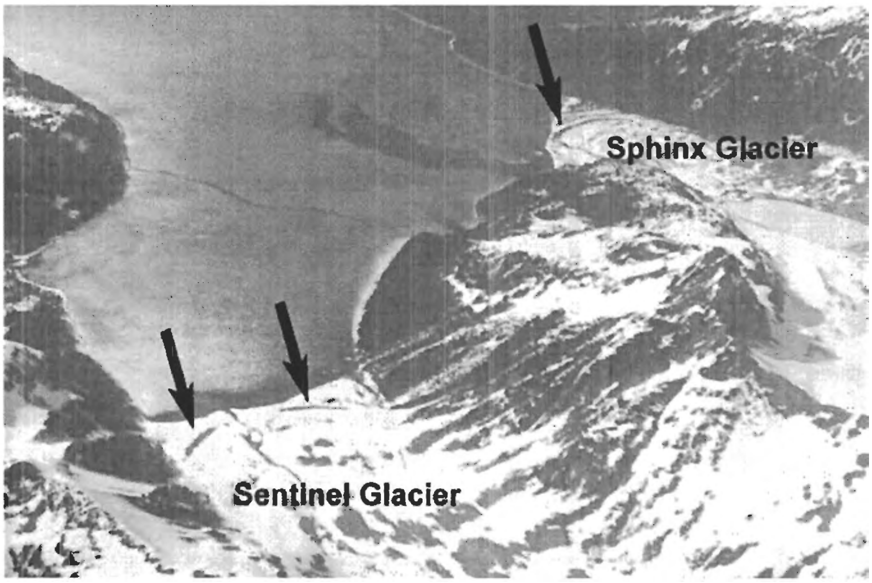

Figure 3.5 Snow cover in the forefields of Sphinx and Sentinel glaciers (photograph taken on June 2, 2003). Most of the forefields are covered by deep snow, but the moraine crests are bare.

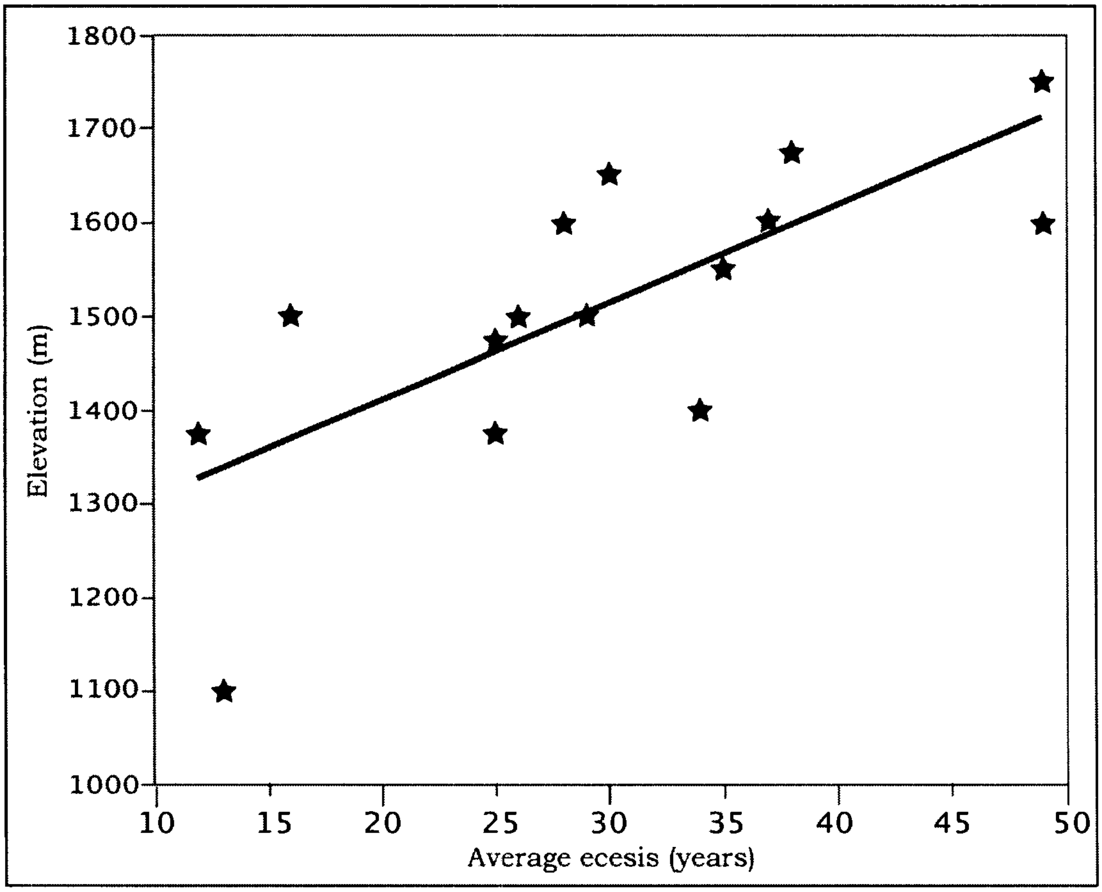

Figure 3.6 Relation between average ecesis values and elevation.

Tables

Table 3.1 Studies considered in this review.

Area	Method of ring count	Age-height correction		Ecesis		Reference
		Value	Method	Value	Method	
Alaska (58-62°N)						
Wrangell Mountains (61-62°N)	Simple counting	None	Negligible as cores taken close to base of tree	30 years	Determined at Chisana Glacier; considered to be representative for area; historic and aerial photos	Wiles *et al.*, 2002
Tana Dunes (61°N)	Crossdating (?)	None	Negligible as cores taken close to base of tree	30 years	Same value as determined for glaciers in nearby Wrangell Mountains; reference to Wiles *et al.*, 2002	Wiles *et al.*, 2003
Western Prince William Sound (60-61°N)	Simple counting	None	Negligible as cores taken close to base of tree	15 years	Determined at Taylor Glacier; considered to be representative for area; method not specified	Wiles *et al.*, 1999
Hubbard Glacier (60°N)	Simple counting	20 cm/year	From fast-growing Sitka spruce, which may not reflect conditions in forefield	Not studied	Poorly understood and therefore not added	Barclay *et al.*, 2001
Kenai Mountains (59-60°N)	Simple counting	Not considered		14 years	Historical records; average from three glaciers in area	Wiles and Calkin, 1990
Kenai Mountains (59-60°N)	Simple counting	None	Negligible as cores taken close to base of tree	15 years	Aerial photographs	Wiles and Calkin, 1994
Juneau (58°N)	Simple counting	None	Negligible as cores taken close to base of tree	3-5, 5-7 years	Historic records; lower values for depressions, higher values for ridge tops	Lawrence, 1950
Juneau (58°N)	Crossdating (?)	6.2-16.7 cm/year	Established at sites from 24 seedlings	>8 years (?)	Estimate and interpretation; ecesis could have changed over time; reference to Lawrence, 1950	Motyka, 2003

Canadian Coast Mountains, British Columbia (50-57°N)						
Stikine-Iskut area (57°N)	Simple counting	4-7 cm/year	Rough estimate from text (p. 1298)	Several decades (40-60 years)	Estimate; not specified	Ryder, 1987
Central Coast Mouintains (52°N)	Simple counting	3.1-25 cm/year	Lower values at higher elevation sites; established at study sites from seedlings	<5–30 years	Aerial photographs	Desloges and Ryder, 1990
Mt. Waddington area (52°N)	Simple counting	1.67 and 5 cm/year	Values for the two dominant tree species; established at sites from 42 seedlings	<10; 18 years	First value considered unrepresentative; regional value (18) added to all sites	Larocque and Smith, 2003
Vancouver Island (50°N)	Simple counting	2.7 cm/year	Average value; established at sites from 10 seedlings; most samples close to base of tree	4 years	Obtained from nearby site stripped bare by a displacement wave of known age	Lewis and Smith, 2004a
Garibaldi Park (50°N)	Crossdating	0.37-4.90 cm/year	Values differ according to site conditions (see Table 3.2)	6-56 years	Values differ according to site conditions (see Table 3.3)	This study
Wedgemount Lake (50°N)	Not specified	Not specified		13-51 years	Airphotos; various species; average of 20-30 years recommended for area	Ricker and Tupper, 1979
Garibaldi Lake area (50°N)	Simple counting	Not considered		20-40 years	Observation	Mathews, 1951
Garibaldi Lake area (50°N)	Simple counting	2-3 cm/year	Estimate; established from whorl counts of seedlings at sites and then corrected for microclimatic conditions	~20 years	Historical photographs	Fraser, 1970
Snowcap Lakes (50°N)	Simple counting	Not specified		Not specified	Likely higher values than at Wedgemount Lake	Ricker, 1979
Cheakamus River (50°N)	Simple counting	Not considered		<10 years	From other sites with different settings	Clague *et al.*, 2003
Canadian Rocky Mountains, Alberta and British Columbia (51-53°N)						
Central Rocky Mountains (51-53°N)	Simple counting	ca. 1-1.5 cm/year	Established in various forefields in study area	12-17 years	Historical photographs	Heusser, 1956
Central Rocky Mountains (51-53°N)	Simple counting	Not specified in these review papers	Information found in specific studies and mostly referenced to McCarthy *et al.*, 1991	10-20 years; up to 70-90 years	Historical photographs; high values where conditions (substrate, microclimate) unfavourable; reference to McCarthy and Luckman, 1993	Luckman, 1986, 1998a, 2000

British Columbia Rocky Mountains (51-52°N)	Not part of this study	2.5-10 cm/year	Average values added; stress that sampling height is minor source of error if sampled close to base	Not part of this study	Not part of this study	McCarthy *et al.*, 1991
Tête and Bennington glaciers (52°N)	Not part of this study	Not part of this study	Not part of this study	5-60 years	Average of 10-20 years is appropriate for these sites	McCarthy and Luckman, 1993
Small River Glacier (52°N)	Simple counting	Not specified	Negligible as cores taken close to base of tree	10-30 years	Reference to McCarthy and Luckman, 1993	Luckman, 1995
Robson Glacier area (52°N)	Simple counting	Not specified	Negligible as cores taken close to base of tree	12 years	Reference to Heusser, 1956	Luckman, 1995
Angel Glacier (53°N)	Simple counting	Not specified	Possibly minor as cores taken at 10-30 cm above ground	15-30 years	Historic photographs	Luckman, 1977
Peyto Glacier (52°N)	Simple counting	Not specified		ca. 30 years	Killed trees; correction of Heusser, 1956 by ca. 20 years	Luckman, 1996, in press
Stutfield Glacier (52°N)	Simple counting	Not specified	Negligible as cores taken close to base of tree	20-30 years	Damaged trees; reference to McCarthy and Luckman, 1993	Osborn *et al.*, 2001
Athabasca and Dome glaciers (52°N)	Simple counting	Not specified	Negligible as cores taken close to base of tree	40-60 years	Tilted and scarred trees; high values due to unfavourable conditions	Luckman, 1988a
Yoho Glacier (52°N)	Simple counting	None	Negligible as cores taken close to base of tree	20-43 years; average of ca. 30 years added	Historical records	Bray and Struik, 1963; Bray, 1964
Kananaskis Valley (51°N)	Simple counting	Not specified	Reference to McCarthy *et al.*, 1991	24 and 28 years	Applied according to tree species; reference to McCarthy and Luckman, 1993	Smith *et al.*, 1995
Olympic Mountains and Cascade Range, Washington State (47-49°N)						
Coleman Glacier, Mt. Baker (49°N)	Simple counting	5 cm/year	Average value; estimated	1-28 years	Damaged trees on same moraines	Heikkinen, 1984
Nooksack Glacier (49°N)	Simple counting	ca. 4.3 cm/year	Approximate value; method not specified	7 years	Not specified	Oliver *et al.*, 1985

Dome Peak area (48°N)	Simple counting	None added	Considered but all ages are cited without age-height correction	None added	No ecesis added to ring count dates	Miller, 1969
Blue and Hoh glaciers (47°N)	Simple counting	None determined	Negligible as cores taken close to base of tree	12 years; and longer	Lower value added to down-valley moraines; higher, unspecified value added to higher elevation sites	Heusser, 1957
Mt. Rainier (47°N)	Simple counting	Not considered		50 years	Historical records	Harrison, 1956
Nisqually Glacier, Mt. Rainier (47°N)	Simple counting	None determined	Negligible, even though cores taken at 30 cm above ground	1-14 years; average of 5 years added	Sampling of surfaces of known age	Sigafoos and Hendricks, 1961
Mt. Rainier (47°N)	Simple counting	None determined	Negligible as cores taken close to base of tree	0-41 years; average of 5 years added to valley sites	Sampling of surfaces of known age	Sigafoos and Hendricks, 1969
Mt. Rainier (47°N)	Simple counting		Reference to Sigafoos and Hendricks, 1969		Reference to Sigafoos and Hendricks, 1969	Burbank, 1981
U.S. Rocky Mountains, Montana (49°N)						
Glacier National Park (49°N)	Simple counting	3 cm/year	From previous nearby study	5 years	Reference to Sigafoos and Hendricks, 1969	Carrara and McGimsey, 1981
Patagonian Andes (41-55°S)						
Glaciar Frias, Mt. Tronador (41°S)	Crossdating	2.7-10 cm/year	Estimate	8-71 years	Historical records; damaged trees; high values on exposed valley bottom, low values in sheltered spots	Villalba *et al.*, 1990
Glaciar San Rafael, West side of HPN[1] (47°S)	Not part of study	Not part of study	Not part of study	<10 years	Historical records; aerial photographs	Warren, 1993
West side of HPN[1] (47°S)	Simple counting	10-20 cm/year	Average growth rate is added	6 years	Reference to Warren, 1993	Winchester and Harrison, 1996

Northwest side of HPN[1] (47°S)	Simple counting	20 cm/year	Average growth rate is added	6 years	Reference to Winchester and Harrison, 1996	Harrison and Winchester, 1998
East side of HPN[1] (47°S)	Simple counting	2.9-22.4 cm/year	Value added according to ring widths near pith; established at site from 12 small trees	‹22 - ›93 years	Airphotos; lichen dates; high values on exposed flanks, low values near water	Winchester and Harrison, 2000
Glaciar Soler, East side of HPN[1] (47°S)	Simple counting	None given	Unspecified value added, extrapolated from the mean height growth rate obtained from the ring count and the height above the coring	50 years	Estimate; extrapolated from lower value on more favourable sites	Sweda, 1987
Glaciar Nef, East side of HPN[1] (47°S)	Simple counting	4.7-17.1 cm/year	Value added according to ring widths near pith and site conditions; established at site from 10 small trees	35 years, 92 years	Lichen dates for same surface; 35 years is added to most sampled trees	Winchester *et al.*, 2001
Southeast side of HPN[1] (47°S)	Simple counting	Considered, but not specified	According to text some factor was considered, according to Table 1 none was added	22, 26, and 93 years	Reference to previous work nearby; low value added to sites near water, middle value added to sites on valley sides and terraces, and high value added to sites on exposed mountainsides	Harrison and Winchester, 2000
Northwest side of HPS[2] (48-49°S)	Simple counting	None added	Not considered	70 years	Damaged tree on same moraine; aerial photographs	Mercer, 1970
Glaciar Ameghino, East side of HPS[2] (50°S)	Simple counting	None	Most likely negligible as cores might have been taken close to base of tree	›70 years; -10 years	High estimate from unvegetated moraine built ca. 1870-1880; low estimate from below trimline	Nichols and Miller, 1951
Glaciar Dickson, East side of HPS[2] (51°S)	Not part of study	Not part of study	Not part of study	‹40 years	Aerial photographs	Dollenz, 1991
Torres del Paine, East side of HPS[2] (51°S)	Simple counting	Not part of study	Not part of study	40-50 years	Estimate	Armesto *et al.*, 1992
Glaciar Serrano, East side of HPS[2] (51°S)	Simple counting	Not part of study	Not part of study	100 years	Estimate	Pisano, 1978

Glaciar Lengua, Gran Campo Nevado (53°S)	Crossdating	7.1-25 cm/year	Value added according to ring widths near pith; established at site from 15 small trees	15 years	Aerial photographs; damaged trees on same moraines	Koch and Kilian, 2005
Bahia Pia, Cordillera Darwin (55°S)	Simple counting	Not part of study	Not part of study	<20 years	Aerial photographs	Holmlund and Fuenzalida, 1995

[1] Hielo Patagónico Norte.
[2] Hielo Patagónico Sur.

Table 3.2 Age-height corrections based on ring counts from seedlings (subalpine fir) cut at ground level in Garibaldi Park.

Site	Elevation (m asl)	Number of samples	Growth rate (cm/year) average (min./max.)
Overlord Glacier	1375	10	3.62 (2.02/4.90)
	1600	9	2.03 (0.95/3.82)
	1675	7	1.67 (0.93/2.98)
Helm Glacier	1750	7	1.98 (0.65/3.04)
Sphinx Glacier	1500 (moraine crest)	10	2.46 (1.13/3.59)
	1500 (forefield)	9	2.06 (0.88/2.98)
	1575 (forefield)	4	1.57 (0.78/2.39)
Sentinel Glacier	1600	6	1.97 (0.79/3.71)
Warren Glacier	1500 (moraine crest)	6	2.53 (1.73/3.54)
	1500 (forefield)	10	2.15 (1.01/3.09)
Lava Glacier	1400	8	1.66(0.37/2.65)
Snowcap Lakes	1475	7	1.78(1.57/3.18)
	1600	4	1.37(0.75/2.23)
Stave Glacier	1100	8	4.29(1.12/5.27)

Table 3.3 Ecesis values for subalpine fir in Garibaldi Park.

Site	Elevation (m asl)	Number of samples	Ecesis (years) average (min.-max.)	Reference
Wedgemount	1850	unknown	13-51	Ricker and Tupper, 1979
Overlord	1375 moraine	8	12 (6-19)	this study
	1375 forefield	10	25 (22-27)	this study
	1550 forefield	7	35 (31-37)	this study
	1675 forefield	4	38 (37-39)	this study
Helm	1750	18	49 (46-51)	this study
Helm, Sphinx, Warren, Lava	1400-1750	unknown	20-40	Mathews, 1951
Sphinx, Warren, Sentinel	1500	unknown	ca. 20	Fraser, 1970
Sphinx	1500	13	26 (24-28)	this study
	1650	10	30 (28-31)	this study
Sentinel	1475	12	25 (22-28)	this study
	1600	6	28 (26-30)	this study
Warren	1500 moraine	7	16 (11-24)	this study
	1500 forefield	13	29 (27-31)	this study
Lava	1400 forefield	11	34 (32-35)	this study
	1600 forefield	3	37 (35-40)	this study
Snowcap Lakes	1500	unknown	>13-51	Ricker, 1979
	1600	10	49 (42-56)	this study
Stave	1100	12	13 (7-16)	this study

Table 3.4 Ecesis values at similar elevations in Garibaldi Park showing the influence of climate.

Site	Elevation (m asl)	Climate[1] (precipitation/temperature)	Ecesis (years) average (min./max.)
Lava	1600	very maritime (very high/cool)	37 (35-40)
Sentinel	1600	maritime (high/cool)	28 (26-30)
Sphinx	1650	maritime (high/cool)	30 (28-31)
Overlord	1550	intermediate (intermediate/cold)	35 (31-37)
	1675	intermediate (intermediate/cold)	38 (37-39)
Snowcap Lakes	1600	continental (low/cold)	49 (42-56)

[1] Precipitation and temperature are inferred from nearest climate stations and from snowdepth measurements (Koch, unpublished data). Climate stations are: Squamish (46 m asl; average annual precipitation - 2370 mm; average annual temperature - 9° C), and Whistler (658 m asl; average annual precipitation - 1230 mm; average annual temperature - 6° C). See Figure 3.2 for locations.

Table 3.5 Estimates of age of the outermost moraine of Warren Glacier, which was abandoned and stabilized in AD 1705.

Factor	Average regional[1]	Average local[2]	Local[3]
Ring count	272	272	268
Height growth	22 years	21 years	14 years
Ecesis	28 years	22 years	11 years
Date obtained	AD 1680	AD 1687	AD 1709

[1] Garibaldi Park.
[2] Warren Glacier forefield.
[3] Incorporates local age-height correction and local ecesis.

CHAPTER 4
GLACIER CHANGE IN GARIBALDI PROVINCIAL PARK, BRITISH COLUMBIA, SINCE THE LITTLE ICE AGE

Abstract

Fluctuations of glaciers during the 20th century in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia, were reconstructed from historical documents, aerial photographs, and fieldwork. At least 630 km^2 (33%) of the park were covered by glacier ice at the beginning of the 18th century. Since then, ice cover has decreased by about 240 km^2, a 38% loss in 300 years. More than half of the wastage has occurred since 1920. Glacier recession was greatest between the 1920s and 1950s, with average annual recession rates of glacier fronts of 30 m. Many glaciers readvanced in the 1960s and 1970s, but all glaciers have receded over the last 20 years, at generally accelerating rates. Glacier recession occurred during warm and relatively dry climate periods, whereas advances occurred during relatively cold periods. Times of recession and advance coincide with states of the Pacific Decadal Oscillation (PDO): retreat during the positive PDO phases between 1925 and 1946 and since 1977, and advance during negative PDO phases between 1890 and 1924 and between 1947 and 1976. However, glacier behaviour in Garibaldi Park in the 20th century is similar to that in Europe, South America, and New Zealand, suggesting a common, global climatic cause. Global temperature change in the 20th century explains much of the behaviour of glaciers in Garibaldi Park and elsewhere.

Keywords: glacier retreat, twentieth century, southern Coast Mountains, Garibaldi Provincial Park, British Columbia

Introduction

Glaciers are sensitive to changes in climate and are an important element of studies that document past climate change (Global Climate Observing System 1995; International Panel on Climate Change, 2001). Monitoring of glaciers around the world, which has been done in part to document and better understand recent climate change, has led to the establishment of worldwide databases such as the World Glacier Inventory (Haeberli *et al.*, 1998a; www.geo.unizh.ch/wgms/) and the World Data Center A for Glaciology (Fetterer *et al.*, 2002; nsidc.org/wdc). However, both databases lack information for about 50% of the world's glaciers (Haeberli *et al.*, 1998b).

Glacier behaviour in the 20th century in Europe and a few other regions is known in detail from photographs, paintings, and written records (Harper, 1993; Warren and Sugden, 1993; Pfister *et al.*, 1994; Holzhauser and Zumbühl, 2002; Motyka *et al.*, 2002; Rivera and Casassa, 2004). In contrast, only a few researchers have reconstructed 20th century glacier variations in Canada in detail (Luckman *et al.*, 1987; Koch *et al.*, 2004a; Koch and Clague, 2005). Studies have revealed, however, a common pattern of glacier behaviour in the western part of the country: recession from the 1900s to the 1920s, the 1930s to the 1950s, and since the 1980s; and advances in the 1920s and from the 1950s through the 1970s. Nevertheless, little is known about areal and volumetric changes of glaciers, and the rates at which the changes occurred.

The objectives of this paper are to document: (1) frontal variations of glaciers in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia during the 20th century; and (2) differences in areal extent of glaciers in the park between the Little Ice Age maximum and today. I discuss the data in the context of regional and global glacier and climate change.

Study Area

Garibaldi Provincial Park is located in the southern Coast Mountains, about 70 km north of Vancouver, British Columbia (Fig. 4.1). Mount Garibaldi, in the southwest corner of the park, reaches 2678 m above sea level (asl) and is less than 20 km from tidewater at the head of Howe Sound. Several other peaks in the park are higher than 2500 m asl. Garibaldi Park has more than 150 glaciers with a total area of about 390 km^2 at present, including two icefields larger than 10 km^2 (Garibaldi Neve and Mamquam Icefield).

The landscape of Garibaldi Park has been strongly shaped by Quaternary continental and alpine glaciation and, in the southwestern part of the park, by Quaternary volcanism (Mathews, 1958). The park is underlain mainly by granitic rocks of the Coast Plutonic Complex, but pendants of metamorphosed Cretaceous conglomerate and volcaniclastic rocks occur in several areas and the southwestern part of the park is dominated by the Mount Garibaldi volcanic complex of Pleistocene age (Mathews, 1958; Monger and Journeay, 1994).

Moist maritime air masses strongly influence the southwestern part of the park, but climate becomes increasingly continental to the north and east. Average annual precipitation in Squamish at tidewater is 2370 mm, but is only 1230 mm at Whistler, 60 km to the north. Overall, the climate is humid and cool, with very wet winters and dry summers. Annual precipitation ranges from 1000 to more than 3000 mm (water equivalent), with most falling as snow between October and March.

Methods

Changes in the fronts of thirteen glaciers in Garibaldi Park were reconstructed from ground photographs dating back to 1928 and vertical aerial photographs taken since 1931 (Table 4.1). Former ice-front positions were transferred from aerial photographs onto transparent overlays by comparing distinctive features close to glacier margins, such as large boulders, ponds, and bedrock outcrops that could be identified on sequential photographs. Differences in photo scale, lighting, surface vegetation, and photographic distortion result in possible errors of up to 10 m in the mapped margins. Former ice-front positions were also mapped in the field by using a tape to measure distances between features that could be identified in successive aerial photographs. Changes in areas of the glaciers from the Little Ice Age maximum to the late 1990s were determined by mapping glacier margins on a digital elevation model (DEM) of the park. Present-day and maximum Little Ice Age extents of the glaciers were mapped using data shown on 1:20,000-scale topographic maps, aerial photographs, oblique photographs taken on overview flights of the park between 2002 and 2004, and ground surveys.

Results

Comparison of ice extent in Garibaldi Park at the Little Ice Age maximum (AD 1690s-1720s; Koch *et al.*, 2004a) and today (1996-2003) provides a good estimate of regional ice loss over the past 300 years. At least 630 km^2 of the park were covered by ice at the maximum of the Little Ice Age. This value is a minimum because past ice extent in some cirques could not be determined and because some cirques that supported small glaciers during the Little Ice Age, but today are ice-free, may have been missed in the inventory. Present ice cover in the park is 390 km^2, thus the decrease in glacier extent over the past 300 years has been at least 38%. More than half of this decrease has happened since about 1920. The following sections and Table 4.2 provide more detailed data for the 13 glaciers that were studied in detail.

Overlord Glacier

Overlord Glacier today has an area of 4.1 km^2, about 65% of its Little Ice Age maximum extent (Fig. 4.2; Table 4.3). The oldest photo, taken in 1929, shows that the glacier had, by then, retreated from its innermost moraine. Recession was rapid until the late 1960s, at which time Overlord Glacier terminated farther upvalley than at any time since the Little Ice Age maximum. The glacier advanced from shortly before 1969 until about 1980. Since 1980, it has left annual push moraines, showing slowly accelerating retreat. Overlord Glacier is presently inside its late 1960s limit and thus has reached its minimum extent since the Little Ice Age maximum.

Black Tusk Glacier

Three snowfields and two small cirque glaciers occupy an area of 0.8 km^2 around Black Tusk. Ice cover is only about 14% of that at the Little Ice Age maximum, when the cirque glaciers coalesced (Fig. 4.3; Table 4.3). The earliest ground photographs show that, in 1928, the glacier covered 2.1 km^2. Total recession between 1928 and 1990 ranges from 200 to 750 m. Since 1990, the cirque glaciers and snowfields have been relatively stable, likely due to their location on north-facing slopes.

Helm Glacier

Helm Glacier covered an area of 6.1 km^2 at the Little Ice Age maximum (Figs. 4.4 and 4.5; Table 4.3). All that is left today is the remnant main body of Helm Glacier and several small independent cirque glaciers and snowfields. Ground photographs from 1928 show that the glacier was still close to its maximum Little Ice Age limit (Table 4.3). Two small push moraines lie between the innermost moraine, which was abandoned in the 1910s, and the glacier terminus in 1928, suggesting that recession dominated, but was interrupted by two short standstills or minor readvances. Recession continued at an average rate of 15-17 m/year until about 1969, although with considerable annual variability in the 1930s (Taylor, 1936, 1937), and likely throughout this time. Helm Glacier began to advance around 1969, and the advance continued until about 1977. Between 1977 and 1990, the western part of the glacier disintegrated into small cirque glaciers. Recession of Helm Glacier has accelerated in the last decade, and cirque glaciers that were formerly confluent with the main glacier lost about half of their area between 1996 and 2003. At present rates of retreat, Helm Glacier will vanish within this century, probably before 2050.

Sphinx Glacier

Sphinx Glacier has lost about 30% of its area since the Little Ice Age maximum (Fig. 4.6; Table 4.3). Two moraines were abandoned in the first and second decades of the 20th century, based on tree rings and lichen measurements (Chapter 5). When Sphinx Glacier was first photographed in 1928, the trunk glacier and the tributary glacier from the south were almost in contact, although the main terminus was 250 m inside the innermost moraine. Retreat continued at varying rates (Taylor, 1936, 1937) until 1964. A readvance began between 1964 and 1969 and continued until about 1977. Sphinx Glacier has retreated continuously since 1977.

Sentinel Glacier

Sentinel Glacier comprises three tongues with a total area of 4.4 km^2 (Fig. 4.7; Table 4.3). Stabilization and abandonment of its two innermost moraines have been dated to the 1910s and 1920s by dendrochronology and lichenometry (Chapter 5). The glacier retreated from the innermost moraine with only short interruptions. Recession in 1935 and 1936 was 73 m and 15 m, respectively (Taylor, 1936, 1937), indicating that retreat was highly variable. Mass balance was positive between 1965 and 1974, yet the terminus retreated 263 m during this period (Mokievsky-Zubok and Stanley, 1976). The three tongues of Sentinel Glacier behaved differently between 1969 and 1977: the western and eastern tongues retreated, whereas the middle tongue advanced 130 m, probably due to a positive mass balance for seven of the nine years. A small moraine in front of the eastern tongue indicates that this part of Sentinel Glacier advanced briefly in the late 1970s or early 1980s. All three snouts have retreated since the late 1970s or early 1980s.

Warren Glacier

Warren Glacier and its three snowfields have an area of 7.8 km^2 (Table 4.3). The first photograph of the glacier, taken in 1912, shows the terminus close to a moraine abandoned in the first decade of the 20th century (Figs. 4.8 and 4.9). The western and eastern halves of Warren Glacier have very different recessional histories, probably because the former is covered by debris. Only the history of the eastern half is presented here. Retreat persisted until about 1973 at highly variable rates (Taylor, 1936, 1937). Lateral loss between 1964 and 1969 was greater than frontal loss. Very rapid recession between 1977 and 1982 was most likely caused by calving in a proglacial lake. Warren Glacier advanced 80 m between 1973 and 1977, but has receded since then. The western half of the glacier, however, has remained relatively stable since 1964 and at present is more advanced than it has been since 1969. However, as previously mentioned, this part of the glacier is blanketed with debris and is thus sheltered from latent and sensible heat.

Garibaldi Glacier

Garibaldi Glacier shares the same accumulation area as Lava and Bishop glaciers, thus its area cannot be reliably determined. Nevertheless, it is 4.6 km^2 smaller today than at the Little Ice Age maximum (Fig. 4.10; Table 4.3). The innermost lateral moraine of Garibaldi Glacier was abandoned in the 1910s (Chapter 5), but the exact position of the glacier terminus at that time is unknown. In 1928, when the first ground photographs were taken, the glacier was still more than half of its Little Ice Age maximum size, as was Diamond Glacier, a cirque glacier to the west that fed Garibaldi Glacier during the Little Ice Age. Recession dominated until 1977 at generally slowing rates. The glacier readvanced slightly between 1977 and 1982, and since then has retreated less than 50 m. Garibaldi Glacier ceased to exist as a discrete ice tongue in the late 1970s, thus the small variations since 1982 are changes in the icefield that feeds it and five other glaciers, including Lava Glacier, which is discussed next.

Lava Glacier

Lava Glacier is 6.3 km^2 smaller today than at the Little Ice Age maximum (Fig. 4.10; Table 4.3). Numerous undated small push moraines are present inside the innermost major moraine, which was abandoned in the 1910s (Chapter 5). At the time of the first photograph in 1928, Lava Glacier was more than half its maximum Little Ice Age size and still had two distinct tongues. Both tongues receded at very high rates until 1969, when the west tongue disappeared. Lava Glacier advanced less than 20 m between 1977 and 1984. It retreated more than 500 m between 1984 and 1996, when downwasting of the ice exposed a bedrock knob around which the glacier now flows. Little change has occurred since 1996.

Snowcap Lakes area

Fluctuations and frontal positions of three glaciers in the Snowcap Lakes area have been reconstructed from aerial photographs (Fig. 4.11). Snowcap Icefield and its four northern outlet glaciers cover 12.8 km^2 at present (Table 4.3). In 1931, when the first aerial photographs were taken, Griffin and Staircase glaciers were still confluent and covered the southern part of Hourglass Lake. Recession dominated throughout the first half of the century, but Griffin and Thunderclap glaciers began to readvance sometime before 1969. All three glaciers advanced between 1969 and 1977. Griffin and Thunderclap glaciers were still advancing in 1978, with Griffin Glacier depositing debris on living vegetation (Ricker, 1979). Shortly thereafter, however, the three glaciers began to retreat at relatively constant rates. The extent of the three glaciers in 1996 was similar to that in 1969, when the advance began. Between 1996 and 2004, Thunderclap Glacier retreated out of Snowcap Lakes. Glacier de Fleur des Neiges, just east of Staircase Glacier, shows a net loss in length of 120 m between 1952 and 1996, almost entirely after 1978 (Ricker, 1979).

Stave Glacier

Stave Glacier covers 13.6 km^2 at present (Fig. 4.12; Table 4.3). Its innermost moraine was abandoned in the first decade of the 20th century. The glacier occupied only the northern embayment of its proglacial lake in 1952, when the first aerial photographs of the glacier were taken. Sometime between 1969 and 1977, the southern tributary lobe ceased to feed the main tongue, leading to rapid recession until 1996 (an average rate of 53 m/year between 1977 and 1996).

Discussion

At the beginning of the 20th century, glaciers in Garibaldi Park were close to their Little Ice Age limits. They retreated slowly during the first two decades of the 20th century, interrupted by small readvances or stillstands during which moraines were built and then abandoned (Tables 4.2 and 4.4). The youngest moraines date to the 1920s. Glaciers retreated very rapidly between the 1920s and 1960s (Fig. 4.13; Tables 4.2 and 4.4). Average and maximum documented retreat rates during this period are about 30 and 80 m/year, respectively (Taylor, 1936). Some glaciers (e.g., Overlord) were smaller in the 1960s than at any other time in the late Holocene. Glaciers readvanced up to 300 m between the 1960s and early 1980s, followed by retreat that has continued to the present at accelerating rates (Fig. 4.13; Tables 4.2 and 4.4). Most glaciers are now receding upvalley of their 1960s limits and are becoming smaller than at any other time in the last several millennia (Koch *et al.*, 2005).

Twentieth-century glacier changes in Garibaldi Park are similar to those in other areas in western Canada. Historical records and photographs from the early 20th century have been analyzed for national parks in the Canadian Rocky Mountains (Luckman *et al.*, 1999); and aerial photographs, available for much of western Canada since the 1930s, have been used to reconstruct glacier fluctuations in many other areas (Baranowski and Henoch, 1978; Ricker, 1979, 1980; Ricker *et al.*, 1981, 1983, Tupper and Ricker, 1982;

Gardner and Jones, 1985; Luckman *et al.*, 1987; McCarthy and Smith, 1994; Luckman, 1998b, 2000; Larocque and Smith, 2003; Evans, 2004; Koch *et al.*, 2004a; Kershaw *et al.*, 2005)

Most glaciers in western Canada generally receded during the first two decades of the 20th century, before readvancing and constructing moraines in the 1920s. The next four decades were a period of rapid and extensive recession, with some glaciers losing up to 1800 m of their length (West and Maki, 1961). Glaciers were stable or readvanced up to 1000 m between the 1950s and early 1980s (Baranowski and Henoch, 1978). Since then, they have retreated at accelerating rates, with length losses of up to 500 m (Kershaw *et al.*, 2005). Total ice loss since the Little Ice Age for individual glaciers and for regions ranges from 10 to 90% (McCarthy and Smith, 1994; Luckman, 1998b; Lewis and Smith, 2004a).

Previous research in the Pacific Northwest has demonstrated the close relation between instrumental climate data and glacier mass balance (Burbank, 1982; Harper, 1993; Hodge *et al.*, 1998; Bitz and Battisti, 1999; Moore and Demuth, 2001; Kovanen, 2003). Monthly mean temperature and total precipitation data from the Agassiz CDA (Canadian Department of Agriculture) climate station (Fig. 4.1) were used to determine indices of regional climate variability. Annual mean temperature and annual total precipitation values were calculated from monthly values. The Agassiz data are highly correlated with data from Vancouver Airport (Fig. 4.1), but as Moore and Demuth (2001) point out, the Agassiz record extends back to the 1890s and the station is less affected by urban development. Agassiz winter precipitation and summer temperature correlate with, respectively, winter and summer mass balances of Place Glacier (Fig. 4.1; Moore and Demuth, 2001), 40 km northeast of Garibaldi Park and, therefore, are deemed suitable for comparison with the glacier behaviour in my study.

The climate data show below-average mean annual temperatures between 1892 and 1919, and 1961 and 1975, and above-average temperatures between 1920 and 1960, and since 1976. Annual total precipitation was lower than the average for the instrumental period between 1892 and 1909, and also between 1923 and 1949, but was higher than average between 1910 and 1922, and since 1950. The periods of glacier advance documented in this study are generally cool and wet, whereas periods of glacier recession are warm with variable precipitation. These findings further show that the response time of glaciers to climate change in the Pacific Northwest is relatively short (5-10 years; Kovanen, 2003).

Glacier behaviour in the Pacific Northwest is also closely linked to the Pacific Decadal Oscillation (PDO; McCabe and Fountain, 1985; Mantua *et al.*, 1997; Hodge *et al.*, 1998; Bitz and Battisti, 1999; Gedalof and Smith, 2001b; Moore and Demuth, 2001; Mantua and Hare, 2002; Kovanen, 2003; Lewis and Smith, 2004b). The PDO is a long-lived, El Niño-like pattern of climate variability characterized by alternating states of higher and lower sea surface temperatures in the North Pacific (Zhang *et al.*, 1997; Mantua and Hare, 2002). The positive phase of the PDO is characterized by an enhanced Aleutian Low and reduced storminess in the Pacific Northwest. During this phase, storm tracks tend to divert towards Alaska, resulting in warmer and drier winters in southern British Columbia, with below-average snow packs and negative winter glacier mass balances. Conversely, the negative phase of the PDO is associated with a diminished Aleutian Low and increased winter storminess in the Pacific Northwest. During this phase, storm tracks divert away from Alaska and towards British Columbia, leading to lower air temperatures, higher precipitation, and greater snow depth in southern British Columbia. Positive PDO phases between 1925 and 1946 and since 1977 are times of glacier recession in Garibaldi Park, and negative PDO phases between 1890 and 1924 and 1947 and 1976 coincide with intervals of stable or advancing glaciers.

The PDO, however, may not be responsible for glacier fluctuations in Garibaldi Park during the last century. Glaciers in most parts of the world have fluctuated in a similar manner to those in Garibaldi Park (Koch and Clague, 2005; Oerlemans, 2005), suggesting that the forcing mechanisms must operate on a global scale. Alpine glaciers in the Americas, Europe, Asia, and New Zealand have receded since the Little Ice Age, and the rate of recession in the late 20th century appears anomalous in the context of the Holocene (Arendt *et al.*, 2002; Reichert *et al.*, 2002; Rignot *et al.*, 2003; Paul *et al.*, 2004). The instrumental record of global temperatures shows that warming in the 20th century occurred during two phases: 1920-1940 and 1975 until the end of the century (Bradley and Jones, 1993; Jones and Moberg, 2003). The two intervals coincide with periods of global glacier recession (New Zealand Alps: Gellatly *et al.*, 1988; western U.S.: Harper, 1993; Alaska: Evison *et al.*, 1996; Patagonian Andes: Aniya, 2001; European Alps: Holzhauser and Zumbühl, 2002; tropical Andes: Georges, 2004; Spanish Pyrenees: Cía *et al.*, 2005; Antarctic Peninsula: Cook *et al.*, 2005; western Canada: Koch and Clague, 2005). The intervening period coincides with glacier advances in Garibaldi Park and elsewhere. Thus global temperature changes can explain most of the behaviour of glaciers in the study area in the 20th century.

Observed historical ice loss in Garibaldi Park and in mountain regions around the world is broadly synchronous and attributable to global 20th century climate warming. If warming continues, glaciers in Garibaldi Park will become smaller and may vanish, which will be detrimental to recreation and tourism. Glaciers are important for summer skiing at Whistler resort, just outside the park (Fig. 4.1), and are a major attraction for outdoor enthusiasts. Glacier loss will negatively affect hydroelectric power generation, agriculture, and salmon runs in the Pacific Northwest, as streams during late summer, which are presently dominated by glacier melt, will carry less water.

Conclusions

Glaciers in Garibaldi Park fluctuated in a similar manner in the 20^{th} century. Stillstands and minor readvances during the first two decades of the century punctuated slow retreat. Glacier recession was particularly pronounced between the 1930s and 1960s and since the 1980s. Between these periods, glaciers advanced up to 300 m or were stable. The areal extent of ice in the park has decreased by about 240 km^2 since the Little Ice Age maximum in the late 17^{th} or early 18^{th} century, a 38% loss in about 300 years. However, the majority of this loss occurred in the 20^{th} century. At present, about 20% (390 km^2) of Garibaldi Park is still ice-covered, but glaciers are retreating rapidly and some will vanish by the end of the century if the present trend continues.

Periods of glacier recession coincide with warm and relatively dry periods, as well as with positive PDO phases, whereas advances occurred during relatively cold periods and negative PDO phases. However, glacier behaviour in Garibaldi Park is also broadly synchronous with that elsewhere in the Northern and Southern hemispheres, suggesting a common, global climatic cause. Global temperature change in the 20^{th} century explains much of the behaviour of glaciers in Garibaldi Park and elsewhere.

Figures

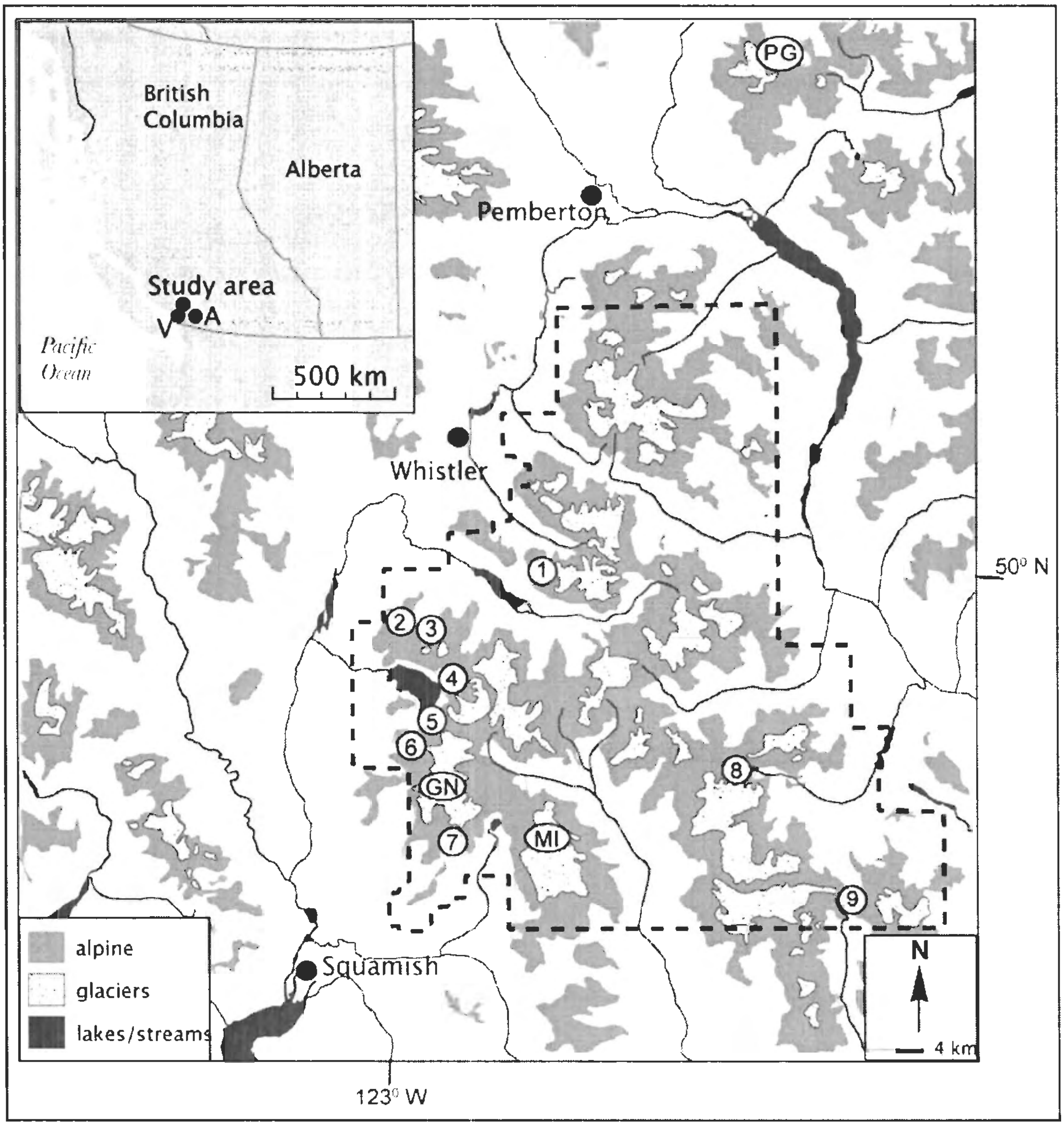

Figure 4.1 Location of Garibaldi Provincial Park and its glaciers. 1, Overlord Glacier; 2, Black Tusk Glacier; 3, Helm Glacier; 4, Sphinx Glacier; 5, Sentinel Glacier; 6, Warren Glacier; 7, Garibaldi/Lava glaciers; 8, Snowcap Lakes; 9, Stave Glacier; GN, Garibaldi Neve; MI, Mamquam Icefield. Also shown are the locations of Place Glacier (PG) and Vancouver and Agassiz (V and A on the inset map).

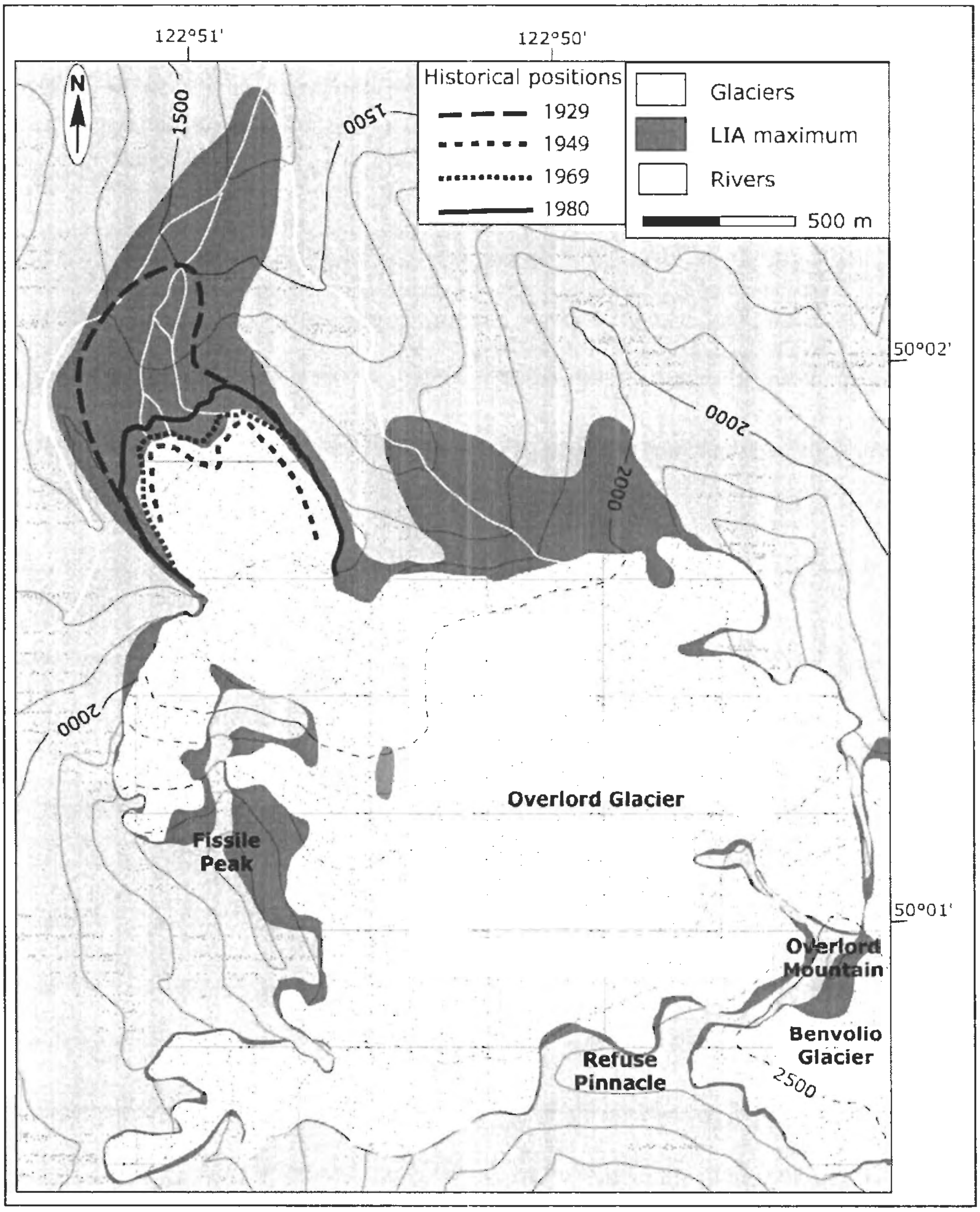

Figure 4.2 Map of Overlord Glacier showing its 1996 and maximum Little Ice Age extents and historical positions of its terminus.

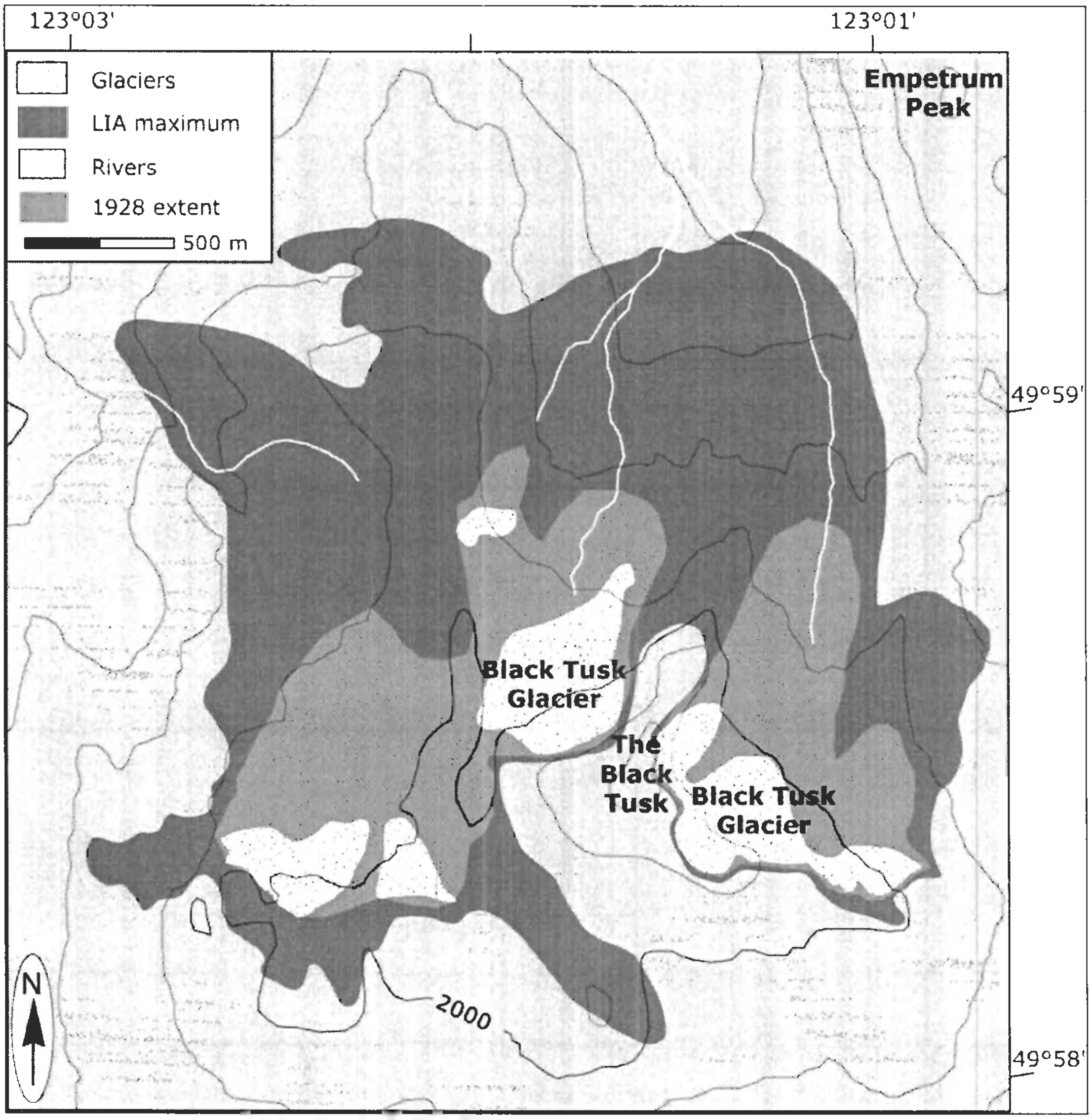

Figure 4.3 Map of Black Tusk Glacier showing its 1996, 1928, and maximum Little Ice Age extents.

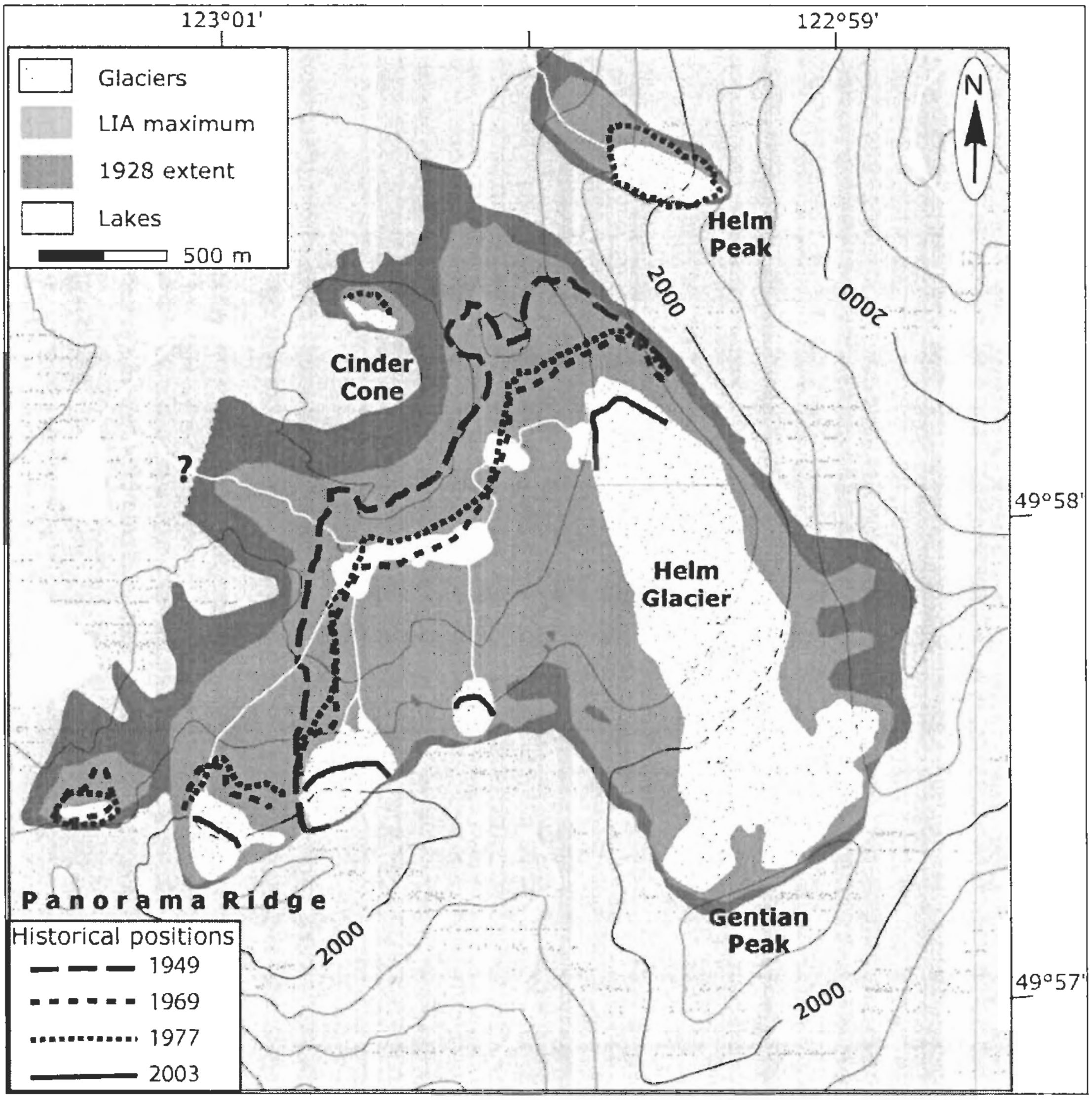

Figure 4.4 Map of Helm Glacier showing its 1996 and maximum Little Ice Age extents and historical positions of its terminus.

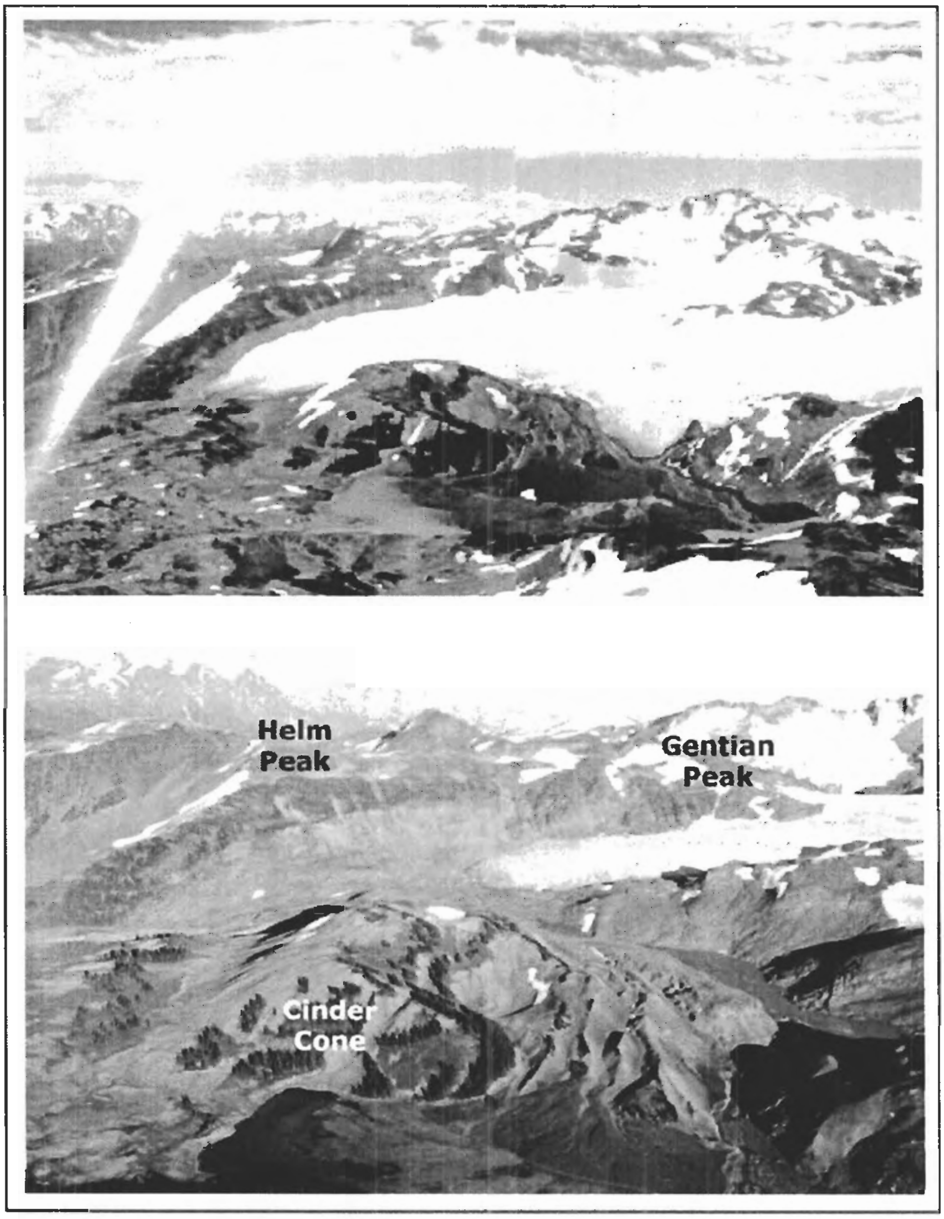

Figure 4.5 Photographs of Helm Glacier in 1928 (top; BC Archives I-67145 and 67146; reprinted with permission of the British Columbia Archives) and 2002 (bottom; J. Koch).

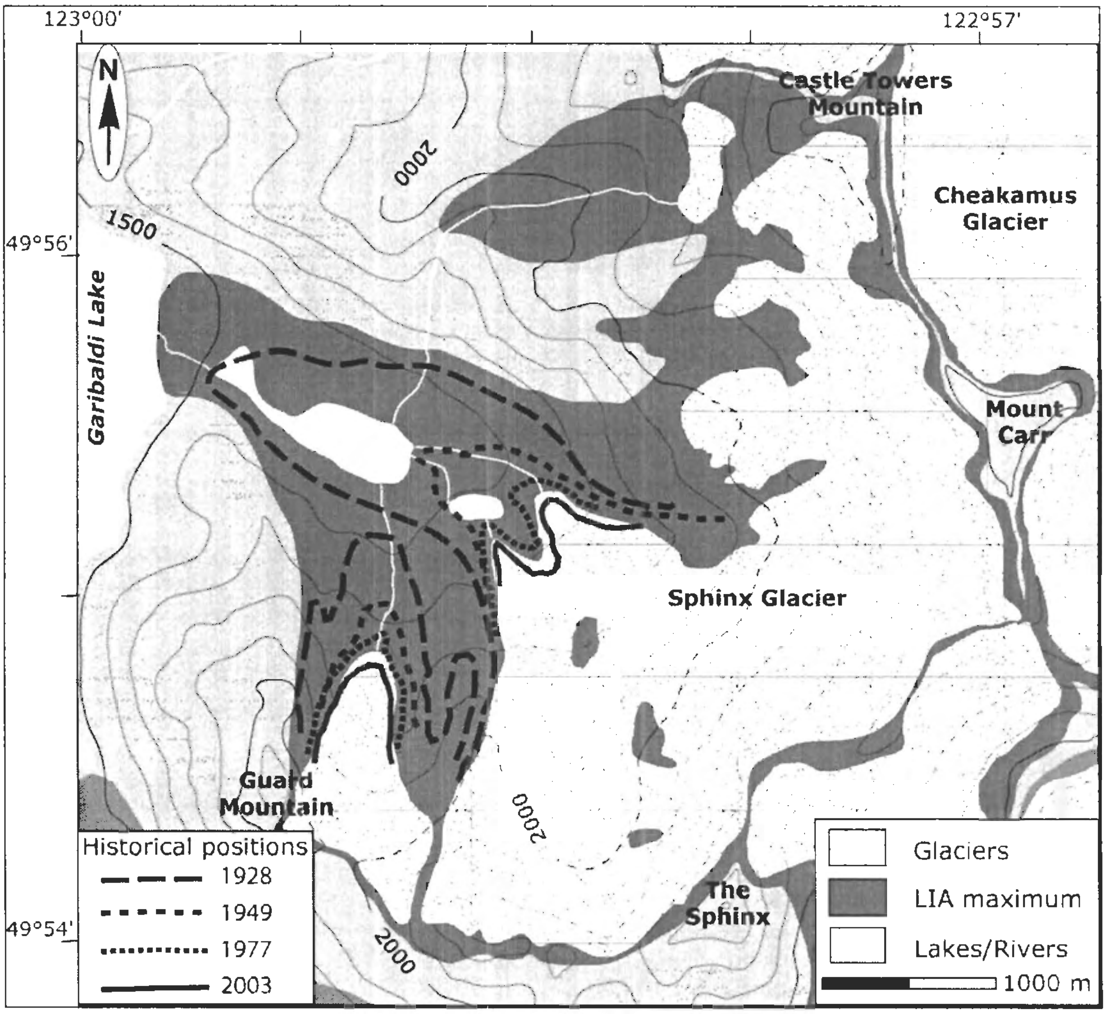

Figure 4.6 Map of Sphinx Glacier showing its 1996 and maximum Little Ice Age extents and historical positions of its terminus.

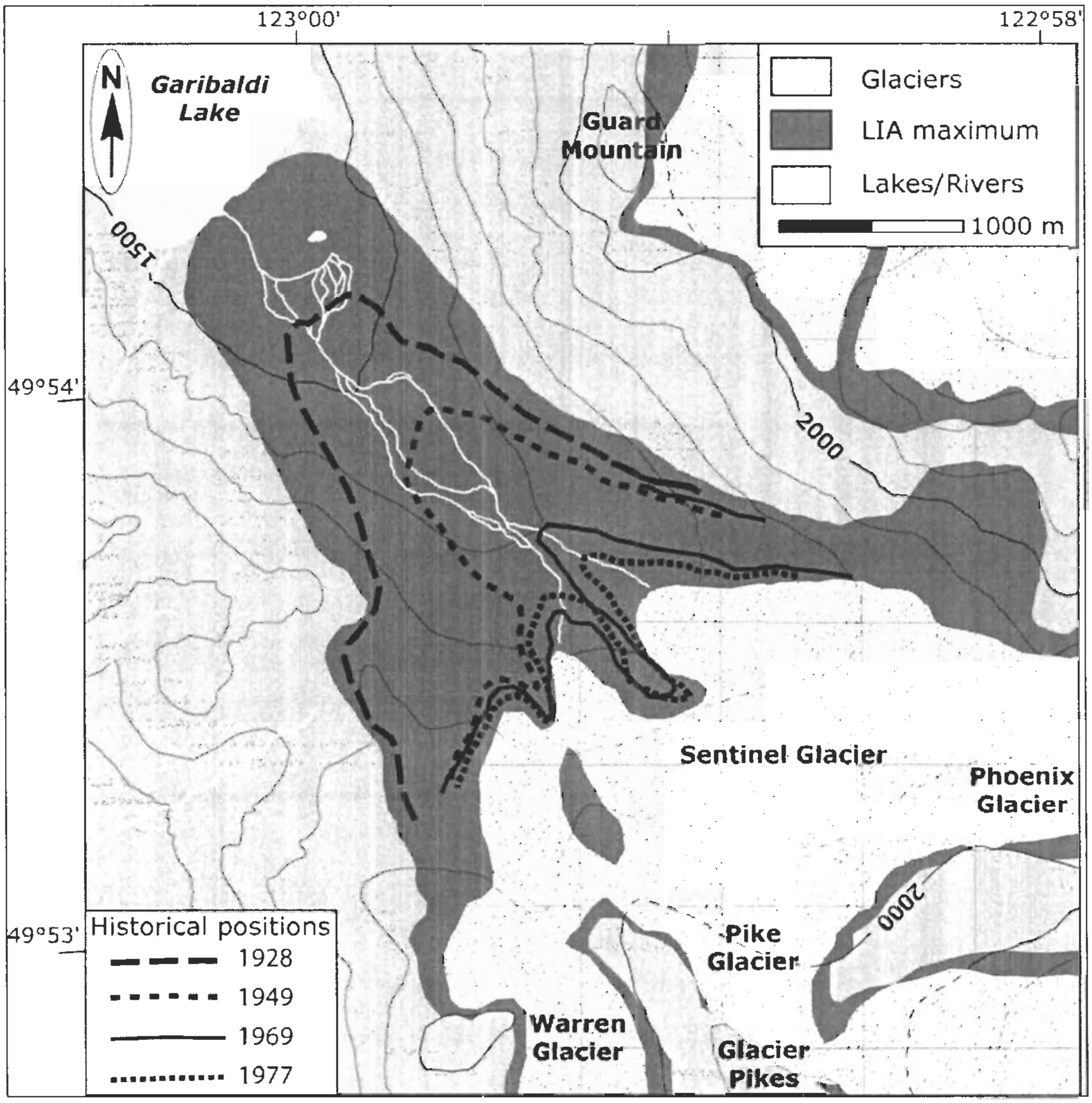

Figure 4.7 Map of Sentinel Glacier showing its 1996 and maximum Little Ice Age extents and historical positions of its terminus.

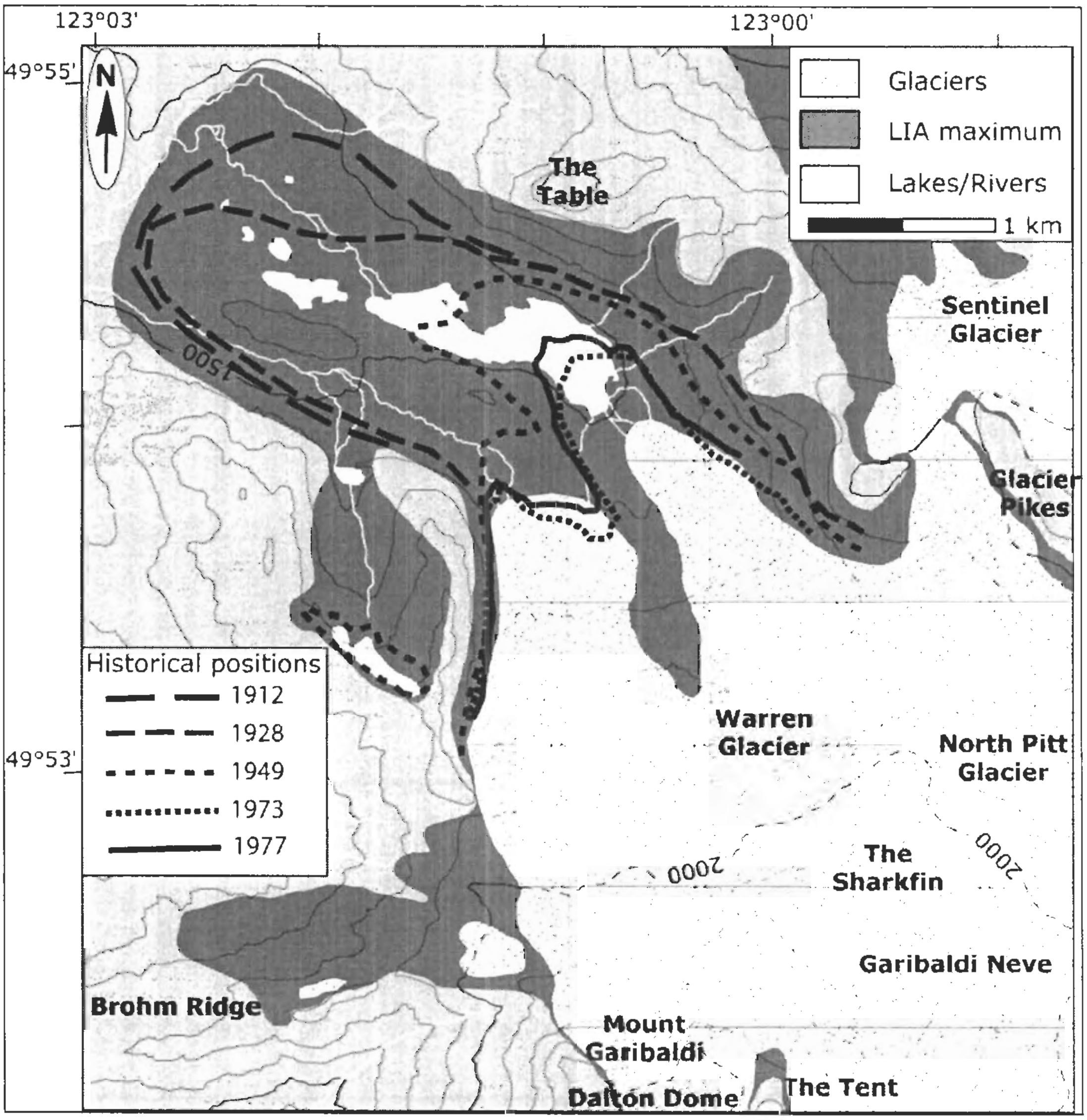

Figure 4.8 Map of Warren Glacier showing its 1996 and maximum Little Ice Age extents and historical positions of its terminus.

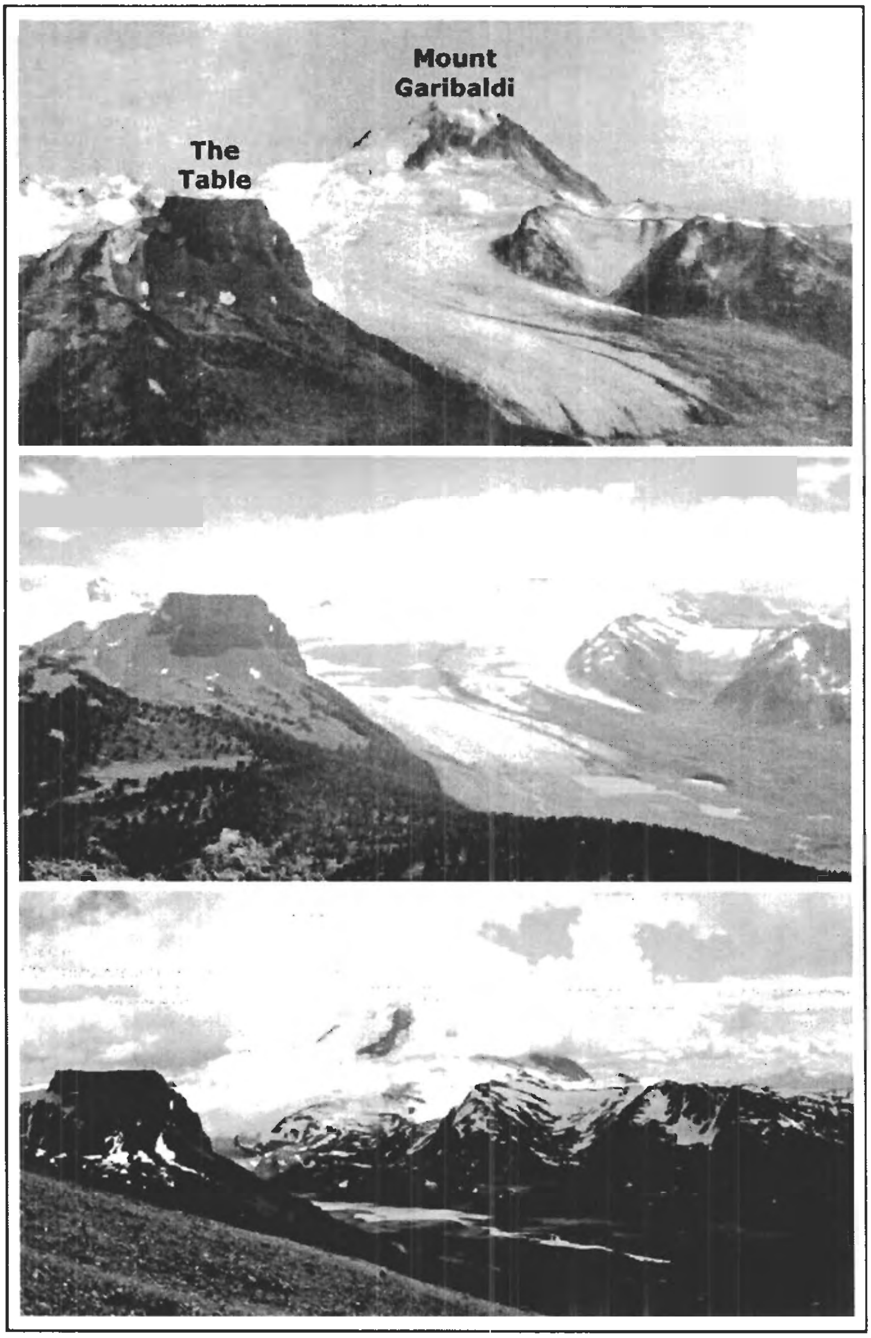

Figure 4.9 Warren Glacier in 1912 (top; W.J. Gray; with permission of the British Columbia Mountaineering Club), 1928 (middle; BC Archives I-67560; reprinted with permission of the British Columbia Archives), and 2001 (bottom; J. Koch).

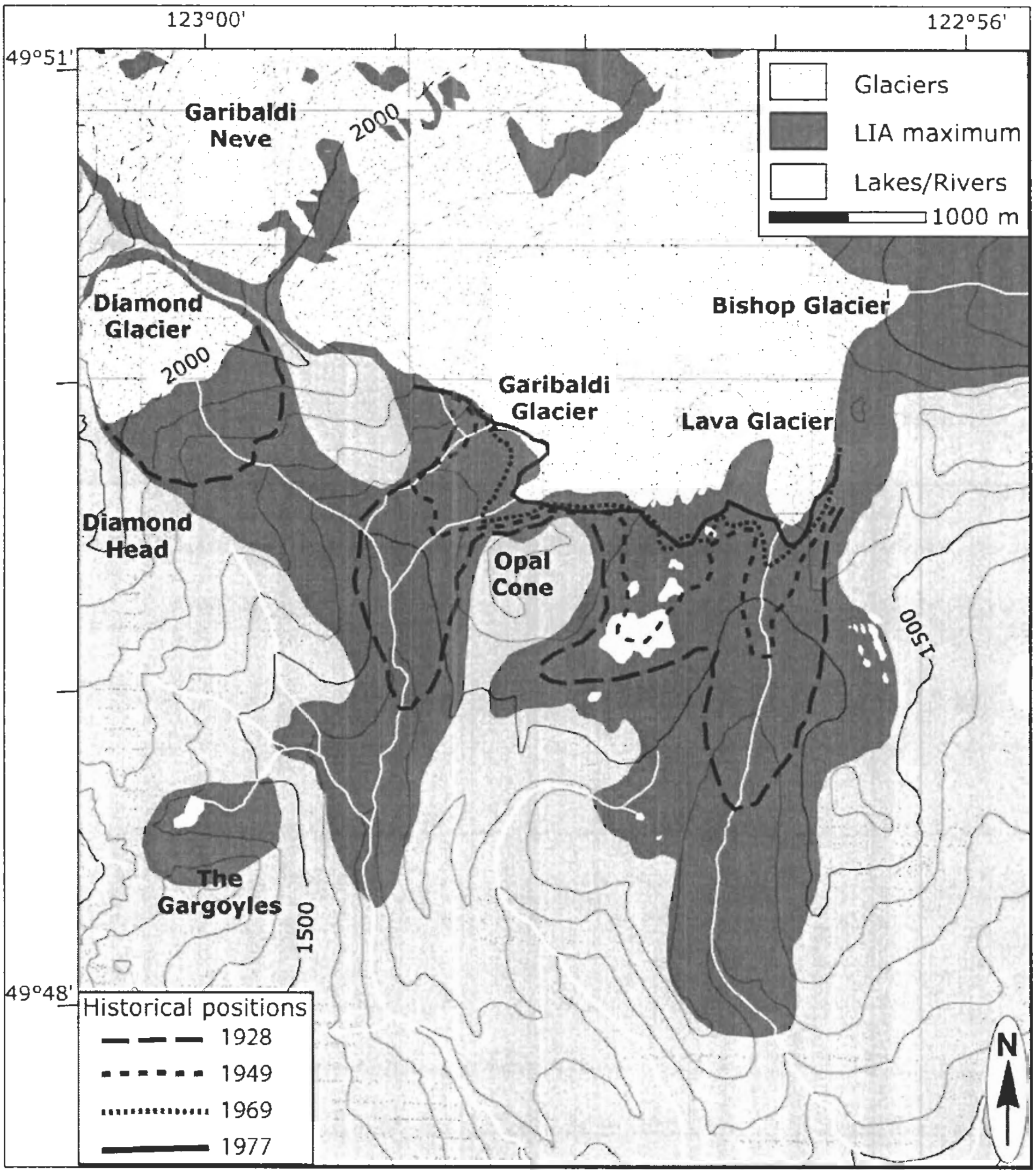

Figure 4.10 Map of Garibaldi and Lava glaciers showing their 1996 and maximum Little Ice Age extents and historical positions of their termini.

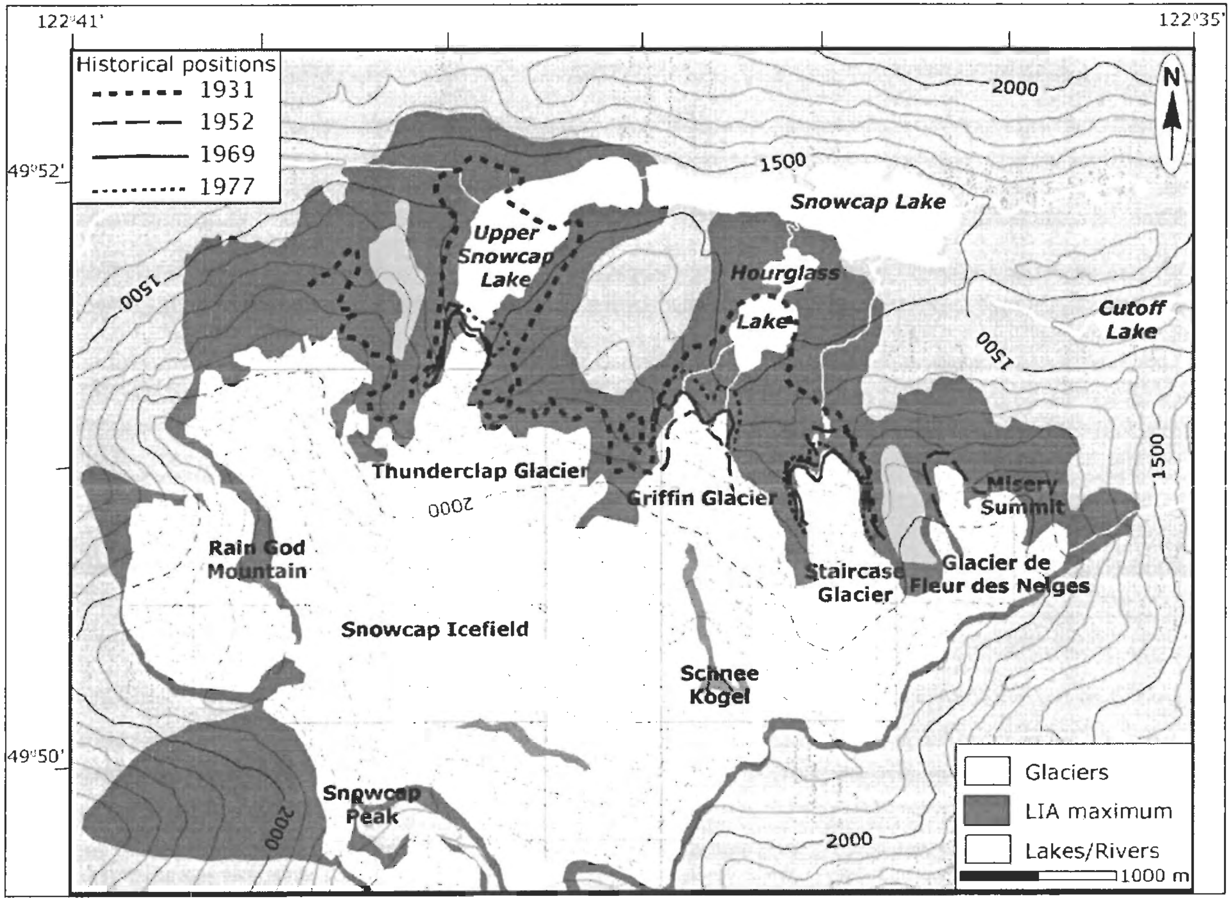

Figure 4.11 Map of Snowcap Lakes area showing the 1996 and maximum Little Ice Age extent of glaciers and their historical positions of their termini.

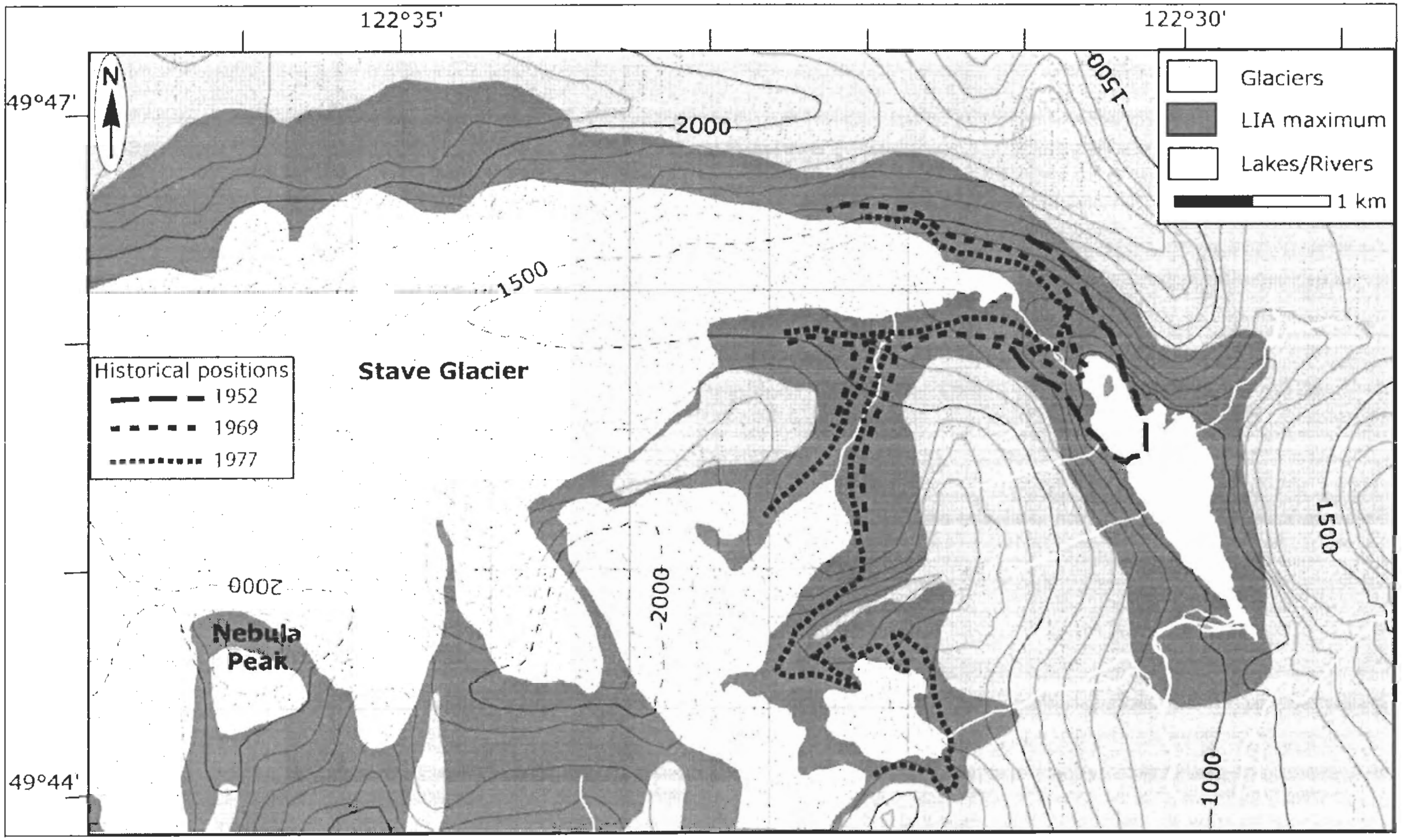

Figure 4.12 Map of Stave Glacier showing its 1993 and maximum Little Ice Age extents and historical positions of its terminus.

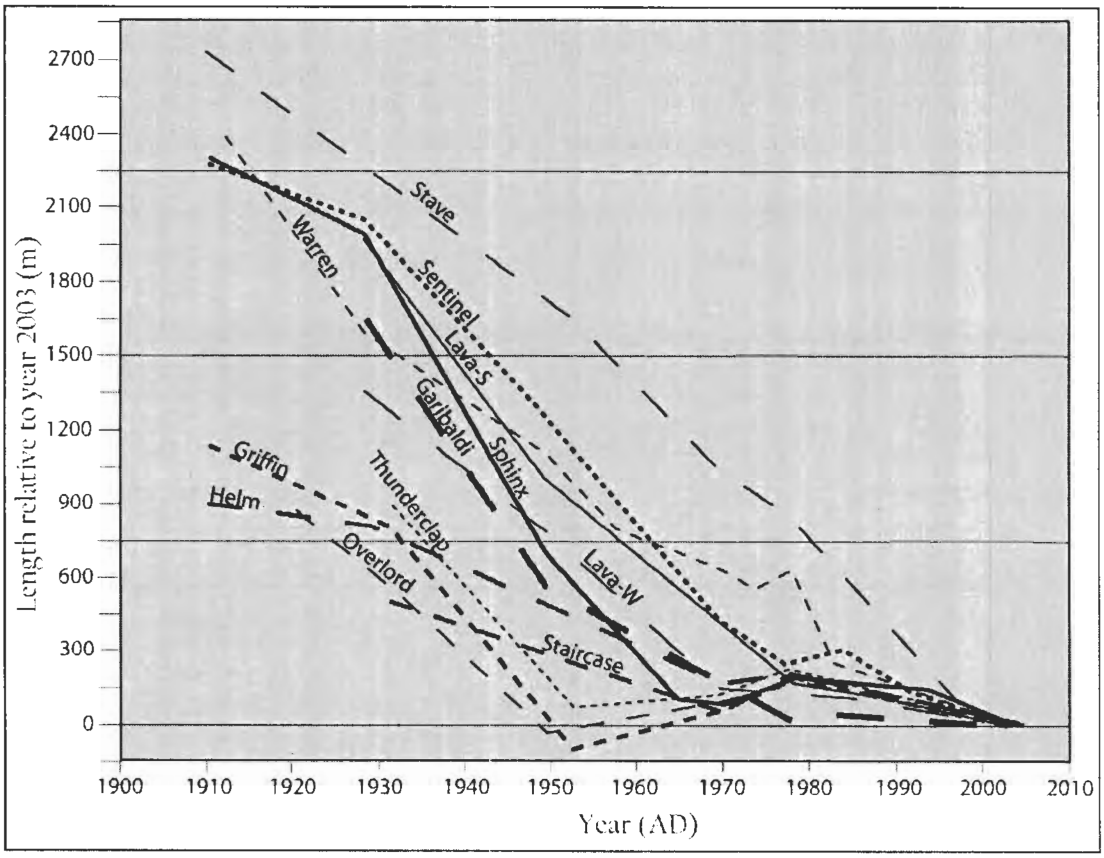

Figure 4.13 Cumulative recession of glaciers in Garibaldi Park in the 20th century. Zero corresponds to glacier extent in 2002-2004 when fieldwork was done for this study.

Tables

Table 4.1 Dates of vertical aerial photographs used in this study.

Glacier	Year of photographs 1931	1949	1952	1957	1964	1969	1973	1977	1980	1982	1984	1990	1993	1994	1996
Overlord	---	X	---	----	----	X	---	---	X	---	---	---	---	---	X
Black Tusk	---	X	---	---	---	X	---	---	---	---	---	X	---	X	X
Helm	---	X	---	----	----	X	---	X	---	---	---	X	---	---	X
Sphinx	---	X	---	----	X	X	---	X	---	---	---	---	X	---	X
Sentinel	---	X	---	----	X	X	---	X	---	---	---	---	X	---	X
Warren	---	X	---	X	X	X	X	X	---	X	---	---	X	X	X
Garibaldi	---	X	---	----	----	X	---	X	---	X	---	---	X	X	X
Lava	---	X	---	----	----	X	---	X	---	---	X	---	X	X	X
Snowcap	X	X	X	----	----	X	---	X	---	---	---	---	X	---	X
Stave	---	---	X	----	----	X	---	X	---	---	---	---	X	---	---

Notes: 1928 and 1929 ground photographs were also used for all glaciers, except Snowcap and Stave glaciers. Ground and oblique aerial photographs of all glaciers were taken by J. Koch in 2002 to 2004.

Table 4.2 Amounts and rates of frontal change of glaciers in Garibaldi Park in the twentieth century.

Year[1]	Behaviour	Amount of change (m)[2]	Rate of change (m/year)
Overlord Glacier			
1920s	moraine abandoned		
1929	retreat	250	28
1949	retreat	650	33
1969	retreat/advance	120	6
1980	advance/retreat	100	9
1996	retreat	120	8
2002	retreat	60	10
Helm Glacier			
1910s	moraine abandoned		
1928	retreat	<100	ca. 5
1949	retreat	350	17
1969	retreat/advance	300	15
1977	advance	50	6
1990	retreat	west-500	38
	retreat	east-100	8
1996	retreat	30	5
2003	retreat	80	11
Sphinx Glacier			
1900s and 1910s	moraines abandoned		
1928	retreat	250	17
1949	retreat	1300	62
	retreat	south-400	19
1964	retreat	600	40
	retreat	south-200	13
1969	retreat/advance	<10	<2
1977	advance	west-90	11
	advance	east-100	13
	advance	south-90	11
1993	retreat	50	3
1996	retreat	40	13
	retreat	east-50	17
2003	retreat	50-80	7-12
Sentinel Glacier			
1900s and 1910s	moraines abandoned		
1928	retreat	200	13
1949	retreat	800	38
1969	retreat	west-80	4
	retreat	east-850	43
1977	retreat	west-60	7.5
	retreat	east-250	31
	advance	middle-130	16
1993	retreat	west-90	8
	advance/retreat	east-350	31
	retreat	middle-220	16
1996	retreat	10-20	3-7
2003	retreat	40-50	ca. 7

Year[1]	Behaviour	Amount of change (m)[2]	Rate of change (m/year)
Warren Glacier			
1900s	moraine abandoned		
1912	retreat	minimal	n/a
1928	retreat	west-minimal	n/a
	retreat	east-800	50
1949	retreat	west-2000	ca. 95
	retreat	east-500	24
1957	retreat	300	38
1964	retreat	90	13
1969	retreat	40-150	8-30
1973	retreat	80	20
1977	advance	80	20
1982	retreat	380	76
1996	retreat	200	14
2003	retreat	50	7
Garibaldi Glacier			
1910s	moraine abandoned		
1928	retreat	nd	nd
1949	retreat	1100	52
1969	retreat	300-500	15-25
1977	retreat	100-200	12-25
1982	advance	20	4
1996	retreat	20-40	1-3
2003	stable	nd	nd
Lava Glacier			
1910s	moraine abandoned		
1928	retreat	nd	nd
1949	retreat	south-1000	47
	retreat	west-600	28
1969	retreat	south-620	31
	retreat	west-650	32
1977	retreat	south-220	28
	retreat	west-20-30	2-4
1984	retreat	west-<20	<3
1996	retreat	south-160	8.5
	retreat	west-40-200	2-11
2003	retreat	20	3
Snowcap Lakes			
1900s and 1910s	moraines abandoned		
1931	retreat	G250	16
	retreat	S: nd	nd
	retreat	T: nd	nd
1952	retreat	G900	43
	retreat	S250	12
	retreat	T800-900	38-43
1969	advance	G150	9
	retreat	S200	12
	advance	T50	3
1977	advance	G150	19
	advance	S150	19
	advance	T100	13

Year[1]	Behaviour	Amount of change (m)[2]	Rate of change (m/year)
1996	advance/retreat	G150	8
	retreat	S150	8
	advance/retreat	T130-180	7-10
2004	retreat	G50	6
	retreat	S40	5
	retreat	T30	4
Stave Glacier			
1900s	moraine abandoned		
1952	retreat	1300	26
1969	retreat	620	36
1977	retreat	200	25
1996	retreat	main-750	40
	retreat	south-200	11
2002	retreat	90	15

Note: nd, no data.
[1] Period of change ends at specified year.
[2] Rates listed for separate tongues where applicable; G: Griffin Glacier; S: Staircase Glacier; T: Thunderclap Glacier.

Table 4.3 Areal extent of glaciers in Garibaldi Park at the Little Ice Age maximum and in 1928, and 1996.

Glacier	Areal extent (km^2/%)			Retreat[1]	Advance[2]
	LIA max	1928	1996	(m)	(m)
Overlord	6.3	nd	4.1/65	1080	200
Black Tusk	5.9	2.1/36	0.8/14	200-750[2]	nd
Helm	6.1	5.4/89	1.6/26	960-1360	50
Sphinx	13.6	nd	9.5/70	2315	100
Sentinel	11.5	nd	4.4/38	2140-2520	130
Warren	14.1	nd	7.8/55	2450	80
Garibaldi	loss of 4.6 km^2 since LIA max			1540-1840[3]	20
Lava	loss of 6.3 km^2 since LIA max			1400-2020[3]	20
Snowcap	22.6	nd	12.8/57	nd	nd
Thunderclap	nd	nd	nd	1110	150
Griffin	nd	nd	nd	1350	300
Staircase	nd	nd	nd	640	150
Stave	25.2	nd	13.6/54	2960	nd

Note: nd, no data.
[1] Total distance of retreat from respective innermost Little Ice Age moraines.
[2] Minimum distance of advance.
[3] Recession since 1928.

Table 4.4 Summary of fluctuations of glacier in Garibaldi Park during the twentieth century.

					Decade					
Glacier	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-00
Overlord	r/s	r/s	m	r	r	r/a	a	a/r	r	r
Helm	r/s	m	r	r	r	r/a	a	r	r	r
Sphinx	m	m	r	r	r	r	r/a	a	r	r
Sentinel	m	m	r	r	r	r	r	r/a	a/r	r
Warren	m	r	r	r	r	r	r	r/a	r	r
Garibaldi	r/s	m	r	r	r	r	r	r/a	a/r	r
Lava	r/s	m	r	r	r	r	r	r	r	r
Thunderclap	?	?	r	r	r	r	a	a	a/r	r
Griffin	m	m	r	r	r	r	a	a	a/r	r
Staircase	?	?	r	r	r	r	r	a	r	r
Stave	m	r	r	r	r	r	r	r	r	r

Notes: r, retreat; s, stable; m, moraine stabilization; a, advance. Dominant behaviour is underlined.

CHAPTER 5
LITTLE ICE AGE GLACIER FLUCTUATIONS IN GARIBALDI PROVINCIAL PARK, SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA

Abstract

The Little Ice Age glacier history of Garibaldi Provincial Park in the southern Coast Mountains of British Columbia was reconstructed through geomorphic mapping, radiocarbon dating of fossil wood in glacier forefields, and dendrochronological and lichenometric dating of moraines. The Little Ice Age began in the 11^{th} century. Glaciers reached their first maximum of the last millennium in the 12^{th} century. They were only slightly more advanced than today in the 13^{th} century but advanced at least twice in the 14^{th} and 15^{th} centuries to near their maximum Little Ice Age positions. Glaciers probably fluctuated around these advanced positions from the 15^{th} century to the beginning of the 18^{th} century. They achieved their greatest extent between AD 1690 and 1720. Moraines were deposited at positions beyond present-day ice limits throughout the 19^{th} and early 20^{th} centuries. Little Ice Age glacier fluctuations appear to be relatively synchronous throughout Garibaldi Park. The Garibaldi Park record agrees well with similar records from other areas and with Northern Hemisphere temperature reconstructions, indicating a global cause for glacier fluctuations in the last millennium. Glacier advances in Garibaldi Park and elsewhere correspond with sunspot minima, thus changes in solar irradiance appear to play an important role in late Holocene climate and glacier change.

Keywords: glacier fluctuations, Little Ice Age, solar forcing, Garibaldi Park, southern Coast Mountains, British Columbia

Introduction

The Little Ice Age, which spans much of the last millennium, is a period of variable, but generally cool climate when glacier cover was more extensive than at other times in the Holocene (Grove, 1988). The event is recorded in all glacierized mountains of the world (Holzhauser, 1985; Grove, 1988; Wiles *et al.*, 1999; Luckman, 2000; Luckman and Villalba, 2001; Koch and Kilian, 2005), and Little Ice Age glacier fluctuations appear to be synchronous on at least a centennial timescale along the length of the Pole-Equator-Pole I transect in the Americas (Luckman and Villalba, 2001). However, glaciers in many areas of the American Cordillera have not been studied, and detailed, well dated records of Little Ice Age glacier fluctuations are still needed (Luckman and Villalba, 2001). Most research on Little Ice Age glacier fluctuations in western Canada has been done in the Rocky Mountains (Luckman, 2000, and references therein). Less is known about glaciers in the Coast Mountains (Mathews, 1951; Ryder and Thomson, 1986; Desloges and Ryder, 1990), although well dated records recently have been reported from Vancouver Island and the adjacent British Columbia mainland (Smith and Desloges, 2000; Larocque and Smith, 2003; Lewis and Smith, 2004a).

The Little Ice Age is commonly thought to include early advances between AD 1100 and 1300 and a series of late advances from AD 1700 to 1900 (Grove, 1988, 2001). The latter were generally more extensive than the former and commonly obliterated evidence of earlier glacier history. Studies of most Northern Hemisphere glaciers thus provide great detail on late- Little Ice Age and 20th century glacier behaviour, but little information on earlier events.

Climate was highly variable during the Little Ice Age (Moberg *et al.*, 2005), probably due to interactions among several forcing mechanisms (Mann *et al.*, 1998). Explosive volcanism has played a role in controlling Northern Hemisphere temperatures during the past 600 years (Bradley and Jones, 1993; Briffa *et al.*, 1998). Some glacier advances coincide with intervals of elevated volcanic aerosols in the atmosphere (Porter, 1986). Other researchers have argued that changes in solar activity have influenced climate over the last millennium (Lean *et al.*, 1995; Crowley and Kim, 1996; Crowley, 2000). Periods of late-Little Ice Age moraine formation are associated with solar minima (Lawrence, 1950; Wiles *et al.*, 2004; Luckman and Wilson, 2005). Ocean-atmosphere interactions have had an important effect on atmospheric circulation during the last millennium and thus glacier behaviour (Hendy *et al.*, 2002; Nesje and Dahl, 2003; Lewis and Smith, 2004b; Mann *et al.*, 2005). Ruddiman (2003) suggested that widespread abandonment of farms during the Black Death plagues and attendant reforestation may explain the cool phases of the Little Ice Age by changing concentrations of atmospheric carbon dioxide and methane.

The objective of this paper is to describe the Little Ice Age histories of glaciers in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia, Canada. Forefields of many glaciers in the park have a particularly rich record of Little Ice Age glacier history that can be reconstructed through dendrochronological and lichenometric analyses and radiocarbon dating. This paper also compares the Garibaldi dataset with (1) published glacial records from other areas of western Canada and elsewhere; (2) climate reconstructions for the extratropical Northern Hemisphere; and (3) reconstructions of solar output.

Study Area

Garibaldi Provincial Park, located in the southern Coast Mountains about 70 km north of Vancouver, British Columbia (Fig. 5.1), contains more than 150 glaciers. Overall, climate is humid and cool, with very wet winters and dry summers. The northwest-trending Coast Mountains constitute an orographic barrier to air masses moving eastward from the Pacific Ocean, and there is a strong west-east environmental gradient across the park. Moist maritime air controls the climate of the southwestern part of the park, and climate becomes increasingly continental to the north and east. Average annual precipitation at Squamish at the head of Howe Sound is 2370 mm, but declines to 1230 mm at Whistler, 60 km to the north. Trees adapted to wet conditions and large snowpacks, notably mountain hemlock (*Tsuga mertensiana*), are common in subalpine forests in the southern and western parts of the park. Species adapted to colder and drier conditions, including Engelmann spruce (*Picea engelmannii*), and whitebark pine (*Pinus albicaulis*), are more common in northern and eastern areas. Subalpine fir (*Abies lasiocarpa*) is an important species in glacier forefields throughout the park.

The landscape of Garibaldi Park has been shaped by Quaternary continental and alpine glaciation and locally by Quaternary volcanism. The park is within the Coast Plutonic Complex, which comprises Mesozoic granitic rocks and pendants of Cretaceous metamorphosed sedimentary and volcanic rocks (Monger and Journeay, 1994). The southern part of the park is dominated by the Mount Garibaldi volcanic complex of Plio-Pleistocene age (Mathews, 1958).

Methods

Fieldwork in Garibaldi Park was conducted between 2002 and 2004. Moraines at nine glaciers were mapped and dated by dendrochronology, lichenometry, or, where possible, both. Detrital and *in situ* (growth position) wood in glacier forefields was radiocarbon dated, and trees damaged by moraine construction were dated by dendrochronology.

Dendrochronology and Radiocarbon Dating

The age of the oldest tree on a moraine provides a minimum value for the date of moraine abandonment and stabilization (Lawrence, 1946; Sigafoos and Hendricks, 1969; Luckman, 1998a). Most moraines in Garibaldi Park have relatively sparse tree cover (Fig. 5.2c), thus the oldest living trees probably were sampled and dated. Corrections, however, must be made for (1) ecesis, which is the time from surface stabilization to seedling germination (Sigafoos and Hendricks, 1969; McCarthy and Luckman, 1993), and (2) the time that it takes trees to grow to coring height (McCarthy *et al.*, 1991; Winchester and Harrison, 2000).

Two cores were extracted from ten to fifteen trees on each moraine using a 4.3-mm-diameter increment borer. Two cores provide replication and minimize the possibility of missing and false rings (Stokes and Smiley, 1968). Cores were air dried, mounted and sanded with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Rings were measured on a Velmex stage with a precision of ±0.001 mm using the software MeasureJ2X. Tree-ring chronologies were built from all trees growing on each moraine. Series were visually examined to identify marker rings and were checked and verified with the International Tree-Ring Data Bank (ITRDB) software program COFECHA (Holmes, 1983). The verified series were crossdated (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32) to create master ring-width chronologies (Holmes, 1983).

Discs were cut from detrital and *in situ* fossil wood in glacier forefields and from trees killed during moraine construction (Fig. 5.2a and b). These samples were prepared like the cores, but in this case up to four radii were measured. Floating chronologies were developed at sites where two or more samples were collected using the same procedure as for the living trees.

Series too old to crossdate with the living ring series were radiocarbon dated. Outer ring samples were dated by Beta Analytic Inc. The radiocarbon ages were calibrated using the program CALIB 5.0 (Stuiver *et al.*, 2005). Calibrated age ranges reported in this paper are 1σ values.

Interpretation of radiocarbon ages requires careful consideration of the provenance and location of the dated material (Osborn, 1986; Röthlisberger, 1986; Ryder and Thomson, 1986; Luckman, 1998a). Only samples in growth position can provide precise dates on the time of glacier overriding at a specific site. Detrital plant fossils in stratigraphic context, such as lateral moraines, provide a maximum age for glacier overriding at the sample site. In some cases, detrital wood may have been transported to the sample site by snow avalanches or may have died of old age or fire. These samples provide little information on ages of glacier advances.

Lichenometry

Of the nine glaciers that were studied, only Overlord, Sphinx, Sentinel, and Griffin glaciers have moraines with lichen cover. The longest and intermediate axes of 60 thalli of *Rhizocarpon geographicum* spp. were measured on each of these moraines to the nearest ±0.1 mm using a dial caliper. Sampling was limited to near-circular lichen to avoid anomalously large or coalesced thalli.

I was unable to construct a local calibration curve and thus used published curves from nearby areas: (1) Vancouver Island, ca. 200 km to the west (Lewis, 2001; Lewis and Smith, 2004a); (2) the Bella Coola/Mt. Waddington area, ca. 200-350 km to the northwest (Smith and Desloges, 2000; Larocque and Smith, 2004); and (3) the Cascade Range in Washington, ca. 100-350 km to the south (Porter, 1981a; O'Neal and Schoenenberger, 2003). All three curves are based on the maximum diameter of the single largest lichen on surfaces of different ages. The largest single lichen on moraines in Garibaldi Park is not anomalous because it correlates closely with the mean of the maximum diameters of the five largest lichen.

Results

Overlord Glacier

Table 5.1 summarizes the characteristics of the Overlord Glacier living tree-ring chronology. A floating chronology based on four radii for a tree killed during construction of the second outermost moraine (moraine B, Fig. 5.3) was crossdated with the living chronology using COFECHA. The highest correlation ($r = 0.485$) was achieved for the period AD 1649-1702, indicating that the tree died in AD 1702.

Average height growth rates of young subalpine fir at three sites in the forefield of Overlord Glacier range from 0.93 to 4.9 cm/year (Fig. 5.3). Ecesis was estimated to be 6-39 years based on the difference between the age of the oldest living tree on the second outermost moraine and the age of the tree killed during construction of that moraine, and by comparing ground and aerial photographs.

The age of the oldest tree on each moraine was corrected for sampling height and ecesis to estimate dates of moraine stabilization (Table 5.2). Lichens on the inner three moraines provide stabilization dates consistent with the tree-ring dates when the Vancouver Island lichen growth curve is used (Table 5.3). Moraine A could not be dated by lichenometry or dendrochronology because the forest growing on the moraine is not first generation.

Helm Glacier

A living tree-ring chronology and seven floating chronologies (sites a, f, i, j, g/h, e/l, and m/n/o; Figs. 5.4 and 5.5) were constructed at Helm Glacier (Table 5.1). Floating chronologies from sites a, f, j, e/l, g/h, and m/n/o crossdate with one another and were combined to create a composite floating chronology spanning about 400 years. Ecesis at Helm Glacier is 46-51 years; the correction for sampling height is 0.65-3.04 cm/years. Mathews (1951) previously estimated ecesis at Helm Glacier to be 20-40 years.

Fossil wood was recovered from thirteen sites at Helm Glacier. A small branch at site b (Figs. 5.4 and 5.5) yielded a radiocarbon age of 810±60 ^{14}C years BP (AD 1180-1270) (Table 5.4). The outer ring of the sample is intact, thus the transport distance is assumed to be short. A radiocarbon age of 690±60 ^{14}C years BP (AD 1260-1310) was obtained on the outer rings of an *in situ* stump at site i, where several other stumps and logs were found. All of the samples at this site crossdate and indicate that Helm Glacier advanced into a forest with trees at least 222 years old. A small log lying on the surface in the westernmost cirque (site p) gave an age of 500±40 ^{14}C years BP (AD 1410-1440). Two *in* *situ* stumps, one with bark and both with intact outer rings, were found at site a; one of these was dated to 490±60 ^{14}C years BP (AD 1390-1460). Crossdating shows that the two trees died in the same year and that Helm Glacier advanced into a forest at least 146 years old. An *in situ* stump with an intact outer ring and seven pieces of wood (branches to small logs) were found at sites g and h. The stump yielded a radiocarbon age of 430±50 ^{14}C years BP (AD 1420-1490). The branches were eroded and thus lacked outer rings, but the trees from which all eight samples came died within 12 years of one another, thus transport was minor. The combined ring series at sites g and h was successfully crossdated with that from site a ($r = 0.531$). The trees at site a died 17 years before that at site g. The correlation between the ring series for sites m, n, and o and that for sites g and h is low (0.365), but a radiocarbon age of 380 ±40 ^{14}C years BP (AD 1450-1520) on an *in situ* stump at site n confirms the crossdating results.

These data indicate that Helm Glacier advanced 380 m from sites g and h to site m over a period of 62 years. Advance rates average 10 m/year between sites g/h and o, 4 m/year between sites o and n, and 7 m/year between sites n and m. The ring series derived from sites m, n, and o crossdates with that of an *in situ* stump from site j ($r = 0.492$), indicating that Helm Glacier thickened over the next 58 years and overran a forest at site j around 330±60 ^{14}C years BP (AD 1490-1600). The ring series from site j crossdates with the series from sites e and l ($r = 0.534$) near the lateral moraine on the east side of Cinder Cone (Figs. 5.4 and 5.5). Trees at these sites died within 15 years of one another. All of the samples retain their outer rings, indicating that post-mortem transport was minor. Therefore, Helm Glacier continued to thicken for at least another 28 years, killing trees 300±60 ^{14}C years ago (AD 1510-1600) and depositing them at sites e and l shortly thereafter. Four pieces of eroded detrital wood were sampled from a wood layer between two tills at site f. A radiocarbon age of 270±60 ^{14}C years BP (AD 1510-1670) was obtained on one of the samples. The samples at site f were successfully crossdated with samples at sites e and l ($r = 0.494$), suggesting that the trees from which the samples were derived were overridden by the glacier at either the same site or at different sites at about the same time.

In summary, Helm Glacier advanced in the 12th century (site b) and reached site i sometime in the late 12th century. It probably deposited the lower till at site f before the middle of the 13th century, when trees started growing at sites a and n. Helm Glacier remained upvalley of sites a and n until the 15th century when it advanced first into forest at site a and, shortly thereafter, at sites g, h, o, n, m, and j. It continued to thicken and finally advanced into a forest at site j in the late 16th and early 17th century. At about this time, Helm Glacier deposited detrital wood near its Little Ice Age maximum position (sites e, f, and l). It probably remained close to this maximum position until the early 18th century. Recessional moraines were built throughout the 19th and early 20th centuries.

Sphinx Glacier

Average annual growth rates for young subalpine fir at two sites at Sphinx Glacier (Fig. 5.6) range from 0.78 to 3.59 cm/year. Ecesis was determined to be 24-31 years from ground and aerial photographs. These values are similar to previous ecesis estimates for Sphinx Glacier: 20-40 years (Mathews, 1951) and about 20 years (Fraser, 1970).

Dates of stabilization of moraines A to E were determined by dendrochronology (Table 5.2). The dates for moraines B to E were corroborated by lichenometry, using the Vancouver Island lichen growth curve (Table 5.3). Lichenometry underestimates the age of moraine A by about 100 years. This moraine is heavily vegetated, which likely retards lichen growth.

Subfossil wood was found at two sites in the forefield of Sphinx Glacier. Wood at one site (f, Fig. 5.6) was collected by Mathews (1951) and radiocarbon dated to 460±40 ^{14}C years BP (AD 1420-1450; Barendsen *et al.*, 1957) (Table 5.4) This site was revisited in 2002, and several *in situ* and detrital stumps were found at the foot of a bedrock knob. One of the *in situ* stumps yielded a radiocarbon age of 580±70 ^{14}C years BP (AD 1300-1360). The two radiocarbon ages do not overlap at the 1σ limits and barely overlap at the 2σ limits, possibly because Mathews' site was farther downvalley and thus the glacier arrived there later. It is also possible, however, that the difference is due to a dating error. Five stumps were sampled at this site and successfully crossdated (Table 5.1). Outer rings of all five stumps are missing due to post-mortem erosion, but the outermost intact rings of all trees date to within three years of each other. The data indicate that Sphinx Glacier advanced into forest containing trees older than 346 years mid-way between the present glacier snout and the Little Ice Age maximum limit in the 14th century. The site had been ice-free at least since the 11th century. A log in the outermost moraine (site g) yielded a radiocarbon age of 370±70 ^{14}C years BP (AD 1450-1630). It was too decayed to extract a core for crossdating, but the radiocarbon age provides a maximum age for the moraine and shows that it was built during the Little Ice Age.

Sentinel Glacier

Tree age below core height was determined at two sites at Sentinel Glacier (Fig. 5.7), and ecesis was estimated from ground and aerial photographs. Average annual growth rates range from 0.79 to 3.71 cm/year, and ecesis is 22-30 years, similar to the value of 20 years reported by Fraser (1970).

Moraine stabilization, as determined by dendrochronology, occurred in the 1710s, 1830s, 1870s, 1900s, and 1910s (Table 5.2). The dates were corroborated by lichenometry (Table 5.3).

Warren Glacier

An *in situ* rootstock in the cirque of a tributary of Warren Glacier (site a in Fig. 5.8) yielded a radiocarbon age of 920±70 ^{14}C years BP (AD 1030-1170; Table 5.4), indicating that this glacier was advancing through forest early in the Little Ice Age. The living tree-ring chronology at Warren Glacier (Table 5.1) includes a tree that was damaged during construction of the outermost moraine. Damage to the tree, indicated by reaction wood and missing rings, dates from AD 1705 to 1711. The beginning of this interval is taken to be the date that Warren Glacier arrived at its Little Ice Age limit. A floating chronology (4 samples, 6 radii) of trees killed during moraine construction was crossdated with the living chronology. The highest correlation (0.459) with the living chronology is for the period AD 1637-1701, suggesting that the trees were killed shortly after AD 1701. All of the dead trees, however, are missing their outer rings, thus the result is consistent with the AD 1705 date obtained from the damaged tree.

Average annual growth rates determined at two sites at Warren Glacier (Fig. 5.8) range from 1.01 to 3.54 cm/year. Ecesis is estimated to be 11-31 years, consistent with previous estimates of 20-40 years (Mathews, 1951) and about 20 years (Fraser, 1970). Moraine stabilization was dated by dendrochronology (Table 5.2).

Garibaldi Glacier

Average annual growth rates and ecesis were determined at one site at Lava Glacier (Fig. 5.9). Growth rates range from 0.37 to 2.65 cm/year and ecesis is 32-40 years. Stabilization of lateral moraines A to F was dated by dendrochronology to the 1720s, 1820s, 1850s, 1870s, 1890s, and1910s (Table 5.2).

Fossil wood was found at five sites at Garibaldi Glacier. An *in situ* stump (site f) gave a radiocarbon age of 670±70 ^{14}C years BP (AD 1270-1390, Table 5.4) and crossdated with a detrital log and a detrital stump at site e and a detrital log at site d (Fig. 5.9). The detrital stump likely was eroded from a bedrock outcrop located above site e and about 80 m upvalley of site f. It came from a tree that died at least 17 years before the death of the tree represented by the *in situ* stump at site f. Neither stump retains bark and outer rings, but the difference in tree-ring ages indicates that Garibaldi Glacier advanced 80 m over a period of more than 17 years in the 14th century. Several detrital logs were found in a gully in the east lateral moraine of Garibaldi Glacier (site g). One of the logs yielded an age of 490±60 ^{14}C years BP (AD 1390-1460). The age indicates that either Garibaldi Glacier receded after its 14th century advance to positions upvalley of site g or the glacier slowly thickened between the 14th and the 15th centuries. Till near the Little Ice Age maximum limit of Garibaldi Glacier (site c) contains detrital logs and branches. One of the logs yielded an age of 290±70 ^{14}C years BP (AD 1490-1600), and this log was successfully crossdated with another log (Table 5.1). Although neither sample retains outer rings, they date to within 12 years of one another and may have been derived from trees that were killed when Garibaldi Glacier advanced to its Little Ice Age limit.

Lava Glacier

Lava Glacier moraines A to F were stabilized in the 1710s, 1800s, 1820s, 1850s, 1880s, and the 1910s (Table 5.2). Fossil wood was recovered at four sites in the glacier forefield. Two distinct wood layers, including logs to branches, are separated by a layer of till in the west lateral moraine (sites f and g, Fig. 5.9). The wood layers can be traced over a distance of 110 m across several gullies. The lower wood layer yielded a radiocarbon age of 860±70 ^{14}C years BP (AD 1150-1250), and the upper wood layer gave an age of 640±40 ^{14}C years BP (AD 1290-1390) (Table 5.4). The intervening till unit probably was deposited in the 13th century, at which time Lava Glacier was almost as extensive as at the Little Ice Age maximum. The younger wood layer and its capping till show that the advance that culminated in the Little Ice Age maximum was underway in the 14th century. Additional evidence that the advance leading to the Little Ice Age maximum started early comes from sites a and b. A log 4 m below the crest of the lateral moraine at site a, on the south side of Opal Cone, dates to 640±50 ^{14}C years BP (AD 1290-1390). *In situ* stumps and detrital logs occur at site b; one stump yielded an age of 530±30 ^{14}C years BP (AD 1400-1430). Two of the *in situ* stumps were successfully crossdated (Table 5.1). The outermost ring of one of the trees was intact, and the other tree died no more than 3 years earlier.

The data from the Lava Glacier forefield show that an early Little Ice Age advance was underway in the late 12th century. The glacier reached to near its Little Ice Age limit in the 13th century. After this advance, the glacier receded an unknown distance before readvancing to near its 13th century limit in the late 14th century. It thickened and overtopped the west side of the main valley where it overrode a forest with trees older than 266 years in the early 15th century. This site had been ice-free since at least the 12th

century. No evidence for subsequent glacier recession was found, and it is likely that the latter advance culminated with the construction of the outermost Little Ice Age moraines in the late 17th or early 18th century.

Snowcap Lakes Area

Average annual growth rates and ecesis values at Snowcap Lakes (Fig. 5.10) are, respectively, 0.75-3.18 cm/year and 42-56 years. The latter are significantly larger than the ecesis values of 13-51 years reported by Ricker (1979).

The two outermost moraines at Snowcap Lakes stabilized in the 1720s and the 1830s based on dendrochronology, or the 1710s and 1820s based on lichenometry (Tables 5.2 and 5.3). Lichen-based ages for moraines C to G are the 1850s, 1870s, 1890s, 1900s, and 1910s (Table 5.3).

Stave Glacier

Average annual growth rates were determined at one site at Stave Glacier (Fig. 5.11) and range from 1.12 to 5.27 cm/year. Ecesis ranges from 7 to 16 years. Moraines A to D were dendrochronologically dated to the 1720s, 1840s, 1890s, and 1900s (Table 5.2).

Fossil wood was found at two sites at Stave Glacier. A small log embedded in till in the north lateral moraine (site b; Fig. 5.11) yielded a radiocarbon age of 830±50 ^{14}C years BP (AD 1170-1260, Table 5.4). The location of the dated sample, some 500 m downvalley of the present snout and 150 m above the valley floor, suggests that Stave Glacier was more extensive in the early Little Ice Age than in 2002. A piece of detrital wood found near a small lake (site c) dates to 310±50 ^{14}C years BP (AD 1510-1600). Its location indicates that Stave Glacier receded to a position similar to that of the present glacier margin after its early Little Ice Age advance and before readvancing late in the Little Ice Age.

Other Glaciers

Fossil wood samples from three other glacier forefields were radiocarbon dated. A small stick from the forefield of Mystery Glacier gave an age of 710±50 ^{14}C years BP (AD 1260-1300, Table 5.4). Its location suggests a fairly extensive advance at this time. A small weathered log near the crest of the lateral moraine of West Stave Glacier yielded an age of 250±50 ^{14}C years BP (AD 1520-1680), which is a maximum age for the glacier's advance to its Little Ice Age limit. Two detrital logs, about 500 m apart, were found near the Little Ice Age limit of Trorey Glacier. The logs were dated at 70±50 ^{14}C years BP (AD 1690-1920) and 60±50 ^{14}C years BP (AD 1690-1920), which are maximum ages for the Little Ice Age maximum of this glacier.

Discussion

Lichenometry in the southern Coast Mountains

Rhizocarpon thalli were found only in four glacier forefields in Garibaldi Park. The absence of lichen in the other forefields is attributed to the Plio-Pleistocene volcanic substrate, which apparently does not allow lichen establishment.

Lichen ages assigned to moraines were checked using independently determined tree-ring ages. The analysis indicated that the lichen growth curve from Vancouver Island reported by Lewis (2001) and Lewis and Smith (2004a) is applicable to Garibaldi Park (Fig. 5.12). Other published lichen growth curves yield ages that are inconsistent with the tree-ring ages and thus cannot be used in Garibaldi Park. The Cascades curve

(Porter, 1981a; O'Neal and Schoenenberger, 2003) seems to work for the youngest moraines, but it fails to produce consistent ages for moraines that are older than the late 19th century. A growth curve from the central Coast Mountains (Smith and Desloges, 2000; Larocque and Smith, 2004) consistently and significantly overestimates the ages of moraines in Garibaldi Park. Growth rates may be higher on Vancouver Island, the Cascade Range, and Garibaldi Park than in the mountains of central British Columbia because of more favourable growing conditions (Larocque and Smith, 2004). It is unclear, however, if these differences are due to latitude, continentality, or some other factors.

Little Ice Age Chronology

The Little Ice Age began in Garibaldi Park before 920±70 ^{14}C years BP (AD 1030-1170; tributary of Warren Glacier). Support for a very early Little Ice Age advance is provided by the advanced positions of Lava Glacier at 860±70 ^{14}C years BP (AD 1150-1250), Stave Glacier at 830±50 ^{14}C years BP (AD 1170-1260), and Helm Glacier at 810±60 ^{14}C years BP (AD 1180-1270). Many glaciers were near Little Ice Age maximum positions sometime between the 11th and 12th centuries. The outermost moraine at Overlord Glacier may have been constructed at this time.

This first advance was followed by recession, possibly back to near-present glacier margins. Evidence for recession comes from the forefield of Stave Glacier, where detrital wood on the surface 650 m downvalley from the present glacier snout dates to 310±50 ^{14}C years BP (AD 1510-1600). Helm, Lava, Sphinx, and Garibaldi glaciers receded to positions more than halfway back from maximum Little Ice Age limits in the 12th century and remained there for at least one hundred years.

These four glaciers advanced into mature forests in the 14th and 15th centuries. Evidence from Lava Glacier indicates that at least two distinct middle Little Ice Age advances were separated by short-lived recession. Helm Glacier affords the most detailed reconstruction of events during this period. It advanced into forests several times during the middle Little Ice Age, each time progressively farther downvalley. It is unclear if this was a single continous advance, or multiple separate advances. This phase of activity culminated with the construction of the outermost Little Ice Age moraines, which stabilized between AD 1690s and 1720s. Subsequent advances, in the 19th and early 20th centuries, were successively less extensive, forming up to five moraines close to the outermost Little Ice Age moraine.

Regional Comparisons

Little Ice Age glacier activity in Garibaldi Park is similar to that in other areas of western North America (Heikkinen, 1984; Luckman, 2000; Larocque and Smith, 2003; Lewis and Smith, 2004a). The beginning of the Little Ice Age in other areas of western Canada dates to between 1000±80 and 810±70 ^{14}C years BP, similar to the time of initiation in Garibaldi Park (Luckman, 1986, in press; Osborn, 1986; Ryder and Thomson, 1986; Luckman *et al.*, 1993; Osborn *et al.*, 2001; Reyes and Clague, 2004).

Little Ice Age moraines older than the middle 17th century were found only at Overlord Glacier. They are also uncommon elsewhere in western Canada, having been found only at Colonel Foster Glacier on Vancouver Island (older than AD 1397; Lewis and Smith, 2004a), at Bridge Glacier, ca. 100 km northwest of Garibaldi Park (ca. AD 1384, Allen and Smith, 2004), and at a few glaciers in the Canadian Rocky Mountains (Luckman, 2000). The outermost moraine of Overlord Glacier may also date to this time or alternatively to any of the advance periods documented in the central Coast Mountains (AD 1200-1230, 1440-1460, 1500-1525, 1560-1575, and 1600-1620; Larocque and Smith, 2003) and the Cascades (AD 1520-1560 and 1620; Heikkinen, 1984). It could even date to the older Tiedemann Advance (ca. 2300 ^{14}C years BP; Ryder and Thomson, 1986) or the recently recognized First Millennium Advance (Reyes *et al.*, 2006).

Reconstructed early Little Ice Age advances of Helm, Garibaldi, Lava, and Sphinx glaciers appear to coincide with advances of Robson, Peyto, and Stutfield glaciers in the Canadian Rocky Mountains between AD 1150 and 1375 (Luckman, 1995, 2000), which reached to within 500 m of the Little Ice Age limit.

Moraines dating to AD 1690-1720, which are common in Garibaldi Park, are also found on Vancouver Island (AD 1690-1710; Lewis and Smith, 2004a) and in the Canadian Rockies (AD 1700-1725; Luckman, 2000). Moraines of about the same age have been identified in the Cascades (AD 1740; Heikkinen, 1984) and the central Coast Mountains (AD 1660 and 1760-1785; Larocque and Smith, 2003). Moraines were built in the 19th and early 20th century, not only in Garibaldi Park, but also in the Cascades (AD 1820-1890, AD 1920; Heikkinen, 1984), on Vancouver Island (AD 1840, 1890, and 1930; Lewis and Smith, 2004a), the central Coast Mountains (AD 1820-1840, 1870-1900, and 1915-1930; Larocque and Smith, 2003), and the Canadian Rocky Mountains (AD 1825-1850 and 1850-1920; Luckman, 2000).

Glacier mass balance for the past 300-400 years has been inferred from tree rings at several sites in western Canada (Lewis and Smith, 2004b; Watson and Luckman, 2004; Larocque and Smith, 2005). Periods of reconstructed positive mass balance generally coincide with times of moraine formation in Garibaldi Park. The park's Little Ice Age history also agrees well with a tree-ring-based reconstruction of summer temperature from the Canadian Rocky Mountains (Fig. 5.12), which spans the last millennium (Luckman and Wilson, 2005). Relatively cold periods coincide with glacier advances, whereas periods of relative warmth are times of glacier recession.

Global Implications of the Garibaldi Chronology

The Medieval Warm Period has been dated to the 9th through 14th centuries (Hughes and Diaz, 1994), AD 900 - 1250 (Grove and Switsur, 1994), AD 960-1050 (Cook *et al.*, 2004), and AD 1100-1200 (Bradley *et al.*, 2003). Its global significance and synchronicity have been questioned by some researchers, who have disputed claims that temperatures during parts of the Medieval Warm Period were as warm as or warmer than today (Grove and Switsur, 1994; Hughes and Diaz, 1994; Bradley *et al.*, 2003; Cook *et al.*, 2004). Temperature-sensitive tree-ring series from the extratropical Northern Hemisphere show persistently above-average temperatures from AD 960 to AD 1050 (Cook *et al.*, 2004). However, the timing appears to be in conflict with the European "High Medieval" warm period (AD 1100-1200; Bradley *et al.*, 2003). Glaciers in Garibaldi Park were relatively small at both times (Fig. 5.12), although they were still more extensive than during the late 20th century. This evidence suggests that temperatures were lower during the periods AD 960-1050 and AD 1100-1200 than in the last two decades. Further, these two periods were interrupted by a significant glacier advance. I conclude that the Medieval Warm Period is an ill-defined term that allows for a large range of possibly unrelated climate anomalies to be grouped under the same name.

The similarity in the timing and extent of glacier fluctuations in western Canada and the US Pacific Northwest argues for regional or global climate forcing. Similar Little Ice Age chronologies have been reported from western Canada, Alaska, Scandinavia, Europe, South America, and New Zealand (e.g., Holzhauser, 1985; Gellatly *et al.*, 1988; Karlén, 1988; Wiles *et al.*, 1999; Luckman, 2000; Nicolussi and Patzelt, 2000; Koch and Kilian, 2005), suggesting global forcing (Koch and Clague, 2005). Differences in the chronologies may be an artefact of imprecise dating or, more likely, may be due to local conditions.

Comparison of the Garibaldi record with a recent Northern Hemisphere temperature reconstruction spanning the last millennium (Fig. 5.13; Cook *et al.*, 2004) shows that the two are in broad agreement. Periods of glacier advance and recession in the park are broadly synchronous with relatively cold and warm periods, respectively.

Researchers have suggested that times of glacier advance and moraine formation during the late stages of the Little Ice Age show a relation to sunspot numbers (Lawrence, 1950; Wiles *et al.*, 2004; Luckman and Wilson, 2005). I compared the timing of Little Ice Age glacier fluctuations in Garibaldi Park with the record of solar activity during the past millennium (Stuiver, 1961; Bond *et al.*, 2001) and a recent reconstruction of sunspot numbers (Solanki *et al.*, 2004) (Fig. 5.14). Glacier advances and times of moraine construction appear to coincide with sunspot minima, specifically the Oort (AD 1020-1080), Wolfe (AD 1290-1370), Spörer (AD 1460-1550), Maunder (AD 1645-1715), and Dalton (ca. AD 1795-1825) minima.

Conclusions

The record of Little Ice Age glacier fluctuations in Garibaldi Park is one of the most complete and best constrained in western North America. The Little Ice Age started as early as AD 1000. Glaciers approached their Holocene maximum positions several times in the early and middle partys of the Little Ice Age. Middle Little Ice Age advances were underway in the 14^{th} and 15^{th} centuries and culminated in the construction of the outermost moraines in Garibaldi Park in the late 17^{th} century. These moraines stabilized between the AD 1690 and 1720. Moraines were also built during less extensive advances in the 19^{th} and early 20^{th} centuries. Little Ice Age glacier advances appear to be relatively synchronous throughout the park.

The Little Ice Age record in Garibaldi Park is in agreement with regional and global glacier records and Northern Hemisphere temperature reconstructions, indicating global forcing of glacier fluctuations during the last millennium. Times of sunspot minima correspond to with glacier advances and thus changes in solar radiation likely play an importan role in late Holocene climate and glacier change.

Figures

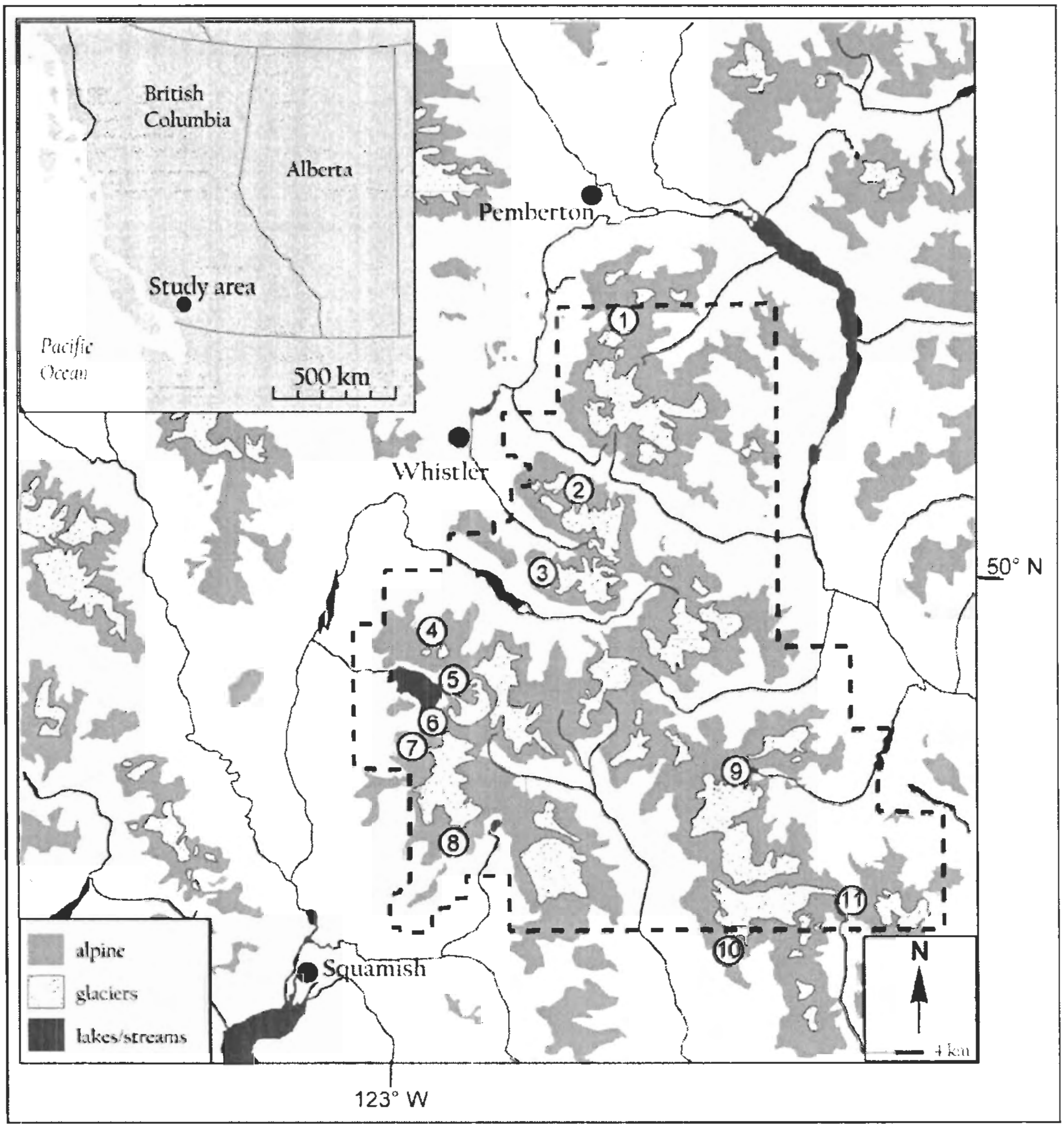

Figure 5.1 Map showing location of Garibaldi Provincial Park and its glaciers. 1, Mystery Glacier; 2, Trorey Glacier; 3, Overlord Glacier; 4, Helm Glacier; 5, Sphinx Glacier; 6, Sentinel Glacier; 7, Warren Glacier; 8, Garibaldi/Lava glaciers; 9, Snowcap Lakes; 10, West Stave Glacier; 11, Stave Glacier.

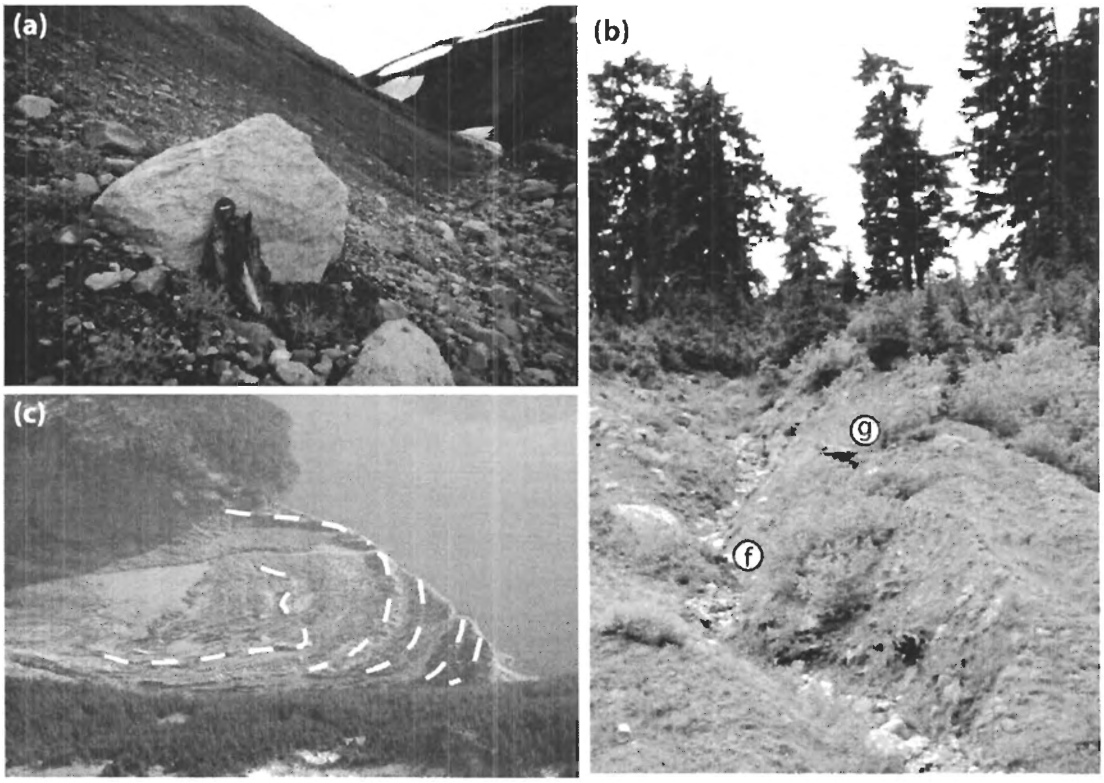

Figure 5.2 Examples of fossil wood and Little Ice Age moraines in Garibaldi Park. (a) *In situ* stump at Helm Glacier (site n, Fig. 5.4). (b) Two wood layers in lateral moraine of Lava Glacier (sites f and g, Fig. 5.9). (c) Little Ice Age moraines of Sphinx Glacier. (Photographs by J. Koch.)

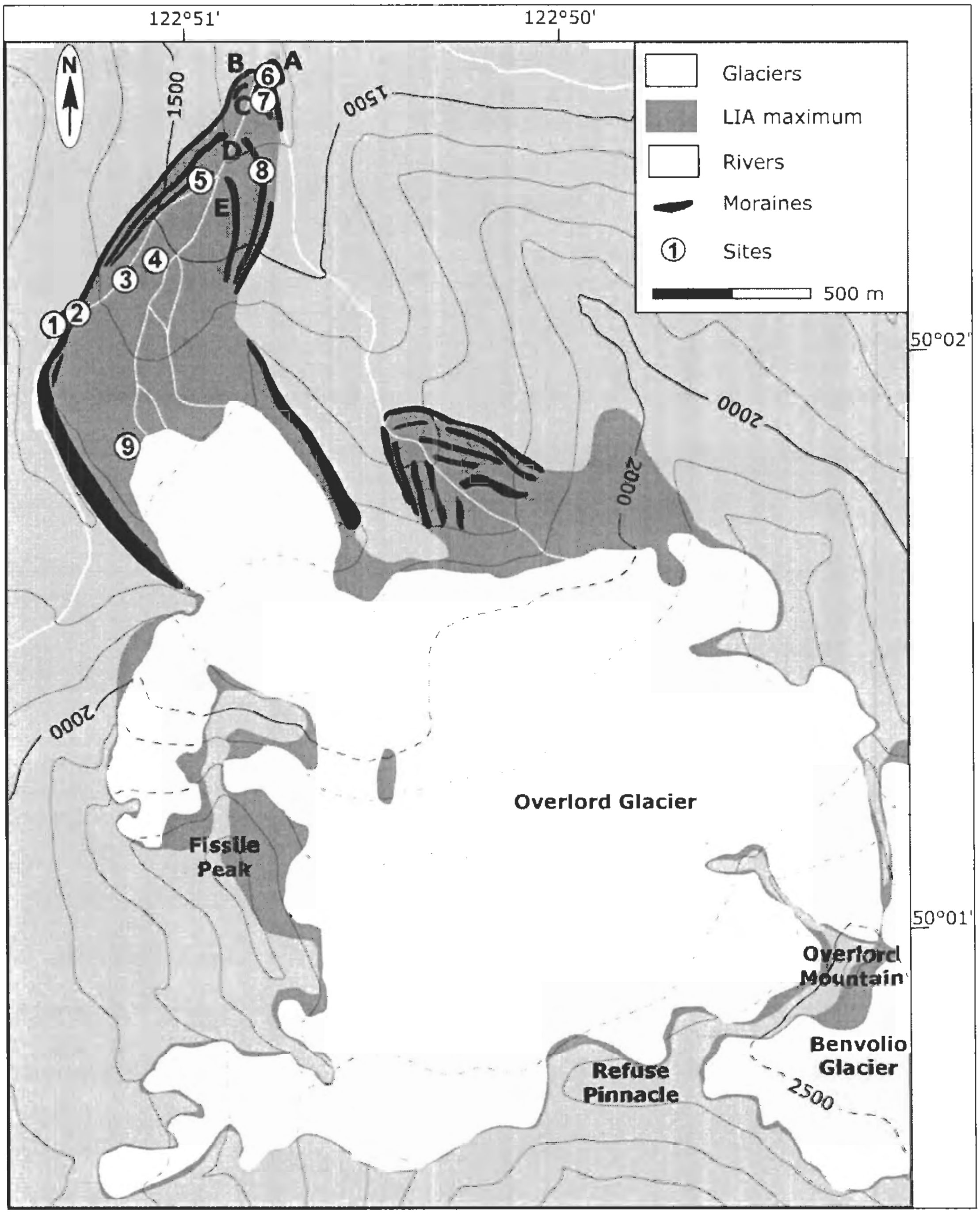

Figure 5.3 Map of Overlord Glacier showing moraines and 1996 and maximum Little Ice Age glacier extents. Trees were sampled and lichens were measured on moraines at sites 1, 2, 5, 6, 7, and 8. Trees were sampled for ecesis and age-height growth determination at sites 3, 4, 7, and 9.

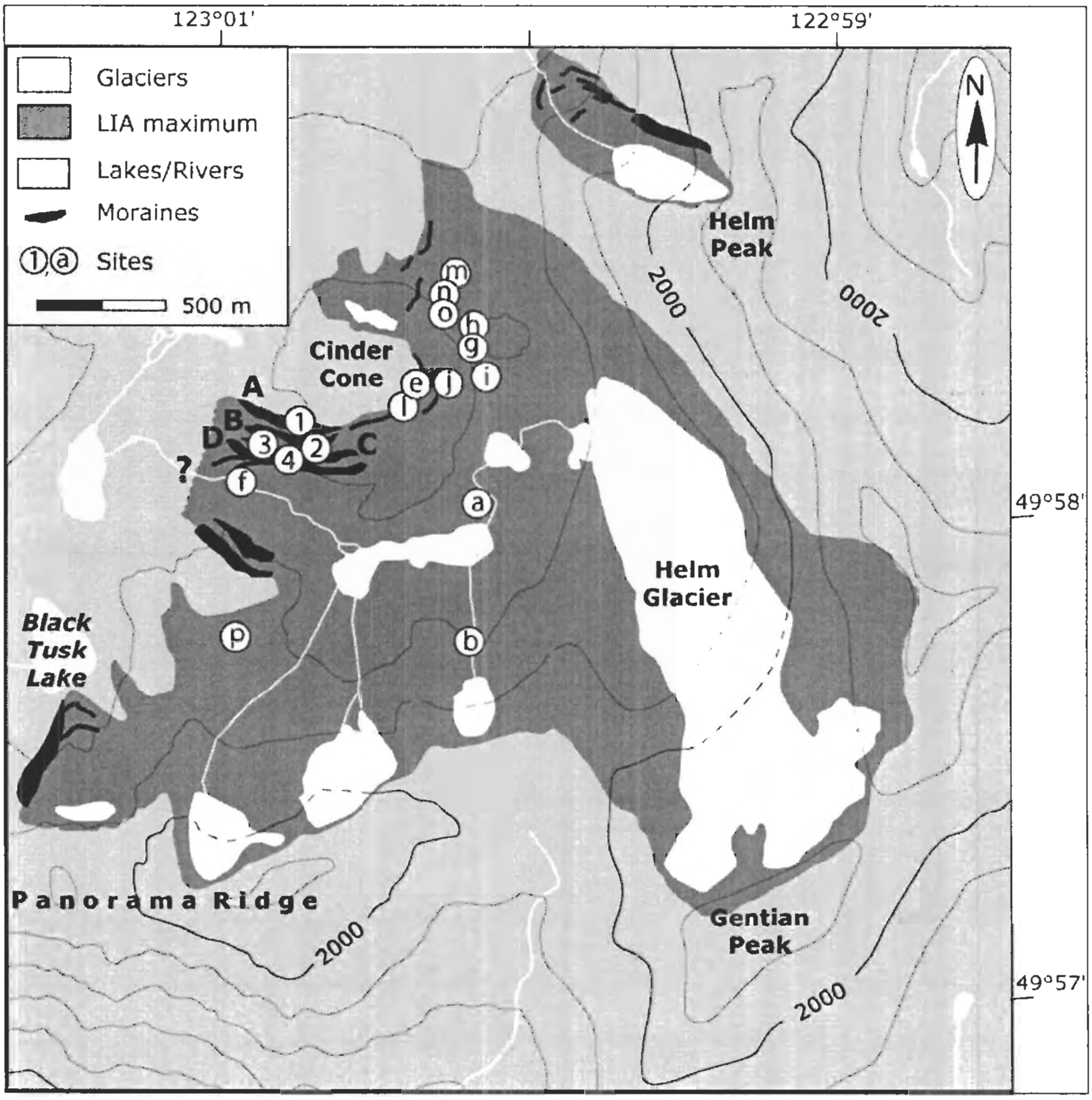

Figure 5.4 Map of Helm Glacier showing moraines and 1996 and maximum Little Ice Age glacier extents. Trees were sampled on moraines at sites 1-4. Fossil wood was sampled at sites a, b, e, f, g, h, i, j, l, m, n, and o.

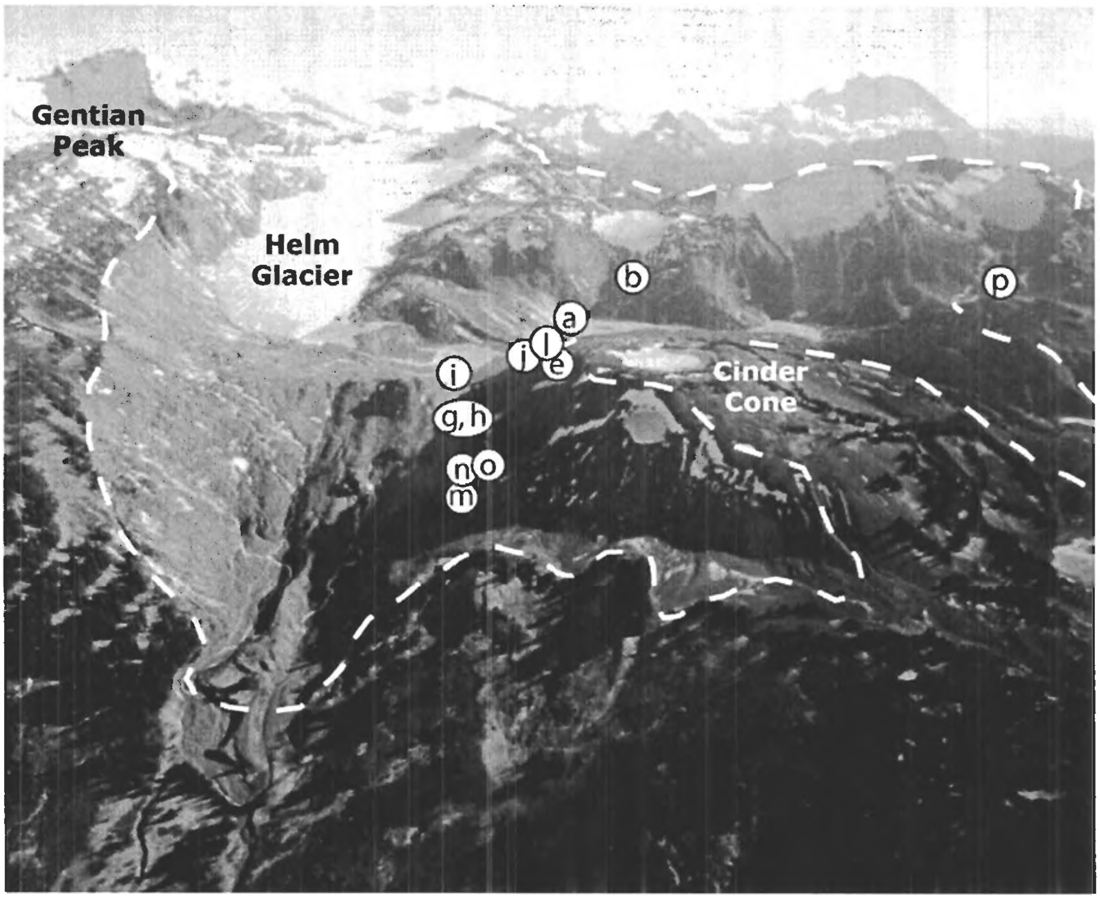

Figure 5.5 Forefield of Helm Glacier showing locations of sites mentioned in the text. Maximum Little Ice extent of Helm Glacier is indicated by white stippled line. (Photograph by J. Koch.)

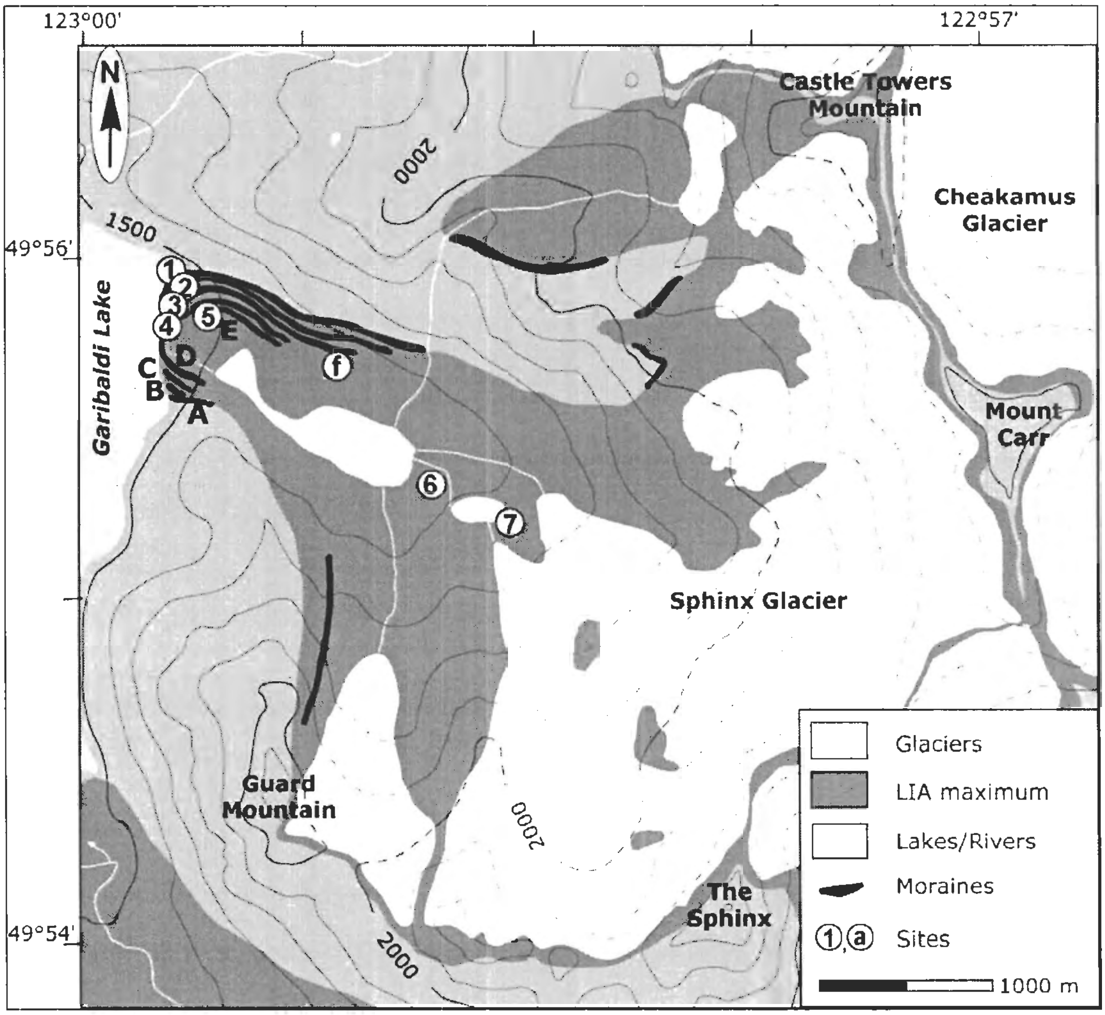

Figure 5.6 Map of Sphinx Glacier showing moraines and 1996 and maximum Little Ice Age glacier extents. Trees were sampled and lichens were measured on moraines at sites 1-5. Trees were sampled for ecesis and age-height growth determination at sites 3, 6, and 7. Fossil wood was sampled at site f. Site g is the same as to site 1.

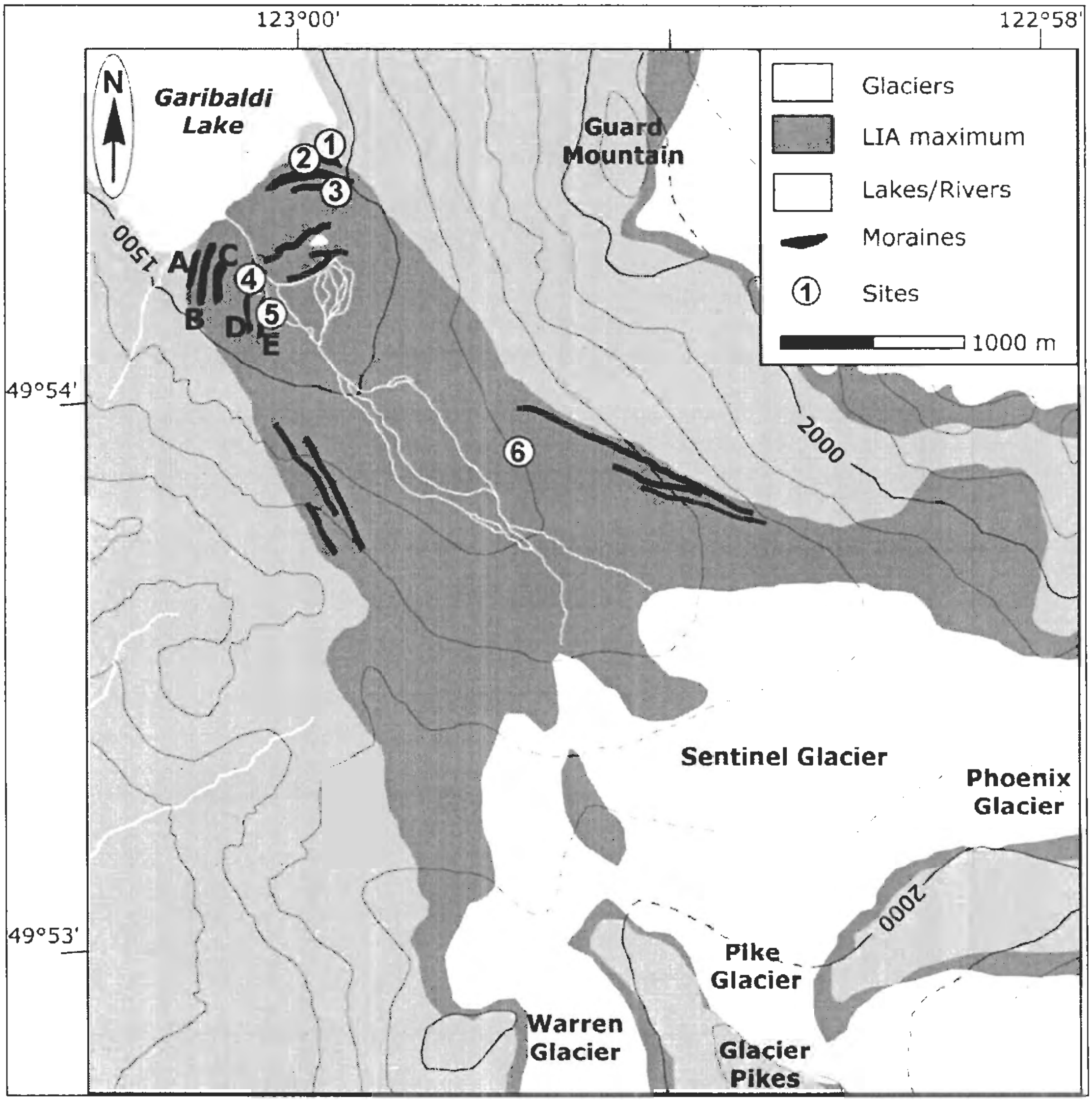

Figure 5.7 Map of Sentinel Glacier showing moraines and 1996 and maximum Little Ice Age glacier extents. Trees were sampled and lichens were measured on moraines at sites 1-5. Trees were sampled for ecesis and age-height growth determination at site 6.

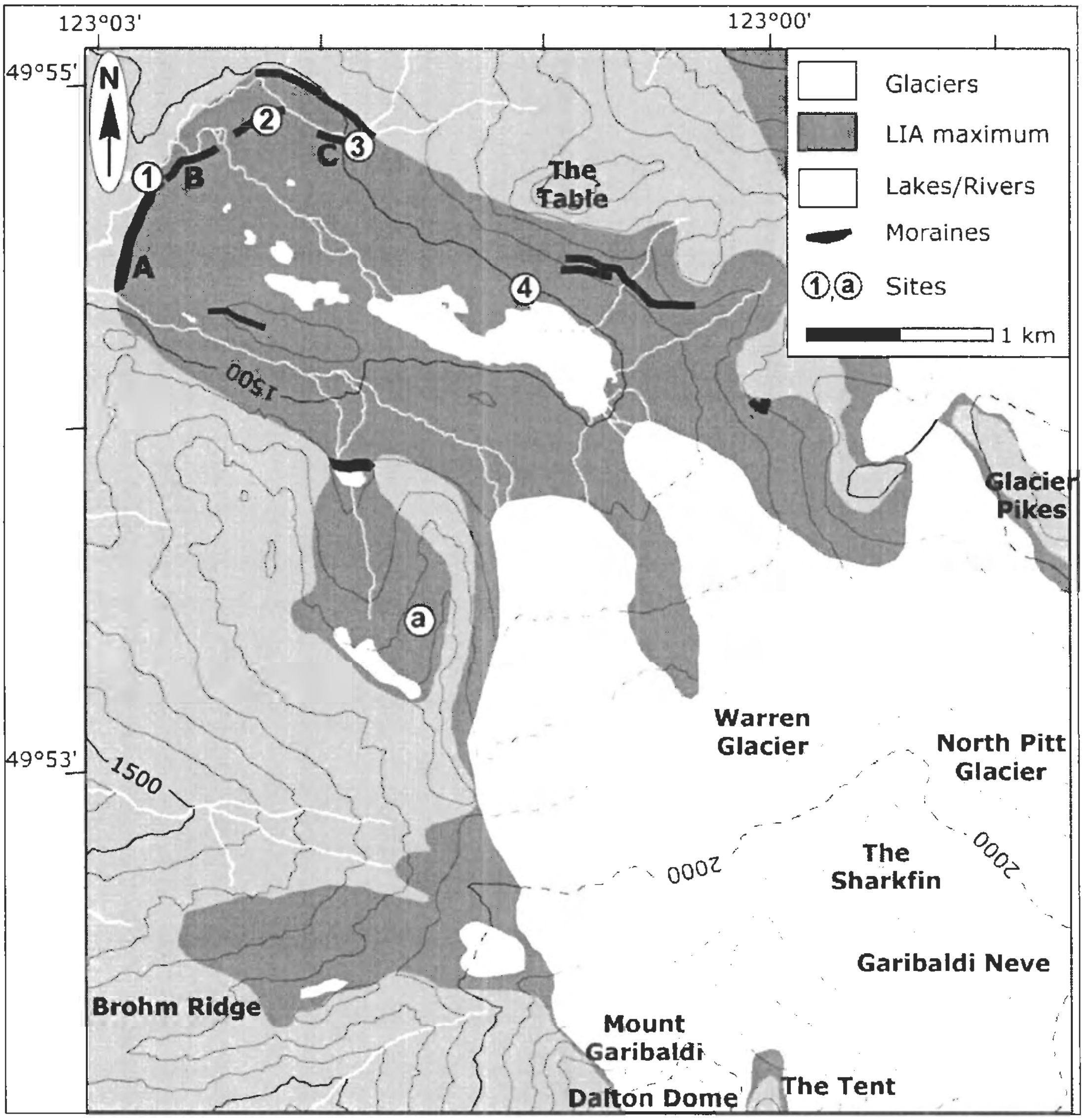

Figure 5.8 Map of Warren Glacier showing moraines and 1996 and maximum Little Ice Age glacier extents. Trees were sampled on moraines at sites 1-3. Trees were sampled for ecesis and age-height growth determination at sites 1 and 4. Fossil wood was sampled at site a.

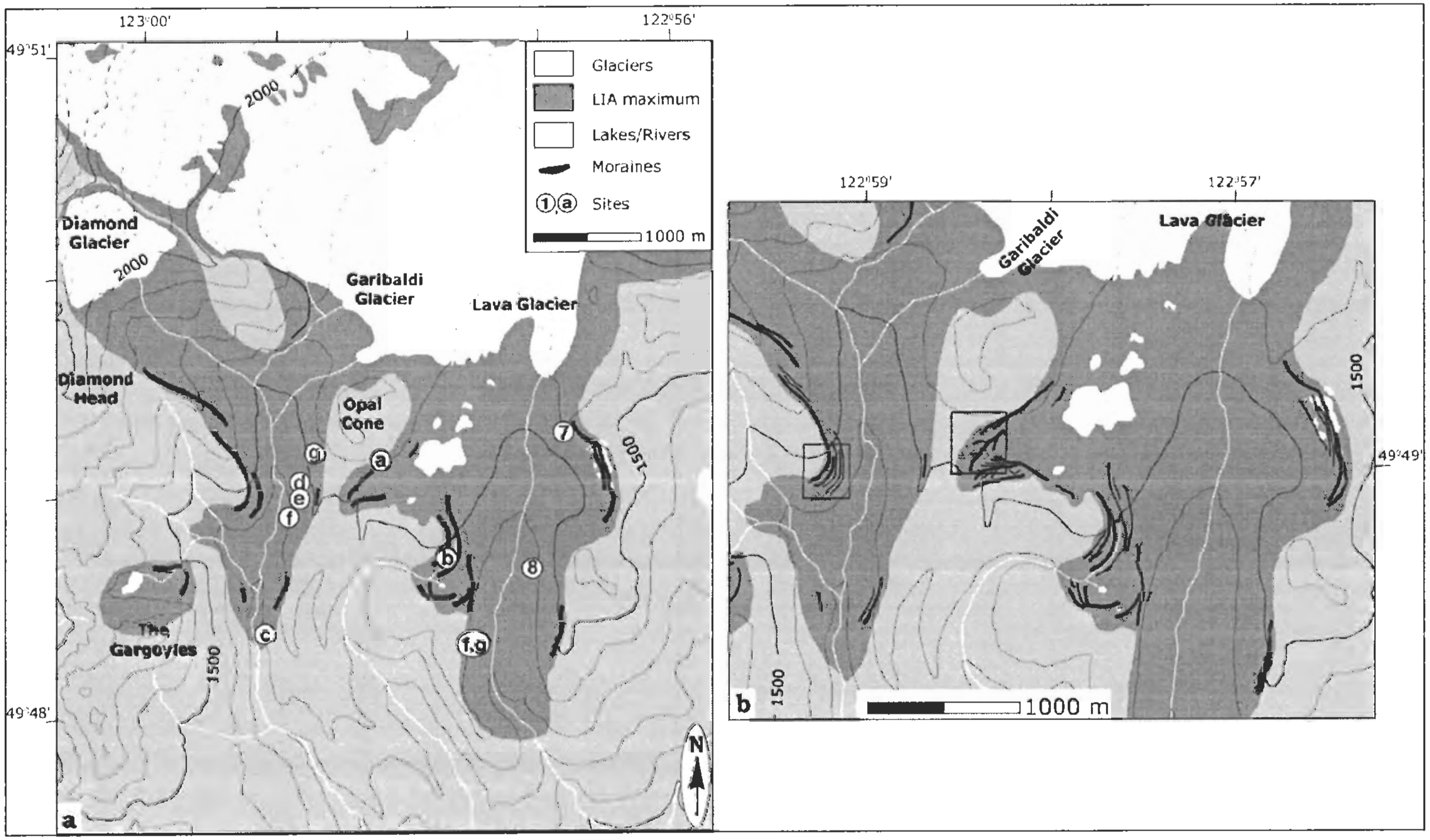

Figure 5.9 Maps of Garibaldi and Lava glaciers showing (a) 1996 and maximum Little Ice Age glacier extents and (b) moraines. Living trees were sampled on each moraine within the rectangle in the Garibaldi Glacier forefield and on the northern moraines within the rectangle in the Lava Glacier forefield. Trees were sampled for ecesis and age-height growth determination at sites 7 and 8. Fossil wood was sampled at sites b, c, d, e, f, and g.

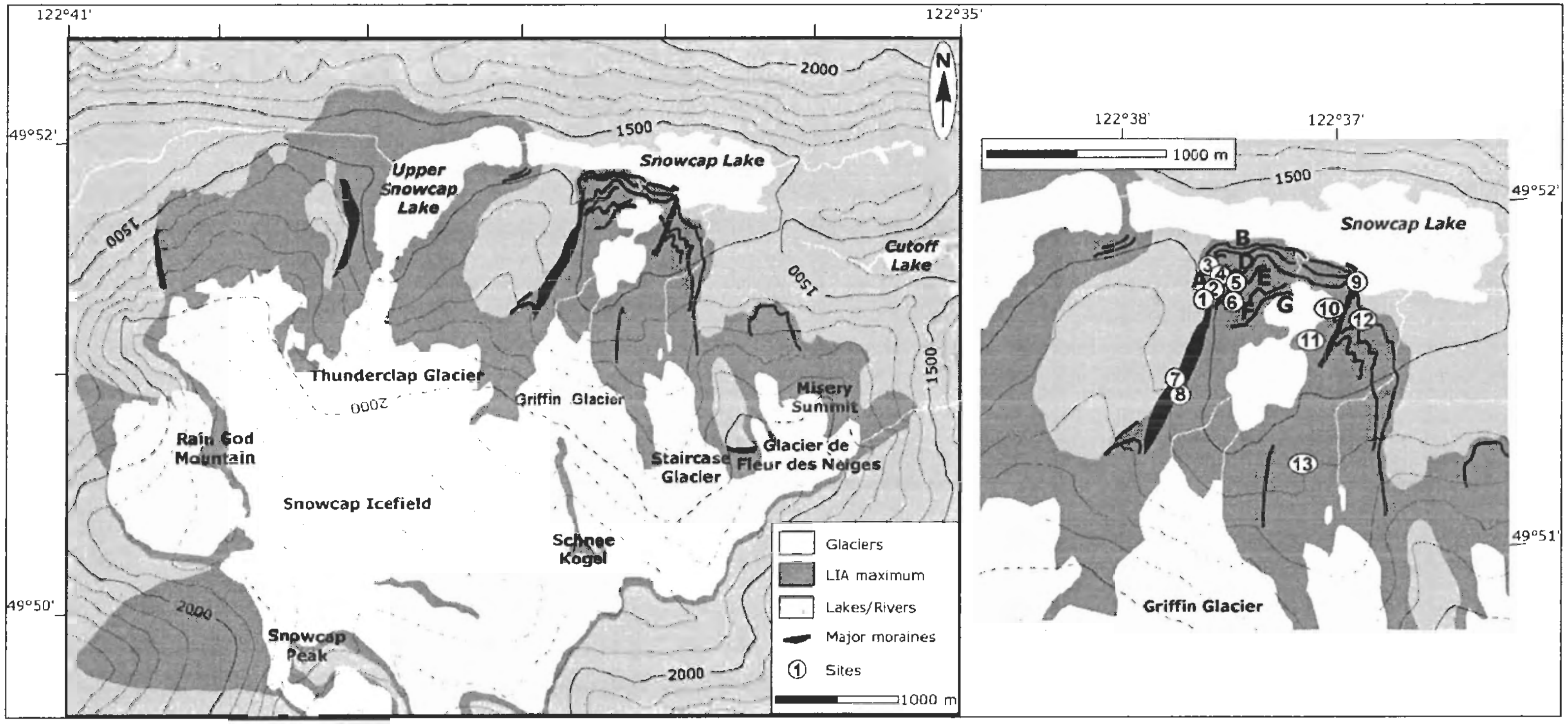

Figure 5.10 Maps of Snowcap Lakes area showing moraines, 1996 and maximum Little Ice Age glacier extents, and sample sites. Trees were sampled and lichens were measured on moraines at sites 1-11. Trees were sampled for ecesis and age-height growth determination at sites 12 and 13.

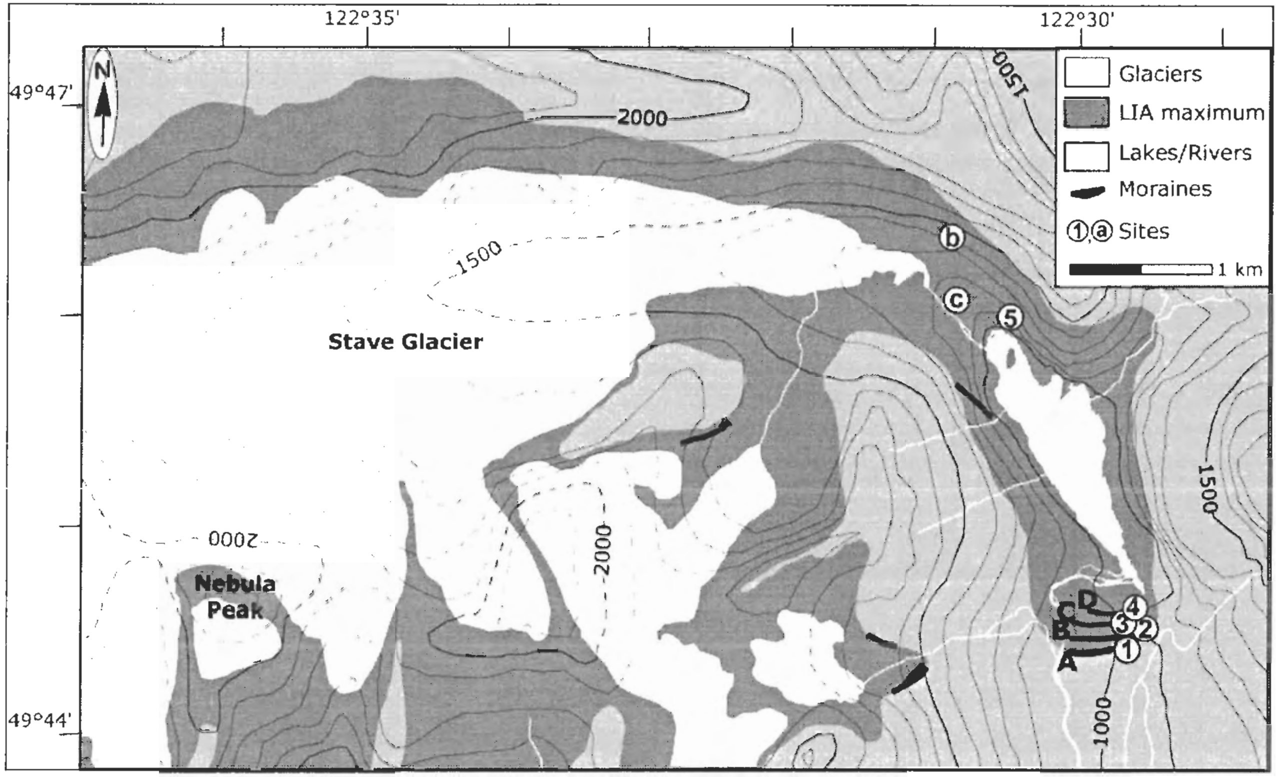

Figure 5.11 Map of Stave Glacier showing moraines and 1996 and maximum Little Ice Age extents. Trees were sampled on moraines at sites 1-4. Trees were sampled for ecesis and age-height growth determination at site 5. Fossil wood was sampled at sites b and c.

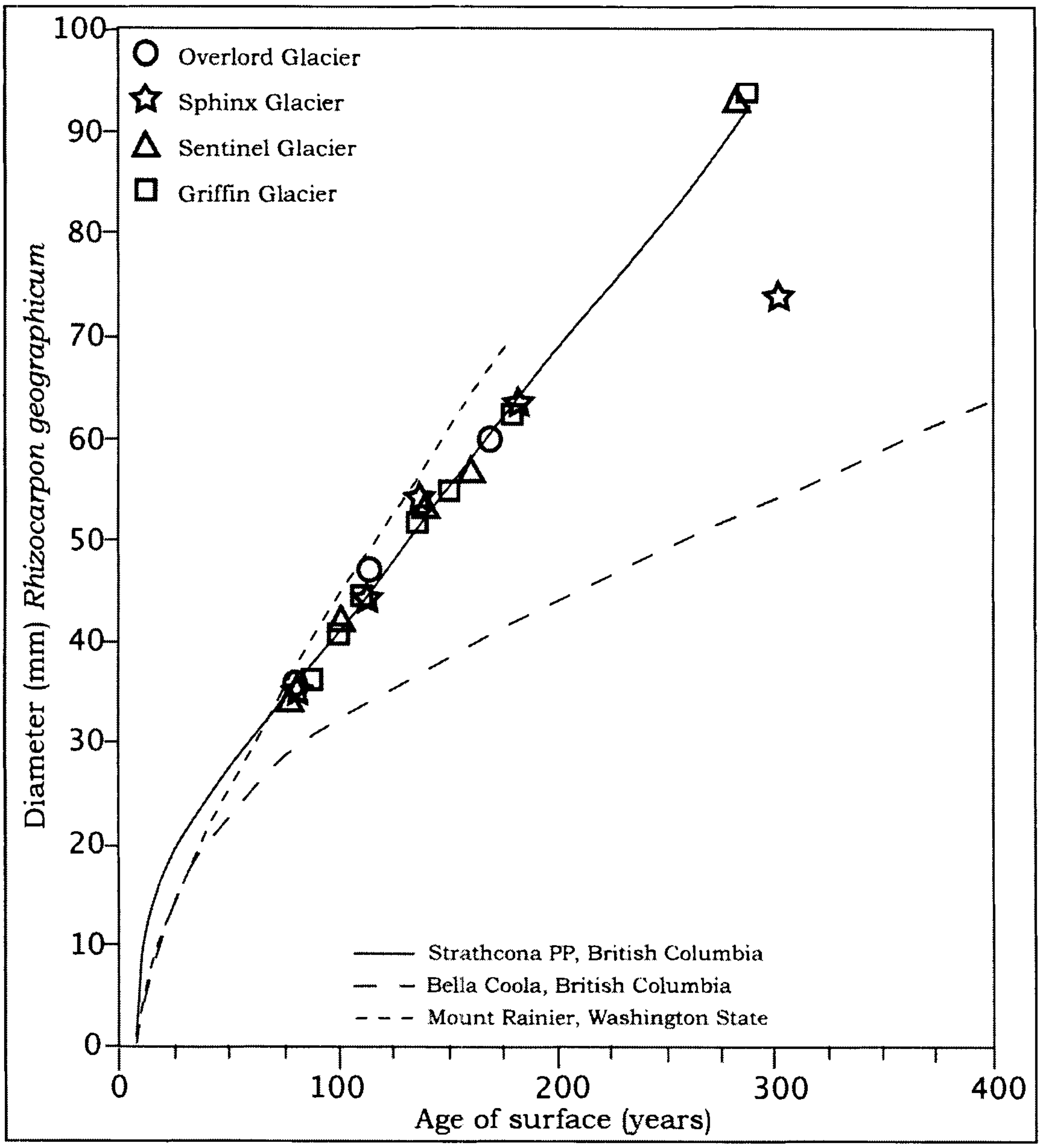

Figure 5.12 Three lichen growth curves considered in this study and data points from four glacier forefields in Garibaldi Provincial Park. The Garibaldi data best fit the curve from Vancouver Island.

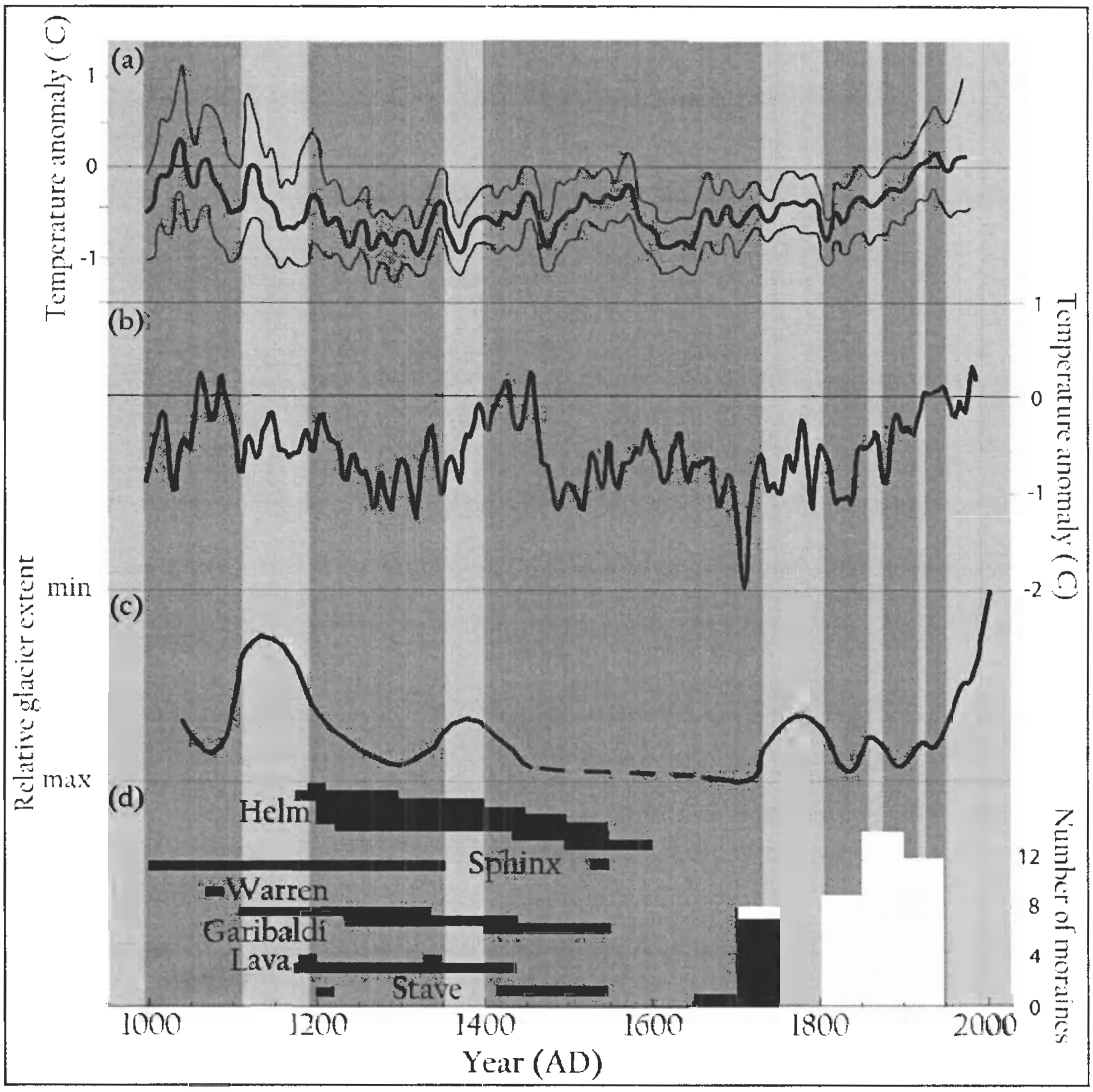

Figure 5.13 (a) Northern Hemisphere temperature change based on extratropical tree ring widths; thin black lines are bootstrap 95% confidence intervals (Cook *et al.*, 2004). (b) Canadian Rocky Mountains temperature change based on a maximum latewood density record (Luckman and Wilson, 2005). (c) Generalized history of glacier extent in Garibaldi Park. (d) Ages of fossil wood overridden by glaciers in the park; each horizontal bar shows the length of a tree-ring series extending back in time from the midpoint of the calibrated radiocarbon age range. The histogram shows the number of dated moraines grouped in 50-year periods; black bars are the outermost moraines. Dark grey vertical bars indicate times of peak advance.

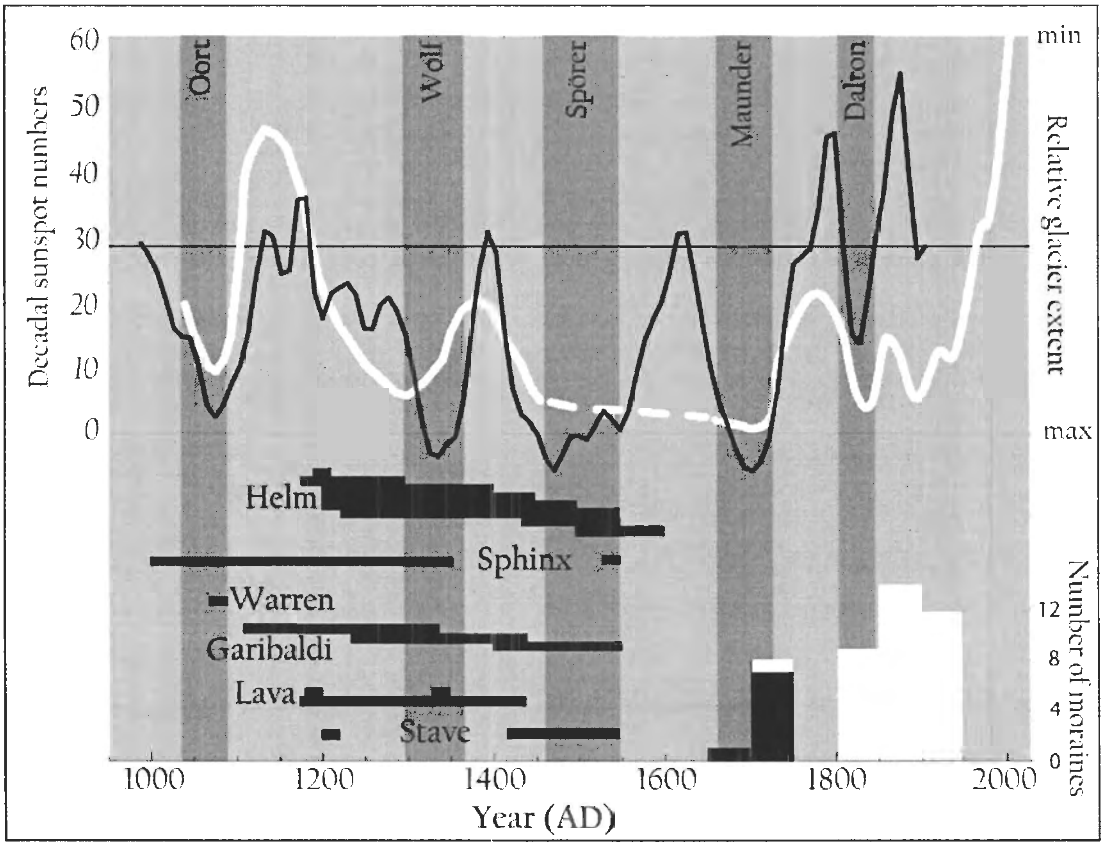

Figure 5.14 Reconstructed decadal sunspot numbers (black line; Solanki *et al.*, 2004) and generalized history of glacier extent in Garibaldi Park (white line). Dark grey vertical bars denote intervals of sunspot minima (Stuiver, 1961; Bond *et al.*, 2001). Lower plot is the same as Figure 5.13d.

Tables

Table 5.1 Living and floating tree-ring chronologies from glacier forefields in Garibaldi Park.

Glacier	Chronology	Period (AD or years)	Correlation	No. radii/trees
Overlord	living	1649-2001	0.531	102/55
Helm	living	1763-2003	0.419	93/52
	site a	146	0.674	5/2
	site f	105	0.432	6/4
	site i	222	0.398	13/7
	site j	89	0.417	3/2
	sites g, h	246	0.497	18/8
	sites e, l	223	0.403	12/6
	sites m, n, o	307	0.485	13/7
Sphinx	living	1718-2001	0.587	128/69
	site f	346	0.384	9/5
Sentinel	living	1743-2001	0.603	129/71
Warren	living	1637-2003	0.497	78/43
Garibaldi	living	1757-2002	0.419	109/60
	site c	141	0.393	4/2
	site g	201	0.498	6/3
	site d, e, f	227	0.597	8/4
Lava	living	1749-2003	0.553	125/75
	site b	266	0.437	3/2
Snowcap	living	1777-2003	0.431	17/9
Stave	living	1737-2001	0.498	86/45

Table 5.2 Ages (years) of oldest trees (subalpine fir) and respective stabilization dates (AD) of moraines in Garibaldi Park.

Glacier	Sample year	Moraine system A		B		C		D		E		F	
Overlord	2002	n/a	n/a	294	1700s	146	1830s	84	1890s	52	1920s	---	---
Helm	2004	241	1710s	129	1820s	83	1870s	43	1910s	---	---	---	---
Sphinx	2002	284	1690s	171	1800s	115	1860s	68	1900s	56	1910s	---	---
Sentinel	2002	259	1710s	134	1830s	96	1870s	77	1900s	64	1910s	---	---
Warren	2004	286	1700s	94	1880s	72	1900s	---	---	---	---	---	---
Garibaldi	2003	246	1720s	139	1820s	111	1850s	96	1870s	73	1890s	49	1910s
Lava	2004	255	1710s	164	1800s	141	1820s	113	1850s	82	1880s	51	1910s
Snowcap	2004	227	1720s	115	1830s	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
Stave	2002	265	1720s	141	1840s	102	1890s	82	1900s	---	---	---	---

Note: n/a, not applicable because moraine supports no trees.

Table 5.3 Lichenometric data for moraines at Overlord, Sphinx, Sentinel, and Griffin glaciers.

Moraine	Largest lichen (mm)		Date AD using growth curves from		
	single	mean of five	Vancouver Island[1]	Cascades[2]	central Coast Mts.[3]
Overlord Glacier					
A	nd	nd	nd	nd	nd
B	nd	nd	nd	nd	nd
C	59.7	58.4	**1830s**	1870s	1600s
D	47.5	46.8	**1890s**	1900s	1730s
E	35.6	34.9	**1920s**	1920s	1870s
Sphinx Glacier					
A	73.2	72.4	1790s	---	1450s
B	62.4	62.0	**1820s**	1860s	1570s
C	53.5	52.6	**1870s**	1880s	1660s
D	43.1	42.8	**1890s**	1900s	1780s
E	35.1	34.5	**1920s**	1920s	1870s
Sentinel Glacier					
A	92.1	90.9	**1720s**	---	---
B	57.5	57.1	**1840s**	1870s	1620s
C	52.1	51.7	**1870s**	1880s	1680s
D	41.1	40.8	**1900s**	1910s	1800s
E	34.7	34.3	**1920s**	1930s	1870s
Griffin Glacier					
A	93.2	92.1	**1710s**	---	---
B	61.4	60.6	**1820s**	1860s	1580s
C	54.7	54.1	**1850s**	1880s	1650s
D	50.8	50.3	**1870s**	1890s	1700s
E	44.3	43.5	**1890s**	1900s	1770s
F	40.5	39.9	**1900s**	1910s	1810s
G	36.3	35.8	**1910s**	1920s	1860s

Notes: Bold dates are in closest agreement with tree-ring ages.
---, beyond range of lichen growth curve.
nd, no data.
[1] Lewis (2001), Lewis and Smith (2004a).
[2] Porter (1981a), O'Neal and Schoenenberger (2003).
[3] Smith and Desloges (2000), Larocque and Smith (2004).

Table 5.4 Radiocarbon ages pertaining to the Little Ice Age in Garibaldi Park.

Glacier	Site	Laboratory no.	^{14}C age (years BP)	Cal age (years AD)	Comment
Mystery		Beta-170664	710±50	1260-1300	stick on surface
Trorey	trgl-a	Beta-157271	70±50	1690-1920	log on surface
	trgl-b	Beta-157272	60±50	1690-1920	log on surface
Helm	hegl-b	Beta-208681	810±60	1180-1270	branch on surface
	hegl-i	Beta-208682	690±60	1260-1310	*in situ* stump
	hegl-p	Beta-168428	500±40	1410-1440	log on surface
	hegl-a	Beta-186522	490±60	1390-1460	*in situ* stump
	hegl-h	Beta-186526	430±50	1420-1490	*in situ* stump
	hegl-n	Beta-208684	380±40	1450-1520	*in situ* stump
	hegl-j	Beta-208683	330±60	1490-1600	*in situ* stump
	hegl-e	Beta-186524	300±60	1510-1600	log on surface
	hegl-f	Beta-186525	270±60	1510-1670	branch between tills
Sphinx	spgl-f	Beta-186512	580±70	1300-1370	*in situ* stump
		Y-347[1]	460±40	1420-1450	*in situ* stump; same as spgl-f
	spgl-g	Beta-186513	370±70	1450-1630	log in outermost moraine
Warren	wagl-a	Beta-148791	920±70	1030-1170	*in situ* rootstock
Garibaldi	gagl-f	Beta-186515	670±70	1270-1390	*in situ* stump
	gagl-g	Beta-208680	490±60	1390-1460	log in lateral moraine
	gagl-c	Beta-186514	290±70	1490-1600	log in till
Lava	lagl-f	Beta-186518	860±70	1150-1260	log in lower wood layer in lateral moraine
	lagl-a	Beta-157266	640±50	1290-1390	log in lateral moraine S of Opal Cone
	lagl-g	Beta-186519	640±40	1290-1390	log in upper wood layer in lateral moraine
	lagl-b	Beta-186516	530±30	1400-1430	*in situ* stump
Stave	stgl-b	Beta-171095	830±50	1170-1260	log in lateral moraine
	stgl-c	Beta-171094	310±50	1510-1600	branch on surface
West Stave	wsgl-b	Beta-170669	250±50	1520-1680	log in lateral moraine

Note: Dated samples were outer-perimeter wood comprising less than 25 rings.
[1]Barendsen *et al.* (1957).

CHAPTER 6
PRE-LITTLE ICE AGE GLACIER FLUCTUATIONS IN GARIBALDI PROVINCIAL PARK, SOUTHERN COAST MOUNTAINS, BRITISH COLUMBIA

Abstract

Holocene glacier fluctuations prior to the Little Ice Age in Garibaldi Provincial Park, in the southern Coast Mountains of British Columbia, were reconstructed from geomorphic mapping and radiocarbon ages on 37 samples of growth-position and detrital wood from glacier forefields. Glaciers in Garibaldi Park were smaller than at present in the early Holocene, although some evidence exists for minor, short-lived advances at this time. The first significant advance dates to 7700-7300 ^{14}C years BP. Subsequent advances date to 6400-5100, 4300, 4100-2900, and 1600-1100 ^{14}C years BP. Some glaciers approached their maximum Holocene size several times during the last 10,000 years. Periods of advance in Garibaldi Park are broadly synchronous with advances elsewhere in the Canadian Cordillera, suggesting a common climatic cause. The Garibaldi Park glacier record is broadly synchronous with the record of Holocene sunspot numbers, supporting previous research that suggests solar activity may be an important climate forcing mechanism.

Keywords: glacier advances, Holocene, solar forcing, Garibaldi Park, southern Coast Mountains, British Columbia

Introduction

Recent studies point to significant, rapid fluctuations of climate throughout the Holocene (Bond *et al.*, 2001; Mayewski *et al.*, 2004). Alpine glaciers have long been used to document these fluctuations (Denton and Karlén, 1973), because they respond rapidly to changes in their mass balance and thus to changes in temperature and precipitation. Unfortunately, most studies of past glacier fluctuations allow reconstruction of climate variability only on centennial and decadal timescales. Furthermore, many studies of Holocene glacier fluctuations suffer from the fact that glacier advances in the Northern Hemisphere during the last millennium (Little Ice Age) were the most extensive of the Holocene and obliterated or obscured most of the evidence of previous advances. Pre-Little Ice Age moraines are rare in western Canada and their ages are generally not well constrained (Osborn, 1985; Ryder and Thomson, 1986; Osborn and Karlstrom, 1988; Osborn and Gerloff, 1996; Larocque and Smith, 2003). Sediments in lakes downvalley of glaciers can provide a more complete record of Holocene glacial activity (Leonard, 1986a, b; Desloges and Gilbert, 1995; Leonard and Reasoner, 1999; Menounos *et al.*, 2004), but the record commonly is complicated by non-climatic factors.

The most direct evidence of pre-Little Ice Age glacier advances is found in recently deglacierized glacier forefields and includes *in situ* tree stumps (Ryder and Thomson, 1986; Luckman *et al.*, 1993; Wiles *et al.*, 1999; Wood and Smith, 2004), detrital logs and branches (Ryder and Thomson, 1986; Luckman *et al.*, 1993; Wiles *et al.*, 1999), and organic soils and detrital wood exposed in composite lateral moraines (Röthlisberger, 1986; Osborn *et al.*, 2001; Reyes and Clague, 2004). Here, we present a detailed study of Holocene glacier fluctuations prior to the Little Ice Age in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia (Fig. 6.1) based on such evidence. Our objectives are to: (1) summarize new data from Garibaldi Park; (2) compare the record from the park with other records of Holocene glacier activity in western Canada; and (3) discuss the likely climate forcing mechanisms. Evidence for Little Ice Age and twentieth century glacier fluctuations in the park is presented elsewhere and is not discussed further here.

Study Area

Garibaldi Provincial Park is located in the southern Coast Mountains about 70 km north of Vancouver, British Columbia (Fig. 6.1). The park contains more than 150 glaciers, which are among the southernmost glaciers in the Coast Mountains. The total area of ice cover in the park is about 390 km^2.

The landscape of Garibaldi Park has been shaped by Quaternary continental and alpine glaciation and locally by Quaternary volcanism (Mathews, 1958). The park is underlain mainly by granitic rocks of the Coast Plutonic Complex and Cretaceous metasedimentary and volcanic rocks of the Gambier Group (Monger and Journeay, 1994). The southwestern part of the park is dominated by rocks of the Plio-Pleistocene Mount Garibaldi volcanic complex (Mathews, 1958).

The northwest-trending Coast Mountains form an orographic barrier to moisture-laden air flowing from the Pacific Ocean, thus there is a strong west-east environmental gradient across Garibaldi Park. Climate is temperate in the southwestern part of the park but becomes increasingly continental to the north and east. Average annual precipitation at Squamish, at the head of Howe Sound, is 2370 mm, but it is only

1230 mm at Whistler, 60 km to the north. Overall, climate is humid and cool, with very wet winters and dry summers.

The study area is located in the Mountain Hemlock biogeoclimatic zone, which is characterized by long, cool, wet winters and short, cool summers (Brooke et al., 1970). The growing season is short due to heavy snowfall in winter. Arboreal vegetation in forefields investigated in this study is dominated by mountain hemlock (*Tsuga mertensiana*) and subalpine fir (*Abies lasiocarpa*), but locally includes Engelmann spruce (*Picea engelmannii*), whitebark pine (*Pinus albicaulis*), and yellow cedar (*Chamaecyparis nootkatensis*).

Methods

Glacier forefields were visited in 2002, 2003, and 2004 and systematically searched for detrital and *in situ* fossil wood. The discs were cut from fossil wood found in lateral and end moraines and at the surface. They were air dried and prepared for analysis by sanding with progressively finer grades of sandpaper to enhance the definition and contrast of annual tree-ring boundaries. Tree rings were measured on a Velmex stage with a precision of ±0.001 mm using the software MeasureJ2X. Two to four radii were measured to replicate data and reduce the possibility of missing rings or "false" rings (Stokes and Smiley, 1968). "Floating" chronologies were developed for sites where more than one tree was sampled. These chronologies show that many trees at a site were killed at about the same time and support the argument that tree death was caused by an advancing glacier. The total number of rings is a minimum for the length of time the site was not covered by ice and thus a minimum for the interval between successive glacier advances. The floating chronologies were visually compared to correlate marker rings and checked and verified using the International Tree-Ring Data Bank (ITRDB) software program COFECHA. They were then crossdated (50-year dated segments lagged by 25 years, with a critical level of correlation [99%] set at 0.32) to create master ring-width chronologies (Holmes, 1983). Floating chronologies that could not be crossdated with living trees were radiocarbon dated. Standard radiocarbon ages on outer rings were calibrated using the program CALIB 5.0 (Stuiver *et al.*, 2005). Calibrated ages, shown in brackets in this paper, are 1σ ranges.

Interpretation of radiocarbon ages from glacier forefields requires consideration of the provenance and location of the dated material (Röthlisberger, 1986; Osborn, 1986; Ryder and Thomson, 1986; Luckman, 1998a). Stumps in growth position in Garibaldi Park show evidence of having been sheared off by glaciers. Bark is commonly preserved due to burial of the stumps in sediment. Detrital wood in glacier forefields shows evidence of glacial transport, including missing bark, abrasion, embedded sediment, and flattening. This wood is interpreted to have been eroded from *in situ* trees by glaciers and transported at basal and englacial positions within the glaciers. Preservation of bark or relatively small branches or roots is interpreted to indicate short transport. Only samples in growth position provide unequivocal evidence for glacier advance and extent at a given time. Detrital wood in a stratigraphic context, such as a lateral moraine or till in a glacier forefield, provides a maximum age for the advance. It also defines the minimum extent of the glacier, because the glacier must have reached at least as far as the wood and probably farther. The possibility must be considered that detrital wood within till could have avalanched into the forefield or died of old age, but in such cases the wood nevertheless provides a maximum age for an advance. If tree-ring or radiocarbon ages on detrital wood in one glacier forefield are similar to those in other forefields, it is unlikely that the samples were introduced by avalanches or died of old age.

Results

Early Holocene

Detrital wood in three glacier forefields in Garibaldi Park suggests that glaciers were generally less extensive in the early Holocene than in 2002-2004, but that they may have advanced on several occasions to near present-day glacier margins. A large, abraded and partially buried log about 140 m from the 1997 snout of Helm Glacier yielded a radiocarbon age of 8900±60 ^{14}C years BP (9920-10,090 cal years BP; Table 6.1). A split and frayed fragment of detrital wood, likely the remains of a small conifer trunk, recovered from the top of a bedrock knob about 90 m from the 2002 margin of Wedgemount Glacier gave an age of 8650±60 ^{14}C years BP (9540-9630 cal years BP). A shredded stick found on a bar of a meltwater stream about 250 m from the 2000 snout of Warren Glacier (site e in Fig. 6.2) yielded an age of 8050±60 ^{14}C years BP (8950-9030 cal years BP).

7700-7300 ^{14}C years BP (8500-8100 cal years BP)

Evidence was found in two glacier forefields for a small advance at the time of the "8.2 ka event", an abrupt cooling event most likely caused by a massive discharge of freshwater into the North Atlantic around 8470 cal years BP (Alley and Ágústsdóttir, 2005). Two small, shattered and partially buried fragments of coniferous wood were found about 100 m from the 2002 snout of Sphinx Glacier (site e in Fig. 6.3). One of the fragments yielded a radiocarbon age of 7720±80 ^{14}C years BP (8420-8560 cal BP; Menounos *et al.*, 2004).

This age agrees with another, obtained on a 2-m-long stem recovered from among large boulders in a meltwater channel near the snout of Sphinx Glacier in the 1970s (7640±80 ^{14}C years BP [8380-8480 cal years BP]; Lowdon and Blake, 1975). The locations of both samples indicate that, prior to the event, Sphinx Glacier was less extensive than at present. Three small pieces of detrital wood 50-400 m from the snout of Sentinel Glacier gave ages of 7720±70 ^{14}C years BP (8430-8550 cal years BP), 7470±80 ^{14}C years BP (8280-8360 cal years BP), and 7380±80 ^{14}C years BP (8160-8330 cal years BP; Menounos *et al.*, 2004). Sentinel Glacier was less extensive at the time of this inferred advance than today. Neither Sphinx nor Sentinel glacier advanced far beyond its present limit during the 8.2 ka event.

6400-5100 ^{14}C years BP (7300-5800 cal years BP)

Evidence for this advance was found in six glacier forefields in Garibaldi Park, showing the regional significance of the event. A degraded, detrital stump recovered from till about 800 m from the 2002 snout of Stave Glacier gave a radiocarbon age of 6250±70 ^{14}C years BP (7150-7260 cal years BP), indicating that the glacier was more extensive at that time than today.

Surface detrital wood 40-200 m from the 2002 snout of Overlord Glacier gave ages of 6170±70 ^{14}C years BP (6980-7160 cal years BP) and 5890±70 ^{14}C years BP (6630-6800 cal years BP). A third sample, embedded in till 40 m farther downstream from the glacier snout, yielded an age of 5980±70 ^{14}C years BP (6730-6910 cal years BP). The locations of the three samples indicate that Overlord Glacier was probably less extensive than today prior to this event and advanced into mature forest around 6000 ^{14}C years BP.

One of the dated samples crossdated with two other pieces of detrital wood, providing a floating chronology (Table 6.2).

Branches and snags were found in a woody layer between two tills and in an adjacent stream about 300 m from the snout of the south tributary glacier of Sphinx Glacier (site a in Fig 6.3). One of the snags gave an age of 5830±60 ^{14}C years BP (6560-6700 cal years BP). A floating ring chronology was built from two of the samples in till and one in the creek (Table 6.2). The evidence from this site indicates that Sphinx Glacier was about its present size prior to an advance that overrode forest around 5800 ^{14}C years BP.

Wood collected from till near the snout of Sentinel Glacier (Fig. 6.1) in 1970 yielded a radiocarbon age of 6170±150 ^{14}C years BP (6890-7250 cal years BP; Lowdon and Blake, 1973). The exact location of this site is unknown, but it is likely the same site that we sampled in 2002 (Fig. 6.4a). Our samples range from small trunks to large snags; one of the snags gave an age of 6040±60 ^{14}C years BP (6790-6950 cal years BP). The two ages overlap at their 1σ limits, supporting the inference that they are from the same site. Two samples from the till and two in a meltwater stream adjacent to the till exposure were used to construct a floating chronology (Table 6.2). An *in situ* stump buried by till was collected in 1973 and dated at 5300±70 ^{14}C years BP (5990-6130 cal years BP; Lowdon and Blake, 1975). Although we were unable to locate this sample, it is within 1 km of the maximum Little Ice Age margin of Sentinel Glacier (Lowdon and Blake, 1975).

The radiocarbon ages from Sentinel Glacier afford a more detailed reconstruction of this event than the ages from Stave, Overlord, and Sphinx glaciers. When Sentinel Glacier advanced into forest 6100 ^{14}C years BP, it was about as extensive as today. The dated wood shows little evidence of transport and thus likely had been growing near the sample site prior to the advance. By 5300 ^{14}C years BP, Sentinel Glacier was at least 1 km more extensive than at present and at least half its Little Ice Age maximum size. The glacier thus expanded over the 800-year period between 6100 and 5300 ^{14}C years BP, although it is not known if glacier growth was slow and continuous or the result of two separate advances.

The Warren Glacier forefield has a similar record (sites b, c, and d in Fig. 6.2). Two *in situ* stumps (Fig. 6.4c) were found at site d about 100 m from the 2000 glacier margin. They yielded ages of 6370±70 ^{14}C years BP (7250-7330 cal years BP) and 6360±80 ^{14}C years BP (7250-7340 cal years BP). An exposed and fragmented *in situ* stump (Fig. 6.4b) at site c about 600 m from the 2000 glacier margin gave an age of 5780±70 ^{14}C years BP (6500-6660 cal years BP). A large weathered log, partially buried in till, at site b yielded an age of 5700±50 ^{14}C years BP (6410-6540 cal years). I interpret these ages as follows. Warren Glacier was about the same size as today when it advanced into forest at site d about 6350 ^{14}C years BP. By 5800 ^{14}C years BP, the glacier had advanced about 600 m downvalley and was overriding a forest at site c. The dated log at site b, farther downvalley, shows that the glacier continued to advance until at least 5700 ^{14}C years BP. As at Sentinel Glacier, it is not known if Warren Glacier advanced slowly over a period of 650 years or two or more times during this interval.

Garibaldi Neve, an icefield east of Mt. Garibaldi, feeds six glaciers, including Lava Glacier (Fig. 6.5). Two *in situ* stumps on a ridge at the northeast corner of the neve (site j in Fig. 6.5) yielded radiocarbon ages of 6170±60 ^{14}C years BP (7000-7160 cal years BP) and 6050±50 ^{14}C years BP (6840-6970 cal years BP). An *in situ* stump on a nunatak in the neve was sampled in the 1950s. It gave ages of 5850±180 ^{14}C years BP (6450-6860 cal years BP;

Preston *et al.*, 1955) and 5260±200 ^{14}C years BP (5890-6280 cal years BP; Stuiver *et al.*, 1960); the latter is assumed to be the more reliable age (Stuiver *et al.*, 1960). The exact location of this sample is unknown, but Figure 6.5 shows the two possible nunataks in the icefield. Two *in situ* and three detrital stumps were recovered along the stream draining Lava Glacier, about 400 m from the 2003 snout (site i, Fig. 6.5). One of the *in situ* stumps yielded an age of 5760±60 ^{14}C years BP (6490-6640 cal years BP). Two more sites with detrital wood were found in the same area, site c ca. 50 m to the southeast of site i and site d ca. 110 m to the northeast of site i. Samples from sites c, d, and i were successfully crossdated, providing a floating chronology of almost 500 years (Table 6.2). Numerous branches, large logs, snags, and stumps were found on an alluvial surface (site h, in Fig. 6.5), 20-100 m downstream of a gorge eroded in bedrock and till. The surface detrital wood is derived from a wood layer separating two tills within the gorge (arrow near site h in Fig. 6.5). Unfortunately, the site could not be safely accessed. Three detrital stumps at site h were crossdated (Table 6.2), and a radiocarbon age of 5130±40 ^{14}C years BP (5890-5930 cal years BP) was obtained on one of them. The dates from Garibaldi Neve indicate a thickening of ice between 6100 and 5900/5200 ^{14}C years BP, either slowly or during two separate events. Lava Glacier advanced into mature forests with trees more than 450 years old 5800 and 5100 ^{14}C years BP. It likely had the same extent 5800 ^{14}C years BP as today. By 5100 ^{14}C years BP, when it deposited a till at site h, Lava Glacier was more than half its Little Ice Age size.

4300 ^{14}C years BP (4900 cal years BP)

Evidence for this event was found only at Sphinx Glacier (site b in Fig. 6.3). Detrital branches and large logs were found on the surface in a meltwater stream (Fig. 6.6) and as a woody layer separating two tills about 500 m from the snout of the southern tributary glacier. The outer 15 rings of one of the logs yielded a radiocarbon age of 4280±70 ^{14}C years BP (4810-4960 cal. BP). A floating chronology, spanning 115 years, was constructed for two samples collected from the till (Table 6.2). It is unknown if the lower till at site b corresponds with the lower till at site a (Fig. 6.3, see Garibaldi Advance), thus indicating a single advance, or if the upper till at site a is the lower till at site b, indicating two separate advances. However, evidence at other forefields indicates that glaciers reached much farther downvalley at the end of the previous advance. It thus is more likely that the tills record two advances, and that Sphinx glacier receded after the previous advance to an unknown position upvalley of site b for at least 115 years. This issue aside, an advance occurred about 4300 ^{14}C years BP, reaching at least site b.

4100-2900 ^{14}C years BP (4600-3000 cal years BP)

Evidence for this advance was found in five glacier forefields in Garibaldi Park. The evidence shows that glaciers became more extensive over time during this event.

Thirteen branches and stumps were found in till near the terminus of Helm Glacier (Fig. 6.7a) in 2003. They appear to be associated with a weathering horizon in the till. A radiocarbon age of 4080±40 ^{14}C years BP (4520-4620 cal years BP) was obtained on the outermost 12 rings of the sample shown in Figure 6.7a, and a floating chronology was constructed from all of the samples (Table 6.2). The evidence suggests that Helm Glacier was less extensive than today for at least 135 years around 4100 ^{14}C years BP. Shortly afterwards, it advanced to a more extensive position than at present.

Small wood fragments about 20 m above the present surface of Spearhead Glacier date to 3900±80 ^{14}C years BP (4230-4430 cal years BP) and 3900±60 ^{14}C years BP (4280-

4420 cal years BP; Osborn *et al.*, in prep). They indicate that Spearhead Glacier was thicker and thus more extensive 3900 ^{14}C years BP than today.

Additional evidence for this event was found along the creek draining the southern tributary of Sphinx Glacier (Fig. 6.1), about 800 m from the 2002 snout (site c in Fig. 6.3). A layer of branches and snags occurs within till, and one of the snags gave an age of 3560±70 ^{14}C years BP (3820-3930 cal years BP). A floating chronology was built from three samples (Table 6.2). The evidence indicates that the glacier was at least 800 m more extensive 3600 ^{14}C years BP than at present.

A large log in the west lateral moraine of Lava Glacier (Fig. 6.7b) yielded a radiocarbon age of 3190±40 ^{14}C years BP (3380-3450 cal years BP). The log is part of a wood layer that can be traced over a distance of 110 m across several gullies. The till overlying the wood layer was deposited by Lava Glacier shortly after 3200 ^{14}C years BP, when it was about as extensive as at the Little Ice Age maximum.

Decker Glacier also was near its Little Ice Age limit at this time. *In situ* snags and stumps on a bedrock cliff 40 to 75 m above the present glacier surface yielded radiocarbon ages of 3200±70 ^{14}C years BP (3350-3480 cal years BP), 2960±40 ^{14}C years BP (3070-3210 cal years BP), and 2920±50 ^{14}C years BP (2990-3160 cal years BP; Osborn et al., in prep). A detrital log below the bedrock cliff gave an age of 2960±50 ^{14}C years BP (3060-3220 cal years BP). Decker Glacier thickened between 3200 and 2900 ^{14}C years BP to near its Little Ice Age maximum extent

1600-1100 ^{14}C years BP (1500-1000 cal years BP)

Evidence for one or more glacier advances in the first millennium AD was found in the forefields of two glaciers in Garibaldi Park. A detrital snag with relatively fine roots, located below a bedrock knob at Sphinx Glacier (site d in Fig. 6.3), yielded an age of 1570±40 ^{14}C years BP (1450-1520 cal years BP). The roots indicate short transport, and it is likely that the stump was rooted on the bedrock knob. The site is only 600 m from the 2002 ice margin, but the glacier would have to thicken considerably to cover it; thus Sphinx Glacier was much more extensive 1600 ^{14}C years BP than at present. Supporting evidence for this event comes from the forefield of West Stave Glacier. A small log embedded in the outermost lateral moraine close to its crest yielded an age of 1080±60 ^{14}C years BP (930-1010 cal years BP).

Discussion

Chronology

Glaciers in Garibaldi Park were likely less extensive than at present for most of the early Holocene. Radiocarbon ages from Wedgemount, Helm, and Warren glaciers may record minor advances between 8900 and 8000 ^{14}C years BP (Fig. 6.8). However, prior to the 8.2 ka event (Menounos *et al.*, 2004), glaciers must have been less extensive than today, because detrital wood recovered near the margins of Sphinx and Sentinel glaciers dates to 7700-7300 ^{14}C years BP.

Warren, Stave, Sentinel, Sphinx, Overlord, and Lava glaciers advanced between 6400 and 5100 ^{14}C years BP. The glaciers advanced over forests up to 800 m downvalley from present snouts between 6400 and 5800 ^{14}C years BP. Sentinel and Lava glaciers were no more than 1-1.5 km from their maximum Holocene limits between 5300 and 5100 ^{14}C years BP. It is possible that this event was a single continuous advance that happened over 1300 years, but more likely it was a period like the Little Ice Age, with several advances.

Evidence for an advance around 4300 ^{14}C years BP was found only at Sphinx Glacier. There, ice advanced at least 500 m farther downvalley than at present (Fig. 6.8). Taken alone, the evidence at Sphinx Glacier could be interpreted to indicate slow growth of glaciers between 6000 and 4300 ^{14}C years BP. Combined with evidence from other forefields, however, it is more likely that glaciers receded between 5300 and 4300 ^{14}C years BP to positions similar to the present before readvancing (Fig. 6.8).

Some glaciers achieved present-day extents prior to 4100 ^{14}C years BP, the time that Helm Glacier advanced into forest and deposited till at the site of its present snout. Glaciers thickened (Spearhead Glacier) and advanced up to 800 m (Sphinx Glacier) between 3900 and 3600 ^{14}C years BP. Lava and Decker glaciers thickened and advanced into mature forests between 3200 and 2900 ^{14}C years BP, reaching to within 500 m of their Holocene maximum positions at this time. It is not known whether this was a single advance with slow growth over 1200 years or was more complex with several advances.

Sphinx Glacier retreated to near its present margins after this event, before readvancing into mature forest around 1600 ^{14}C years BP. Stave Glacier was near its Holocene maximum by about 1100 ^{14}C years BP. This advance was also followed by recession, before the start of the Little Ice Age about AD 1000.

Regional Comparisons

Evidence of glacier activity in the early Holocene in western Canada is sparse, but available data indicate that glaciers either disappeared or were smaller than today at that time (Ryder and Thomson, 1986; Luckman, 1988b). Advances during the early Holocene were likely minor and short-lived. Menounos *et al.* (2004) summarized evidence for an advance in Garibaldi Park at the time of the 8.2 ka cooling event, and a glacier forefield in the Rocky Mountains (Luckman, 1988b) also has evidence for this event. Dated samples in Garibaldi Park are near present-day glacier margins, indicating that ice extent was less than today prior to the advance and that the advance was minor.

Glacier advances between 6000 and 5000 ^{14}C years BP in western Canada are termed the "Garibaldi phase" (Ryder and Thomson, 1986). Evidence for this event has previously been limited to a few sites in the Coast Mountains (Ryder and Thomson, 1986; Laxton *et al.*, 2003; Smith, 2003). Detrital wood in the Canadian Rocky Mountains dating to this period has been interpreted to record treelines higher than today (Luckman *et al.*, 1993). However, it may also indicate glacier advance at this time. The Garibaldi phase evidently was a lengthy period during which glaciers achieved fairly extensive positions. It is likely a much more complex event than evidence currently suggests.

Glacier advances between 3300 and 1900 ^{14}C years BP are termed the "Tiedemann Advance" in the Coast Mountains (Ryder and Thomson, 1986). The same event in the Rocky Mountains, although there dated to between 3300 and 2500 ^{14}C years BP, is termed the "Peyto Advance" (Luckman *et al.*, 1993). Evidence for these advances is widespread in western Canada (Denton and Stuiver, 1966; Rampton, 1970; Denton and Karlén, 1977; Osborn, 1986; Osborn and Karlstrom, 1989; Luckman *et al.*, 1993; Luckman, 1995, in press; Jackson and Smith, 2005; Lewis and Smith, 2005; Smith *et al.*, 2005). In most areas, glaciers reached extents only slightly smaller than during the Little Ice Age. Tiedemann Glacier was more extensive at this time than at any other time in the Holocene (Ryder and Thomson, 1986). The Tiedemann/Peyto phase was probably as complex as the Little Ice Age and includes multiple advances (Luckman, 1995; Reyes and Clague, 2004; Haspel *et al.*, 2005).

Evidence for an advance in the first millennium AD is widespread in western North America (Reyes *et al.*, 2006). Glaciers probably achieved extents at the maximum of this phase that were comparable to those of the preceding and following phases.

Climate Forcing

Researchers have noted a relation between Holocene glacier fluctuations and changes in solar activity (Denton and Karlén, 1973; Karlén and Kuylenstierna, 1996). There is a decadal-scale correspondence of sunspot numbers and glacier fluctuations in Alaska and western Canada over the past millennium (Lawrence, 1950; Wiles *et al.*, 2004; Luckman and Wilson, 2005). Solanki *et al.* (2004) inferred sunspot numbers over the past 11,000 years from differences in the production of atmospheric ^{14}C recorded in trees. Comparison of this record with the record of Holocene glacier fluctuations in Garibaldi Park suggests that the major periods of glacier advance correspond to times of low sunspot numbers (Fig. 6.8). This correspondence suggests that changes in solar activity may affect glacier behaviour in Garibaldi Park and likely elsewhere. The period between 3000 and 4500 cal years BP, however shows little correspondence between glacier activity and solar activity and requires other explanations.

Conclusions

Holocene glacier fluctuations in Garibaldi Provincial Park were determined through geomorphic mapping and radiocarbon dating of detrital and *in situ* fossil wood in glacier forefields. Glaciers in the park were smaller than at present in the early Holocene. Five major periods of pre-Little Ice Age glacier advance date to 7700-7300, 6400-5100, 4300, 4100-2900, and 1600 ^{14}C years BP. These periods are broadly synchronous with advances documented elsewhere in western Canada. The evidence from Garibaldi Park suggests that Holocene climate was much more varied than previously thought. Glaciers approached their Holocene maximum positions on three occasions prior to the Little Ice Age. Glaciers in Garibaldi Park, and notably Sphinx Glacier, afford the most complete record of Holocene glacier activity in western Canada. The glacial record is in good agreement with the record of reconstructed sunspot numbers during the Holocene, suggesting that glacier fluctuations in Garibaldi Park may have been forced by changes in solar activity.

Figures

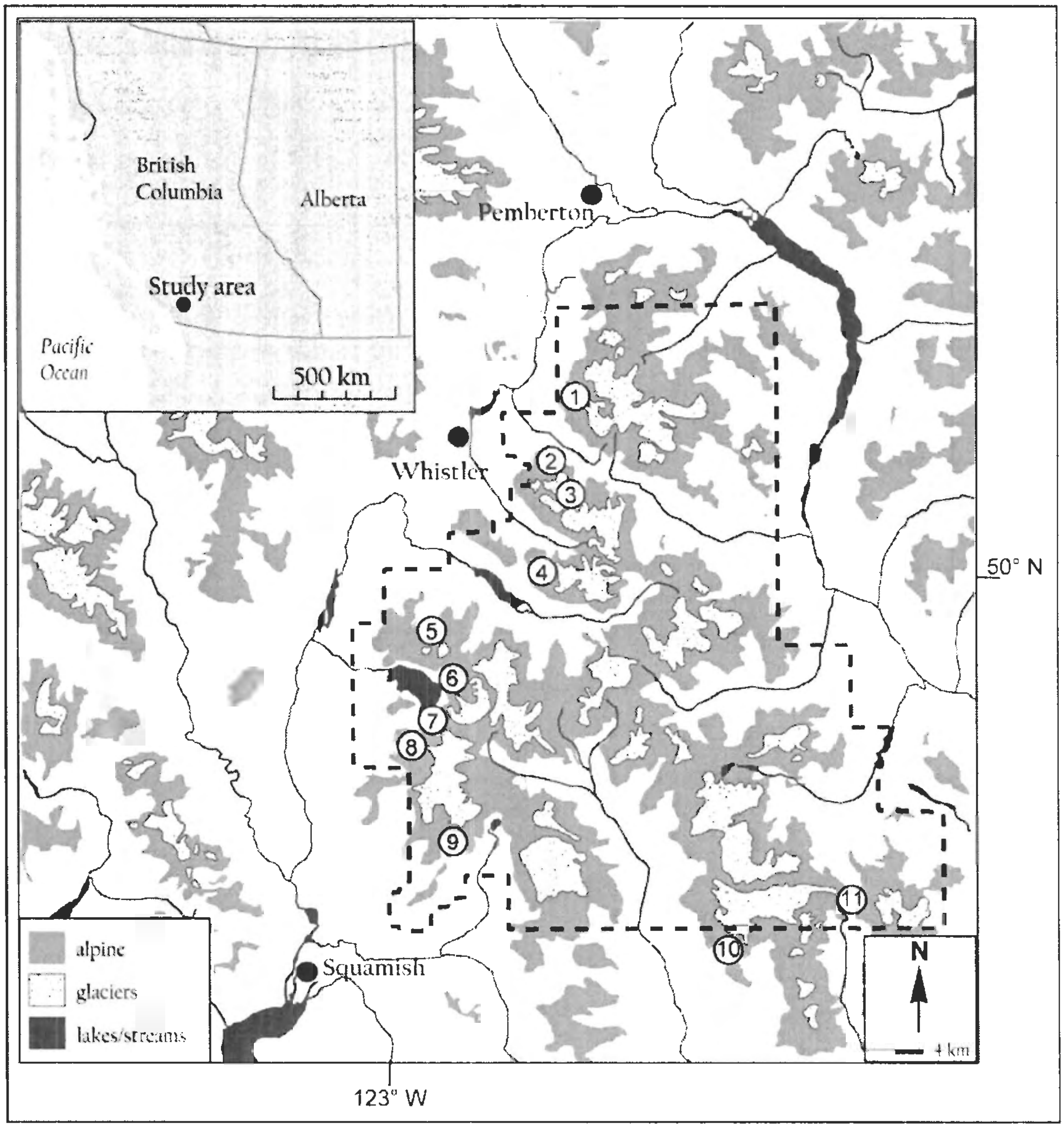

Figure 6.1 Location of Garibaldi Provincial Park and glaciers investigated in this study. 1, Wedgemount Glacier; 2, Spearhead Glacier; 3, Decker Glaciers; 4, Overlord Glacier; 5, Helm Glacier; 6, Sphinx Glacier; 7, Sentinel Glacier; 8, Warren Glacier; 9, Lava Glacier; 10, West Stave Glacier; 11, Stave Glacier.

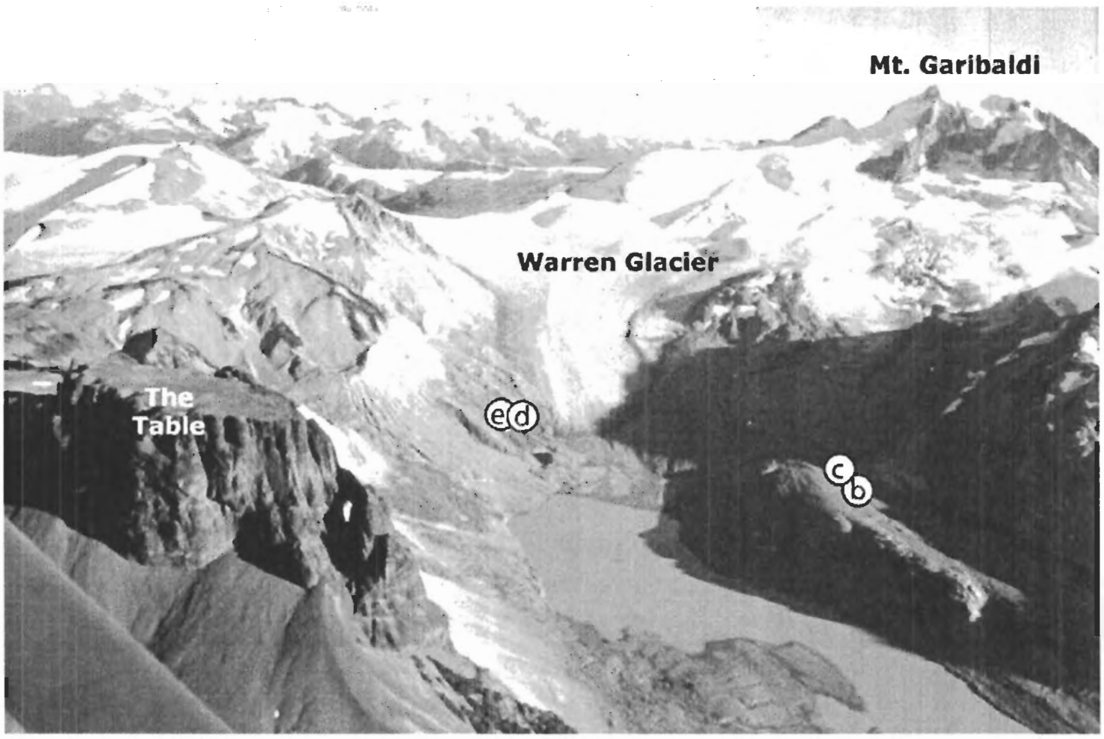

Figure 6.2 Forefield of Warren Glacier, showing study sites (photograph by J. Koch). View is to the southeast.

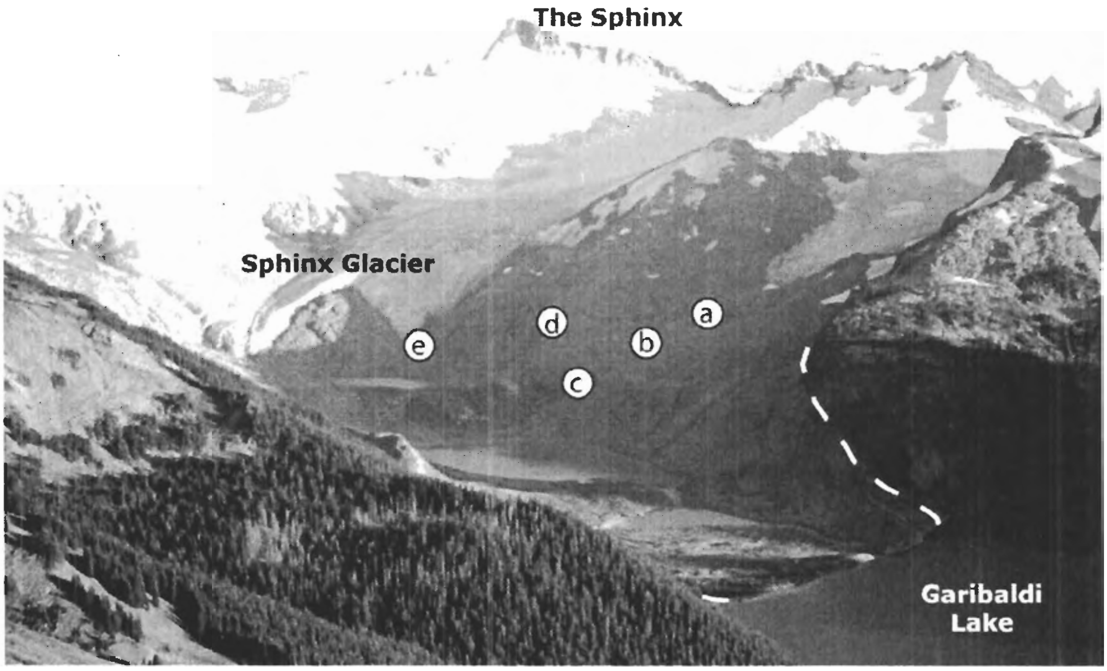

Figure 6.3 Forefield of Sphinx Glacier and study sites (photograph by J. Koch). View is to the southeast.

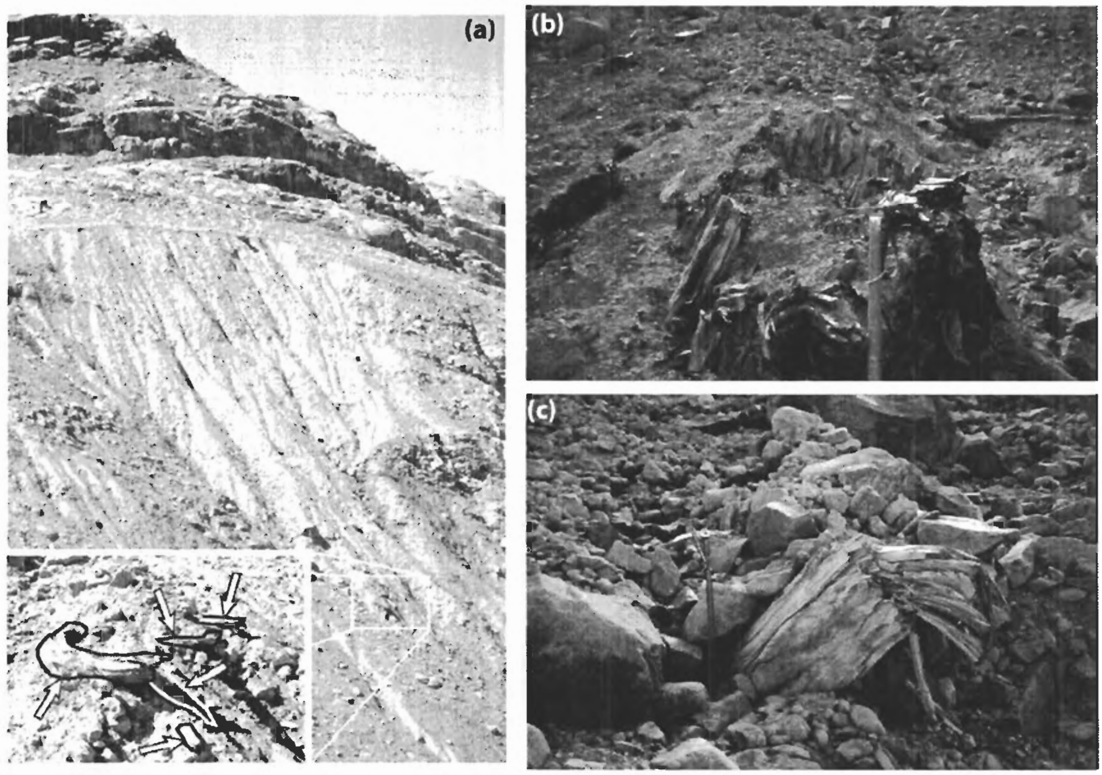

Figure 6.4 (a) Wood in lateral moraine of Sentinel Glacier (site segl-b; 6040±60 ^{14}C years BP; photograph by J. Koch). (b) *In situ* stump at Warren Glacier (site wagl-d; 6360±80 ^{14}C years BP; photograph by G. Osborn, with permission). (c) *In situ* stump at Warren Glacier (site wagl-c; 5780±70 ^{14}C years BP; photograph by G. Osborn, with permission).

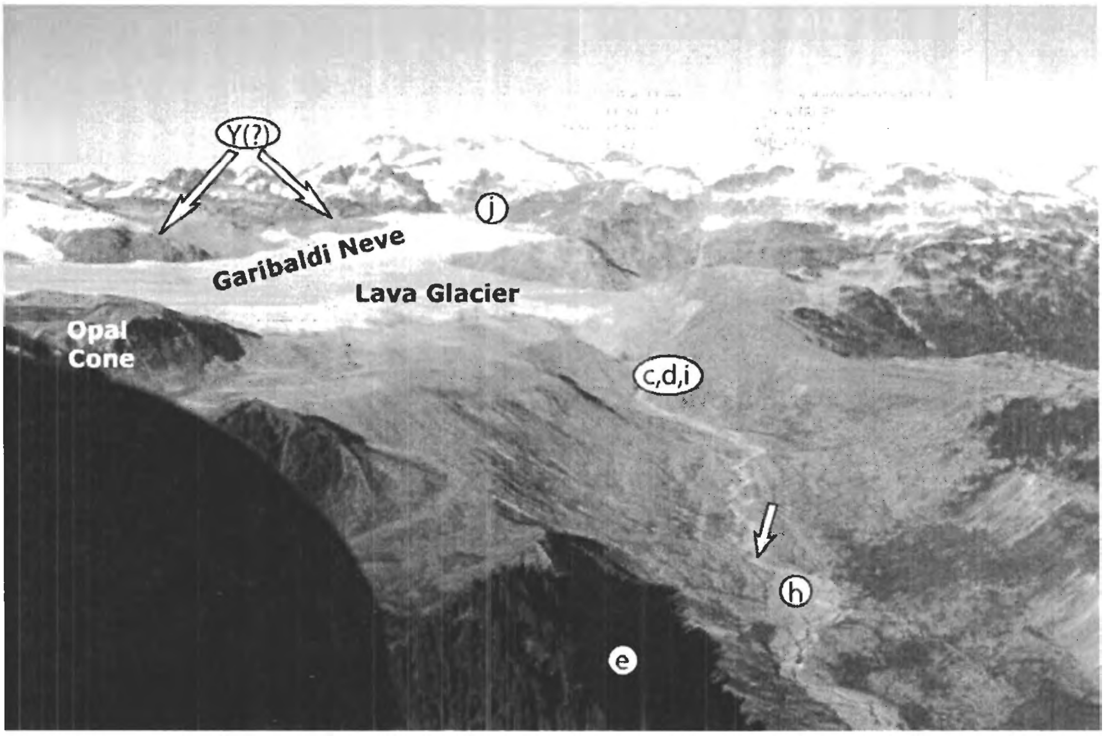

Figure 6.5 Forefield and study sites at Lava Glacier and Garibaldi Neve (photograph by J. Koch). View is to the north. The exact location of site y is unknown. Wood sampled on the floodplain (site h) was eroded from a wood layer in a gully (white arrow).

Figure 6.6 Remnants of trees killed by a glacier advance between the Garibaldi and Tiedemann events. The wood is located in the forefield of a tributary glacier (arrowed) of Sphinx Glacier (site spgl-b; 4280±70 ^{14}C years BP; site b in Fig. 6.3; photograph by J. Koch).

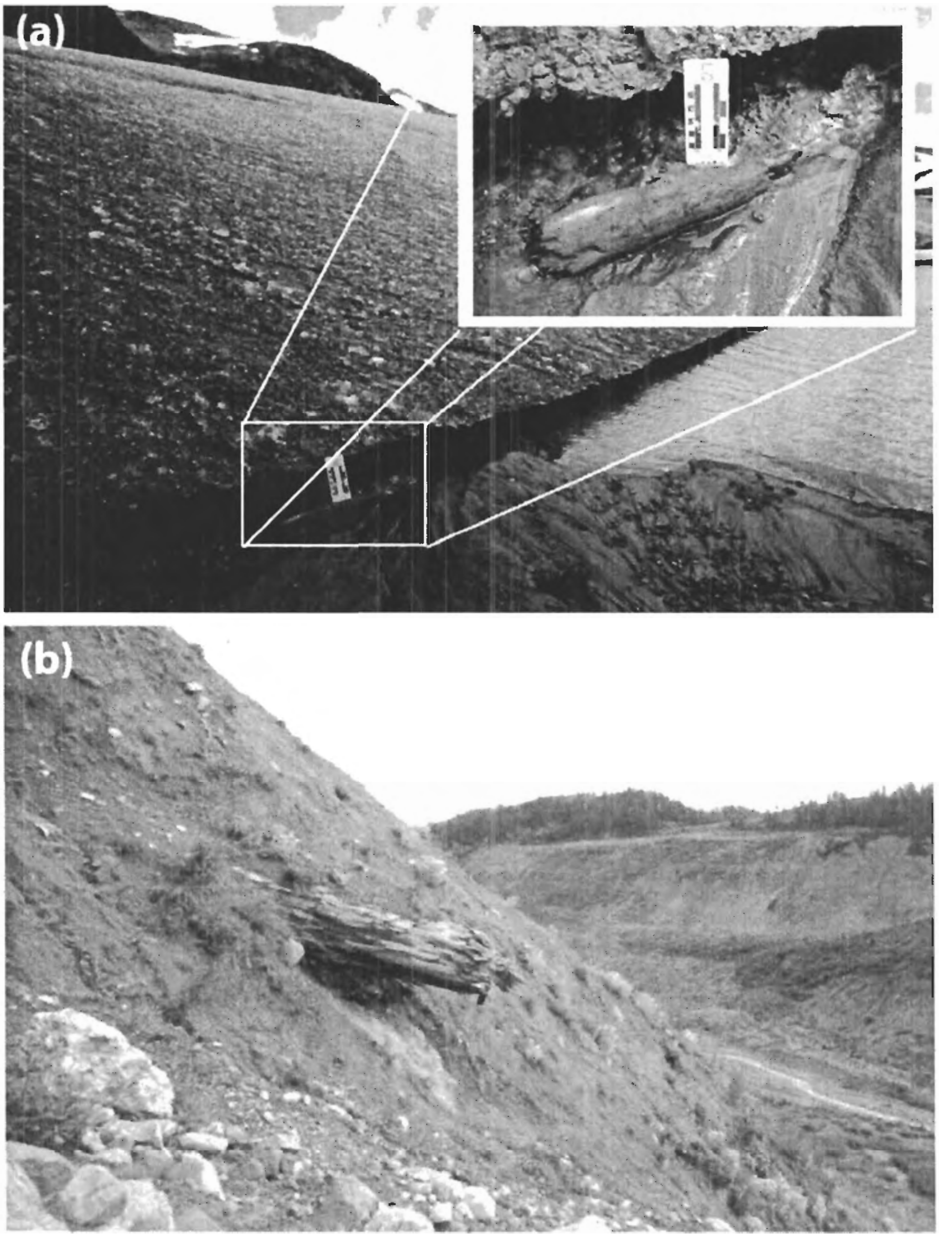

Figure 6.7 Fossil wood dating to the Tiedemann Advance. (a) Wood melting out of Helm Glacier (site hegl-d; 4080±40 ^{14}C years BP). (b) Wood layer in the lateral moraine of Lava Glacier. (site lagl-e; 3190±40 ^{14}C years BP). (Photographs by J. Koch.)

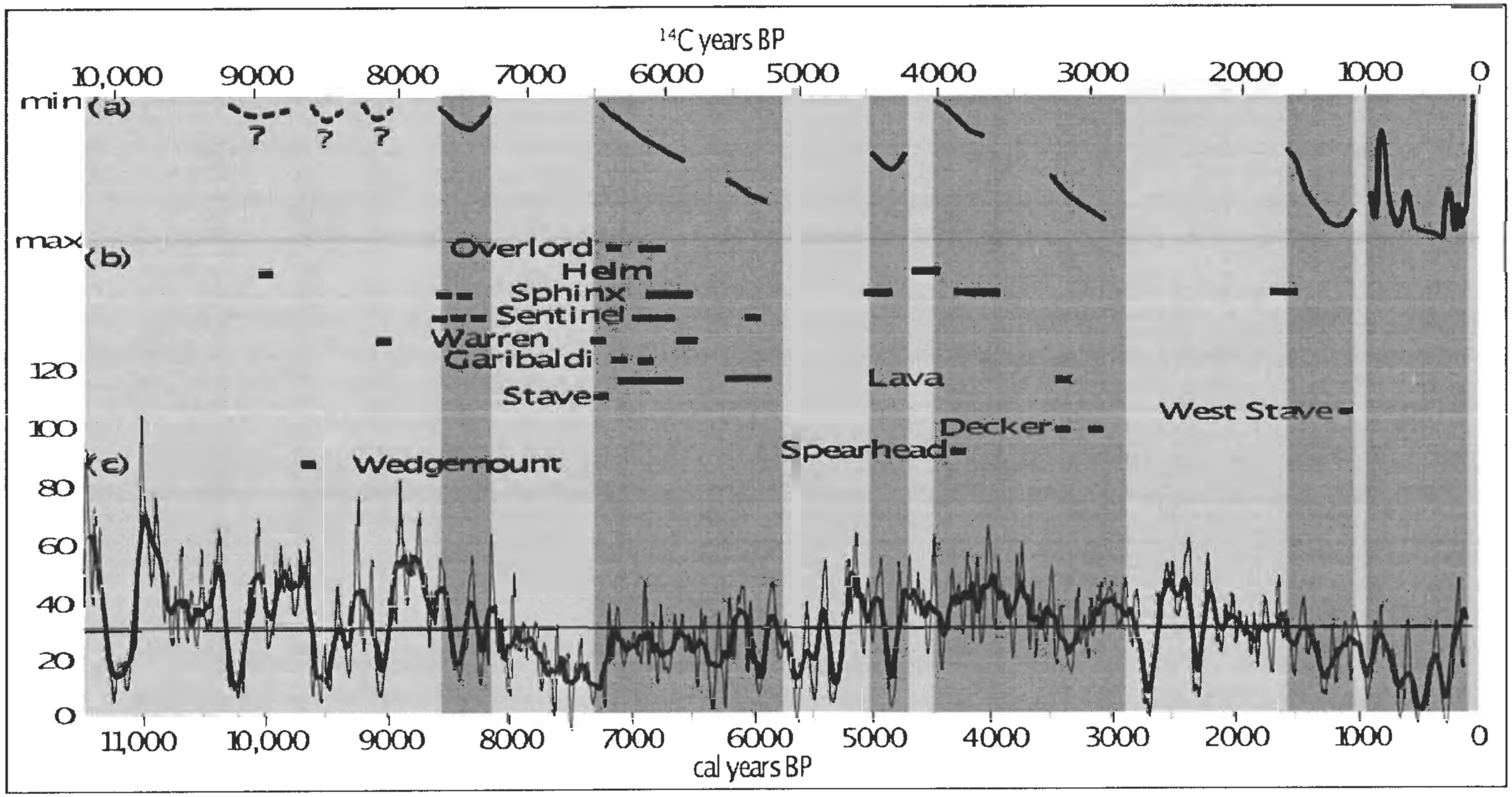

Figure 6.8 Relation between Holocene glacier activity in Garibaldi Park and sunspot numbers. (a) Generalized reconstruction of relative glacier extent in Garibaldi Park. (b) Lifespans of trees killed by glacier advance. (c) Reconstructed decadal (fine line) and smoothed (bold line) sunspot numbers (Solanki *et al.*, 2004). Vertical dark grey bars indicate periods of glacier advance in Garibaldi Park.

Tables

Table 6.1 Pre-Little Ice Age radiocarbon ages in Garibaldi Park.

Glacier	Site	Laboratory no.	^{14}C age (years BP)	Cal years BP	Comment
Wedgemount		Beta-170671	8650±60	9540-9630	branch; 90 m from snout
Spearhead		Beta-157268[1]	3900±80	4230-4430	branch; near snout
		Beta-168423[1]	3900±60	4280-4420	branch; near snout
Decker		Beta-157265[1]	3200±70	3350-3480	*in situ* stump on cliff
		Beta-157262[1]	2960±50	3060-3220	log near stumps
		Beta-157263[1]	2960±40	3070-3210	*in situ* snag on cliff
		Beta-157264[1]	2920±50	2990-3160	*in situ* stump on cliff
Overlord	ovgl-b	Beta-170665[1]	6170±70	6980-7160	log; on surface 50 m from snout
	ovgl-a	Beta-170660[1]	5980±70	6730-6910	log; in till 140 m from snout
	ovgl-a	Beta-170667[1]	5890±70	6630-6800	log; on surface 100 m from snout
Helm	hegl-r	Beta-168430	8900±60	9920-10,090	partially buried log 140 m from 1997 snout
	hegl-d	Beta-186523	4080±40	4520-4620	stump; melted out of ice in 2003
Sphinx	spgl-e	GSC-6770[2]	7720±80	8420-8560	branch; 100 m from snout
		GSC-1993[3]	7640±80	8380-8480	log; on surface; location uncertain
	spgl-a	Beta-186509	5830±60	6560-6700	snag; in till 300 m from snout
	spgl-b	Beta-208685	4280±70	4810-4960	log; in till 500 m from snout
	spgl-c	Beta-186510	3560±70	3820-3930	snag; in till 800 m from snout
	spgl-d	Beta-186511	1570±40	1450-1520	snag; on surface below bedrock knoll 600 m from snout

Glacier	Site	Laboratory no.	^{14}C age (years BP)	Cal years BP	Comment
Sentinel	segl-c	Beta-148787[2]	7720±70	8430-8550	branch; on surface near snout
	segl-c	Beta-157267[2]	7470±80	8280-8360	branch; on surface near snout
	segl-c	Beta-148786[2]	7380±80	8160-8320	branch; on surface near snout
		GSC-1477[4]	6170±150	6890-7250	branch; in till 2 km inside Little Ice Age limit
	segl-b	Beta-186508	6040±60	6790-6950	snag in till 300 m from present snout
		GSC-2027[3]	5300±70	5990-6130	*in situ* stump 1 km inside Little Ice Age limit
Warren	wagl-e	Beta-168425	8050±60	8950-9030	stick 250 m from 2000 snout
	wagl-d	Beta-148789	6370±70	7250-7330	*in situ* stump 95 m from 2000 snout
	wagl-d	Beta-148790	6360±80	7250-7340	*in situ* stump 100 m from 2000 snout
	wagl-c	Beta-148788	5780±70	6500-6660	*in situ* stump 600 m from 2000 snout
	wagl-b	Beta-168424	5700±50	6410-6540	partially buried large log
Lava	lagl-j	Beta-168426	6170±60	7000-7160	*in situ* stump, Garibaldi Neve
	lagl-j	Beta-168427	6050±50	6840-6970	*in situ* stump, Garibaldi Neve
	lagl-Y	Y-140 bis[5]	5850±180	6450-6860	*in situ* stump, Garibaldi Neve
	lagl-Y	Y-140 bis[6]	5260±200	5890-6280	*in situ* stump, re-date of Y-140 bis
	lagl-i	Beta-186521	5760±60	6490-6640	*in situ* stump 400 m from snout
	lagl-h	Beta-186520	5130±40	5890-5930	stump on surface
	lagl-e	Beta-186517	3190±40	3380-3450	log in woody layer in lateral moraine
West Stave	wsgl-a	Beta-170668	1080±60	930-1010	small log in lateral moraine
Stave	stgl-f	Beta-171096	6250±70	7150-7260	detrital stump in till

Note: Dated samples are outer-perimeter wood comprising less than 25 rings.
[1] Osborn *et al.* (in prep).
[2] Menounos *et al.* (2004).
[3] Lowdon and Blake (1975).
[4] Lowdon and Blake (1973).
[5] Preston *et al.* (1955).
[6] Stuiver *et al.* (1960).

Table 6.2 Floating tree-ring chronologies from glacier forefields in Garibaldi Park.

Glacier	Chronology	Length (years)	Correlation	No. radii/trees
Overlord	site ovgl-a	138	0.562	13/4
Helm	sites hegl-c and -d	135	0.612	22/13
Sphinx	site spgl-a	184	0.494	6/3
	site spgl-b	115	0.698	4/2
	site spgl-c	197	0.427	5/3
Sentinel	sites segl-a and -b	149	0.574	8/4
Lava	sites lagl-c, -d, and -i	482	0.437	15/8
	site lagl-h	263	0.477	7/3

CHAPTER 7 SYNTHESIS

Holocene Glacier Fluctuations

This thesis summarizes Holocene glacier fluctuations in Garibaldi Provincial Park in the southern Coast Mountains of British Columbia. The detail of the reconstruction differs over time due to inherent limitations of the research methods and the availability of evidence, but the record is presently unequaled in western North America.

Glacier fluctuations over the last century have been documented with sub-decadal resolution (Chapter 4). Glaciers in Garibaldi Park fluctuated more or less synchronously throughout the 20^{th} century, with recession dominating overall. They retreated slowly during the first two decades of the 20^{th} century, interrupted by short periods of moraine construction. Glaciers retreated rapidly between the 1930s and 1960s, at average annual rates of ca. 30 m, and since the 1980s at average annual rates of 5-10 m. In the 1960s and 1970s, glaciers were stable or advanced as much as 300 m.

The areal extent of ice in Garibaldi Park has decreased by about 240 km^2 (38%) since the Little Ice Age maximum in the late 17^{th} or early 18^{th} century. However, most of this loss was in the 20^{th} century. Glaciers continue to recede rapidly, and some will vanish by the end of this century if the present trend continues.

Glacier behaviour during the last millennium has been reconstructed with decadal to multi-decadal resolution (Chapter 5). The record is nearly continuous if the histories of individual glaciers are combined. The rapid and extensive glacier recession of the 20^{th} century has exposed evidence of glacier fluctuations of the last millennium and earlier. Evidence at Helm Glacier affords the most detailed reconstruction of any glacier in western Canada, and the inferred record of its advances is supported by evidence from other glaciers in the park. The studied glaciers appear to have fluctuated synchronously.

The Little Ice Age started as early as AD 1000, with an early maximum sometime in the 12^{th} century. Recession followed until the 14^{th} century, when glaciers advanced over forests at several glaciers in the park. This advance likely culminated with the construction of the outermost moraines in Garibaldi Park. The moraines stabilized and presumably were abandoned between the AD 1690 and 1720. Moraines were constructed during subsequent, lesser advances during the 19^{th} and early 20^{th} centuries.

Pre-Little Ice Age Holocene glacier fluctuations in Garibaldi Park have been reconstructed on multi-decadal to centennial timescales (Chapter 6), but the record is not as continuous as it is for the Little Ice Age. Five major periods of glacier advance date to 7700-7300, 6400-5100, 4300, 4100-2900, and 1600-1100 ^{14}C years BP. The Sphinx Glacier forefield contains evidence for all five periods and has the most complete record of Holocene glaciation in western North America. The evidence suggests that Holocene climate was more variable than previously thought. On at least three occasions prior to the Little Ice Age, glaciers in the park approached their maximum Holocene extents.

Climate Forcing

The times of glacier advances in Garibaldi Park during the last 10,000 years are similar to those inferred elsewhere in the Northern and Southern hemispheres, suggesting common global forcing (Chapters 5 and 6). Global temperature change can explain most of the glacier fluctuations in the park in the 20^{th} century (Chapter 4) and during the last millennium (Chapter 5). Changes in solar activity have been implicated by several researchers as a likely forcing mechanism. The record from Garibaldi Park was compared with a recent reconstruction of decadal sunspot activity. Correspondence was found for both the Holocene (Chapter 6) and the Little Ice Age (Chapter 5), suggesting that changes in solar activity may play an important role in global climate change.

Limitations of Methods

Dendrochronology was used to establish the late-Little Ice Age chronology of glaciers in Garibaldi Park (Chapter 5). During my first field season, I realized the limitations of dendrochronology and therefore undertook a detailed study to examine potential errors in the use of tree rings to date landforms (Chapter 3). The limitations have been discussed before, but my research showed that further improvements in dendrochronological methods are both possible and necessary if events are to be correlated on regional, hemispheric, and global scales. Otherwise, such efforts may be compromised by apparent age differences that are the result of the inherent inaccuracies in the method. In spite of the uncertainties, dendrochronology is a superior method for dating landforms than lichenometry and other methods, with the exception of historic photographs.

Lichen were measured in four glacier forefields in Garibaldi Park, but no local lichen growth curve could be constructed because independent age control could not be established. However, a lichen growth curve for subalpine environments on Vancouver Island was successfully applied in Garibaldi Park (Chapter 5).

Future Research

A conclusion of Chapter 2 is that a combination of climate proxies yields more information and a more confident reconstruction of glacier fluctuations than one proxy alone. The terrestrial data that I obtained from glacier forefields in Garibaldi Park were combined with high-resolution records derived from lake sediments in the southern Coast Mountains (Menounos, 2002) to argue that the 8.2 ka cooling event had an impact on southwestern British Columbia (Menounos *et al.*, 2004). Other proxy data sets would strengthen and refine the record presented in this thesis. For example, treeline and alpine meadows are sensitive to climate change (Rochefort *et al.*, 1994; Woodward *et al.*, 1995; Rochefort and Peterson, 1996; Luckman and Kavanagh, 1998, 2000; Laroque *et al.*, 2000/2001), and their study in the park would complement the work that I and others (Menounos, 2002; Schiefer, 2004) have done.

The abundance of wood in glacier forefields in Garibaldi Park could provide an opportunity for researchers to build ring series with sufficient sample depth to reconstruct climate for much of the middle and late Holocene. For example, the gap between the ring series from site h and sites c, d, and i at Lava Glacier (Chapter 6) might be bridged, and enabling the construction of an annually resolved chronology over 900 years during the Garibaldi Advance. Similarly, the gap between the living chronology at Helm Glacier and the floating ring series from sites a, g/h, m/n/o, j, e/l, and f might be bridged, permitting construction of a chronology extending back to the 13^{th} century and enabling reconstruction of climate during the last 700 years.

Research such as that presented here has been carried out in many alpine areas around the world. Many other areas, however, remain to be studied. Fossils that become exposed as glaciers retreat are rapidly lost due to biological decay and weathering. As Porter (1981b) suggested, glacier forefields in unstudied and poorly studied areas should be studied and sampled before critical evidence for Holocene glacier fluctuations is lost.

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APPENDICES

Appendix A

Airphotos used in reconstruction of 20th century glacier behaviour in Garibaldi Provincial Park.

Glacier	Year	Flight number	Photo numbers
Overlord	1949	BC911	9
	1980	15BC80136	87
	1996	15BCB96099	113
Black Tusk	1949	BC866	52
	1969	BC5341	217
	1990	30BCB90049	154, 155
	1994	30BCC94116	79, 80, 139, 140
	1996	15BCB96099	96
Helm	1949	BC866	22
	1969	BC5341	173
	1977	A24757	18
	1990	30BCB90049	152
	1996	15BCB96099	97
Sphinx	1949	BC866	25
	1949	BC912	41
	1964	BC5106	242
	1969	BC5341	171
	1977	A24757	18
	1993	30BCB93040	146, 147, 246
	1996	15BCB96099	85
Sentinel	1949	BC866	26
	1964	BC5106	242
	1969	BC5341	171
	1977	A24757	18
	1993	30BCB93040	247
	1996	15BCB96099	67
Warren	1949	BC866	47
	1957	BC2348	58, 59
	1964	BC5106	81
	1969	BC5341	221
	1973	BC7521	174
	1977	A24757	19
	1982	30BC82057	107
	1993	30BCB93027	47
	1994	30BCC94121	47-49
	1996	15BCB96099	66
Garibaldi	1949	BC866	30
	1969	BC5341	168
	1977	A24757	53
	1982	30BC82057	37
	1993	30BCB93027	48, 49, 87
	1994	30BCC94121	138-140
	1996	15BCB96099	55

Glacier	Year	flight number	photo numbers
Lava	1949	BC866	30
	1969	BC5341	168
	1977	A24757	53
	1982	30BC82057	37
	1993	30BCB93027	48, 49, 87
	1994	30BCC94121	138-140
	1996	15BCB96099	55
Snowcap Lakes	1931	A4154	54-56
	1952	BC1618	88
	1969	BC5341	192
	1977	A24757	58
	1993	30BCB93027	16-20
	1996	15BCB96099	74
Stave	1952	BC1619	99
	1969	BC5340	104
	1977	A24757	79
	1993	30BCB93027	150, 151

Appendix B

TRIM and glacial mapping.

This appendix describes how present-day and Little Ice Age maximum glacier extents were mapped to estimate areal ice loss in Garibaldi Park. Dr. Brian Menounos obtained electronic topographic and land use (TRIM) data for Garibaldi Provincial Park from the B.C. Ministry of Environment. Positional accuracy associated with the TRIM topographic data is 10 m. Dr. Menounos determined contemporary glacier cover from the TRIM data (ice and snowfields layer) for his Ph.D. research (Menounos, 2002). The TRIM ice extent was checked by comparing it with snow and ice cover on 1996 aerial photographs and was found to be in error for many glaciers, especially smaller ones. The discrepancies probably result because the photographs used to produce the TRIM maps were taken early in the summer when seasonal snow obscured ice extent. In addition, glaciers have retreated during the interval between 1986, when the TRIM photos were taken, and 1996. I corrected glacier margins to reflect ice cover on the more recent (1996) photographs. Most of the ice cover in the TRIM dataset consists of polygons comprising many individual glaciers. Menounos (2002) delimited individual glaciers on the TRIM overlay. I checked margins of the glaciers in the field during this study, and some were modified based on these observations.

The maximum extent of ice during the Little Ice Age was mapped on the TRIM ice and snowfields layer. Some moraines are large enough to be visible in the TRIM data. In most cases, however, the Little Ice Age limit was mapped by transferring interpreted boundaries from uncorrected colour and black and white photographs to the TRIM layer through screen digitization. Errors were estimated by repeat measurements for two glaciers (Helm and Griffin) and by comparing glaciers for which maximum Little Ice Age extent is clearly demarcated in the TRIM data. Average errors are 5-15 percent.

Appendix C

Tree ring and lichen age estimates of moraines in Garibaldi Provincial Park.

Glacier	Moraine	Tree age (years)	Age-height correction (years)	Ecesis (years)	Year (AD) tree rings	Year (AD) lichen
Overlord	A	nd	nd	nd	nd	nd
	B	294	n/a	6	1700s	nd
	C	146	n/a	22	1830s	1830s
	D	84	n/a	25	1890s	1890s
	E	52	n/a	31	1920s	1920s
Helm	A	241	n/a	51	1710s	nd
	B	129	4	46	1820s	nd
	C	83	n/a	49	1870s	nd
	D	43	n/a	49	1910s	nd
Sphinx	A	284	n/a	24	1690s	1790s
	B	171	n/a	26	1800s	1820s
	C	115	n/a	24	1860s	1870s
	D	68	n/a	28	1900s	1890s
	E	56	3	26	1910s	1920s
Sentinel	A	259	2	28	1710s	1720s
	B	134	9	22	1830s	1840s
	C	96	n/a	28	1870s	1870s
	D	77	n/a	25	1900s	1900s
	E	64	n/a	25	1910s	1920s
Warren	A	268	14	11	1700s	nd
	B	94	n/a	24	1880s	nd
	C	72	9	16	1900s	nd

Glacier	Moraine	Tree age (years)	Age-height correction (years)	Ecesis value (years)	Year (AD) tree rings	Year (AD) lichen
Garibaldi	A	246	n/a	35	1720s	nd
	B	139	n/a	40	1820s	nd
	C	111	n/a	37	1850s	nd
	D	96	n/a	35	1870s	nd
	E	73	n/a	35	1890s	nd
	F	49	5	35	1910s	nd
Lava	A	255	n/a	37	1710s	nd
	B	164	n/a	35	1800s	nd
	C	141	3	35	1820s	nd
	D	113	5	35	1850s	nd
	E	82	n/a	40	1880s	nd
	F	51	n/a	40	1910s	nd
Snowcap Lakes	A	227	n/a	49	1720s	1710s
	B	115	n/a	56	1830s	1820s
	C	nd	nd	nd	nd	1850s
	D	nd	nd	nd	nd	1870s
	E	nd	nd	nd	nd	1890s
	F	nd	nd	nd	nd	1900s
	G	nd	nd	nd	nd	1910s
Stave	A	265	n/a	13	1720s	nd
	B	141	n/a	16	1840s	nd
	C	102	n/a	7	1890s	nd
	D	82	8	7	1900s	nd

Notes: nd, no data.
n/a, not applicable