# Late Holocene glacial history of Scimitar Glacier,
# Mt. Waddington area,
# British Columbia Coast Mountains, Canada

by

**Jessica Aileen Craig**
B.Sc., University of Victoria, 2010

A Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of

MASTER OF SCIENCE

in the Department of Geography

# Supervisory Committee

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## Abstract

Scimitar Glacier originates below the northeast face of Mt. Waddington in the southern British Columbia Coast Mountains and flows 18 km down valley to calve into a proglacial lake. The purpose of this research was to describe the late Holocene glacier history of Scimitar Glacier using stratigraphic analysis in conjunction with dendroglaciologic and radiocarbon dating techniques.

Downwasting of the glacier surface has exposed stacked till units separated by wood-bearing horizons in the proximal slopes of lateral moraines flanking the glacier at several locations. Historical moraine collapse and erosional breaching has also revealed the remains of standing trees buried in sediments from a lake originally ponded against the distal moraine slope. Radiocarbon dating of detrital wood remains revealed that Scimitar Glacier expanded down-valley at least three times in the late Holocene. The earliest period of expansion occurred 3167-2737 cal yr BP in association with the regional Tiedemann Advance. Following this the glacier receded and downwasted prior to advancing to reconstruct the lateral moraine in 1568-1412 cal yr BP during the First Millennial Advance. The most recent phase of moraine construction was initiated during late Little Ice Age glacial expansion before 1742 AD and extended until at least 1851 AD, after which Scimitar Glacier began to recede and downwaste.

Field investigations at Scimitar Glacier allowed for the construction of a late Holocene history of glacier expansion and lateral moraine construction that spans the last 3000 years. This record is comparable to that recorded at other glaciers in this region, and confirms the long-term relationship between regional climate trends and glacier behaviour in this setting.

# Table of Contents

## List of Tables

# List of Figures

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Last, but not least, a heartfelt thank you to my family. You may not have always had a good idea of what I was doing or where this was leading me, but you were always behind me every step of the way through my triumphs and tribulations. You let me seek out adventure and challenge my limits. To you I dedicate this thesis, thank you.

# Chapter 1 – Introduction

## 1.1 Introduction

Scimitar Glacier is a large sinuous valley glacier that originates on the northeast slopes Mt. Waddington. Fed by multiple tributary glaciers, Scimitar Glacier extends ca. 18 km before terminating in a proglacial lake close to terminal moraines demarking its maximum Holocene extent. Don and Phyllis Munday (Munday, 1933, 1934-1935) were among the first to describe the glacier and their historical photographs provide a visual impression of what Scimitar Glacier looked like during its maximum Holocene extent (Figure 1.1).

Figure 1.1: View looking down Scimitar Glacier from Fury Gap. Photo by Phyllis Munday (Munday, 1928).

Despite a long history as a popular access route for skiers and mountaineers in the Mt. Waddington area (Watson and King 1935; Serl 2003), there have been no previous attempts to describe the long-term behavior of Scimitar Glacier. Over the last century most glaciers in the Mt. Waddington area have retreated and significantly downwasted from terminal and lateral moraines constructed following Little Ice Age (LIA) expansion (Larocque and Smith, 2003). The attendant melting of glacier ice and subsequent erosion of glacial landforms have exposed buried deposits useful for describing prior glacial activity (Ryder and Thomson, 1986; Larocque and Smith, 2003; Menounos et al., 2008; Coulthard et al., 2013). While these investigations have enhanced our understanding of Holocene glacier activity in this area, a focused investigation was necessary to establish in detail the behaviour of Scimitar Glacier.

### 1.2 Research Purpose and Objectives

This purpose of this research was to describe the late Holocene glacier history of Scimitar Glacier using stratigraphic analysis in conjunction with dendroglaciologic techniques and radiocarbon dating. The findings of this study were compared to those of previous researchers to enhance understanding of late Holocene glacier activity in the central and southern British Columbia (BC) Coast Mountains.

The research had three specific objectives:

1. To conduct field investigations to locate geomorphic and stratigraphic evidence illustrating the Holocene behaviour of Scimitar Glacier.
2. To complete dendroglaciologic and radiocarbon dating of wood remains to describe fluctuations of Scimitar Glacier during the Holocene.
3. To compare the findings of this research to prior research, with a focus on linking the long-term activity of Scimitar Glacier to Holocene ice expansion trends.

### 1.3 Thesis Format

This thesis consists of seven chapters. Chapter 1 introduces the subject matter and outlines the goals and objectives of the thesis. Chapter 2 describes the physical and geographical setting of the Waddington Range and current knowledge of Holocene glacier activity in the Mt. Waddington area. Chapter 3 describes the physical and geographical setting of Scimitar Glacier. Chapter 4 describes the research methods used in this study. Chapter 5 details the observations made at each of the three study sites and describes spatial and temporal ice margin fluctuations of the glacier over the last century. Chapter 6 provides an overview, summarises the research findings, and compares the findings to previous research in the region. Chapter 7 provides a brief summary of the findings and recommendations for further research.

# Chapter 2 – Study Area

## 2.1 Introduction

Scimitar Glacier originates from an icefall on the northeast face of Mt. Waddington (4019 m asl) in the British Columbia (BC) Coast Mountains (Figure 2.1). This heavily glaciated area is characterized by prominent peaks and large valley glaciers that extend to positions below the local treeline. While most glaciers in the Mt. Waddington area reached their maximum Holocene extent during the 'Little Ice Age' (LIA) (Larocque and Smith, 2003), there is evidence at a limited number of sites suggesting that earlier Holocene advances were of equal or slightly greater extent (Ryder and Thomson 1986; Coulthard et al., 2013).

## 2.2 The Waddington Range

Scimitar Glacier is located in the Waddington Range of the Pacific Ranges of the southern BC Coast Mountains. The bedrock of the region is dominated by large batholithic intrusions of granodiorite of the Coast Plutonic Complex and gneiss and migmatites of the Central Gneiss Complex (Lappin and Hollister. 1980). This high mountain landscape is characterized by steep snowy jagged peaks, deep fjords, and U-shaped valleys shaped by glaciers during the Wisconsinan Glaciation which ended ca. 11,000 years ago (Calgue et al.,1990).

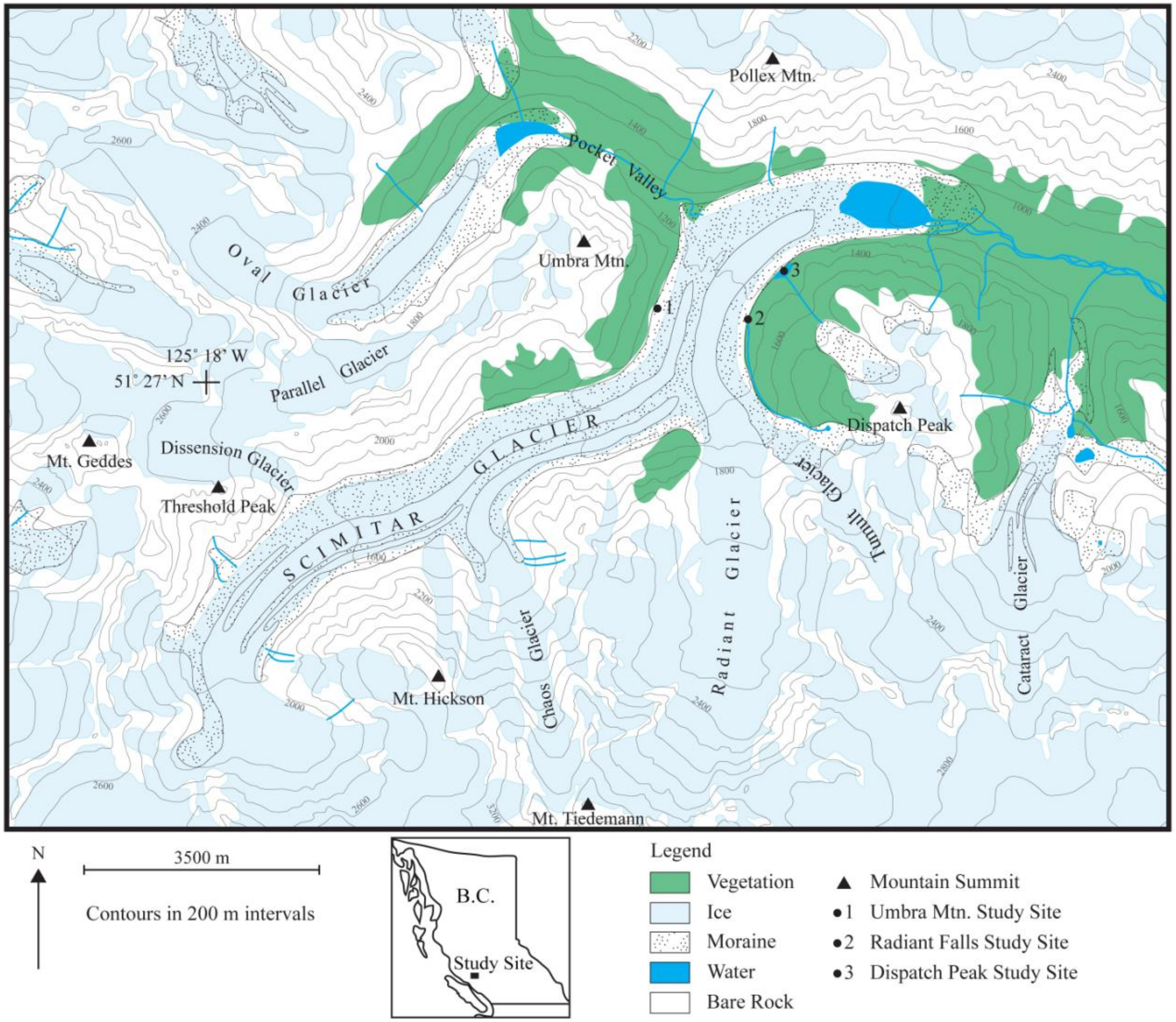



Figure 2.1: Map of the Scimitar Glacier study area showing study sites.

The Coast Mountains force moist air originating in the Pacific Ocean to rise abruptly on windward slopes, resulting in orographic precipitation and hyper-maritime environments at lower elevations. At higher elevations deep snowpacks accumulate in the winter months, nourishing large temperate icefields. Runoff flows to the Klinaklini and Homathko rivers, which empty into Knight and Bute inlets respectively. Rain-shadow effects along the eastern slopes of the Coast Mountains result in markedly drier conditions and a climate controlled in part by continental air masses.

The windward slopes of the Waddington Range are covered by western hemlock (*Tsuga heterophylla*) and red cedar (*Thuja plicata*) forests at low elevation and montane mountain hemlock (*Tsuga mertensiana*) forests at higher elevations (Klinka et al., 1991). On the leeward slopes of the Coast Mountains, Engelmann spruce (*Picea engelmannii*) and subalpine fir (*Abies lasiocarpa*) forests dominate high elevation sites (Klinka et al., 1991; Meidinger et al., 1998).

Holocene paleoclimates in the Mt. Waddington area have likely varied in response to solar insolation fluctuations influenced by short-term solar variability and  long-term Milankovitch cycles, and changing albedo due to shifts in ice cover (Walker and Pellatt, 2003; Arsenualt et al., 2007). In the early Holocene (ca. 11,000 to 8000 cal yr BP), climates were warmer and drier in the summer than present, possibly due to a persistent strong Pacific high pressure system (Walker and Pellatt, 2003). A shift to cooler and wetter conditions occurred in the mid-Holocene (ca. 8000 to 3000 cal yr BP), likely resulted from the strengthening of an Aleutian low pressure system during fall, winter, and spring (Walker and Pellatt, 2003).

Vegetation shifts interpreted from palynological studies in the Mt. Waddington area suggest that between ca. 3300-1900 cal yr BP cooler, moister conditions occurred in concert with glacier expansion (Arsenualt et al., 2007). The same study concluded that from 1700 to 1400 cal yr BP warmer, drier conditions prevailed, whereas by ca. 1100 cal yr BP cooler and wetter conditions were initiated that persisted until 500 cal yr BP (Arsenualt et al., 2007).

## 2.3 Previous Research

Documentation of glacier activity in the Mt. Waddington area began with the pioneering observations of Munday (1931, 1934-1935, 1939). Targeted investigations over the last three decades at Franklin, Confederation, Jambeau, Tiedemann and Oval glaciers provide a perspective on Holocene behaviour of glaciers in the Mt. Waddington area (Coulthard et al., 2013).

Franklin Glacier is located on the western slopes of the Waddington Range and flows ca. 12 km southwestward from Mt. Waddington toward Knight Inlet to a terminus position at 610 m asl in 2008 (Figure 2.2). Ryder and Thomson (1986) located the remains of a tree root between two till units in a lateral moraine flanking Franklin Glacier and used this evidence to suggest the glacier was expanding down valley ca. 801-675 cal yr BP (ca. 1149-1275 AD). Recent dendroglaciological investigations by Coulthard et al. (2013) near the confluence of Confederation and Franklin glaciers confirmed this early LIA period of expansion and suggested the glacier continued to thicken until ca. 1330-1410 AD.

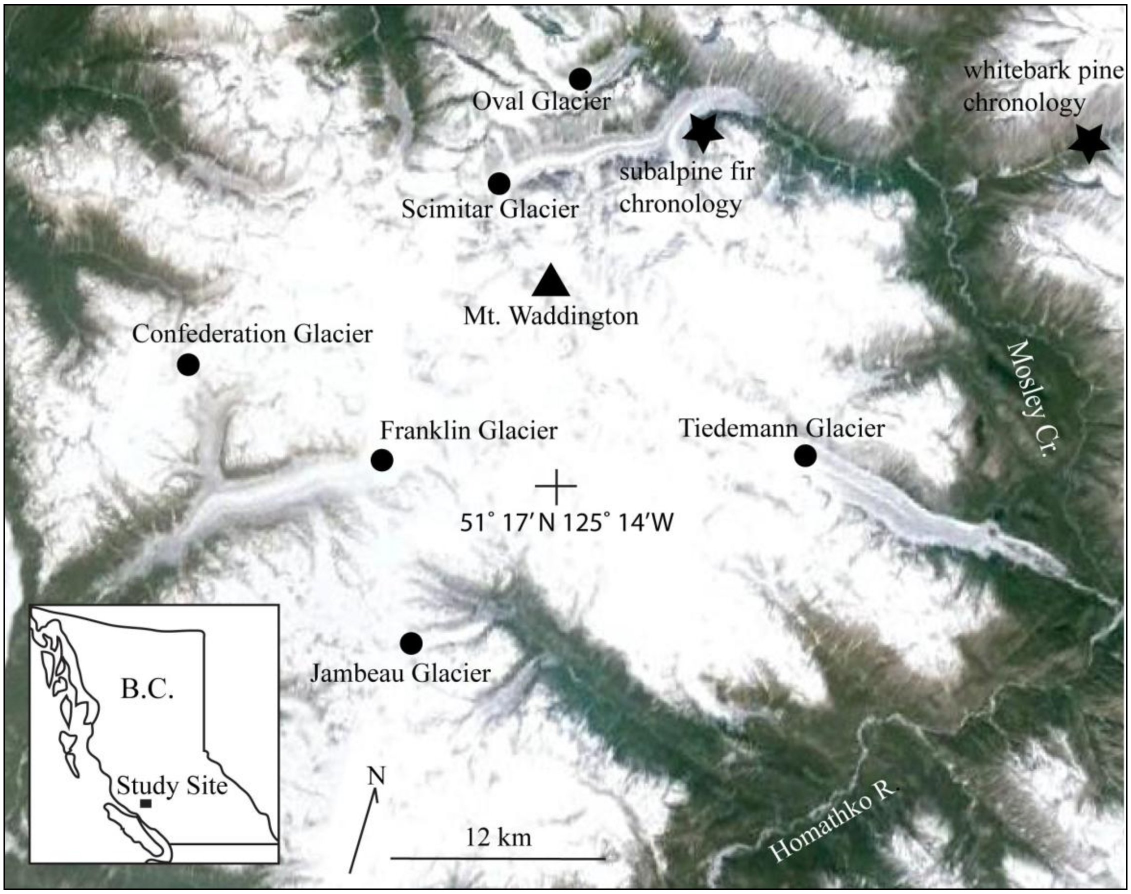



Figure 2.2: Google Earth image of the Mt. Waddington Range area showing the locations of Confederation, Franklin, Tiedemann, Oval and Jambeau glaciers. Locations of living tree-ring width chronologies used in this study are also indicated.

Confederation Glacier flows southwest from Bezel Peak down Confederation valley towards Franklin Glacier. When first photographed in the mid-1920s, Confederation Glacier was close to its LIA maximum and was confluent with the Franklin Glacier (Munday 1948). By 2008, the glacier terminus was located at 1400 m asl, ca. 4 km up-valley from Franklin Glacier (Figure 2.2). Investigations by Coulthard et al. (2013) revealed that Confederation Glacier was expanding down valley by ca. 5700 cal yr BP, with subsequent ice front advances recorded at ca. 3700 and 3500 cal yr BP.

Jambeau Glacier is located ca. 15 km south of Mt. Waddington and flows ca. 6 km down valley from the Whitemantle Range to Scar Creek (Figure 2.2). When first photographed in 1926, Jambeau Glacier extended across Scar Creek and blocked meltwater flowing from Avalanche Glacier (Munday, 1934-35). Field investigations by Coulthard et al. (2013) revealed that Jambeau Glacier was advancing down valley ca. 3000 cal yr BP and 1740 AD.

Tiedemann Glacier flows 24 km eastward from the southeast face of Mt. Waddington to a terminus position at ca. 620 m asl in 2005 (Figure 2.2). Investigations at Tiedemann Glacier were initiated by Fulton (1971) who showed that the glacier expanded to its maximum Holocene extent ca. 3100 cal yr BP. Subsequent investigations by Ryder and Thomson (1986), Arsenault et al. (2007) and Menounos et al. (2008) led to the discovery of buried organics that provide evidence for advances of Tiedemann Glacier about 5700, 4200, 3600, 3100, 2400 cal yr BP, 1200 (ca. 850 AD), 390 (ca. 1560 AD) cal yr BP and about1870 AD. Lichenometric dating of lateral and terminal moraines constructed by the Tiedemann Glacier (Larocque and Smith, 2003) indicate construction of LIA moraines in ca. 620, 925, 1118, 1392, 1575 and 1621 AD.

Oval Glacier is located ca. 10 km north of Mt. Waddington and flows ca. 6 km down Pocket Valley to terminate in a proglacial lake at 1290 m asl (Figure 2.2). Lichenometric investigations of nested moraines at Oval Glacier indicate periods of moraine stabilization and abandonment in 1031, 1443, 1601-1762 and 1830-1894 AD (Larocque and Smith, 2003).

## 2.4 Summary

Previous field investigations show that glaciers in the Mt. Waddington area expanded and retreated at least eight times during the Holocene. The earliest glacier advances recorded at Confederation and Tiedemann glaciers appear associated with the 'Garibaldi Phase' of ice expansion between 6400 and 5800 cal yr BP (Ryder and Thomson, 1986; Coulthard et al., 2013). Following this period of expansion, most glaciers appear to have receded and downwasted before readvancing to bury forests such as along the margin of the Tiedemann and Confederation glaciers ca. 3800-3500 cal yr BP (Menounos et al., 2008; Coulthard et al., 2013), at Tiedemann and Jambeau glaciers ca. 3300-2900 cal yr BP (Ryder and Thomson, 1986; Coulthard et al., 2013) and at Tiedemann Glacier ca. 2400-2200 cal yr BP (Ryder and Thomson, 1986; Arsenault et al., 2007). Clague et al. (2009) refer to this sequence of expansion episodes as associated with early, middle, and late phases of the Tiedemann Advance.

Only scattered evidence has been found in the Mt. Waddington area for the First Millennium Advance (FMA) of Reyes et al. (2006). At Tiedemann Glacier Fulton (1971) describes basal peat from a moraine bog dating to between 620 and 925 AD that may record the FMA. Additional, equivocal FMA evidence includes a transported subfossil wood sample located by Ryder and Thomson (1986) in a lateral moraine at Tiedemann Glacier and a cluster of apparently very old lichens found growing on a moraine surface in the same area (Larocque and Smith, 2003).

Little Ice Age glaciation in the Mt. Waddington area is distinguished by distinct advances ca. 1100-1300, 1600-1700, and 1850-1900 AD (Ryder and Thomson, 1986; Larocque and Smith, 2003; Coulthard et al., 2013).

The last significant advance of glaciers in this area appears to have ended by the mid-19th to early 20th century (Munday 1930, 1931; Larocque and Smith, 2003). At Oval and Tiedemann glaciers, largely unvegetated terminal and lateral moraines demarcate the maximum extent of late LIA expansion at 1850-1900 AD (Larocque and Smith, 2003).

During the historical period (1900-present) most glaciers in the Mt. Waddington area retreated and downwasted significantly, interrupted by brief pauses in recession or short-lived re-advances (VanLooy and Forster, 2008). Munday (1939) discusses evidence of a re-advance in the 1920s in the area. Historical photographs show many glaciers remained close to their LIA maximum extent until early in the 20th century (VanLooy, and Forster, 2008; Larocque and Smith, 2003).

Previous research on glaciers in the Mt. Waddington area demonstrates that their activity during the Holocene was similar to that of glaciers elsewhere in the Coast Mountains and southern Canadian Cordillera (Osborn and Luckman, 1988; Menounos et al., 2009). A challenge for recognizing distinct glacial advances in this setting is the lack of chronological evidence of distinct expansion events (Koch, 2009).

# Chapter 3 – Scimitar Glacier

Scimitar Glacier originates in the Waddington-Combatant Col at ca. 3000 m asl below the northeast face of Mt. Waddington (Figure 2.1). The glacier spills over an icefall and follows a sinuous pathway down Scimitar Valley. Over the first 5 km, the glacier flows to the northwest, after which it turns abruptly to the northeast to parallel Umbra Ridge before flowing eastward to stagnate and calve in proglacial Scimitar Lake at ca. 984 m asl. Water flows from the lake into Scimitar Creek, which joins Mosley Creek. Mosley Creek flows into the Homathko River to discharge into Bute Inlet (Figure 2.2).

Several additional icefalls and tributary glaciers contribute to Scimitar Glacier. Chaos Glacier, the uppermost significant tributary glacier, originates below the north face of Mt. Tiedemann and flows ca. 4 km before joining Scimitar Glacier at 1530 m asl. Radiant Glacier joins Scimitar Glacier at 1310 m asl after flowing 7 km northeast from Mt. Tiedemann. Dissension Glacier flows from Threshold Peak and was confluent with Scimitar Glacier until sometime in the late 1930s (Hendricks, 1940). Cataract Glacier flows north from peaks adjacent to Mt. Shand and presently terminates in a tributary valley ca. 2 km down valley from the terminal moraine of Scimitar Glacier. Meltwater from Oval Glacier in south-facing Pocket Valley discharges into Scimitar Valley and flows beneath Scimitar Glacier ca. 2.3 km upvalley from the present-day glacier snout (Figure 2.1).

The terminus of Scimitar Glacier has receded ca. 1.5 km upvalley from a bouldery crescent-shaped terminal moraine located immediately down valley from proglacial Scimitar Lake. The moraine rises ca. 40 m above the valley floor but has been extensively modified by debris avalanched from the surrounding mountain walls and is obscured by thick alder (*Alnus ruba*) and willow *(Salix* spp.).

The upper reaches of Scimitar, Chaos, Cataract, and Radiant glaciers entrain sediments originating from the Tiedemann Pluton. This intrusive Tertiary-age igneous body consists of medium- to coarse-grained granodiorite (Roddick and Tipper, 1985). The pluton extends north to Mt. Tiedemann and is surrounded by the Central Gneiss Complex, which consists mainly of granitic gneiss (Roddick and Tipper, 1985).

The climate in the vicinity of Scimitar Glacier is strongly influenced by North Pacific maritime polar air masses (Kendrew and Kerr, 1955; Tuller, 2001) and is characterised by short cool summers and long cold winters. Deep snowpacks accumulate in winter at higher elevations and persist until July.

Vegetation in the study area is within the Engelmann Spruce-Subalpine Fir (ESSF) biogeoclimatic zone (Meidinger et al. 1998). The forested slopes surrounding Scimitar Glacier are dominated by subalpine fir (*Abies lasiocarpa*) trees, with scattered whitebark pine (*Pinus albicaulis*) and mountain hemlock (*Tsuga mertensiana*) trees present to the upper treeline at ca. 1700 m asl.

# Chapter 4 – Research Methods

## 4.1 Introduction

The Holocene behaviour of Scimitar Glacier was determined from an assessment of historical documents, photographs and imagery, and fieldwork completed in July 2011. The latter focused on locating and collecting the remains of trees found within and below stratigraphically constrained field sites. Dendrochronological, dendroglaciological and radiocarbon dating techniques were employed to determine the age of the wood samples, from which glacier expansion episodes were inferred.

Dendrochronology is founded on the principle that trees at temperate latitudes produce annual rings that differ in thickness as a function of climate (Speer, 2010). Dendroglaciology is the application of dendrochronologic techniques to dating glacial events or the formation of glacial landforms (Luckman, 1998; Smith and Lewis, 2007). When glacially damaged or killed trees cannot be cross-dated to living tree ring chronologies (Luckman, 1986; Smith and Lewis, 2007), radiocarbon dating of perimeter wood can be used to provide a relative kill date (Wood and Smith, 2004; Allen and Smith, 2007).

## 4.2 Aerial Photographic Interpretation Methods

Historical temporal and spatial fluctuations of the margin of Scimitar Glacier, the surrounding moraines, and a moraine dammed lake were determined using vertical aerial photographs from 1949, 1978, 1994, and 2005 (Table 3.1). To assess the extent of retreat, the images were layered and manipulated in Google Earth (Ver. 6.2) with trimlines, moraine crests and avalanche tracks serving as control points. Geometric distortions due to tilt, focal length and lens distortion were not considered. Using Google Earth, retreat was estimated as the horizontal distance from prominent benchmarks on moraine crests to the nearest ice margin (Figure 5.2).

**4.3 Field Methods**

Study sites were identified during reconnaissance investigations of the margins of Scimitar Glacier (Figure 2.1). A hand-held GPS was used to locate field sites (+/- 6 m). Field notes, sketches and photographs of each site were used to construct figures illustrating the site stratigraphy with Adobe Illustrator CS3 (Ver. 13.0.2) software.

Cross-sectional discs of representative subfossil wood samples were collected using a chainsaw and wrapped in duct tape to prevent fragmentation. Samples of mature trees in the surrounding forest were collected with a 5-mm-diameter increment borer to establish a master tree-ring chronology. Two cores were collected from each living tree at breast height (180° from each other) to reduce the possibility of sampling growth anomalies.

**4.4 Laboratory Preparation and Analysis**

All samples were transported to the University of Victoria Tree-Ring Laboratory for preparation and analysis using standard dendrochronological methods (Grissino-Mayer, 2001; Speer, 2010). Increment core samples were glued to slotted boards and the subfossil discs were glued along fractures to prevent further fragmentation. After sanding and polishing to a 600-grit finish, digital images were captured using a high-resolution scanner. The width of the annual rings along two or more pathways was subsequently measured to 0.001 mm using WinDendro (Ver. 2008d) software (Guay et al. 1992).

Tree-ring series from the living and subfossil samples were first internally cross-dated to prevent the inclusion of missing and/or false rings, growth anomalies or areas of poor ring preservation. A living tree-ring chronology was then constructed from the increment cores using the International Tree Ring Database software program COFECHA (Homes, 1999; Grissino-Mayer, 2001). Attempts were made to cross-date the subfossil wood samples to the living subalpine fir chronology developed as part of this study, as well as to previously established chronologies (Larocque and Smith, 2005). Where cross-dating failed, perimeter wood from selected subfossil samples was submitted to Beta Analytic Inc. (Miami, Florida, USA) for standard $^{14}C$ analysis. Attempts to cross-date to living tree-ring chronologies were not attempted for fragmented samples nor samples containing less than 50 annual rings. Samples selected for radiocarbon dating were chosen with preference given to samples collected from lower stratigraphic positions as these samples were likely to be too old to crossdate to a living tree ring chronology (based on the stratigraphic principle of superposition). The cost of radiocarbon analysis was also a limiting factor. The age assigned to each sample is a calibrated radiocarbon age calculated from the best-fit intercept of the radiocarbon age to the calibration curve using INCAL09 (Reimer et al. 2009).

# Chapter 5 – Observations

## 5.1 Prior Exploration and Aerial Photograph Interpretation

The area surrounding Scimitar Glacier was first explored in the early 1930s. Beginning in 1927, Don and Phyllis Munday began a series of annual mountaineering expeditions from the Pacific Coast to the Mt. Waddington area (Munday 1928, 1931, 1934-1935). They produced a series of hand-drawn maps showing and naming the majority of glaciers and mountains in this remote landscape. The final version of their map shows the locations and terminus positions of glaciers throughout the Mt. Waddington area (Munday, 1948).

In 1933 the Mundays joined an American Alpine Club expedition led by Henry Hall to Mt. Waddington by an inland route that led them up Scimitar Glacier (Hall, 1933). During the summer of 1931, Henry Hall made a reconnaissance trip to the area. His photograph of Scimitar Glacier taken during his reconnaissance trip showed the right lobe of the snout of Scimitar Glacier (the left lobe is hidden by the mountainside in the foreground) (Figure 5.1).

Figure 5.1: Historical photo taken by Henry Hall Jr. showing the terminus of Scimitar Glacier as of 1931 (Hall, 1932).

The Mundays' glaciological notes from 1933 include observations that Scimitar Glacier “seemed to have advanced recently” to form a small (~12 m high) push moraine about 90 m in front of the glacier snout (Munday, 1934-1935:67). At that time Scimitar Glacier “showed no evidence of extensive shrinkage" (Munday, 1934-1935:67), a fact supported by negligible ice recession from the lateral moraine constructed by Scimitar Glacier where it blocked Pocket Valley (Figure 5.2) to form a moraine-dammed lake. The lake has since in-filled with sediment and overgrown with vegetation. Munday (1934-1935:62) reports evidence of recent ice expansion in the form of ice "plowing debris over the crest, showing a distinct 'grading' of the fragments such as occurs in an artificial embankment of the same materials". Munday (1934-1935) also noted an older, forest-covered, lateral moraine approximately 30 m high built by Scimitar Glacier around the base of Umbra Mountain into Pocket Valley. Munday (1934-1935:65) notes that this moraine bears trees about 700 years old and “slopes down into the silt of the valley floor” showing that at some point in the past, Scimitar Glacier extended farther into Pocket Valley.

During a mountaineering expedition to the Waddington area in 1946, Becky (1949:280) noted that “Scimitar and Parallel Glaciers…seem to have held their own" without any notable recession from the terminal position Hall observed in 1932 (Figure 5.1). He also comments, however, that the surface of Scimitar Glacier appeared to be retreating and downwasting along its lateral margins.

Aerial photographs showing Scimitar Glacier in 1949 provide a benchmark to which morphological and terminus position changes over the following 63 years can be evaluated (Table 5.1). By 1949 the glacier had receded ca. 110 m from where it was observed by Munday in 1933 at the Pocket Valley lobe. A vertical aerial photograph taken in 1960 (R6026-F47) suggests only minimal lateral recession (ca. 40 m) between 1949 and 1960 (Figure 5.2, Table 5.1), but an oblique aerial photograph (69R5-168) from 1969 shows the snout of Scimitar Glacier had receded to the base of a moraine mound (Figure 5.3). It is believed that at its maximum extent, Scimitar Glacier expanded as two lobes of ice at its snout around a mound of previously deposited morainal material. The lobes of ice gave the mound a crescent shape which can be seen best in Figure 5.3. Aerial photographs from 1978 (BC7863-127) indicate that while the Pocket Valley lobe of Scimitar Glacier changed little in the intervening decade, the snout of Scimitar Glacier had receded approximately 270 +/- 10 m from the crest of the mound. Aerial photographs from 1994 and 2005, as well as contemporary Google Earth images, illustrate the ice front is presently stagnant and calving into an enlarging proglacial lake (Figure 5.4). The ice margin along the Pocket Valley lobe had receded about 240 +/- 10 m from the LIA maximum by 1994 and about 310 +/- 10 m by 2005.

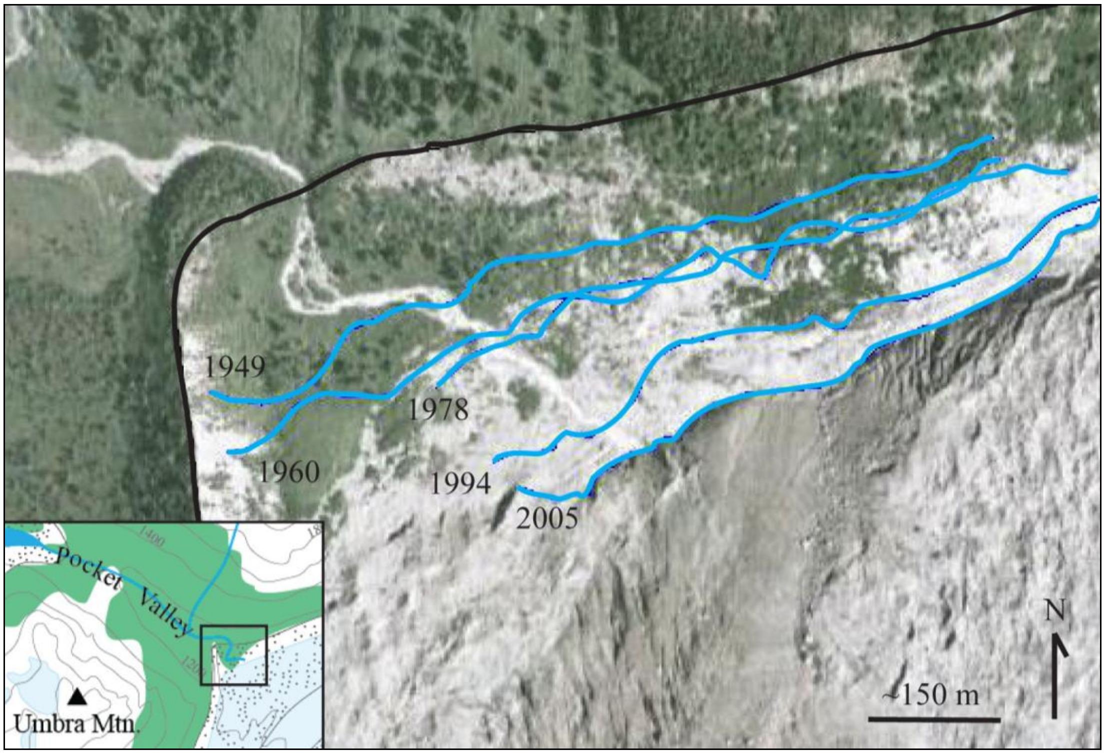



Figure 5.2: Illustration of lateral recession of Scimitar Glacier from Pocket Valley, 1949-2005. The locations of the ice margin are derived from overlays of historical aerial photographs (A12973-171, NRCan; R60 26-F47, Austin Post Collection; BC7863-127, BC Government; BCC94010-195, BC Government; BCC05040-157, BC Government). The solid black line delineates the position of the maximum late LIA moraine crest.

Table 5.1: Vertical and oblique aerial photographs of Scimitar Glacier, 1949-2005.

| Date | Source | Roll # | Photo # | B&W Colour | Area Shown |
|---|---|---|---|---|---|
| 1949 | NRCan | A12973 | 171 | B&W | All sites |
| 1960 | Austin Post collection* | R60 26 | F47 | B&W | Pocket Valley |
| 1969 | Austin Post collection | 69R5 | 168 | B&W | Oblique image of terminus |
| 1978 | BC Government | BC7863 | 127 | B&W | All sites |
| 1994 | BC Government | BCC94010 | 195 | Colour | All sites except Umbra Mountain |
| 2005 | BC Government | BCC05040 | 157 | Colour | All sites |

* University of Alaska, Fairbanks, Geophysical Institute. http://www2.gi.alaska.edu/cgi-bin/gdftp/imageFolio.cgi

During the 1933 trip to Scimitar Glacier, a few members of the party (Hall, Fuhrer and the Mundays) summited Mt. Geddes (Hendricks, 1940). To access the mountain, they climbed an ice fall (Dissension Glacier) which descended from Threshold Peak to Scimitar Glacier directly across from Mt. Hickson (Figure 5.5). In 1939 Hendricks (1940) retraced this route, but had to stop partway down the glacier, finding the terminus by then was ca. 200 ft (ca. 60 m) from the surface of Scimitar Glacier. By 1970 (NTS 92 N/6 topographic map published in 1980), Dissension Glacier had retreated ca. 200 m (1939-1970, average 5 m/yr), and by 2011 it had receded upslope ca. 500 m (1970-2011, average 7 m/yr).

Figure 5.3: Oblique aerial photograph of terminus of Scimitar Glacier in 1969 (69R5-168, Austin Post collection).

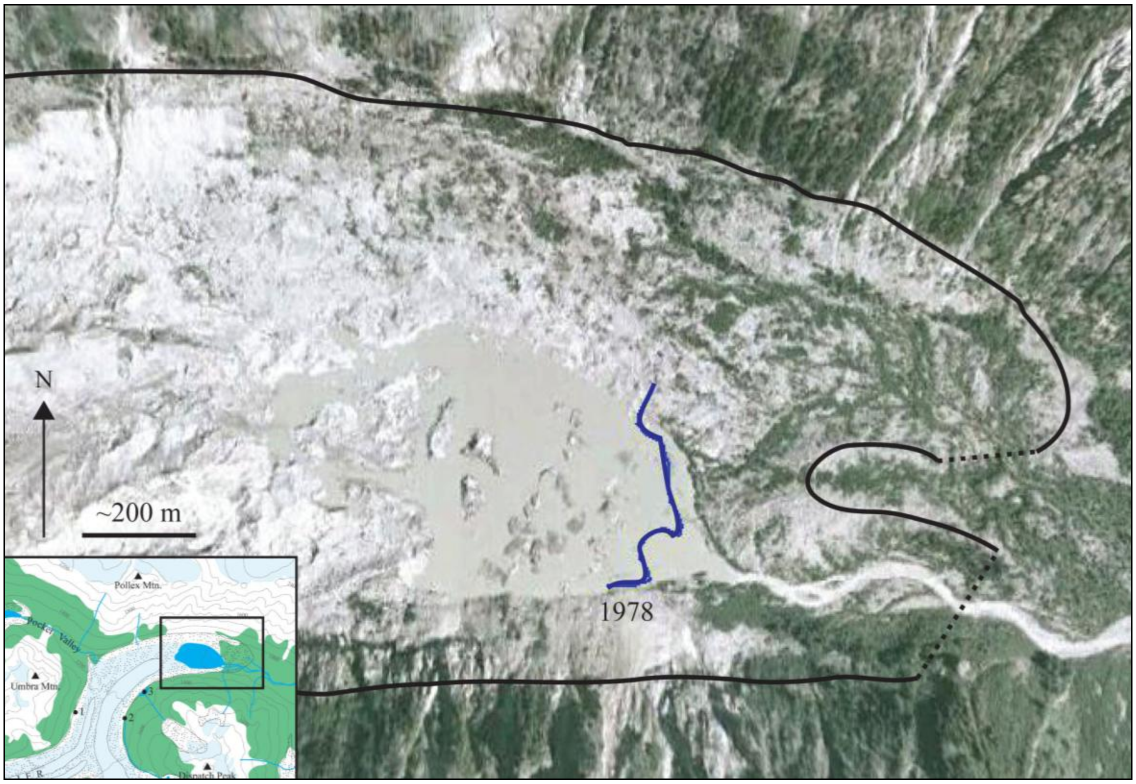



Figure 5.4: Google Earth image of Scimitar Glacier terminus in 2005. The glacier extent in 1978 is marked in blue (BC7863-127, BC Government), and the maximum Little Ice Age down valley extent of the glacier is delineated by the black line.

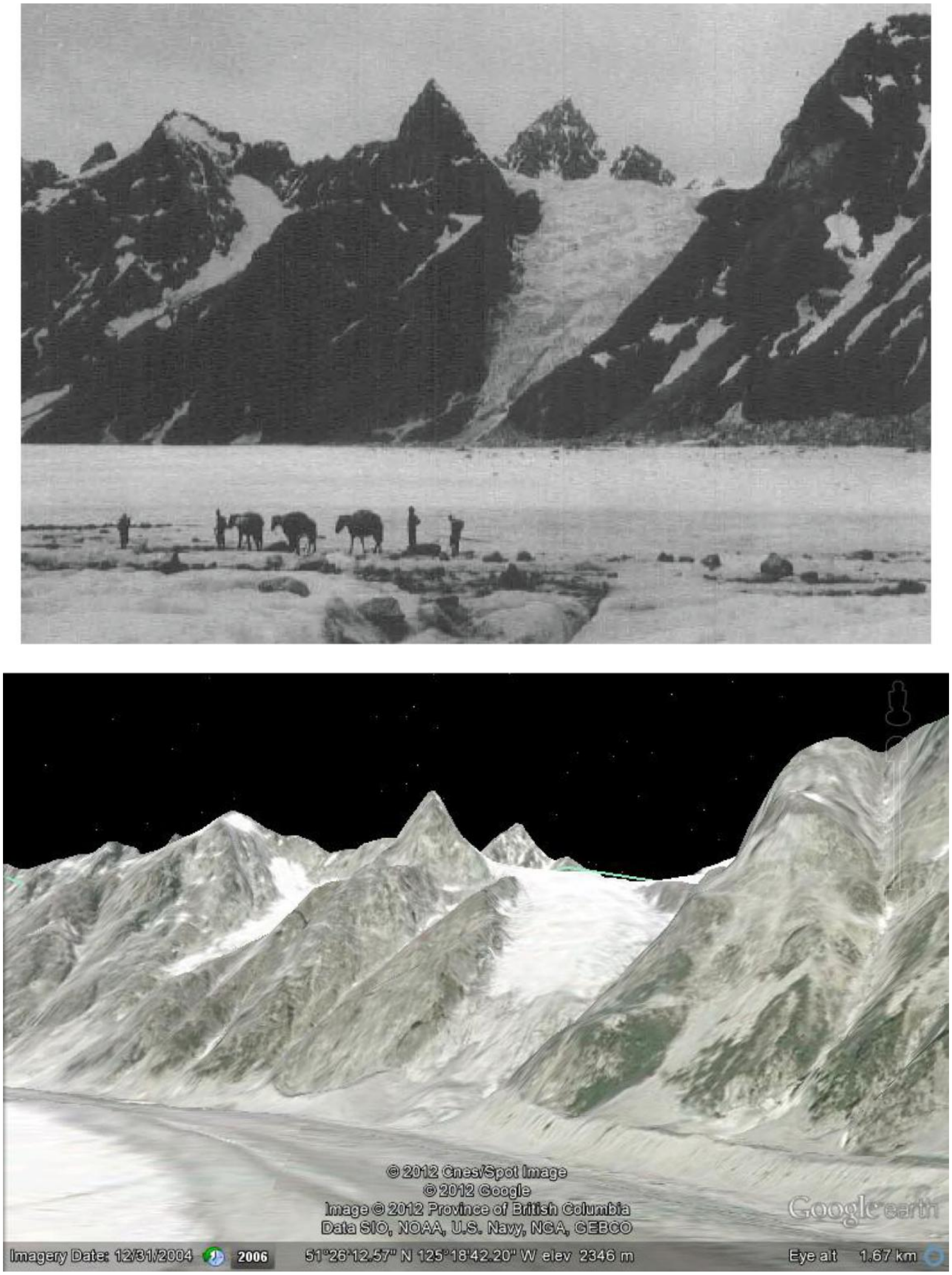



Figure 5.5: Comparison of a historical photo of Dissention Icefall taken by Henry S. Hall Jr. in 1933 (above) and a similar view using 2005 imagery in Google Earth (below).

### 5.2 Living tree-ring chronologies

Two living tree-ring chronologies were assembled to attempt cross-dating to undated subfossil samples (Smith and Lewis 2007). The first consisted of a white bark pine chronology (01B600) established from trees found growing on a southwest-facing slope adjacent to Pagoda Glacier (Figure 2.2, Table 5.2) at 1860 m asl in 2001 (Larocque and Smith, 2003). The chronology, which was constructed from 36 series (19 trees), spans 593 years (1408-2001 AD) and has a mean series correlation of r = 0.529 (Larocque and Smith 2005) (Table 5.2). The second chronology was derived from subalpine fir cores collected in 2011 for this research, from a mixed stand of mature subalpine fir and mountain hemlock trees found on a northwest-facing slope at ca. 1250 m asl adjacent to Scimitar Glacier near site 3 (Figure 2.2, Table 5.2). The chronology comprises 43 series from 22 trees, spans 350 years (1662-2011 AD), and has a mean series correlation of r = 0.520.

Table 5.2: Chronology statistics for the locally derived living subalpine fir and whitebark pine chronologies.

| Species | Location | No. of trees | No. of Series | Interval (years) | Total length (years) | Pearson's value | Mean sensitivity |
|---|---|---|---|---|---|---|---|
| Subalpine fir | N 51.45 ° W 125.18° | 22 | 43 | 1662-2011 | 350 | 0.520 | 0.157 |
| Whitebark pine | N 51.5° W 124.9° | 19 | 36 | 1408-2001 | 594 | 0.529 | 0.215 |

### 5.3 Dendroglaciological samples

Downwasting of the surface of Scimitar Glacier, fluvial erosion, and moraine collapse have exposed buried detrital wood in the proximal slopes of prominent lateral moraines at several locations. Erosion at one site has exposed stacked till units separated by wood-rich horizons and the remains of standing trees buried in sediments deposited in a lake ponded against the distal moraine slope. At other locations, portions of the proximal moraine face have collapsed onto the ice surface, exposing stratified fine sediments originally deposited in ponds abutting distal moraine slopes (Figure 5.6).

Figure 5.6: Photograph showing stratified sands and silts deposited on the distal flank of the lateral moraine and exposed due to failure of the moraine ca. 2 km southwest of site 1.

### 5.3.1 Site 1 - Umbra Mountain

Site 1 is located on the proximal face of a southeasterly-facing lateral moraine below Umbra Mountain ca. 1.7 km upvalley from the mouth of Pocket Valley (51°27’32” N, 125°13’12” W; Figure 2.1). The steep moraine face at this site extends from the debris-covered glacier surface at ca. 1250 m asl to the moraine crest at ca. 1300 m asl

(Figure 5.7). Gully incision and moraine collapse have produced an erosional amphitheater that bisects the lateral moraine (Figure 5.7).

Two buried wood mats separate till units at site 1. The lower wood mat is demarcated by a horizontal seepage line at ca. 1236 m asl and consists of a laterally extensive assemblage of detrital boles located immediately below a bouldery till unit. The wood detritus composing the mat rests on a sandy till and is partially buried within a small (<0.5 m thick) massive coarse silt and sand that are in turn overlain by the bouldery till unit. A disk sample comprising at least 24 rings was excavated from a log found within this wood mat (S11-04-02; Table 5.3).

The upper wood mat is located in the erosional amphitheater ca. 5 m below the moraine crest. Small scattered wood fragments and branches separating two till units extend across the amphitheater backwall (Figure 5.7). A fragment of a tree branch or bole with at least 27 rings was collected at the contact between the two till units (S11-04-03; Table 5.3).

Table 5.3: Subfossil wood samples collected at three sites along the margins of Scimitar Glacier in July 2011.

| Sample | Species* | Location | Dating method | Total no. rings |
|---|---|---|---|---|
| S11-01-01 | Fir | Site 3 sec. 1 | Cross-dated to living chronology | 60 |
| S11-01-02 | Fir | Site 3 sec. 1 | Cross-dated to living chronology | 118 |
| S11-01-03 | Fir | Site 3 sec. 1 | NA | 245 |
| S11-01-04 | Fir | Site 3 sec. 1 | Cross-dated to living chronology | 180 |
| S11-01-05 | Fir | Site 3 sec. 1 | Cross-dated to living chronology | 135 |
| S11-02-01 | MH/Fir | Site 3 sec. 4 | NA | 18 |
| S11-02-02 | Pine | Site 3 sec. 4 | Cross-dated to living chronology | 126 |
| S11-02-03 | MH | Site 3 sec. 4 | NA | 54 |
| S11-02-04 | Fir | Site 3 sec. 4 | NA | 54 |
| S11-02-05 | Fir | Site 3 sec. 3 | NA | 85 |
| S11-02-06 | Fir | Site 3 sec. 3 | NA | 65 |
| S11-03-01 | MH/Fir | Site 3 sec. 6 | NA | NA** |
| S11-03-02 | MH/Fir | Site 3 sec. 3 | Radiocarbon | 25 |
| S11-03-03 | MH | Site 3 sec. 6 | Radiocarbon | 87 |
| S11-03-04 | Pine | Site 3 sec. 3 | Radiocarbon | 64 |
| S11-04-01 | MH/Fir | Site 1 | NA | 256 |
| S11-04-02 | MH/Fir | Site 1 | Radiocarbon | 24 |
| S11-04-03 | MH/Fir | Site 1 | Radiocarbon | 27 |
| S11-05-01 | Pine | Site 2 | Cross-dated to living chronology | 256 |
| S11-05-02 | MH/Fir | Site 2 | NA | 165 |
| S11-05-03 | MH | Site 2 | NA | 195 |
| S11-05-04 | Fir | Site 2 | Cross-dated to living chronology | 95 |
| S11-05-05 | Pine | Site 2 | Cross-dated to living chronology | 214 |
| S11-05-06 | Pine | Site 2 | NA | 97 |
| S11-05-07 | MH | Site 2 | NA | 250 |
| S11-05-08 | Pine | Site 2 | NA | 460 |

* Species include subalpine fir (Fir), mountain hemlock (MH), or whitebark pine (Pine).
** Not Applicable (NA). Under 'Total no. rings', this sample was intended for radiocarbon dating but was withheld due to cost constraints. When used under 'Dating method' the sample was either not sent for radiocarbon dating or was not successfully dated to a living tree ring chronology.

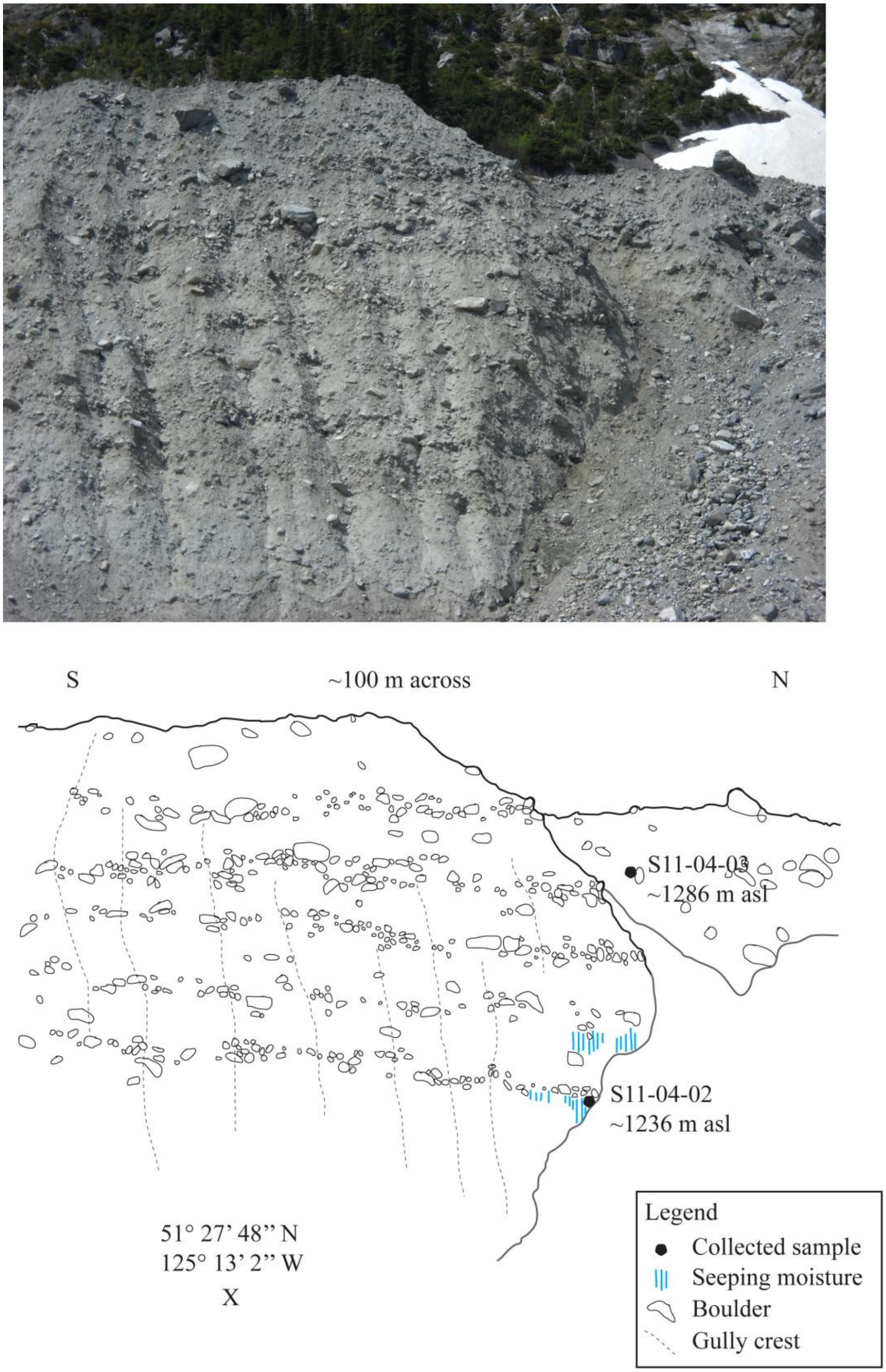



Figure 5.7: Photograph and schematic of site 1 (Umbra Mtn.) showing moraine stratigraphy and sample locations.

### 5.3.2 Site 2 – Radiant Falls

Site 2 is located on the proximal face of a west-facing lateral moraine segment down valley of Tumult Glacier (51°27'28" N, 125°12'11" W; Figure 2.1). The steep slope at this location extends from the moraine crest at ca. 1275 m asl to the debris-covered ice surface at ca. 1200 m asl (Figure 5.8).

Buried logs extend out of till along a single laterally extensive wood mat positioned ca. 20 m below the moraine crest (Figure 5.8). Although the logs were inaccessible, the remains of large whitebark pine and subalpine fir boles and branches derived from the mat lie on the talus at the base of the exposure. Samples of the boles and branches contain between 95 and 460 annual rings (Table 5.3).

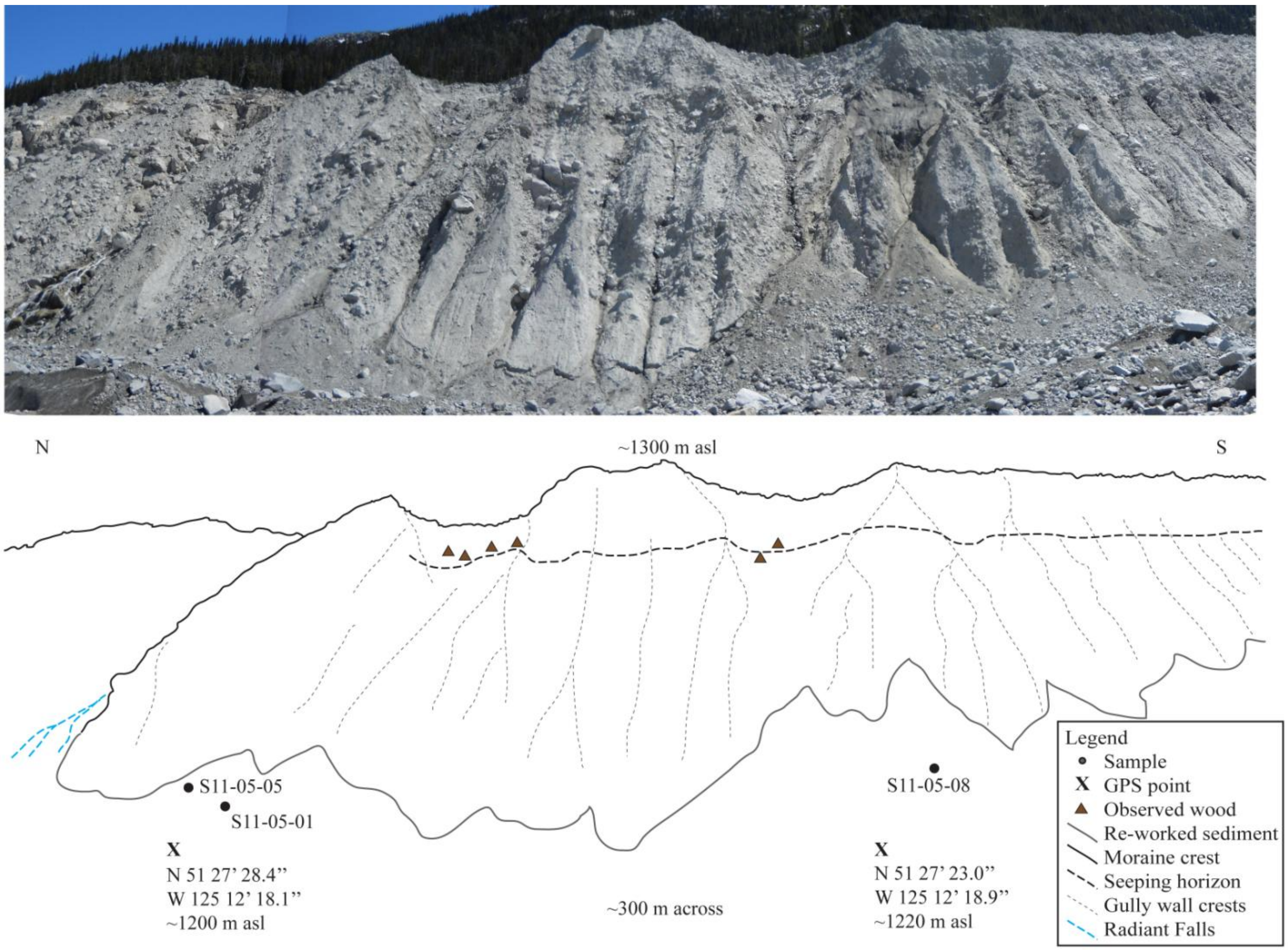



Figure 5.8: Photograph and schematic of site 2 (Radiant Falls) showing moraine stratigraphy and sample locations.

### 5.3.3 Site 3 - Dispatch Lake

Site 3 is located 1.7 km up-valley from the 2005 terminus position of Scimitar Glacier along a northwest-facing lateral moraine segment (51°27'55'' N, 125°11'40''W; Figure 2.1). Downwasting of the glacier has lowered the ice surface at this location to ca. 1140 m asl, exposing over 100 m of moraine sediment. The site is distinguished by an erosional breach of the moraine that reveals several massive till units and interbedded lacustrine and alluvial sequences (Figure 5.9).

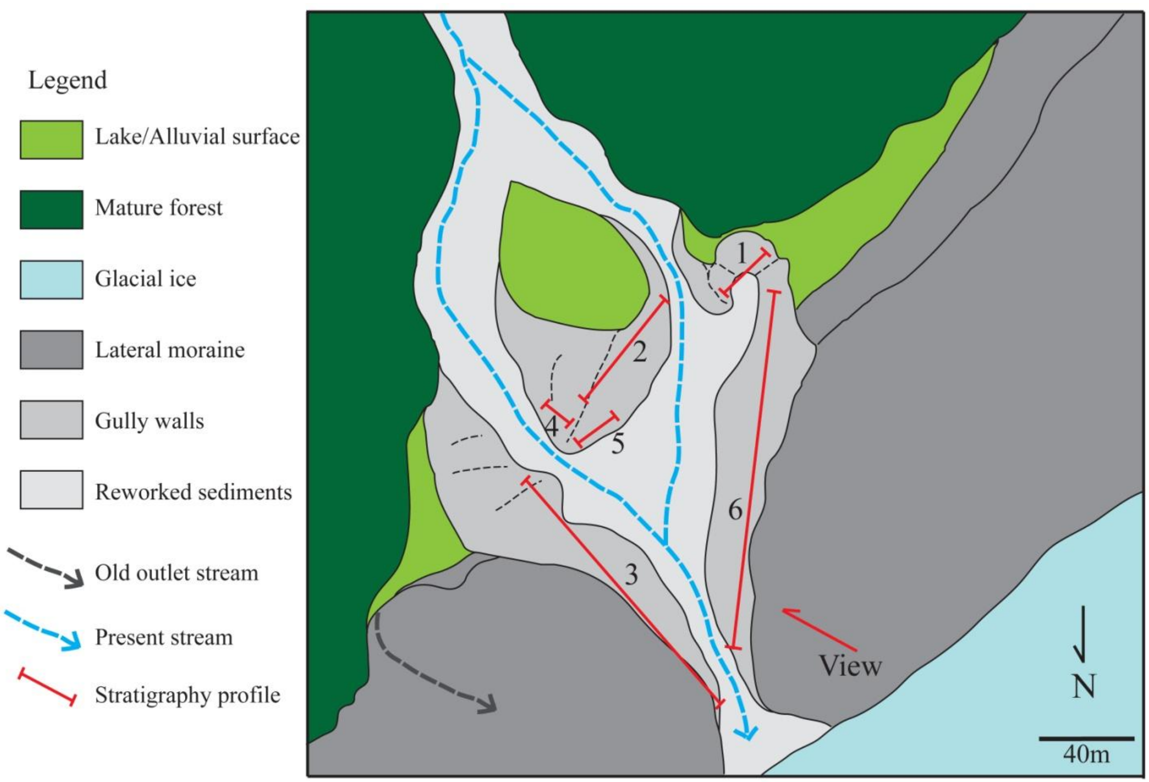



Figure 5.9: Map showing the gully system at the Dispatch Lake site (site 3). The locations and orientations of sections 1-6 are marked in red. The map also shows past and present stream locations and the direction of the view into the gully shown with section 3.

The incised lacustrine and alluvial units were deposited in a small lake (hereafter referred to as 'Dispatch Lake') that until recently was ponded between the distal moraine slope and the mountainside (Figure 5.10). At its maximum extent, the lake covered an area of ca. 20 x$10^3$ $m^2$ and was fed by a stream flowing down an avalanche track that transported meltwater, sediment and snow avalanche debris from a small cirque glacier basin located below Dispatch Peak.

Aerial photographs indicate the lake existed as early as 1949 (A12973-171, NRCan), at which time an unvegetated alluvial and colluvial fan extended from the base of the avalanche track into Dispatch Lake (Figure 5.10) At that time, the lake drained through an incision in the moraine onto the glacier surface, which was only a few metres below the lake surface. By 1978 (BC7863-127, BC Government), the glacier surface had downwasted significantly and the fan was continuing to build out into the lake (Figure 5.10). Vegetation had become established on part of the fan surface. By 1994 (BCC94010-195, BC Government), the fan extended across the lake and was nearly completely vegetated with its toe abutting the lateral moraine (Figure 5.10). By 2005 (BCC05040-150, BC Government), the moraine dam had breached and the lake was empty (Figure 5.5). Estimates of the age of seedlings found growing on the former lake bottom in 2011 indicate that the lake had fully drained in 2001. Since that time, deep erosional gullies have incised through the lake sediments.

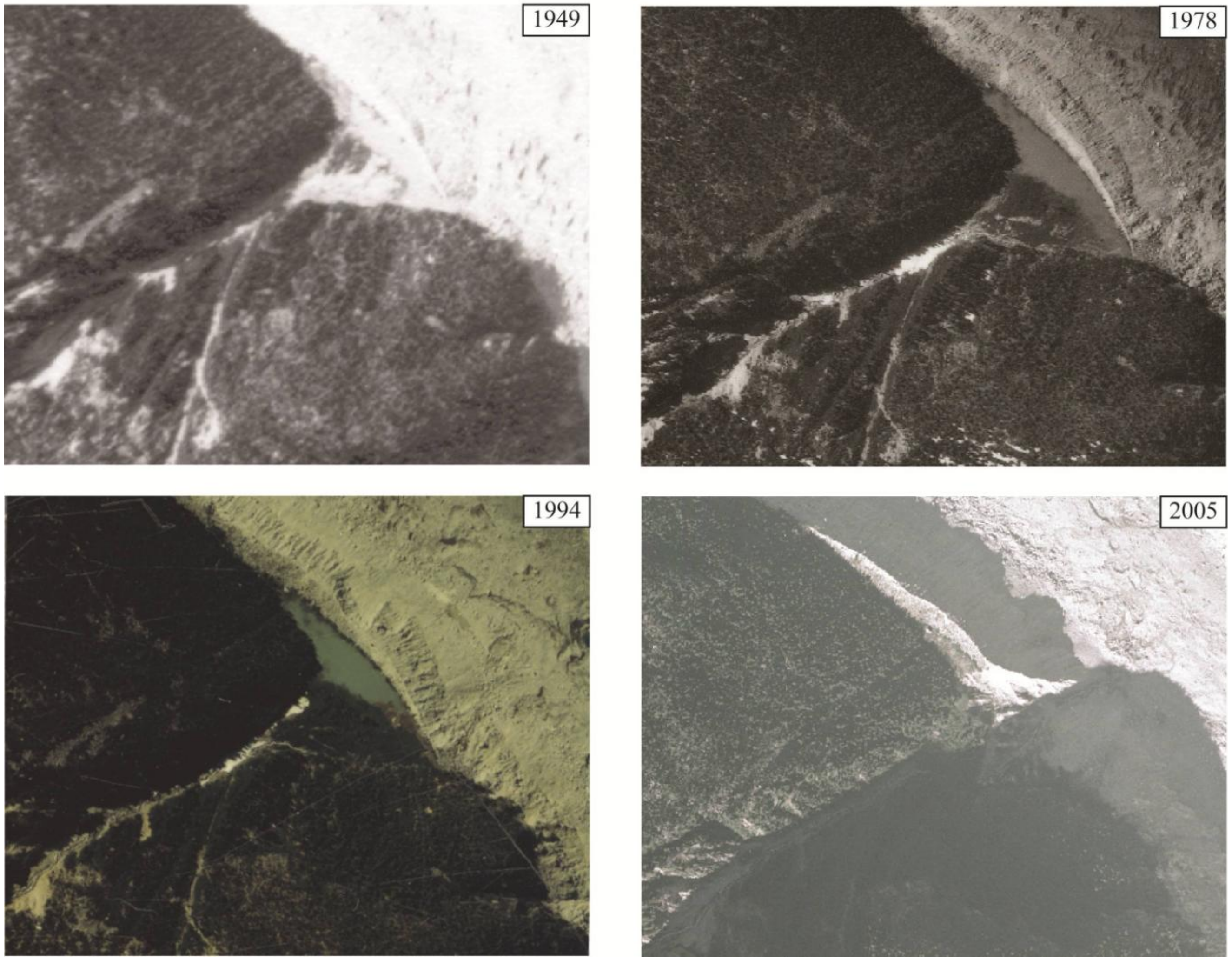



Figure 5.10: Historical aerial photographs illustrating the evolution of Dispatch Lake from 1949 to 2005 (1949:A12973-171, 1978:BC7863-127, 1994:BCC94010-195, 2005:CC05040-157).

Stratigraphic descriptions were completed at six locations (Figures 5.11-5.16). The first section faces northwest and is located ca. 40 m from the crest of the lateral moraine where fluvial erosion has exposed the most recently deposited lake bottom sediments (section 1, Figure 5.9 and 5.11). The section consists of a 13-m-thick sequence of stratified medium-grained sand with discontinuous laminae of fine sand and silt. The sediments are exposed over ca. 20 m of the former lake bottom at 1225 m asl. Detrital and rooted standing remains of subalpine fir trees occur at different levels within the sand unit. Cross-sectional discs were cut from five standing trees at various depths in the sediment sequence for cross-dating (Table 5.3). Due to the potential for perimeter wood loss (no bark present) and the height of each sample (unknown depth to roots), perimeter dates assigned to these samples must be considered earliest kill dates (Gärtner, 2007).

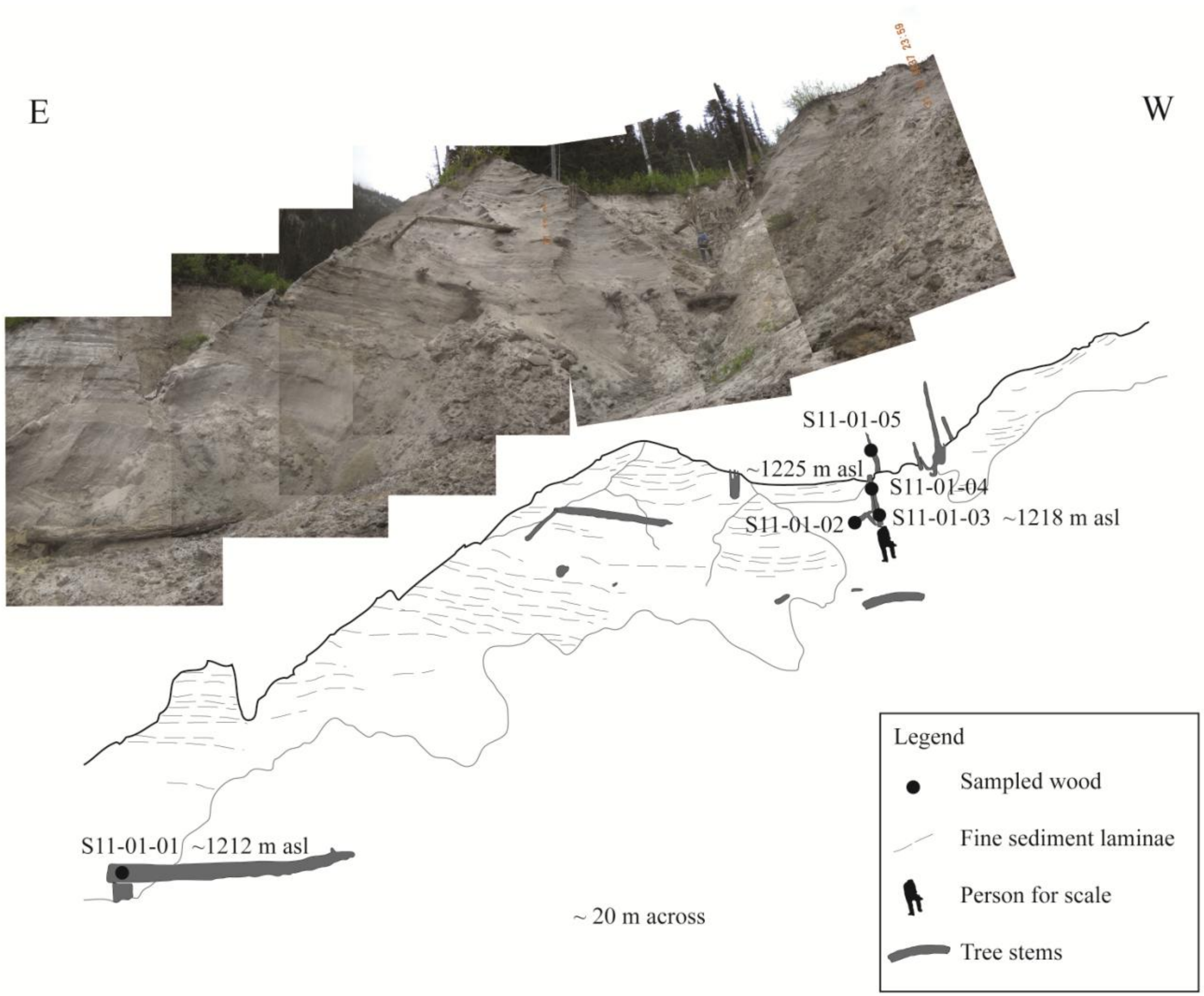



Figure 5.11: Photograph and schematic of section 1 at site 3 (Dispatch Lake) showing stratigraphy and sample locations. Images show standing in situ sample S11-01-01 after sampling.

The second section is oriented northeast-southwest, is ca. 60 m across, and is located in the middle of the gully network at site 3 (section 2, Figure 5.9 and 5.12). Fluvial erosion has exposed about 50 m of sediments that have been placed into three sedimentary units. The lowest unit extends ca. 10 m upward from the talus apron at the bottom of the section to an abrupt contact at ca. 1187 m asl. This unit is a matrix-supported diamicton containing subrounded to angular granodiorite and gneissic clasts up to 2 m in diameter. No wood detritus was found in this unit. Resting on this unit is ca. 38 m of medium-grained sand containing discontinuous laminations of finer sand and silt, as well as discontinuous lenses of gravel that increase in clast size and frequency to the northeast. Logs and branches protrude from this unit. While these remains could not be accessed, their appearance and orientation suggests they were transported and deposited by streamflow or snow avalanches from the mountain slope above. The third unit at the top of section 2 is a ca. 1m thick diamicton comprising subrounded to angular granodiorite and gneissic boulders of up to ca. 2 m set in a matrix of poorly sorted coarse sand and fine gravel. Due to the perspective of the photos, this small third unit at the top of the section (ca. 1225 m asl) is shown yet smaller when compared to the lower two units.

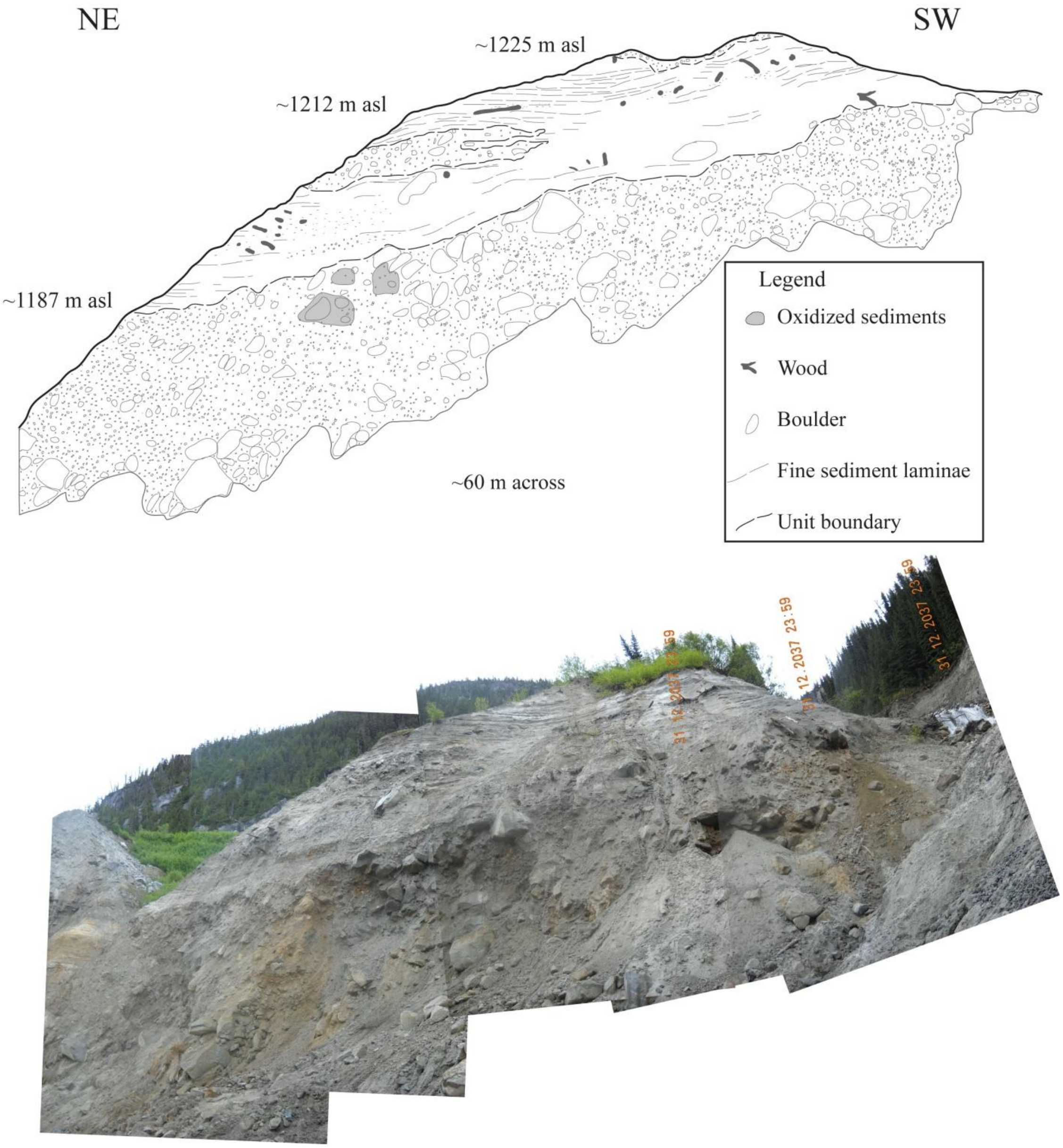



Figure 5.12: Schematic and photograph of section 2 at site 3 (Dispatch Lake) showing stratigraphy and locations of wood remains.

The third section is oriented northwest-southeast and extends over a distance of ca. 80 m wide at the northeastern end of the former lake, where stream incision has cut perpendicularly through the moraine (section 3, Figures 5.9 and 5.13). Two units were recognized at this section. The lower unit extends from the talus apron upward ca. 80 m to ca. 1230 m asl. It is a matrix-supported diamiction containing subrounded to angular granodiorite and gneissic boulders up to 2 m across. Scattered woody detritus (likely branch or stem fragments) were found and sampled within this unit at ca. 1145-1159 m asl (S11-03-04 and S11-03-02; Table 5.3). At the southeast end of the section, this unit is overlain by stratified medium-grained sand containing discontinuous laminations of finer sand and silt. Sediments in the lowest part of this unit at ca. 1180–1210 m asl are visibly darker and oxidized to a rusty orange colour. Stumps and logs within this sandy unit at ca. 1212 m asl were sampled (S11-02-05 and S11-02-06; Table 5.3). The sandy unit is then overlain by further deposition of the first diamict unit.

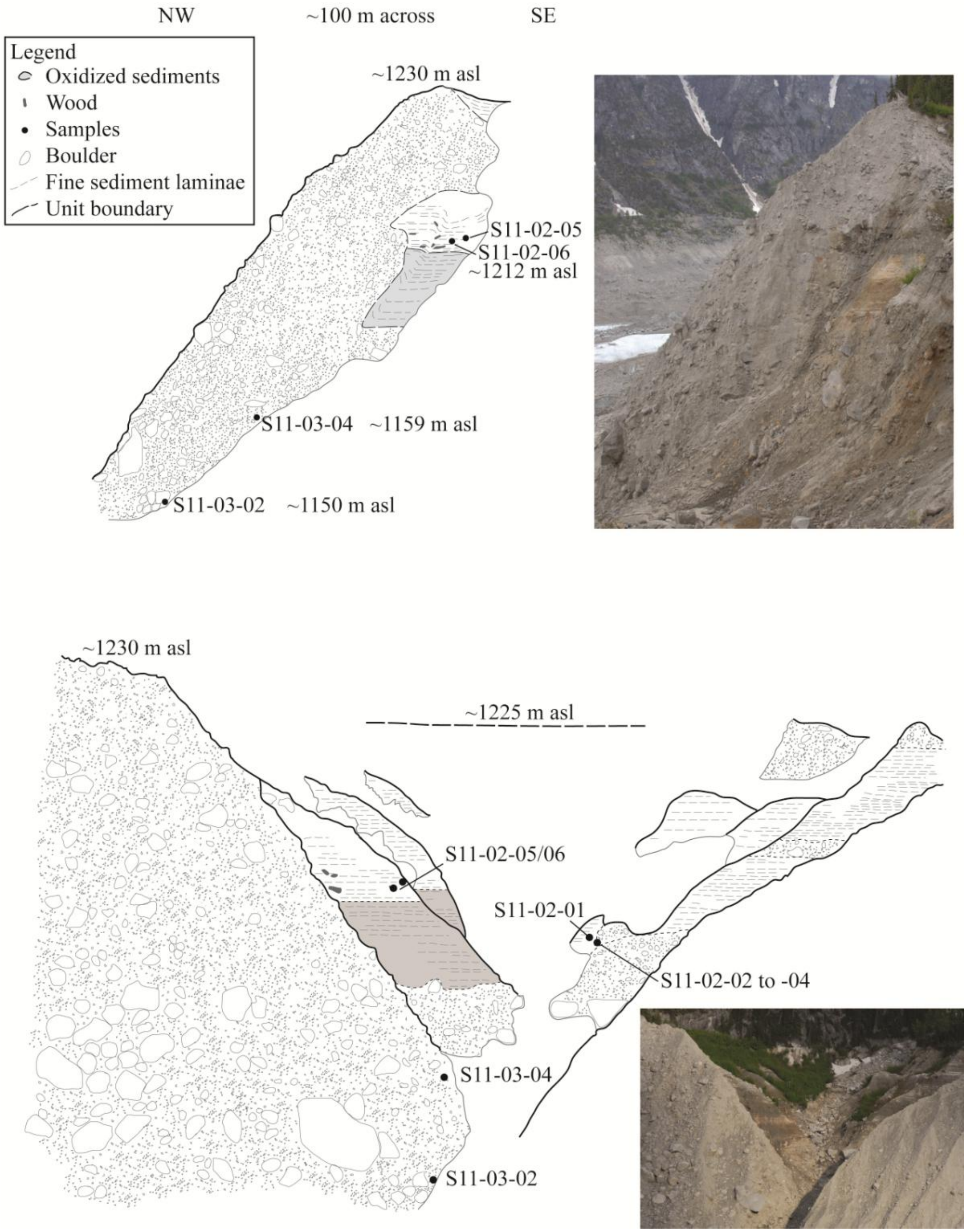



Figure 5.13: Photograph and schematic of section 3 at site 3 (Dispatch Lake) showing stratigraphy and sample locations, as well as a second view into the gully.

The fourth section is near the northeast end of section 2 and is ca. 10 m across, 5 m high, and oriented approximately northwest-southeast (section 4, Figures 5.9 and 5.14). Fluvial erosion has exposed three sedimentary units. The lowest unit, which is exposed at the northwest end of the section and dips toward the southeast, extends ca. 2 m above the debris covering its base. It is a matrix-supported diamicton containing subrounded to angular granodiorite and gneissic boulders up to 2 m in diameter. The second unit is located at the southeast end of the exposure and extends ca. 3 m above the debris covering its base. It consists of stratified medium-grained sand with discontinuous laminations of fine sand and silt. A third unit, composed of matrix-supported granodiorite and gneissic boulders up to ca. 2 m in diameter set in a matrix of poorly sorted coarse sands and fine gravel overlies the first two units. This bouldery unit lies above the sandy unit with an abrupt, irregular and dipping contact. The contact between the diamiction and the upper bouldery unit at 1187 m asl is indistinct and dips slightly to the southeast. Below the contact the predominant size of the boulder clasts in the diamiction is smaller than those in the bouldery unit just above. There was also the presence of coarse woody debris along the contact. Three of these subfossil trees found at the contact between the diamiction and upper bouldery unit were sampled (S11-02-02 to -04, Table 5.3). Another sample was collected at the same elevation at the southeast end of the section in the sandy unit (S11-02-01, Table 5.3). The appearance and orientation of these remains suggests they were transported and deposited by gravity, streams, or snow avalanches originating from the mountain slope above.

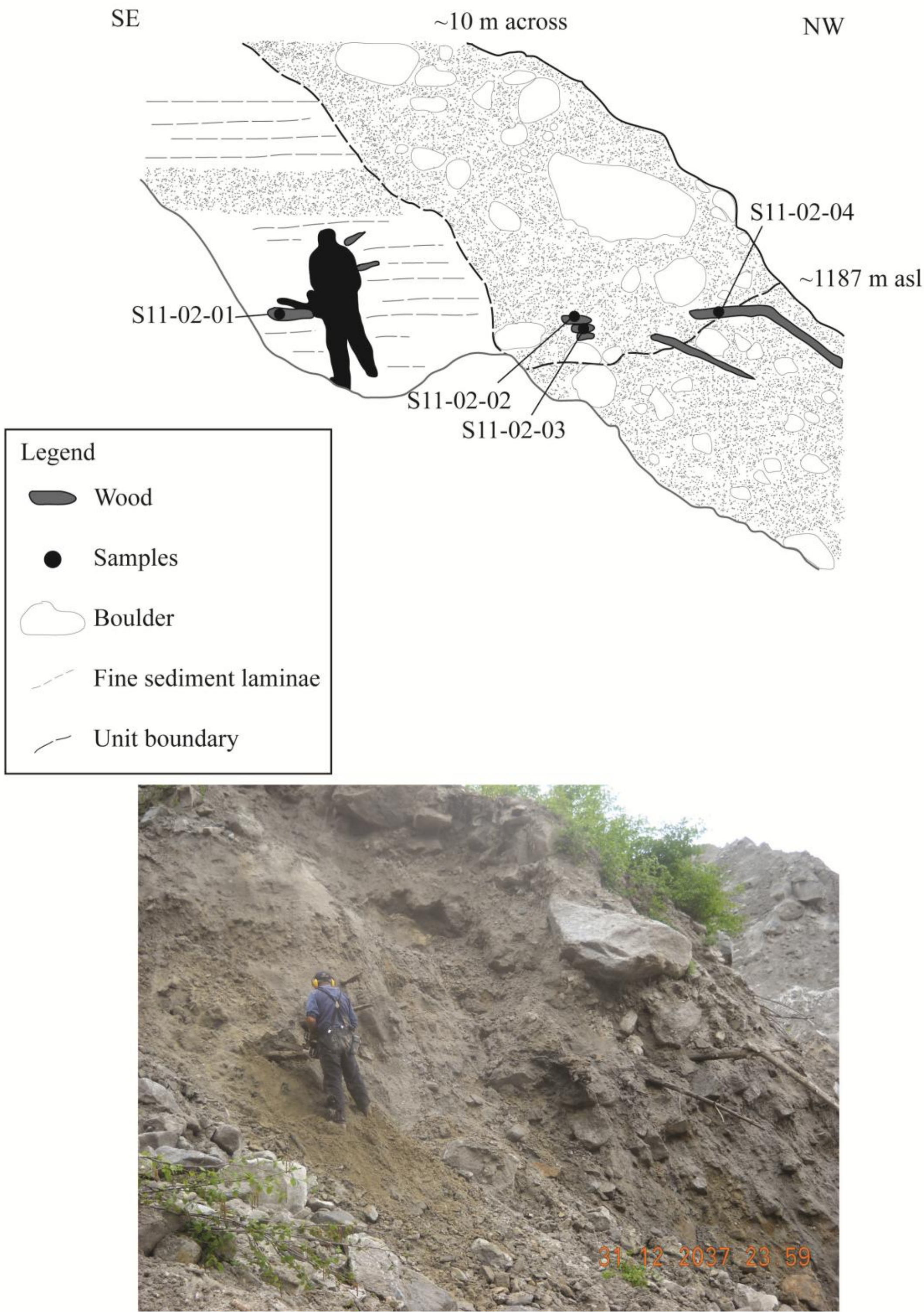



Figure 5.14: Schematic and photograph of section 4 at site 3 (Dispatch Lake) showing stratigraphy and sample locations.

Section 5 is located below the northeast end of section 2 and extends over a horizontal distance of ca. 10 m (section 5, Figures 5.9 and 5.15). Fluvial erosion has exposed ca. 35 m of sediments extending from the sloping debris-covered base of the section to the abrupt contact in section 2 at 1187 m asl. The section is dominated by a unit of matrix-supported diamicton, between 1159 and 1187 m asl, containing subrounded to angular granodiorite and gneissic boulders up to 2 m in diameter. Two thin units of stratified medium-grained sand containing discontinuous laminations of inter-bedded finer sands and silts can be found along the irregular base of the section. The unit below 1159 m asl, on the northeast end of the section, extends ca. 5 m above the debris covered base. This lower sandy unit has a channel eroded into the contact at 1159 m asl which has been in-filled by the diamict unit. The unit found at ca. 1177 m asl, on the southwest end of the section, extends ca. 0.5 m above the debris covered base. No wood detritus was found in any of the units.

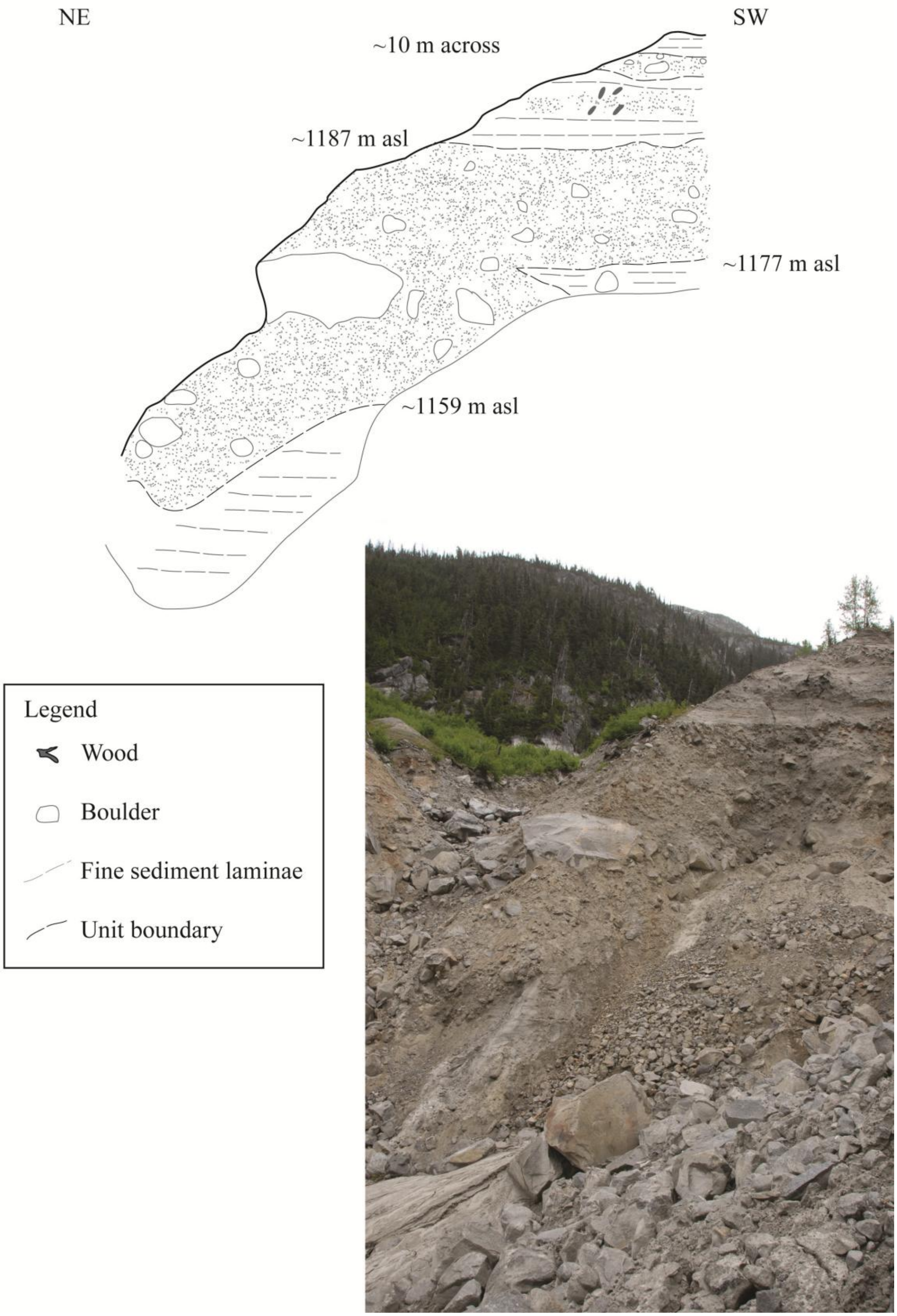
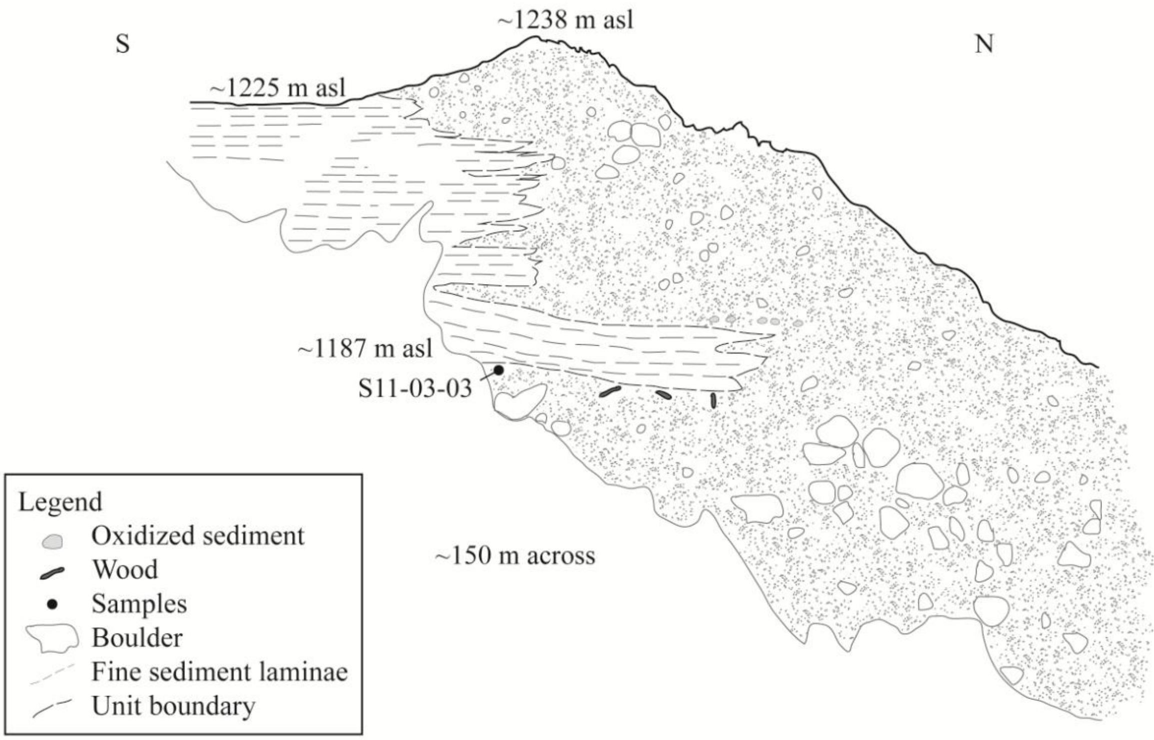



Figure 5.15: Schematic and photograph of section 5 at site 3 (Dispatch Lake) showing stratigraphy.

Section 6 extends ca. 150 m in a north-south direction obliquely through the lateral moraine (Figures 5.9 and 5.16). Below the crest of the moraine at ca. 1238 m asl erosion has vertically exposed ca. 50 m of sediment. At the south end of the section, the section extends ca. 15 m from the surface of the stratified sediments at ca. 1225 m asl down to the debris-covered base. Here, the entire section consists of a unit of stratified medium-grained sand containing discontinuous laminations of finer sand and silts. At the north end of the section, the section is entirely composed of a unit of a matrix-supported diamicton containing subrounded to angular granodiorite and gneissic clasts up to 2 m in diameter. At the middle of the section, below the crest of the moraine, the diamicton unit interfingers with the sand unit. The lowest ‘finger’ of the sand unit at ca. 1187 m asl extends significantly farther into the diamicton unit than the other ‘fingers’ above. Just below this longest and lowest sand finger is an assemblage of woody branches and stem fragments, from which sample S11-03-03 (Table 5.3) was collected.



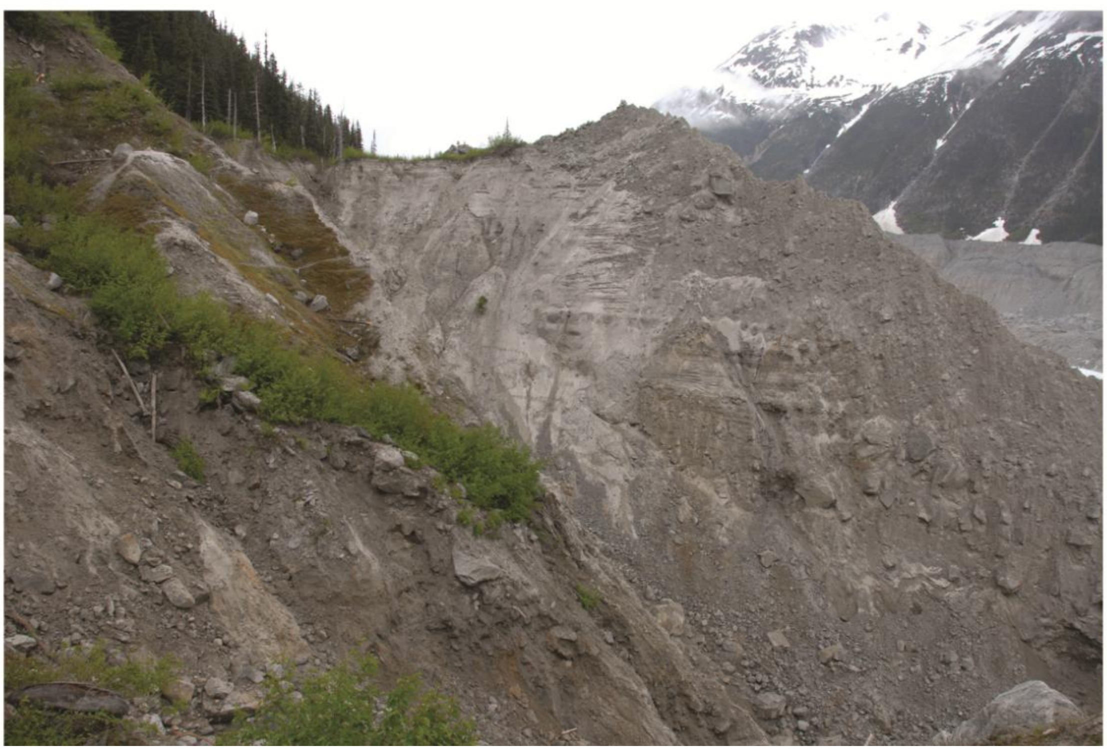



Figure 5.16: Schematic and photograph of Section 6 at site 3 (Dispatch Lake) showing stratigraphy and sample locations.

***Stratigraphic interpretation***

The sediments exposed at site 3 record three episodes of moraine construction and lake sediment deposition, each of which was followed by breaching of the moraine and incision of lake sediments (Figure 5.17). The oldest morainal sediments consist of the diamiction exposed at low elevations at sections 3 and 6, where the distal slope of the moraine is overlain by the ponded sandy lake sediment (Figure 5.15). This early lake drained to create the eroded channel at ca. 1159 m asl. Following this episode, Scimitar Glacier advanced a second time and constructed a new moraine dam consisting of diamiction (section 6, below ca. 1187 m asl), causing the lake to reform and the sandy lacustrine sediments to again accumulate (ca. 1177 m asl in Figure 5.15 and just above ca. 1187 m asl in Figure 5.16). Another period of incision followed, until a final phase of moraine construction (sections 2, 3, 4 and 6) blocked the moraine breach with diamiction, forming the lake a third time. Deposition of the final sandy lake sediments appears to have continued without any significant interruption. Localized pulses of coarse material, such as the bouldery unit seen along the top of section 4, eroded into the lake sediments. Such material likely originated from the mountain slope above and was transported by meltwater streams, avalanche and/or gravity to form a fan which prograded out toward the moraine dam. About 40 m of lacustrine and fan sediments (section 2) were deposited on the distal slope of the moraine before the moraine was breached for the last time ca. 2001. The bouldery horizons seen along the proximal face of the lateral moraine at site 1 may indicate avalanche deposits are intermixed within the moraine material.

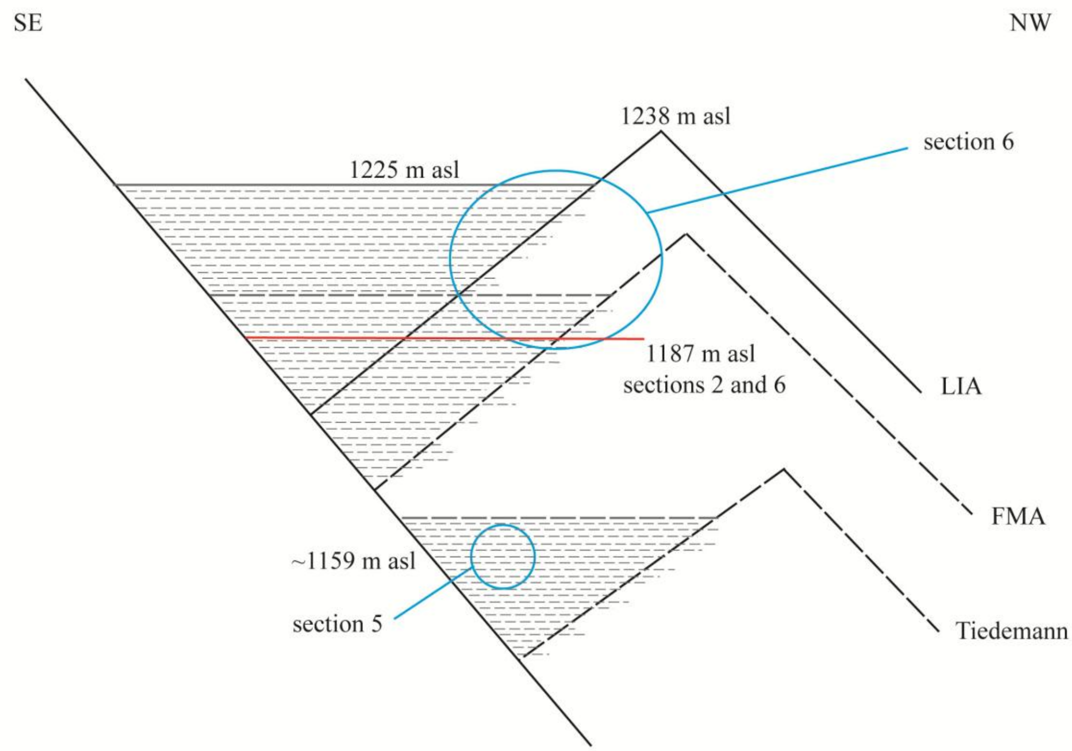



Figure 5.17: Schematic diagram showing the evolution of Dispatch Lake and deposition of sediments exposed at the six sections at site 3. Interactions with the fan built from the SE have been excluded.

# Chapter 6 – Discussion

## 6. 1 Introduction

Field reconnaissance of the lateral moraines flanking the lower reaches of Scimitar Glacier led to the discovery of detrital wood buried in lateral moraine sediments suggesting several events of lateral ice expansion during the late Holocene. The standing remains of trees buried by infilling of a distally-ponded lake and growth of a fan provide additional insights into times of lateral moraine construction.

## 6.2 Dating and Interpretation

***Radiocarbon dating***

The oldest wood samples recovered at Scimitar Glacier were found deeply buried within lateral moraine sediments at sites 1 and 3 (Table 6.1). Perimeter wood from S11-04-02, from the boundary between two till units at site 1 ca. 50 m below the moraine crest, dates to 2798-2737 cal yr BP (Figure 5.7). Across the valley, at site 3, perimeter rings of detrital wood samples exposed in a massive till unit ca. 90 m below the lateral moraine crest range in age from 3167- 2973 (S11-03-04) to 2867-2760 cal yr BP (S11-03-02) (Table 6.1). The ages were interpreted to be kill dates related to glacier advance, in which case Scimitar Glacier overwhelmed lower valley-side forests between ca. 3200 and 2700 cal yr BP.

At site 3 perimeter wood of a mountain hemlock branch or stem (minimum 87 rings; sample S11-03-03) at the contact between morainal deposits and lacustrine sediments (Figure 5.16) died at 1568-1412 cal yr BP (Table 6.1). Its burial by lake sediments on the distal slope of the moraine suggests that it may represent the remains of a tree killed by an avalanche and transported to the site which would give a maximum age for the lake sediments.

At site 1 a fragment of a tree branch or bole of an unidentified tree species was found ca. 5 m below the moraine crest at the contact between two till units (S11-04-03; Table 6.1). This tree was at least 27 years old when the glacier expanded to bury it soon after 315-267 or 214-145 cal yr BP.

Table 6.1: Summary of radiocarbon-dated dendroglaciological evidence recovered along the margins of Scimitar Glacier at sites 1 and 3.

| Sample # | Conventional $^{14}C$ yr BP | 95.4% (2σ) cal yr BP age ranges | Percent of distribution | Latitude | Longitude | Elevation (m asl) | No. of Rings | Description |
|---|---|---|---|---|---|---|---|---|
| S11-03-02 | 2720 +/- 30 | 2760 - 2867 | 1.000 | 51° 27' 57.0" | 125° 11' 43.0" | 1150 | 25 | hemlock/fir fragment lowest in moraine |
| S11-03-03 | 1620 +/- 30 | 1412 - 1568 (AD 382-538)<br>1588 - 1592 (AD 358-362) | 0.994<br>0.006 | 51° 27' 55.1" | 125° 11' 44.2" | 1187 | 87 | hemlock fragment low in lake sediments |
| S11-03-04 | 2930 +/- 30 | 2973 - 3167<br>3180 - 3208 | 0.927<br>0.073 | 51° 27' 56.7" | 125° 11' 42.8" | 1159 | 64 | pine fragment low in moraine |
| S11-04-02 | 2650 +/- 30 | 2737 - 2798<br>2819 - 2844 | 0.939<br>0.061 | 51° 27' 49.7" | 125° 13' 07.1" | 1236 | 24 | perimeter wood, fir, mid-moraine |
| S11-04-03 | 260 +/- 30 | 267 - 315 (AD 1635- 1683)<br>145 - 214 (AD 1736- 1805)<br>414 - 418 (AD 1532-1536)<br>0 - 15 (AD 1935-1951) | 0.481<br>0.419<br>0.004<br>0.096 | 51° 27' 50.2" | 125° 13' 09.9" | 1287 | 27 | hemlock/fir wood fragment, near top of moraine |

***Tree-ring dating***

Tree-ring cross-dating techniques were used to establish the absolute age of tree remains collected at sites 2 and 3 (Table 6.2). Three of the detrital samples collected at site 2 (S11-05-01, S11-05-04, and S11-05-05) cross-date to the white bark pine or subalpine fir (S11-05-04) chronologies constructed from living trees collected at nearby Pagoda Glacier (Larocque 2003; Larocque and Smith 2005) or above Dispatch Lake. While no bark was present and some perimeter wood had been lost, cross-dating established that these trees were killed sometime after 1770 AD, 1784, and 1851 AD, respectively (Figure 5.8, Table 6.2).

At site 3, section 1, tree remains were cross-dated to the locally constructed subalpine fir chronology (Table 6.2). Four of the five standing subalpine fir boles buried in sands at section 1 (60-180 tree rings) cross-date to the subalpine fir tree-ring chronology (r = 0.503; Table 5.2) and died sometime after 1806 AD (Table 6.2). The death of these trees appears to be related to rapid burial by sand originating either from the nearby distal moraine slope or, more likely, by the stream flowing into Dispatch Lake from the adjacent mountain side (Figure 5.11).

At site 3, section 4, the remains of a detrital whitebark pine stem (S11-02-02) cross-dates to the Pagoda Glacier whitebark pine chronology (Larocque and Smith 2005). The stem is part of a tree that died after 1742 AD (Table 6.2). The location of this stem within alluvial/colluvial sediments overlying distal moraine sediments suggests that it is either snow avalanche or glacier-killed detritus transported into Dispatch Lake.

Table 6.2: Summary of cross-dated tree-ring ages of samples recovered along the margins of Scimitar Glacier at sites 2 and 3.

| Sample | Species* | Location | Calendar range | No. of rings | Pearson's r values |
|---|---|---|---|---|---|
| S11-01-01 | Fir | Site 3 sec. 1 | 1747-1806 AD | 60 | 0.447 |
| S11-01-02 | Fir | Site 3 sec. 1 | 1678-1795 AD | 118 | 0.277 |
| S11-01-04 | Fir | Site 3 sec. 1 | 1639-1818 AD | 180 | 0.384 |
| S11-01-05 | Fir | Site 3 sec. 1 | 1671-1805 AD | 135 | 0.447 |
| S11-02-02 | Pine | Site 3 sec. 4 | 1623-1742 AD | 119 | 0.423 |
| S11-05-01 | Pine | Site 2 | 1596-1851 AD | 255 | 0.261 |
| S11-05-04 | Fir | Site 2 | 1689-1784 AD | 95 | 0.369 |
| S11-05-05 | Pine | Site 2 | 1556-1770 AD | 214 | 0.285 |

* Species include subalpine fir (Fir) and whitebark pine (Pine).

***Interpretation***

The earliest advances documented at Scimitar Glacier coincide with the Holocene Tiedemann Advance (Ryder and Thomson 1986; Arsenault et al. 2007). Wood fragments in till at sites 1 (2798-2737 cal yr BP) and 3 (3167-2973 and 2867-2760 cal yr BP) suggest the glacier was expanding down-valley between 3200 and 2700 cal yr BP. It is uncertain whether these represent one continuous expansion of the glacier or multiple short-lived advances over a period of 500 years.

Moraine building at Scimitar Glacier created a Tiedemann-age lake between the lateral moraine and mountainside below Dispatch Peak at site 3. The existence of an older and smaller moraine that Munday (1934-35) describes on the distal side of the late LIA moraine at Pocket Valley indicates that prior to the late LIA an advance of Scimitar Glacier was more laterally extensive, although perhaps did not fill the valley to the same extent. This older and smaller moraine may be of Teidemann age.

After Scimitar Glacier downwasted following the Tiedemann Advance, the moraine dam failed and the lake drained, leaving a channel incised into the earliest lake sediments exposed below 1159 m asl at site 3, section 5 (Figure 5.15). It is not known when this erosion occurred, but the burial of S11-03-03 in lake sediments at site 3, section 6, indicates that by 1568-1412 cal yr BP the moraine dam had been restored and Dispatch Lake had refilled. This period of glacial expansion and moraine building is associated with the regionally extensive First Millennium Advance (FMA, Reyes et al., 2006). Lake sediments deposited during the FMA, and perhaps during subsequent early LIA advances, are present at site 3, section 5 (1177 m asl, Figure 5.15) and section 6 (1187 m asl, Figure 5.16) and comprise a <10-m-thick unit of lacustrine sand.

Following either the FMA or early Little Ice Age (LIA) glacial advance, Dispatch Lake drained once again, most likely when the glacier surface lowered and the lateral moraine breached. By 1639 AD trees were colonizing the exposed lake bottom, based on the age of the standing dead firs seen at site 3, section 1. Shortly afterwards, in 1635-1683 or 1736-1805 AD, (S11-04-03 radiocarbon date) Dispatch Lake reformed when Scimitar Glacier expanded and constructed a lateral moraine that blocked the moraine breach. By 1742 AD (S11-02-02, site 3, section 4) the lake had partially re-established, and by 1806 AD (S11-01-01) >180 year old trees were being buried in growth position as sand progressively in-filled the lake to a final height of 1225 m asl (Site 3, section 1, Figure 5.11).

Over 39 $x10^4$ $m^3$ of sediment accumulated in Dspatch Lake during the late LIA and 20$^{th}$ century prior to its final draining in 2001. Remnants of these LIA lake deposits were eroded and transported through the moraine breach, ongoing incision is continuing to expose older deposits, that include remains of trees buried during earlier periods of lake development in 3167-2760 and 1568-1412 cal yr BP (Table 6.1). The late LIA advance re-established a terminal moraine from two lobes of ice on either side of a crescent shaped morainal mound. Part of this terminal moraine has since been obscured by fluvial action.

### 6.3 Regional Synthesis

The late Holocene history of Scimitar Glacier is in general accord with that of other studied glaciers throughout the Pacific Northwest (Menounos *et al*., 2009). The Tiedemann-aged expansion of Scimitar Glacier is generally coeval with advances of glaciers at other sites in the Waddington Range (Fulton, 1971; Ryder and Thomson, 1986; Coulthard *et al*. 2013) and elsewhere in the Coast Mountains (Desloges and Ryder, 1990; Clague and Mathews, 1992; Reyes and Clague, 2004; Lewis and Smith; 2005; Allen and Smith, 2007). Broadly coincident intervals of moraine construction have been documented in the Cariboo Mountains (Maurer et al., 2012), the Canadian Rocky Mountains (Luckman et al., 1993; Osborn et al., 2001; Wood and Smith, 2004), Alaska (Ellis and Calkin, 1984; Barclay et al., 2009), and Washington State (Osborn et al., 2012), showing that this advance is a regional response to large-scale climate forcing (Menounos et al., 2009; Harvey et al., 2012). The findings of this study are consistent with paleotemperature reconstructions showing an overall shift to cooler conditions during Tiedemann time (Walker and Pellatt, 2003; Patterson et al., 2007).

Wood remains associated with moraine-dammed Dispatch Lake 1568-1412 cal yr BP supports an FMA in the Waddington Range. The date assigned to the advance of Scimitar Glacier is similar those reported at Tiedemann Glacier – one on a transported log in glaciofluvial sediments (Ryder and Thomson, 1986), another on bog sediments (Fulton, 1971), and lichen dates on boulders (Laroque and Smith, 2003). These ages, along with the Scimitar Glacier age, are generally coeval with FMA ages throughout the

Coast Mountains (Reyes and Clague, 2003; Allen and Smith, 2004; Laxton, 2005; Lewis and Smith 2005), Alaska (Johnson et al., 1997; Wiles et al., 1999; Calkin et al., 2001; Barclay et al., 2005), the Cariboo Mountains (Maurer et al., 2012), and Washington State (Osborn et al., 2012). Scimitar Glacier thus responded in concert to climate forcing mechanisms during the FMA (Reyes et al., 2006), probably due to a shift to wetter and cooler conditions in the region at this time (Hallett et al., 2003; Patterson et al., 2007; Gavin et al., 2011).

The late LIA expansion of Scimitar Glacier during the $18^{th}$ and $19^{th}$ centuries is similar to expansion events recorded at nearby glaciers (Ryder and Thomson, 1986; Larocque, 2003; Coulthard *et al*. 2013), when cooler climatic conditions (Graumlich and Brubaker, 1986; Wiles et al., 1996) led to positive glacier mass balances (Larocque and Smith, 2005). This late LIA expansion occurred at a time similar to advances reported from glaciers elsewhere in the Coast Mountains (Desloges and Ryder, 1990; Smith and Desloges, 2000; Laxton and Smith, 2005; Allen and Smith, 2007; Jackson et al. 2008; Harvey, 2011), Alaska (Wiles et al. 1999; Capps et al. 2011), Washington State (Heikkinen, 1984; Osborn et al., 2012), and the Canadian Rocky Mountains (Luckman, 1986, 2000). The broadly coincident evidence for glacier advances at this time suggests alpine glaciers in Pacific North America were advancing in response to regional climate forcing during the late LIA.

# Chapter 7 – Conclusions

## 7.1 Summary

The late Holocene history of Scimitar Glacier has been described using stratigraphic analysis in conjunction with dendroglaciologic and radiocarbon dating. These findings have been compared to those of previous researchers to enhance understanding of late Holocene glacier activity in the central and southern Coast Mountains.

Evidence found at three sites shows that Scimitar Glacier expanded and advanced down-valley several times during the late Holocene. These advances occurred in concert with the regionally recognized Tiedemann Advance (ca. 3167-2737 cal yr BP), First Millennium Advance (FMA) (1568-1412 cal yr BP), and late Little Ice Age (LIA) advance (ca. 1742-1851 AD). During each of these advances, a lake (Dispatch Lake) formed when drainage was blocked by construction of a moraine at the lateral margin of Scimitar Glacier. Final breaching of the moraine dam in 2001 AD, resulted in incision and erosion of lake, alluvial, and lateral moraine sediments, providing the stratigraphic and dendroglaciological data that were crucial for reconstructing the history of late Holocene glacier activity.

Scimitar Glacier achieved its maximum extent during the most recent, late LIA advance (ca. 1742-1851 AD). At that time a lobe of the glacier advanced into Pocket Valley (Figure 5.2), dammed a lake below Dispatch Peak (Figure 5.10), and flowed as two lobes of ice around a mound of previously deposited moraine material to create a new terminal moraine (Figures 5.1 and 5.4). The margin of Scimitar Glacier began to significantly recede sometime after the 1930s and has continued to do so until the present. The glacier snout now calves into a growing proglacial lake ca. 1 km from the maximum LIA terminus.

The research at Scimitar Glacier provides the first dendroglaciological evidence for ice expansion during the FMA in the Waddington Range. The discovery of wood remains at Dispatch Lake dating to 1568-1412 cal yr BP provides support for an FMA in the Waddington Range and shows that Scimitar Glacier was responding in concert with regional glacier expansion during this period.

The lack of evidence for early and mid-Holocene glacier advances of Scimitar Glacier may be because the later Holocene advances removed sediments deposited during earlier advances. Alternatively, Scimitar Glacier may not have yet receded and downwasted sufficiently to expose sediments and organics dating to the early and middle Holocene.

### 7.2 Limitations and Future Research

Scimitar Glacier is large, which posed a significant difficulty for field work. Traversing the stagnant ice and steep moraines of the lower part of the glacier was time-consuming, arduous, and sometimes hazardous. As a result, only three sites less than 2 km from each other were documented. Further insights could be obtained by examining other locations along the glacier margin, particularly along the terminal moraine and sites along the south lateral moraine near the confluence of Scimitar and Radiant glaciers.

The provenance of some of the subfossil wood samples could not be established with confidence. Boles and branches found within the lateral moraines lack bark or finer branches and thus may have been transported by the glacier ice from their *in situ* positions. Avalanches are very common in the area and therefore may be the cause of mortality and transportation to the lateral moraine area of some of the collected subfossil samples. Although less precise than in situ samples, an avalanche deposited sample excavated from within a moraine still manages to give a maximum age to the overlying deposit. A search should be made for *in situ* glacially sheared stumps or rooted boles in paleosol horizons.

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