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Neoglaciation and Dendroglaciology at the Saskatchewan Glacier,  
Banff National Park, Canadian Rocky Mountains

by

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Master of Science

in the Department of Geography

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### Abstract

The purpose of this study was to examine the Neoglacial history of the Saskatchewan Valley in Banff National Park. Geomorphic history was explored through an examination of exposed facies and a proxy climate record was established during a two-century interval of the Neoglacial Advance using dendroclimatological techniques.

An exposed Neoglacial subfossil forest was discovered in the proglacial environment of the Saskatchewan Glacier. This *in-situ* forest was sampled extensively, as were other detrital logs in the area. The samples were then identified to species and built into floating tree-ring chronologies. Of three sampled species, only subalpine fir formed a significantly strong chronology that could be statistically analysed. Nearby living forests were sampled to build master chronologies that could be compared to meteorological climate records and examined for their response to local climate.

The derived response function for the living subalpine fir chronology established that July temperature was the primary variable determining tree-growth. This response function was then applied to floating chronology to establish a proxy-climate record of July temperature.

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## Chapter 1 Introduction and Background

### 1.0 Introduction

The late-glacial and Holocene history of the Canadian Rocky Mountains is distinguished by three glacial advances (Luckman and Osborn 1979; Bobrowsky and Rutter 1992). The oldest of these glacial advances is known as the *Crowfoot Advance* in the Canadian Rockies (Leonard and Reasoner 1999) and is assumed to be coeval with the Younger Dryas event in the period from *ca.* 11,300 to 10,000  $^{14}\text{C}$  yr BP (Osborn *et al.*, 1995). Following this advance, glaciers throughout the Canadian Rockies retreated or disappeared entirely during the Hypsithermal warming event from *ca.* 8500 to 5500  $^{14}\text{C}$  yr BP (Kearney and Luckman 1983a). Cooler and moister conditions by *ca.* 4000  $^{14}\text{C}$  yr BP (Beaudoin and King 1990; Reasoner and Huber 1999) heralded mid and late-Holocene glacier advances during the Neoglacial period.

Porter and Denton (1967) introduced the term Neoglaciation to describe a world-wide glacial event that followed a lengthy period during which glaciers were at their Holocene minimum. The Neoglacial is regarded as an asynchronous event because glacial advances attributed to this period range from *ca.* 8000  $^{14}\text{C}$  yr BP (Denton and Karlen 1973) to *ca.* 3000  $^{14}\text{C}$  yr BP (Luckman *et al.* 1993). Within the Canadian Rocky Mountains, the onset of the Neoglacial activity is recorded by soil layers and trees dating to 3800 and 4200  $^{14}\text{C}$  yr BP buried by till at Boundary Glacier (Gardner and Jones 1985; Smith 2001). Corresponding detrital deposits at several sites within the Canadian Rocky Mountains suggest that by *ca.* 3300 and 2800  $^{14}\text{C}$  yr BP most glaciers within this region were advancing rapidly downvalley (*Peyto Advance*, Luckman *et al.* 1993). Following

the Peyto Advance, glaciers throughout this region receded upvalley and only began to readvance during the well-documented late-Holocene Little Ice Age glacial events (*Cavell Advance*) of the last 900 years (Luckman 1986, 1993, 1995, 2000)

The intent of this thesis is to undertake an analysis of recently exposed ice proximal *in-situ* stumps and detrital boles found at the Saskatchewan Glacier in the 1999 and 2000 field seasons (Figure 1.1). The discovery of these sub-fossil samples provides indisputable evidence of a period of glacial activity at the Saskatchewan Glacier that remains inadequately understood. The stumps and detrital wood found at this site were exceptionally well-preserved and allow for a thorough dendroglaciological assessment of the glacial advance responsible for killing them. In addition, the sub-fossil wood occurs in sufficient quantity and variety to permit a paleoenvironmental assessment of the growing conditions immediately prior to their demise.



**Figure 1.1** An *in-situ* subfossil stump found in front of the Saskatchewan Glacier, September, 1999.

## 1.1 Objectives

The objectives of this research programme were to:

1. Complete a geomorphological and dendrochronological assessment of the recently exposed subfossil forest site at the Saskatchewan Glacier.
2. Describe the glaciological events that led to the preservation of the site.
3. Undertake a paleodendroclimatological assessment of the environment at the time of this event.

## 1.2 Outline of the Thesis

Following Chapter One, Chapter Two introduces the physical geography of the study area and documents the existing evidence for glacial activity at the site. Chapter Three examines the dendroglaciological evidence from the site and assesses the Holocene glacial record of the Saskatchewan Glacier. Chapter Four examines the floating chronologies developed from the *in-situ* stumps and detrital wood found at the Saskatchewan Glacier and uses dendroclimatological relationships determined from living tree-ring chronologies to develop paleoenvironmental records of growth conditions. Chapter five provides a summary.

## **Chapter Two**

### **Study Site and Previous Research**

#### **2.0 Introduction**

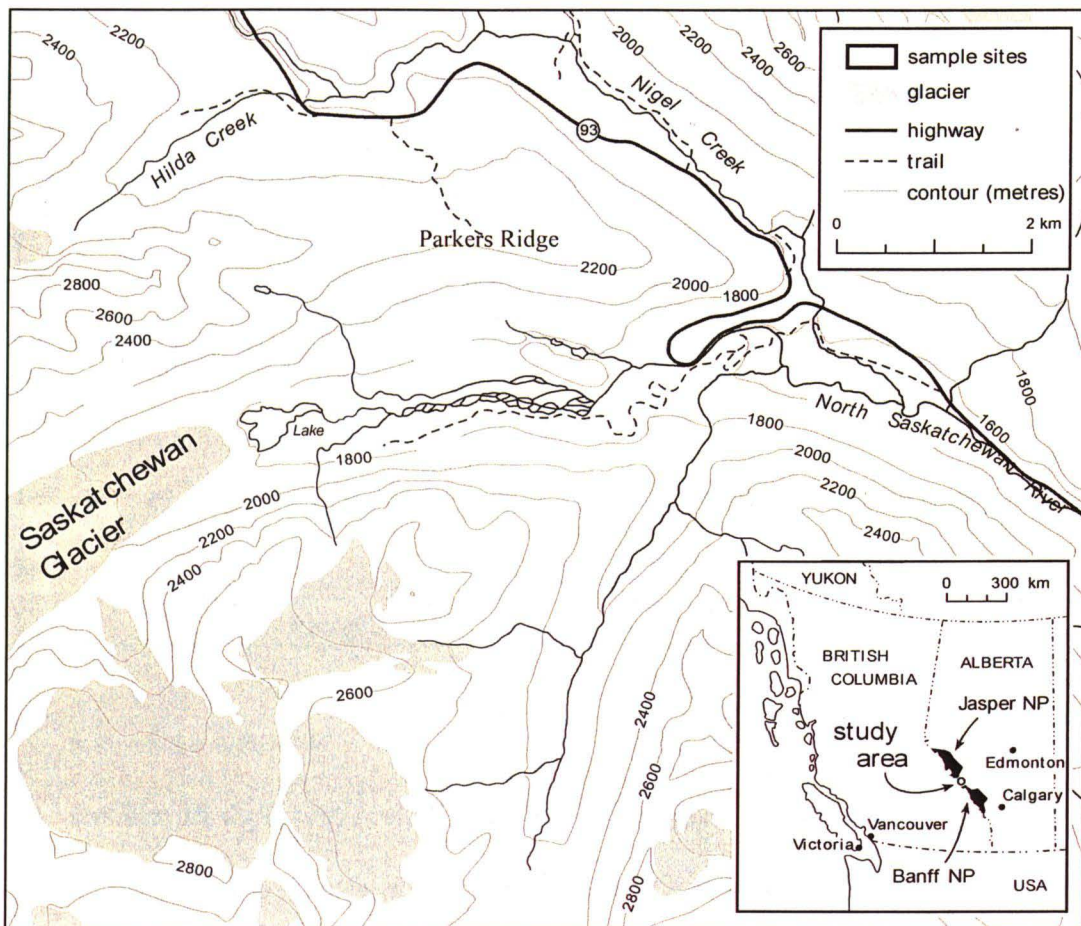
This chapter examines the physical geography of the Saskatchewan Valley. Past research is combined with local observations to present a contemporary portrait of the conditions that exist within the local region of the Saskatchewan Glacier, as well as an overview of what is known about the Holocene history of the area.

#### **2.1 Study Area**

The Saskatchewan Glacier is the largest outlet glacier of the Columbia Icefield. Located in northern Banff and southern Jasper National Parks (Lat  $52^{\circ}06'30''$  N, Long.  $117^{\circ}15'10''$ W), the Columbia Icefield straddles the Alberta-British Columbia interprovincial border (Figure 2.1).

#### **2.2 Geologic and Physiographic Setting**

The Columbia Icefield is located within the Main Ranges structural province of the Canadian Rocky Mountains. Folded and thrust-faulted mountains composed of limestones with shale and dolomite interbeds dominate the local terrain (Ford 1983). The local relief is greater than 2000 m, with the summits of several peaks found above 3300 m asl and major valley bottoms positioned below 1500 m asl (Ford *et al.* 1981). Limestone beds within the Columbia Icefield area are characterized by prominent karst features including sinkholes and Canada's largest underground caves (Ford 1971; Smart and Ford 1983).



**Figure 2.1** Location of the Saskatchewan Glacier study site in Banff National Park.

### 2.3 Late Glacial and Holocene Glacial History

Glaciers emanating from the Columbia Icefield advanced several times during the late Pleistocene (Jennings 1951; Baranowski and Henoeh 1979). Radiocarbon evidence indicates that most major valleys and passes within this region were ice-free by  $9600 \pm 300$   $^{14}\text{C}$  yr BP (Henoeh *et al.* 1979; Kearney and Luckman, 1981) to  $8230 \pm 80$   $^{14}\text{C}$  yr BP (Luckman 1988). Subsequent readvances during the Holocene, for which there is evidence of several (Table 1.1), were of limited extent and duration (Luckman 1977; Luckman and Osborn 1979; Leonard 1981; Osborn 1982).

**Table 1.1** Late Glacial and Holocene history of glacial activity in the Canadian Rocky Mountains

Late Glacial and Holocene Glacial Episodes	Correlated Global Advance
<b>Crowfoot</b> (11,070-9970 <sup>14</sup> C yr. BP) (Leonard and Reasoner 1999; Luckman and Osborn 1979)	Younger Dryas
<b>Peyto</b> (3,300-2,800 <sup>14</sup> C yr. BP) (Luckman 1993; Luckman, 1996; Osborn and Luckman 1988)	Neoglacial
<b>Cavell</b> (600-150 yr. BP) ( Luckman and Osborn 1979; Luckman 2000)	Little Ice Age

- Crowfoot Advance** – The Crowfoot Advance is represented in the Canadian Rockies by moraines, rock-glacier deposits overlain by Mazama ash (6600 yr B.P.) and varve chronologies ( Luckman and Osborn 1979; Reasoner *et al.* 1994; Reasoner 1996; Leonard and Reasoner 1999). A relatively minor readvance that occurred between *ca.* 11,300 and 10,000 ± 80 <sup>14</sup>C yr BP, the Crowfoot Advance is thought to be related to the Younger Dryas climatic reversal (Osborn *et al.* 1995; Osborn and Gerloff 1997).
- Peyto Advance** - The Peyto Advance was identified as the type representative of the Neoglacial glacial advances in the Canadian Rockies (Luckman 1993, 1996; Osborn and Luckman 1988; Luckman *et al.* 1993). Investigations in the Peyto Glacier forefield led to the discovery of sheared *in situ* stumps and detrital boles killed by an advance of Peyto Glacier dated to between 3000 and 2800 <sup>14</sup>C yr BP. Additional radiocarbon evidence for the widespread character of the Peyto Advance has been found at Boundary Glacier (Gardner and Jones 1985), Robson

Glacier ( Luckman *et al.* 1993; Luckman 1995;), Saskatchewan Glacier (Luckman *et al.* 1993; Luckman 1996), Stutfield Glacier (Osborn *et al.* 2001) and Yoho Glacier (Luckman *et al.* 1993). With the exception of Boundary Glacier, where the advancing glacier overrode an *in situ* krummholtz stand of subalpine fir in  $3880 \pm 40$   $^{14}\text{C}$  yr BP, the Peyto Advance is constrained to the interval between 3300 to  $2800 \pm 80$   $^{14}\text{C}$  yr BP.

- **Cavell Advance** – The Cavell Advance describes a well-defined series of synchronous (Little Ice Age) glacier advances in the Canadian Rockies that occurred in the 12<sup>th</sup>-13<sup>th</sup>, early 18<sup>th</sup> and throughout the 19<sup>th</sup> centuries (Luckman 2000). Within the Columbia Icefield area, the Cavell Advance is well constrained by cross-dated tree-ring series from trees pushed over or killed during periods of extensive ice advance (Heusser 1956; Luckman 1986, 1988; Robinson 1998).

Ongoing research in the Columbia Icefields area (Carter *et al.* 1999; Luckman 2000) and corroborative evidence from Pacific North and South America (Markgraf 2000), suggests that glaciers in this region attained coeval maximum terminal positions during both the Crowfoot and Cavell Advances (e.g. Luckman and Osborn 1979). The Peyto Advance, on the other hand, has the least amount of associated empirical evidence, though its apparent association with the Tiedemann Advance of the Coast Mountains further corroborates the likelihood of its existence. The dates acquired for the Tiedemann Advance (2940 and 2250  $^{14}\text{C}$  yr BP; Fulton 1971; Ryder and Thomson 1986) correspond closely to those bracketing the Peyto Advance in the Canadian Rockies, suggesting this was a widespread regionally significant event (Luckman *et al.* 1993).

## 2.4 Climate and Paleoclimate

The present climate of the Columbia Icefield area is generally cool and wet (Janz and Storr 1977). At Parkers Ridge (2270 m asl) located north of the Saskatchewan Glacier (Figure 2.1), the average annual temperature is  $-1.3^{\circ}\text{C}$  and the annual precipitation totals 642 mm (Smith 1985:56). Historical reconstructions demonstrate that average April-August temperatures from 1101-1900 AD were  $0.71^{\circ}\text{C}$  below the 1961-1990 reference period and  $0.33^{\circ}\text{C}$  below the 1891-1990 mean instrument record. The coldest interval was the first half of the nineteenth century and the major cold intervals *ca.* 1200-1350; 1690s and the nineteenth century, coincide with local and regional periods of glacier expansion (Luckman *et al.* 1997; Luckman 2000).

Paleoclimatic records in the vicinity of the Columbia Icefield indicate that by 9700  $^{14}\text{C}$  yr BP environmental conditions were similar to those experienced presently (Kearney and Luckman 1981, 1983a; Beaudoin 1984, 1986; Beaudoin and King 1990). Cooler conditions prevailed from 9000 to 7500  $^{14}\text{C}$  yr BP, around 4800  $^{14}\text{C}$  yr BP, from 3500 to 2800  $^{14}\text{C}$  yr BP and from 1700  $^{14}\text{C}$  yr BP to shortly before present (Beaudoin and King 1990). Based on diatom evidence from cored lakes, conditions immediately preceding the Peyto Advance were also notably wetter (Reasoner and Huber 1999). The climax of the warm, dry, Altithermal hiatus extended from 7500 to 5900 years in this region (Kearney 1981; Kearney and Luckman 1981). There is some indication that climates in the last 500 years are amongst the most severe in this region since early Holocene time (Bowyer 1978; Kearney and Luckman 1983a, 1983b; Luckman *et al.* 1997).

## 2.5 Vegetation

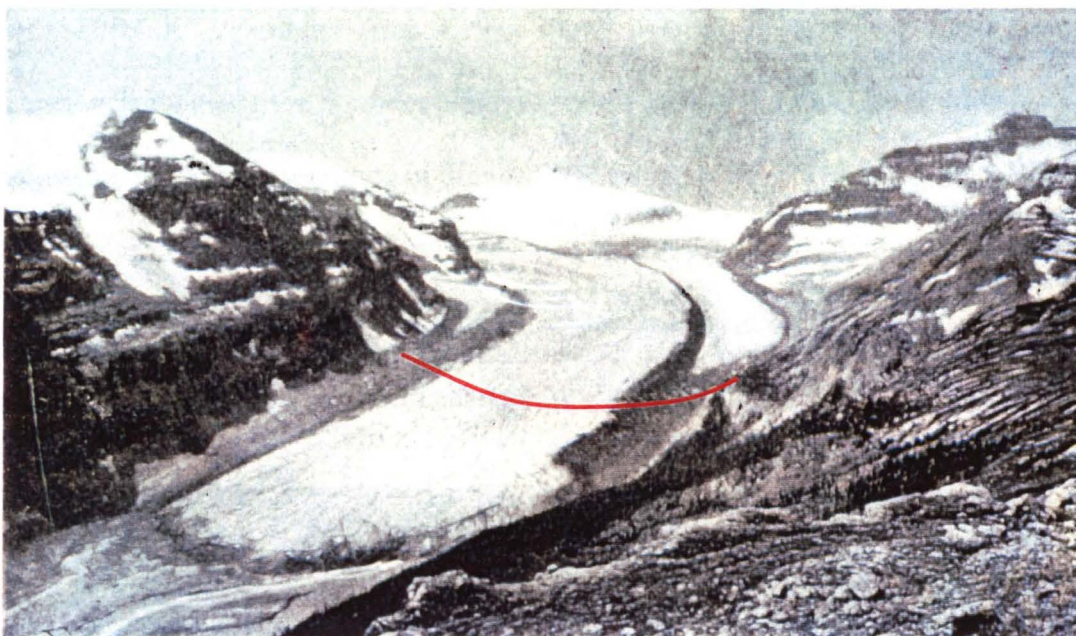
The vegetation of the Columbia Icefield area is characterized by subalpine forests and expansive alpine tundras (Holland and Coen 1983). Most valley bottoms are characterized by mature engelmann spruce (*Picea engelmanni*) and lodgepole pine (*Pinus contorta*) forests, with restricted stands of subalpine fir (*Abies lasiocarpa*) (Luckman and Kavanagh 1998, 2000). At higher elevations above *ca.* 1800 to 2100 m asl, whitebark pine (*Pinus albicaulis*) trees are present (Luckman and Youngblut 1999). From 2100 to *ca.* 2300 m asl, the vegetation consists largely of subalpine fir krummholtz interspersed with various grasses and heathers.

## 2.6 Study Site

### 2.6.1 Location

The Saskatchewan Glacier flows in a north-easterly direction for *ca.* 10 km through a steep-walled valley between Mt. Castleguard and Mt. Andromeda. Meltwater currently flows into a proglacial lake formed at the terminus at *ca.* Lat. 52° 06' 30" N, Long. 117° 15' 10" W at an elevation of *ca.* 1710 m asl. The glacier is the source area for the North Saskatchewan River and plays an important hydrological role in western Canada (Derikx and Loijens 1970; Paton 2001).

Since it was first photographed in the early 1900's the Saskatchewan Glacier has experienced substantial downwasting and frontal retreat (Figure 2.2). As a result of its accessibility, the historical (Field 1949; Henoeh 1971; McPherson and Gardner 1969, Gardner 1972; Robinson 1988) and present-day glaciological behaviour of the Saskatchewan Glacier is relatively well documented (Field 1949; Heusser 1956; Meier 1957; Meier *et al.* 1954; Vachon *et al.* 1996)



**Figure 2.2** Early photo of the Saskatchewan Glacier as viewed from Parkers Ridge in 1919 (Field 1949). The approximate position of the terminus in 2001 is shown by the red line.

The Little Ice Age (LIA, 1200-1900 AD) behaviour of the Saskatchewan Glacier has been described by Heusser (1956) and Robinson (1998). Results from their studies revealed dendroglaciological evidence for multiple LIA events, including a significant mid 19<sup>th</sup> century advance and a less extensive event during the early and middle parts of the 18<sup>th</sup> century. Evidence of a pre-Little Ice Age event comes from detrital wood washed out of the glacier (Luckman *et al.* 1993, 1994). The wood (dating between 3200 and 2500 <sup>14</sup>C yrs BP) provides compelling circumstantial evidence for an advance equivalent to the *Peyto Advance* (3300-2800 yrs. B.P.) at the Saskatchewan Glacier (Luckman *et al.*, 1993).

### 2.6.2 Sub-fossil Study Site

The sub-fossil forest site under investigation was exposed at an ice proximal site located along the northeastern flank of the Saskatchewan Glacier (Lat. 117° 08' 45" N;

Long. 52° 09' 30" W). In late-August 1999, a severe rainstorm caused significant stream channel incision along the northern periphery of the Saskatchewan Glacier. Stream erosion through a thick sequence of till and underlying glacial outwash exposed 26 *in situ* stumps rooted within a well-preserved paleosol (Figure 2.3). The accompanying channel bank erosion left a vertical (*ca.* 2-3 m in height) embankment on the south side of the channel and a steeply sloping north channel bank (*ca.* 4-5 m in height) (Figure 2.4).

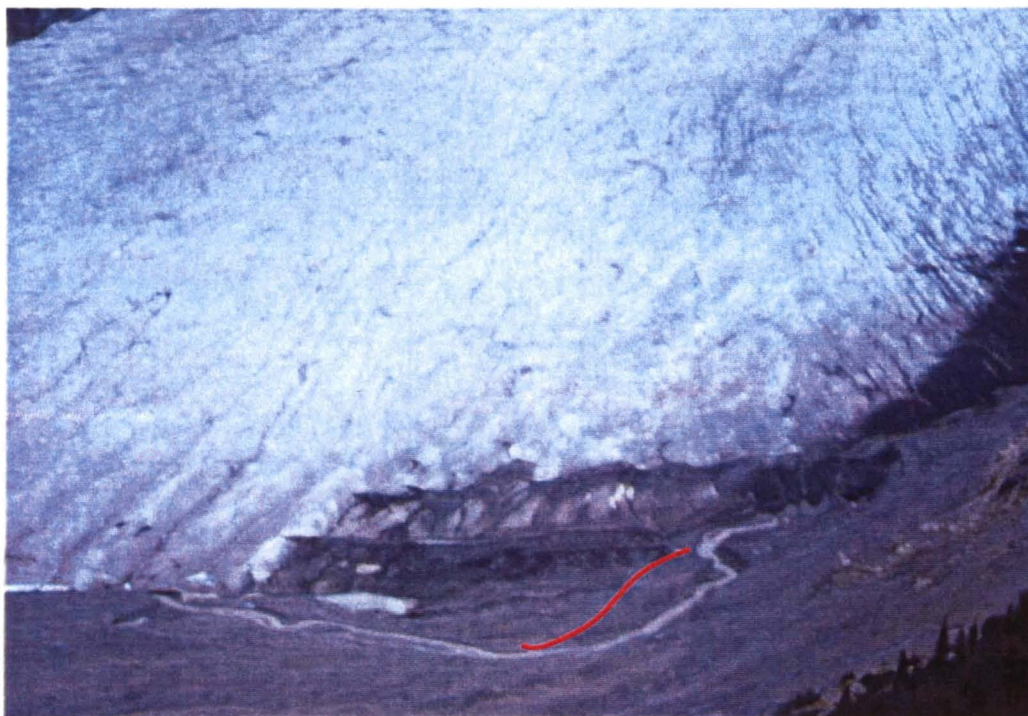


**Figure 2.3** Neoglacial paleosol found below glacial till at the Saskatchewan Glacier in 2000. Note the well-preserved conifer needles on the surface of the field note book that were found within the buried organic horizon.



**Figure 2.4** Detrital logs embedded in upper layers of diamicton; directly above and beside the main study site.

When first examined in September 1999, channel migration was causing point bar development and active erosion of a minor erosional terrace positioned 0.5 - 1 m above the stream on the north side of the channel. By September 2000, the river course had shifted southward away from the sub-fossil forest site and was eroding through 5 m of fluted moraine deposits exposing substantial accumulations of masticated stumps and boles (Figure 2.5).



**Figure 2.5** Oblique view of Saskatchewan Glacier terminus and ice proximal river channel in July, 2000. The red line shows the approximate position of the river by September, 2000.

### 2.6.3 Stratigraphic Setting

A general representation of the stratigraphic setting of the sub-fossil forest site is presented in Figures 2.6 and 2.7.

#### Unit Descriptions

1. **Unit 1** is a heavily cemented layer of clast-supported gravel. There is little sorting or stratification within this layer, though only the upper 30 cm of the unit was visible. The clasts consist of imbricated sub-rounded to sub-angular limestones and dolomites, with an average clast size of 8-10 cm with little variation. The matrix volume composed 10-15 percent of the total unit, and consisted primarily of clay with some coarse sand. The fabric for this unit was relatively weak with  $S_1$  values of  $\sim 0.60$ .

Unit 1 is considered to be an ice-proximal glaciofluvial braided stream deposit. While the fabric is less strongly expressed than expected for a fluvial deposit (Eyles *et al.* 1983), the bi-directional expression (Figure 2.6) is characteristic of high-energy water-borne deposits.

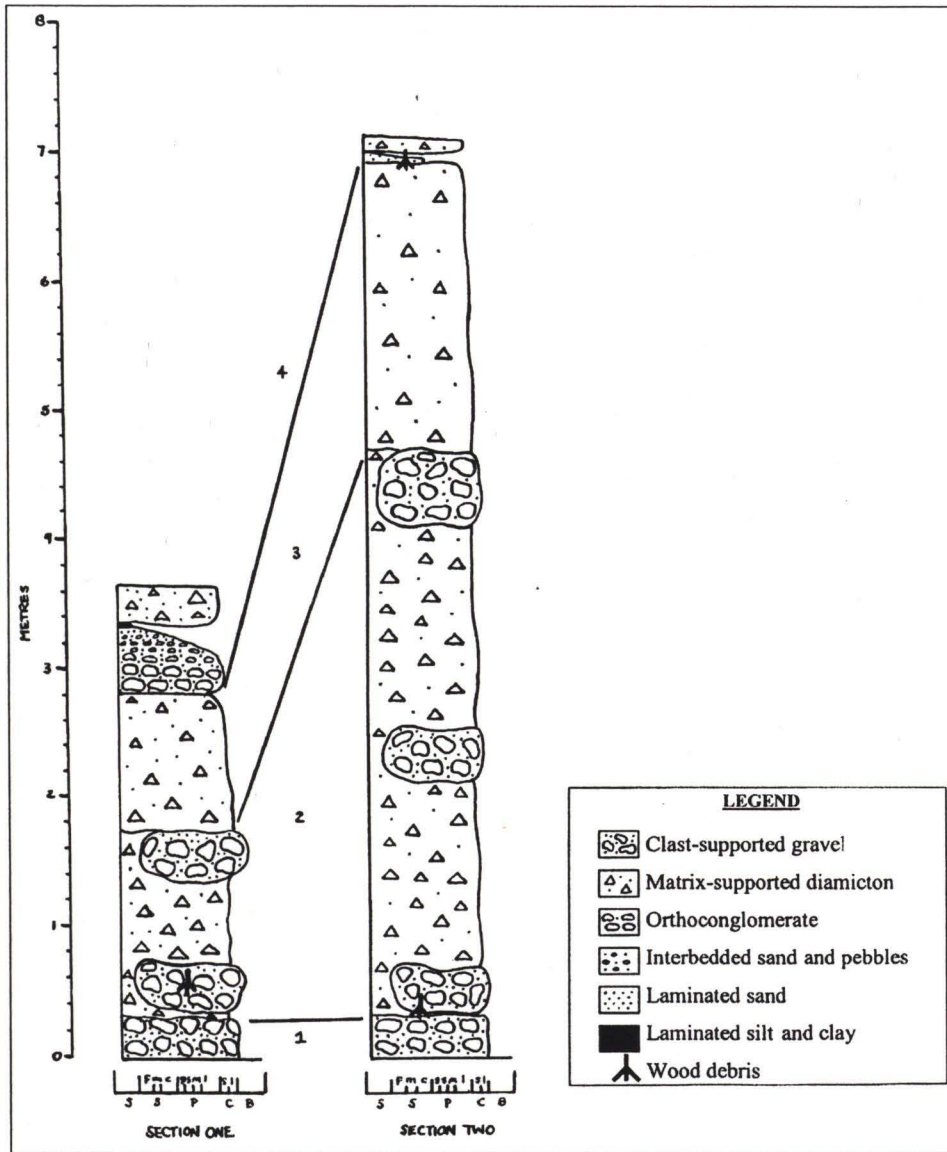


Figure 2.6 Cross-sectional schematic of stratigraphic setting within the two river channels (see Figure 2.5) (Walker 2000)

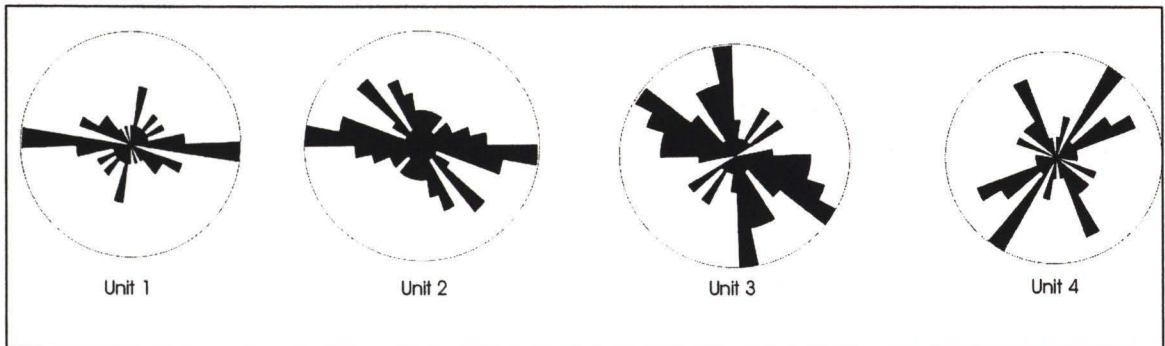


Figure 2.7 Till fabric representations from each of the four units.

2. **Unit 2.** The boundary between Units 1 and 2 is marked by an unconformable contact. Unit 2 is matrix-supported with no obvious organization. The matrix makes up *ca.* 35 percent of the unit and consists of a silty-clay sediment. The clasts are sub-rounded to sub-angular in shape with striations present on their surfaces. The size of the clasts vary from small pebble to large cobble and has a relatively weak fabric ( $S_1=0.60$ ). Within Unit 2 there are extensive gravel lenses that extend laterally for up to 4.5 m. Detrital wood fragments were found throughout the unit (Figure 2.4).

Unit 2 is interpreted as basal till unit composed of reworked glaciofluvial gravels. The large number of detrital wood fragments visible within the deposit are consistent with this interpretation and suggest a short transport distance.

3. **Unit 3.** A massive matrix-supported (50% by volume) gravely deposit, Units 3 is similar in composition and appearance to Unit 2. It is distinguished from the latter by a diffuse contact above which the matrix volume increases. The clasts within Unit 3 average 4-5 cm in size and have only a weak fabric ( $S_1=0.44$ ). No detrital wood was found within this unit, nor was their evidence of sorting or sedimentary structures.

Unit 3 is interpreted as a till, with the contact between Units 2 and 3 possibly marking the boundary between two glacial events.

4. **Unit 4.** The transition from Unit 3 to 4 is distinguished a thin bedded layer of coarse sand. The clasts within Unit 4 consist of sub-rounded to sub-angular cobbles of highly variable size (consistently less than 8 cm) and have only a weak fabric ( $S_1=0.49$ ). The matrix ratio was highly variable among several subunits that appear and disappear throughout the unit. While detrital wood fragments were found throughout unit, they were few in number. On the surface several glacial flutings were present, with one containing a 2 m long bole and stump section.

Unit 4 is interpreted as a subglacial meltout till. While the presence of glacial flutes on the surface of this unit suggest some form postdepositional till deformation did occur (McPherson and Gardner 1969; Boyce 1993), the weak fabric characterizing Unit 4 is characteristic of some meltout tills (see Paul and Eyles 1990; Hicock *et al.* 1996).

## 2.7 Chapter Summary

During the last 10,000 years there have been three major episodes of glacial re-advancement. Each subsequent advance has had the deleterious effect of damaging and/or destroying the biological and geomorphological evidence deposited by previous

advances. Evidence for these advances has come in the form of scattered remains of biological and sedimentary evidence preserved within bogs, lakes, or in some cases beneath layers of sediment within the glacial forefields. Chapter 3 will describe the findings of a dendroglaciological investigation of a Neoglacial sub-fossil forest found at the current terminus of the Saskatchewan Glacier.

## **Chapter Three**

### **Dendroglaciological Studies at the Saskatchewan Glacier**

#### **3.0 Introduction**

Dendroglaciology is a subdiscipline of dendrochronology that uses tree ring evidence to study the past movement of glaciers (e.g. Ryder and Thompson 1986; Luckman 1988; Luckman *et al.* 1993). The amount of information that can be inferred from ring-width data is a direct result of two major factors: the presence or absence of bark, and whether or not the tree is still in growth position. Detrital wood samples with bark have the potential to provide the exact date of death for the tree, as the presence of bark ensures that there has been no abrasion or loss of the outermost ring-width. In contrast, subfossil detrital wood without bark may include older samples incorporated into younger sediments (Luckman *et al.* 1993). Wood that is recovered in growth position, with evidence that the top of the tree was sheared by ice movement, has the potential of providing an absolute age for the glacial advance that killed the trees. In recent studies within the southern Canadian cordillera, accurate dates have been established for advancing Little Ice Age glaciers by cross-dating recently exposed *in-situ* stumps with living chronologies (Luckman 1995, 1996; Smith and Laroque 1996).

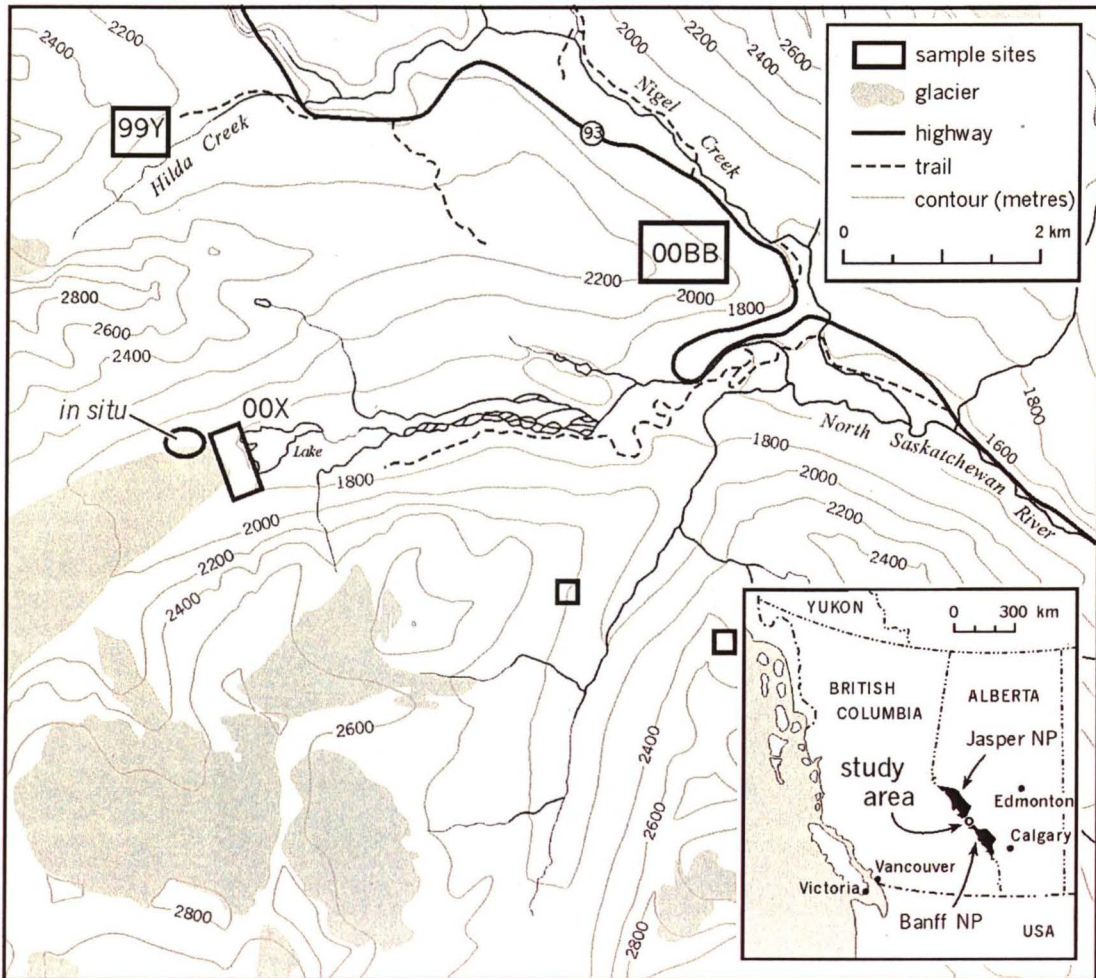
#### **3.1 Investigations at the Saskatchewan Glacier**

Sub-fossil wood samples were collected within the Saskatchewan Glacier forefield during two field seasons. In September 1999, cross-sectional discs were collected from approximately 18 *in-situ* stumps located within or adjacent to the stream channel incised into recently exposed proglacial sediments (Figure 3.1). Disc samples were also collected from 29 recently deposited ice-proximal detrital boles/stumps.

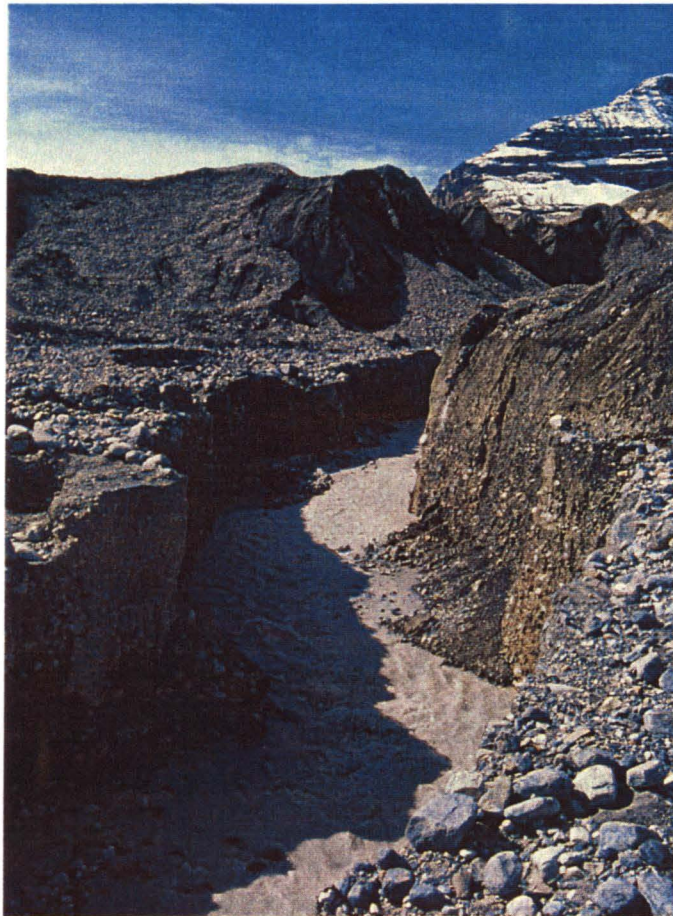


**Figure 3.1** Photo of *in-situ* stumps in the proglacial waters of the North Saskatchewan River.

Sampling in 2000 occurred throughout July and in early-September. During July an exhaustive search for sub-fossil wood on the Saskatchewan Glacier outwash surface resulted in the collection of an additional 40 detrital discs. Over this period, increment core samples were also collected from living stands of englemann spruce, subalpine fir, lodgepole pine and whitebark pine found within or adjacent to the Saskatchewan Valley (Figure 3.2). A return visit to the *in-situ* stump site in early-September 2000, revealed that the proglacial stream had shifted course and had eroded a new channel adjacent to that created in 1999 (Figure 3.3). Exposed within the channel and channel cutbanks were two *in-situ* stumps and a number of detrital logs. Cross-sectional discs were collected from an additional 6 stumps/logs, bringing the total number of sub-fossil discs collected to 93.



**Figure 3.2** Sample site locations. OOB is the big bend site where the majority of the living chronologies were collected. 99Y is the subalpine fir sample location (Bachrach *et al.* 2000). OOX is the area of collection for sub-fossil detrital wood. Other areas indicated sites where samples were collected from living whitebark pine trees.



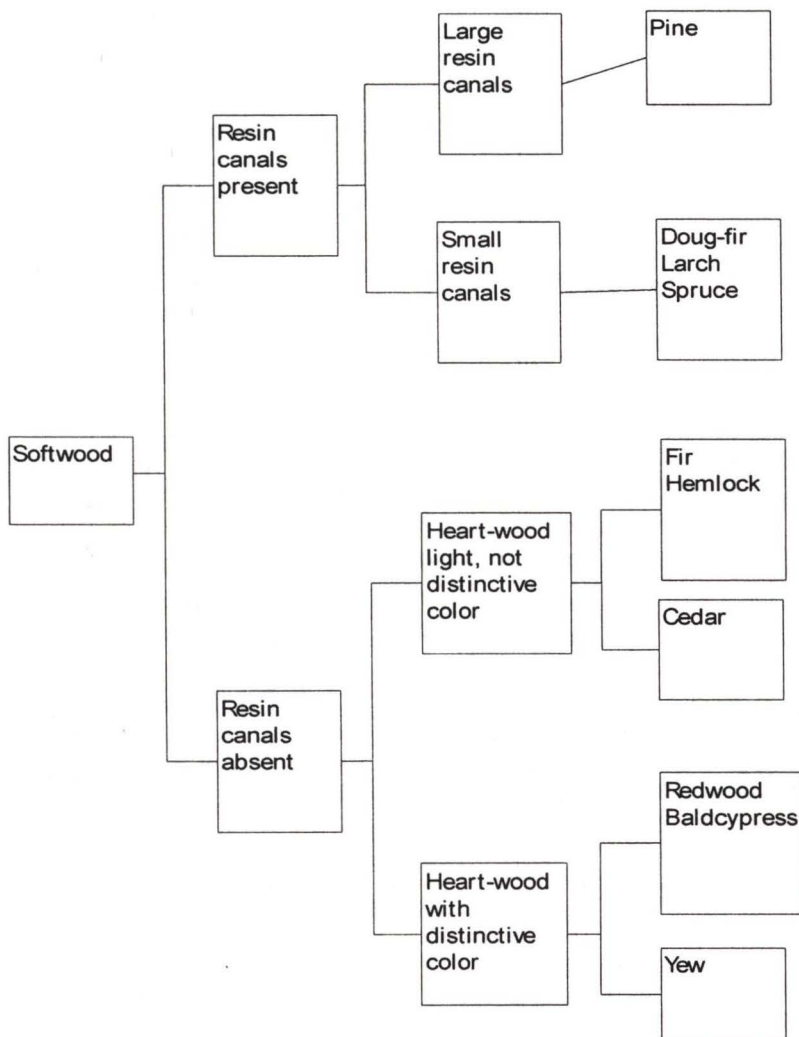
**Figure 3.3** Photo of the new river channel (September 2000) taken from the position of the channel in September, 1999.

### **3.2 Sample Preparation**

The sub-fossil discs and increment core samples were prepared for measurement and analysis according to standard dendrochronological procedures (Stokes and Smiley 1968). After air drying, the cores were glued into grooved boards and sanded with progressively finer grades of sand paper (100 to 600 grit). Like the core samples, one surface of each detrital disc was finished to a polish using progressively finer grained sandpaper. Discs that were partially rotted or had missing fragments were soaked in melted paraffin wax to provide additional support.

### 3.3 Sample Identification

Living trees were identified to species at each site using a standard reference key (Hoadley 1993). Species identification of the sub-fossil discs was based on a cell structure analysis viewed with a 40X microscope using the criteria outlined by Hoadley (1993) (Figure 3.4).



**Figure 3.4** General guidelines for softwood identification based on cell structure (adapted from Hoadley 1993).

The primary criteria used for species identification were the presence/absence of resin canals, and tracheid size and distribution. Within the Columbia Icefields region, only true firs have a complete absence of resin canals (Hoadley 1993) and any wood lacking this feature was assumed to be subalpine fir. Spruce and pine discs were differentiated based on the size of the resin ducts (Hoadley 1993).

Ascertaining whether the discs identified as pines were lodgepole pines or whitebark pines was problematic. Although whitebark is a soft pine and lodgepole is a hard pine, the sub-fossil nature of the discs made the appropriate density tests virtually useless (Hoadley 1993). Two criteria were, therefore, established to differentiate the samples based on procedures described by Hoadley (1993). First, the tracheid's of lodgepole pine tend to be very homogeneous in nature, growing in approximately the same size and shape throughout the ring-width and tree-diameter. On the other hand, whitebark pine tend to have tracheids of varying size and shape scattered randomly throughout the annual rings. The second criterion, used only for verification of results, was an examination of the annual ring boundaries that show a more abrupt transition from early-wood to late-wood in hard pines (lodgepole) than in soft pines (whitebark).

If there was any doubt as to species identification, the disc in question was not included in subsequent analyses. A total of 22 samples were excluded because they could not be identified to species with any certainty.

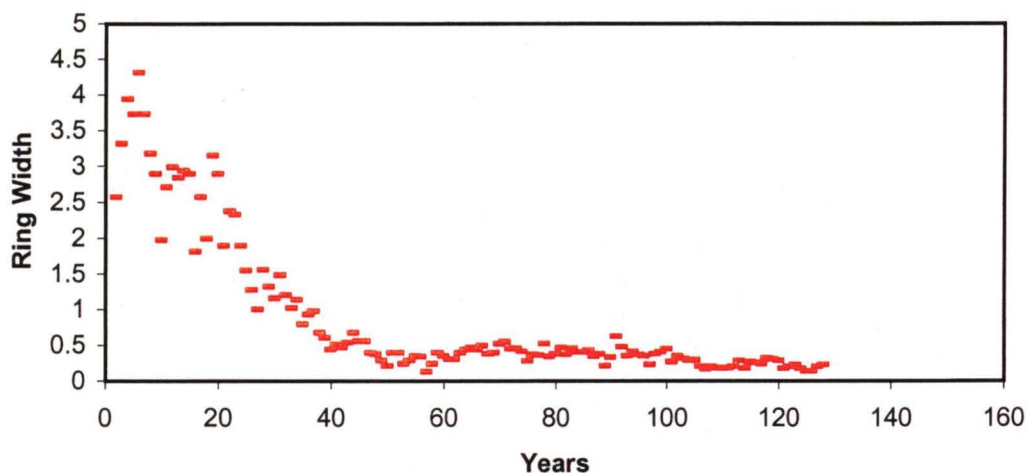
### **3.4 Ring-width Measurement**

Each ring-width sample was measured using either a Velmex-type measuring stage or a computerised WinDENDRO™ digital tree-ring measurement system (Guay *et al.* 1992). WinDENDRO acquires a high-resolution digital image (800 to 2000 DPI) of

the sample with an Agfa Duoscan flatbed scanner, and was used to count and measure the annual ring-widths to the nearest  $1/100^{\text{th}}$  of a millimetre. The larger sub-fossil discs were measured on a movable stage used in combination with a microscope to achieve results to the nearest  $1/100^{\text{th}}$  of a millimetre.

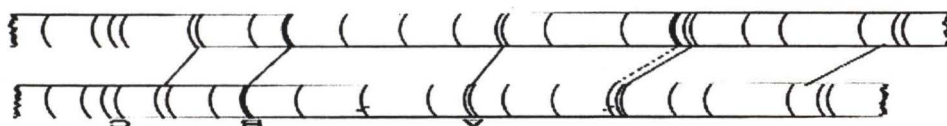
### 3.5 Tree-ring Analysis

Prior to the completion of any analysis of tree ring measurements two important steps must first be completed: standardisation of tree ring series and cross-dating of the samples into a single series. Annual ring-widths tend to decrease in size with increasing tree age, with increasing height in the young stem, and with decreasing apical growth (Fritts and Swetnam 1989). Standardisation is the elimination of tree growth trends that occur as the result of age. In a situation of limited competition, the differential growth pattern is one where the widest rings appear near the base and central portions of the stem (Figure 3.5).



**Figure 3.5** Radial growth measurements of a subalpine fir from sample location 99Y (see Figure 3.2).

Once ring-width measurements have been obtained, they must be measured and checked for accuracy. Quality control in dendrochronology is accomplished through a process called cross-dating, which can be defined as both a principle and a practice. The principle of cross-dating refers to the agreement of annual ring-width characteristics between different trees, whereas the practice involves the correction of any lack of synchronicity between trees. The practice of cross-dating ring-width is performed for virtually all branches of dendrochronology. Cross-dating is accomplished by developing a 'living' chronology through coring live specimens, and combining them into a single 'master' chronology. By cross-matching anomalously small and large rings, or 'marker years', between cores from individual trees, a master chronology is produced (Figure 3.6)



**Figure 3.6** Cross dating tree cores using significant 'pointer years' to align multiple cores.

In this study, the ring-width measurements were cross-dated and standardized by species using the software programs COFECHA (Holmes 1994) to check for quality and ARSTAN (Holmes 1994) to remove life-cycle growth trends. ARSTAN maximizes the signal to noise ratio within the measurements to create standardized tree-ring chronologies composed of ring-width indices ("signal" is the relevant information contained in the tree-ring-widths, whereas "noise" is the information irrelevant to growth features of the tree).

### 3.6 Radiocarbon Dating

Previous investigations of detrital wood found within the Saskatchewan Glacier outwash suggested that the detrital and *in-situ* samples collected in 1999 and 2000 were likely a result of the Neoglacial Peyto Advance (Luckman 1993; Robinson 1998). After preliminary attempts to cross-date samples to living chronologies failed, three pieces of sub-fossil wood were submitted for standard radiocarbon analysis to Beta Analytic Inc. (Miami, Florida) in October, 1999. Two of these samples were from near-perimeter tree-ring sequences taken from *in-situ* stumps (UVTRL 99W07, 27 annual rings [Figure 3.7] and UVTRL 99W24, 55 annual rings). A third near-pith tree-ring sample was carved from a fragmented bole collected within the detritus band shown in Figure 2.4 (UVTRL 99W031, 75 annual rings).



**Figure 3.7** Sample 99W07 prior to being cut for C14 dating.

At Beta Analytic Inc., the samples were first gently crushed in deionized water and then given hot HCl acid washes to eliminate any carbonates. A final alkali wash

(NaOH) removed any secondary organic acids. The alkali washes were followed by a final acid rinse to neutralize the solution prior to drying. The samples were then analyzed by synthesizing the sample carbon to benzene (92% C), measuring for  $^{14}\text{C}$  content in a scintillation spectrometer, and then calculated for radiocarbon age (Wong *et al.* 1975).

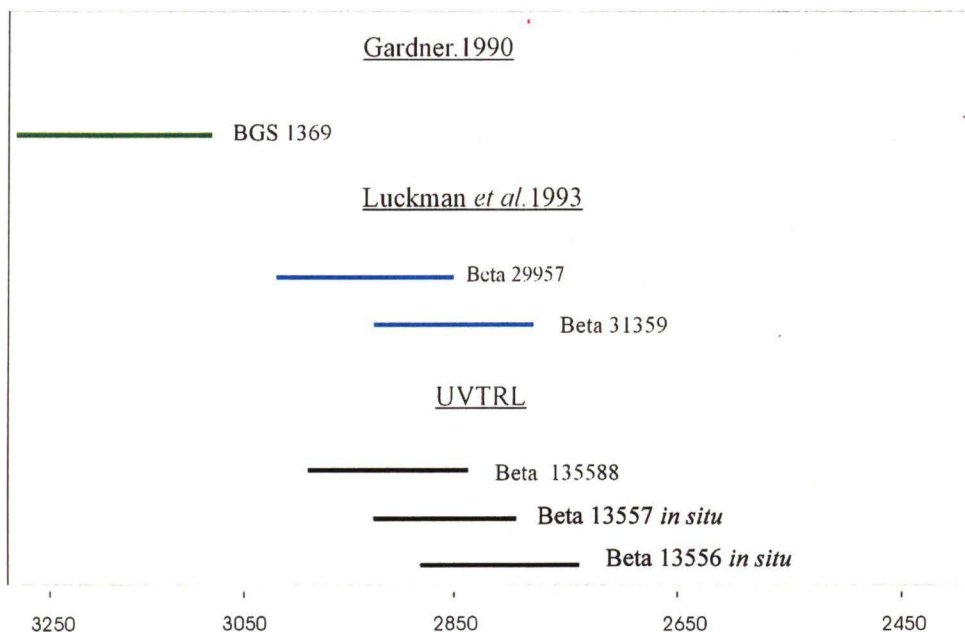
### 3.7 Results

#### 3.7.1 Radiocarbon Dating

The three radiocarbon-dated samples (99W07, 99W31, 99W24) have contemporaneous ages that range from  $2910 \pm 60$  to  $2830 \pm 60$   $^{14}\text{C}$  yrs BP (Table 3.1). They are comparable in age to those previously dated at this site (Figure 3.8) and confirm that the Saskatchewan Glacier was advancing into a mature forest *ca.* 3000 years ago.

**Table 3.1 Radiocarbon dated wood samples**

UVTRL Sample Number	Beta sample number	Species	Sample weight (grams)	Growth years analyzed (yrs)	Conventional $^{14}\text{C}$ age (yrs BP)	Calendar age (yrs BP)
99W07	135586	Subalpine fir	87.5	27	2830 +/-60	3090-2785
99W31	135588	Whitebark pine	105.2	75	2870 +/-60	3255-2860
99W24	135587	Englemann Spruce	78.8	55	2910 +/- 70	3195-2845



**Figure 3.8** Radiocarbon dating of wood samples from the Saskatchewan valley during the last 12 years. The bars indicate predicted errors in  $^{14}\text{C}$  dates.

### 3.7.2 Floating Chronologies

The eighteen ice proximal *in situ* stumps sampled in 1999 consist of a mixed stand of 10 subalpine fir, 5 englemann spruce and 2 whitebark pines. Dendrochronological analysis of discs collected from these stumps and from detrital wood from the outwash surface resulted in the development of two floating tree-ring chronologies (Table 3.2):

- a floating whitebark pine chronology compiled from 13 samples that spans a 262 year interval. The chronology has a series correlation of 0.402; a mean sensitivity of 0.176 and autocorrelation value of  $-0.021$ . The subsample signal strength (SSS) recorded for the chronology is 0.789.
- a floating subalpine fir chronology compiled from 26 samples that spans a 225 year interval. The chronology has a series correlation of 0.437; a mean sensitivity of 0.186 and autocorrelation value of  $-0.012$ . The subsample signal strength (SSS) recorded for the chronology is 0.888.

**Table 3.2** Summary statistics of floating sub-fossil chronologies

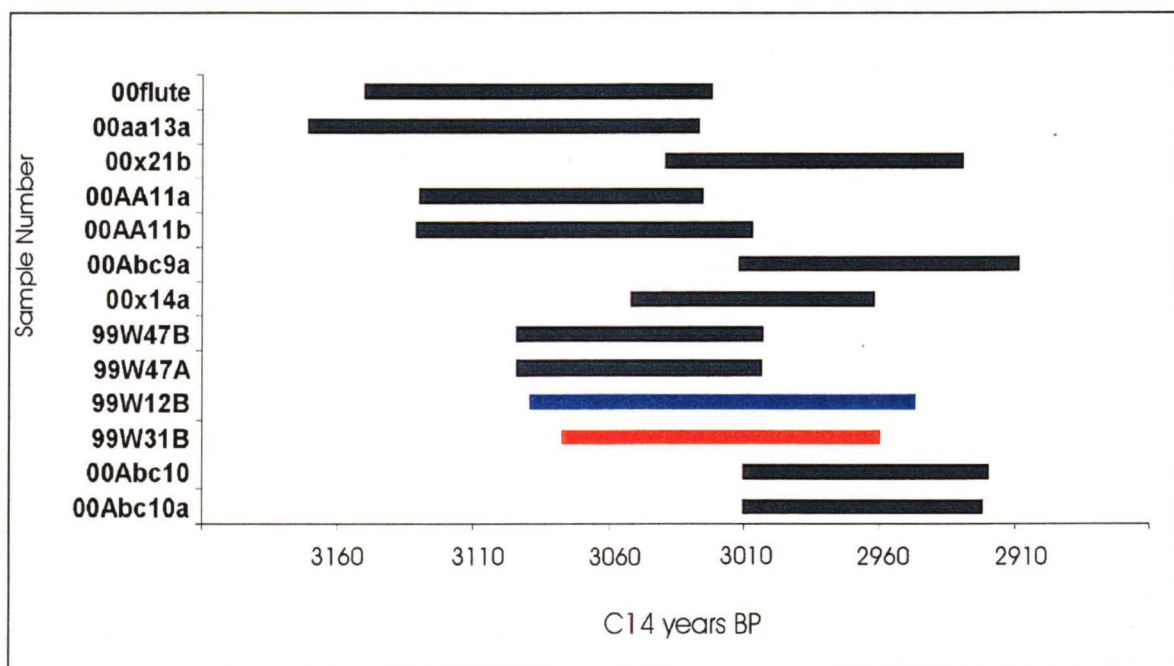
Species	No. samples	Duration (yrs)	Correlation with master	Mean sensitivity	Auto-correlation	SSS	Standard deviation
Subalpine fir	26	225	0.437	0.186	-0.012	0.888	0.333
Whitebark Pine	13	262	0.402	0.176	-0.021	0.789	0.371

1. The “correlation with master” statistic is a measure of the common signal within the series and is significant at values greater than +/-0.3281 at the 99% confidence interval (Holmes 1994).
2. Mean sensitivity is the mean percentage change from each measured yearly ring value to the next (Douglass 1936, cited by Fritts 1976). It is viewed as a measure of complacency with a value of 0 indicating little or no variation in ring-width values and 1 indicating extreme ring-width variation or a high sensitivity to change
3. Autocorrelation is a measure of the outcome that one years growth will have on the next. This value is measured on a scale of 0 to +/-1 with a value of 0 having no effect and a value of 1 being the sole contributor the next years ring-width.
4. The subsample signal strength (SSS) statistic indicates whether there is enough signal in the data to be able to use the series as a predictive tool. An SSS value of greater than 0.80 is considered significantly strong to be used for further analysis (Wigley *et al.* 1984).

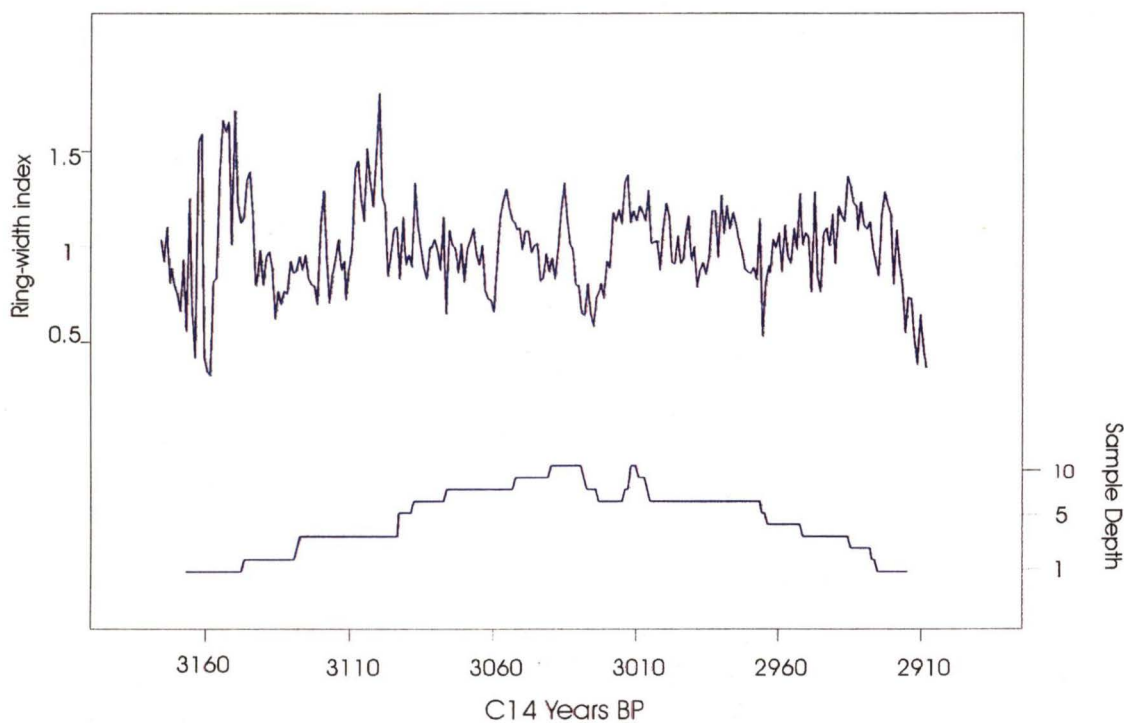
### 3.7.2.1 Whitebark Pine Chronology

The floating whitebark pine chronology was developed from eight detrital wood samples and discs from two of the *in-situ* stumps (99W12B and 99W31B). The radiocarbon age assigned to 99W31B (2870 +/-60 <sup>14</sup>C yrs BP, see Table 3.2) was corrected for ring position/number and used to provide relative ages for the thirteen measurements included in the chronology (Figure 3.9).

The master floating whitebark pine is shown in Figure 3.10 as a ring-width index extending from 3174 to 2912 <sup>14</sup>C yrs BP. The chronology illustrates considerable variation in annual growth over this 262 year interval, with notable pointer years shown in *ca.* 2968, 3036 and 3075. Of particular interest is the decline in ringwidth growth over the last 15 years of the chronology. This decline may signal deteriorating growth conditions as the Saskatchewan Glacier encroached upon the trees composing this part of the chronology.



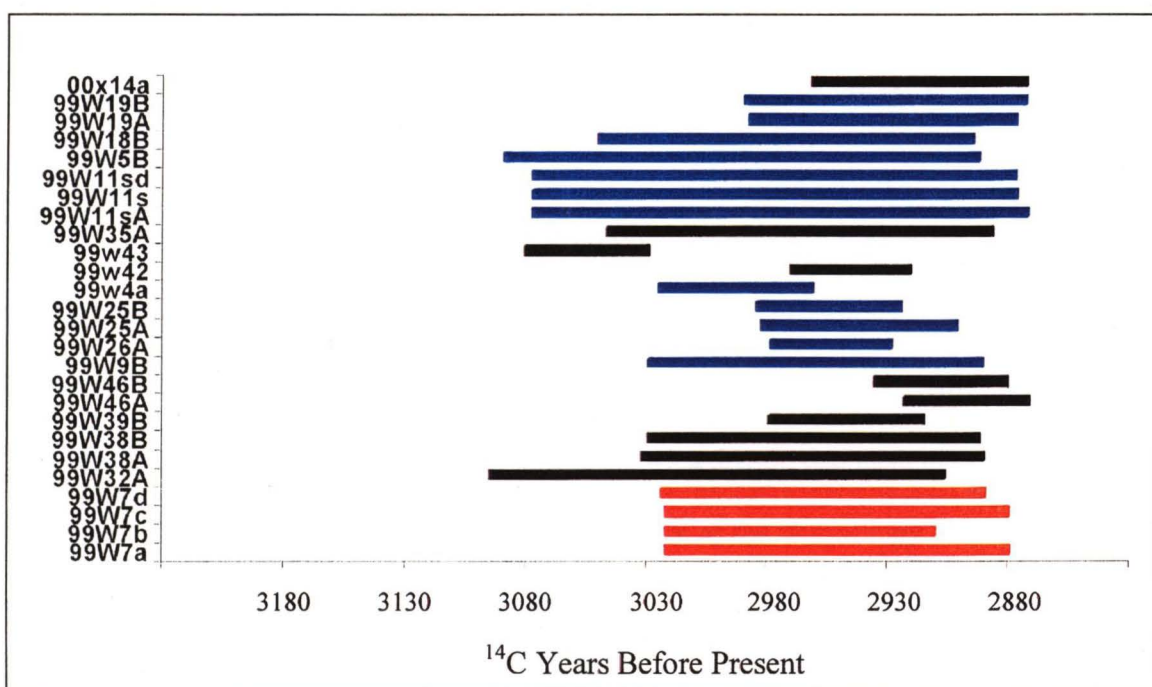
**Figure 3.9** Individual series included within the floating whitebark pine chronology. Black bars represent detrital samples, the blue bar represents samples that were discovered in growth position, and the red bar represents *in-situ* samples with radiocarbon control.



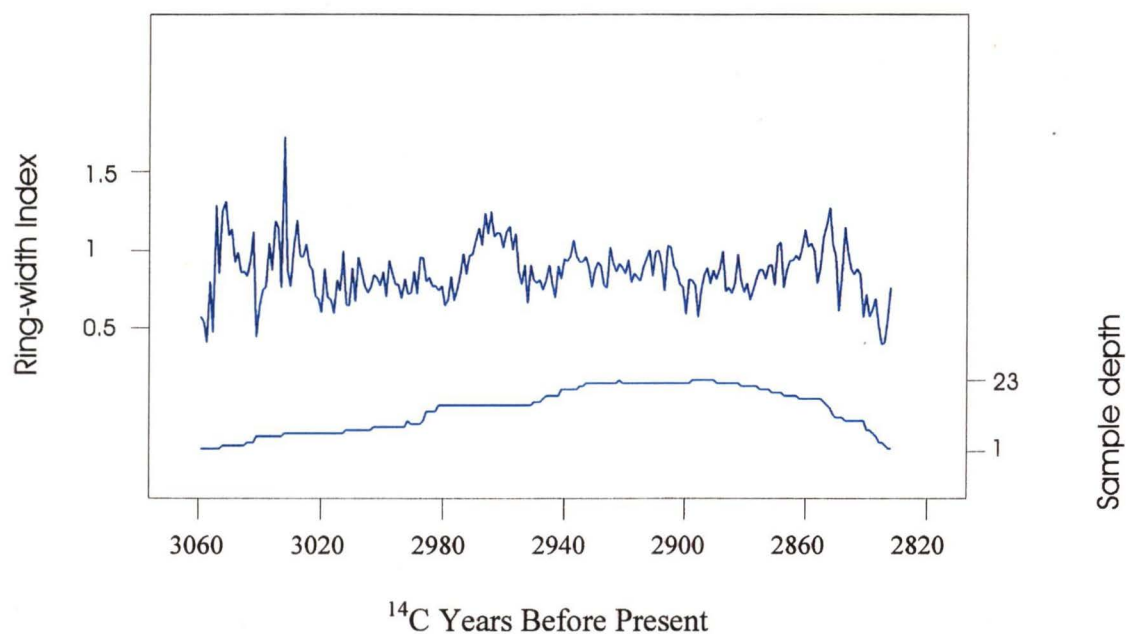
**Figure 3.10** 262 year floating whitebark pine master chronology from 13 samples.

### 3.7.2.2 Subalpine Fir

The floating subalpine fir chronology was developed from eighteen detrital wood samples and discs from 9 of the *in-situ* stumps. The radiocarbon age assigned to 99W7 (2830 +/-60  $^{14}\text{C}$  yrs BP, see Table 3.2) was corrected for ring position/number and used to provide relative ages for the 26 measurements included in the chronology (Figure 3.11).



**Figure 3.11** Individual series included within the floating subalpine fir chronology. Black bars represent detrital samples, the blue bars samples that were discovered in growth position, and the red bars represent *in-situ* samples with radiocarbon control.



**Figure 3.12** 225 year floating subalpine fir master chronology from 26 samples.

The master floating subalpine fir chronology is shown in Figure 3.12 as a ring-width index extending from 3047 to 2823  $^{14}\text{C}$  yrs BP. The chronology illustrates only limited variation in annual growth over this 225 year interval. Similar to the whitebark pine chronology, the subalpine fir chronology shows a drastic decrease in the annual increment of ring-width growth over the last 15 years of the chronology. The large number of *in-situ* ring-width series included within the chronology and the close correspondence of kill dates indicate that the trees shown in Figure 3.10 were most likely killed shortly after 2823  $^{14}\text{C}$  yrs BP by the advancing terminus of the Saskatchewan Glacier.

### 3.8 Discussion

The Peyto Advance was designated in a paper by Luckman *et al.* (1993) to describe a Neoglacial advance of Peyto Glacier in Banff National Park. Dated at between *ca.* 3000 and 2800  $^{14}\text{C}$  yrs BP by the discovery of *in-situ* stumps associated with

paleosols, the Peyto Advance appears to correlate with Neoglacial advances at Boundary Glacier (Gardner and Jones 1985, Smith 2002, *personal communication*), Yoho Glacier (Luckman 1993), Robson Glacier (Luckman *et al.* 1993) and the Saskatchewan Glacier (Luckman *et al.* 1993; *this thesis*) in the Canadian Rocky Mountains.

Wood flushed out of these glaciers or found *in-situ* dates to between 4000 to 2800  $^{14}\text{C}$  yrs BP, with most sub-fossil sites showing that the majority of glaciers advancing into forests that occurred upvalley of present glacier termini between 3300 to 2800  $^{14}\text{C}$  yrs BP. Comparative evidence from the Columbia Icefield area now suggests that small cirque glaciers like Boundary Glacier responded quickly to changing Neoglacial climates (*in-situ* stump dating to 4050  $^{14}\text{C}$  yrs BP [Gardner and Jones, 1985]), whereas large valley glaciers like the Saskatchewan Glacier had slower response times and were still actively advancing some 1200 years later.

The findings of this dendroglaciological investigation substantiate the Peyto Advance as a regional glaciological response to changing mass balance conditions. This glacial episode appears throughout the glacial record in the Southern Canadian Cordillera, with coeval events at the Tiedemann Glacier in British Columbia's Coast Range. The Neoglacial advance at Tiedemann Glacier was first studied by Fulton (1971), who used conventional radiocarbon techniques to bracket an advance between 2940 and 2250  $^{14}\text{C}$  yrs BP. Comparative evidence for a general regional cooling during this interval has also been derived from palynological studies on the Queen Charlotte Islands (Pellatt and Mathewes 1997).

## Chapter 4

### Dendroclimatic Reconstruction of July Temperature Trends at the Saskatchewan Glacier; 3047 to 2823 <sup>14</sup>C BP

#### 4.0 Introduction

This chapter presents a proxy record of ice proximal climatic conditions in the Saskatchewan River Valley prior to ca. 2800 <sup>14</sup>C yrs BP. Recent dendroclimatological studies have shown how radiocarbon-controlled floating chronologies offer a unique insight into past climate variability (Grudd *et al.* 2000; Roig *et al.* 2001). A comparison of the radial growth trends derived from living subalpine fir in this region show clear similarities to those recorded within the 3000 year-old floating subalpine fir chronology described in Chapter 3. This similarity suggests that the growth response of the two chronologies contain comparable climatic information (Fritts *et al.* 1971), providing an opportunity to construct a proxy record of paleoclimatic conditions at the Saskatchewan Glacier between 3047 to 2823 <sup>14</sup>C yrs BP.

#### 4.1 Growth Response of Subalpine Fir to Climate

The growth response of subalpine fir trees to climate has been studied at a number of sites in the Pacific Northwest (Colenutt and Luckman 1991; Ettle and Peterson 1995a, 1995b; Smith and Desloges 2000). Generally, mid to high-elevation stands of subalpine fir display positive radial growth responses to July and/or August temperature; and negative responses to above normal winter precipitation and warmer than normal August temperatures in the preceding year of growth (Ettle and Peterson 1995b). These growth-climate relationships suggest that warm late-summer temperatures (July/August) prolong the growing season (normally June-July in this setting) (St. George and Luckman 2001), resulting in the production of larger than average annual ring-width. Conversely,

abnormally warm August temperatures also lead to a greater allocation of carbon to stem growth, limiting the amount of carbon storage and thereby potentially reducing radial growth in the following year (Kozlowski and Keller 1966). Deep, lingering, winter snowpacks likely shorten the growing season and limit radial growth of treeline tree species (e.g. Gedalof and Smith 2001).

#### 4.2 Living Subalpine Fir Chronology

A master living subalpine fir chronology was developed from samples collected at two sites within close proximity of the Saskatchewan Glacier:

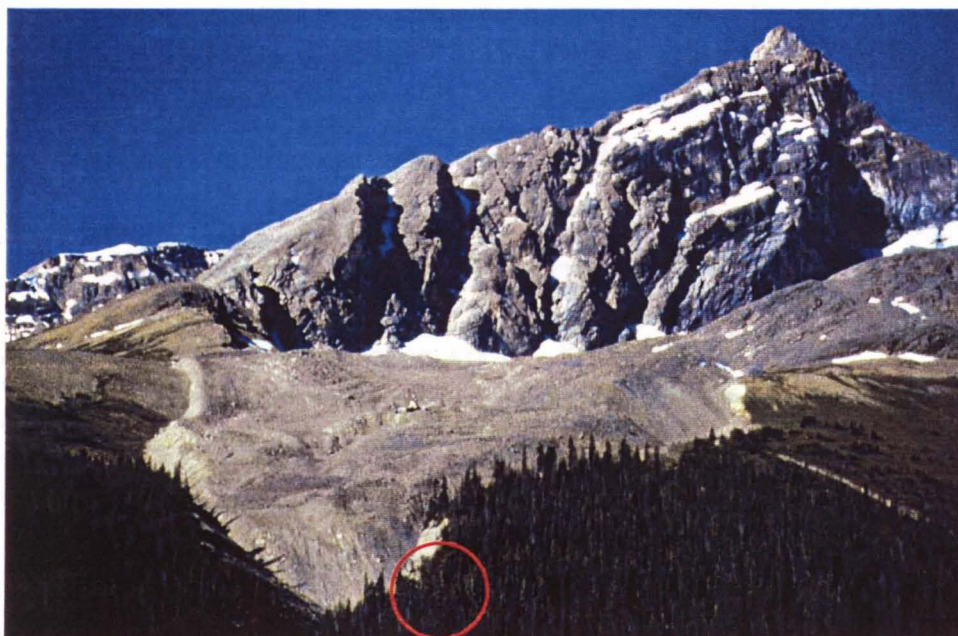
- **Site 00BB** – a treeline site positioned above the Big Bend of Highway #93 at *ca.* 1900 m asl (Table 4.1; Figure 4.1). This site was chosen because the mixed stand of englemann spruce, subalpine fir, lodgepole pine and whitebark pine at the site is similar to that found at the sub-fossil forest site. Increment core samples from all three tree species found growing at the site indicated that the stand established *ca.* 300 years ago, perhaps recording a well-documented episode of seedling establishment that followed a decade of catastrophic dieback during the late 1600s (Luckman and Kavanagh 1998, Kavanagh 2000).
- **Site 99Y** - a treeline site located adjacent to Hilda Rock Glacier at *ca.* 1900 m asl 4 km north of the Big Bend site (Table 4.1; Figure 4.2). This series was built from both living and recently killed trees (Bachrach *et al.* 2000).

**Table 4.1** Site characteristics of living subalpine fir chronologies.

	Elevation (m asl)	Aspect	Slope
<b>Site 00BB:</b> Big Bend	1900	112 <sup>0</sup>	10-30%
<b>Site 99Y:</b> Hilda Glacier	1900	30 <sup>0</sup>	10%



**Figure 4.1** Tree-ring sample site (00BB) at Big Bend, Banff National Park.



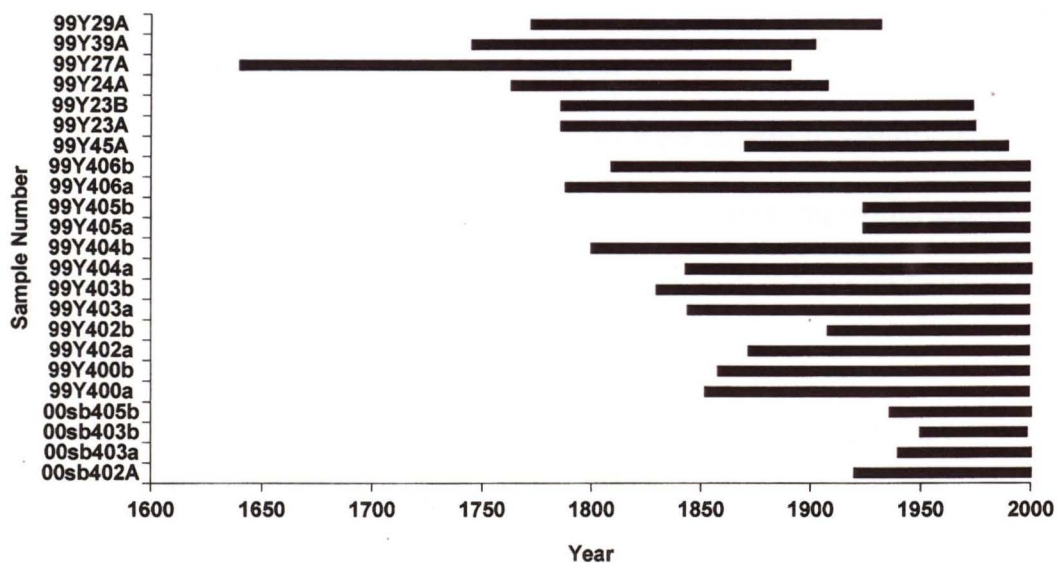
**Figure 4.2** Tree-ring sample site (99Y) at Hilda Rock Glacier, Banff National Park.

Samples from both sites were collected from trees located adjacent to the forest edge, near openings in the forest or on slopes where the soil was well-drained. The identification of well-drained sites was essential because of *a priori* information provided by Luckman *et al.* (1997) that most coniferous trees in this area are more temperature than precipitation sensitive.

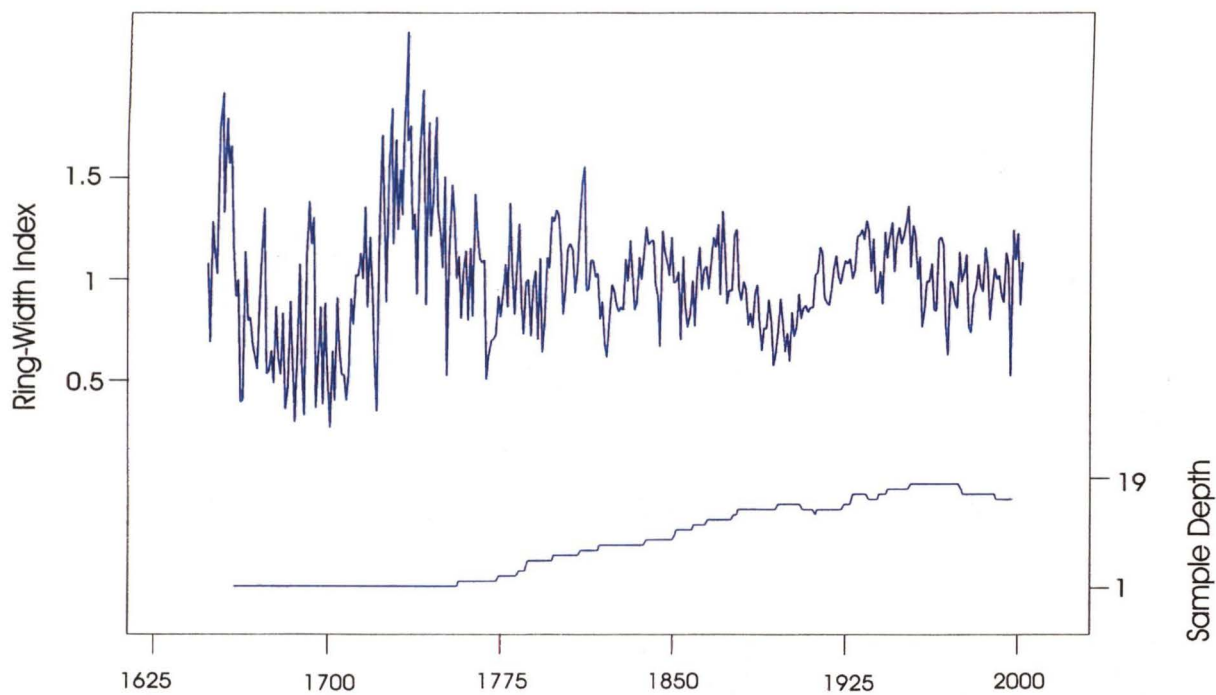
The living subalpine fir chronology was constructed from 23 tree cores (15 trees), including 16 from living trees and 7 from recently killed trees (Figure 4.3). The majority of samples were collected at the Hilda Rock Glacier (99Y) site in September 1999 (Figure 4.3), with only four samples from the Big Bend site collected in 2000 included in the living chronology (00BB, Figure 4.3). The master living subalpine fir chronology (Figure 4.4) is 366 years long, with an internal correlation of 0.529, a standard deviation of 0.222, an autocorrelation of 0.806 and a mean sensitivity of 0.193 (Table 4.2).

**Table 4.2** Summary statistics of subalpine fir chronologies

<b>Master chronology</b>	<b>No. samples</b>	<b>Length (years)</b>	<b>Duration</b>	<b>Mean correlation</b>	<b>Standard deviation</b>	<b>Mean sensitivity</b>	<b>Auto-correlation</b>
Living subalpine fir	23	366	1634-2000 AD	0.529	0.222	0.193	0.806
Floating subalpine fir	26	225	3047 - 2823 <sup>14</sup> C BP	0.437	0.333	0.186	-0.012



**Figure 4.3** Duration of individual tree-ring series used to construct the living subalpine fir chronology. Samples with the prefix 00SB are from the Big Bend site and those with the prefix 99Y were collected at the Hilda Rock Glacier site.



**Figure 4.4** The living subalpine fir master chronology constructed from tree-ring samples collected at both the Big Bend and Hilda Rock Glacier sites.

### 4.3 The Bootstrapped Response Function Analysis

Standard dendroclimatic analytical techniques were applied to identify the environmental parameters responsible for the annual variations in ring-width growth shown in Figure 4.4. In this instance, a 'response function analysis' was undertaken to relate the inter-annual variability to the historical climate records.

A response function may be represented as a regression equation with varying degrees of complexity. The simplest case involves calibration based upon a linear regression of a single tree-ring chronology  $x$  with climate data  $y$  (Blasing *et al.* 1981). More commonly in dendroclimatological studies, however, a response function involves a process of transposing the significant principle components from various climate variables, and applying them in a multiple regression equation to explain the annual variation in tree-ring growth (Blasing *et al.* 1971; Fritts 1976).

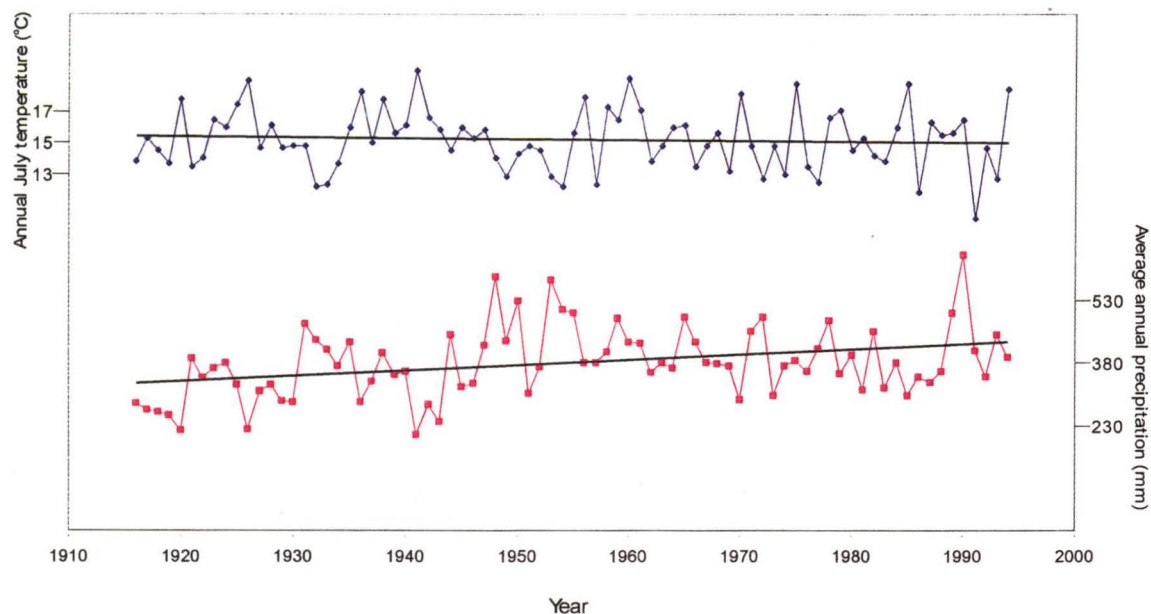
Variable selection in a bootstrapped response function must be based on *a priori* considerations or the significance of the coefficients will be overestimated (Guiot 1991). There must, therefore, be a method for determining a criterion for accepting loading scores as significant. The most commonly employed technique in dendrochronology is based on the cumulative eigenvalues product (CEP or PVP) that recognizes when the predictors are independent and the eigenvalue products are equal to one. This criterion, applied in a dendroclimatologic context, means that the first  $n$  eigenvalues are included until the total is as close to one as possible. This test is useful for estimating the pseudo-rank of a correlation matrix thereby providing a filtering step for removing components that explain too little variance (Guiot 1985). By incorporating the PVP criterion as a

variable selection technique, a standard, rather than stepwise, multiple regression analysis is possible.

One problem with this technique is that the significance of the coefficients is often overestimated because of the correlation between climate and prior growth data sets (Briffa and Cook 1990). A bootstrap procedure is often incorporated in the analysis to obtain an unbiased estimate of the standard error of the response function weights, thus providing a robust significance test. This is usually done by replicating the calculation  $m$  times by randomly drawing  $n$  sets of data with replacement values that simulate the  $n$  years of data (Briffa and Cook 1990).

#### **4.4 Climate Data**

The climatic information required for this response function analysis consists of a set of homogenised average annual air temperature and total monthly precipitation data from Jasper town site (Luckman 1997). The data were supplied to the author by researchers from the Dendrogeomorphology Laboratory, University of Western Ontario (Figure 4.5). The data set is complete from 1916 to 1994 and contains no missing values. Comparisons with climatic data from sites in Banff, Lake Louise, and Canmore indicate the data are regionally representative (St. George and Luckman 2001) and are thus a reasonable proxy for environmental conditions in the vicinity of the Saskatchewan Glacier (Luckman *et al.* 1997).

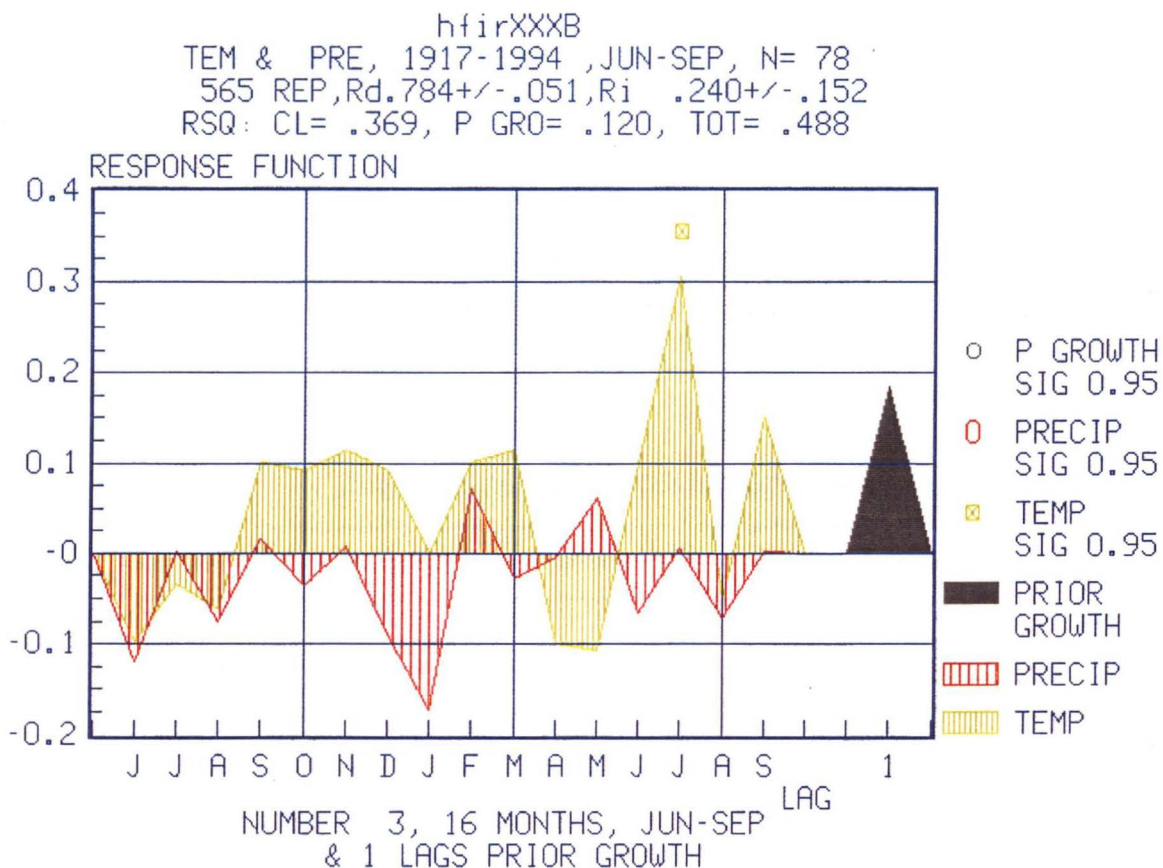


**Figure 4.5** Historical record of average annual temperature and total annual precipitation, Jasper townsite, Jasper National Park (source: Luckman, *personal communication*).

#### 4.5 Response Function Analysis

The computer software package PRECON 5.17<sup>TM</sup> was used to undertake a response function analysis of the climate (Fritts *et al.* 1971; Fritts 1976). PRECON is a software suite that statistically examines the environmental factors controlling tree ring variation. In this instance, PRECON was used to analyze the relationships among temperature, precipitation, and tree growth increments. This was accomplished by completing a correlation analysis that measured the variance shared between the subalpine fir chronology and each monthly climate variable, employing a step-wise linear regression to determine which variables best explained the annual variation, and then completing a response function analysis that used a principal components regression to resolve any colinearity (Fritts *et al.* 1971).

Figure 4.6 shows that average monthly temperature and total monthly precipitation explained 49 percent of the variability in subalpine tree growth. The primary climatic factor affecting the growth of subalpine fir was July temperatures that explained 37 percent of the current year's growth.



**Figure 4.6** Illustration of the graphical response function output showing that average July air temperature plays a significant role in determining the annual ring-width increment of subalpine fir.

The high level of correlation between July temperature and ring-growth (0.316 at  $\alpha=95\%$ ) implicit in Figure 4.6 is in agreement with the findings reported by Ettl and Peterson (1995a, 1995b). Although Figure 4.6 does demonstrate that there is some correlation between prior ring-growth (positive) and January precipitation (negative), these relationships are not significant at  $\alpha=95\%$ . The apparent sensitivity to July

temperature in the growth year suggests subalpine fir chronologies are well-suited for use in a dendoclimatic reconstruction.

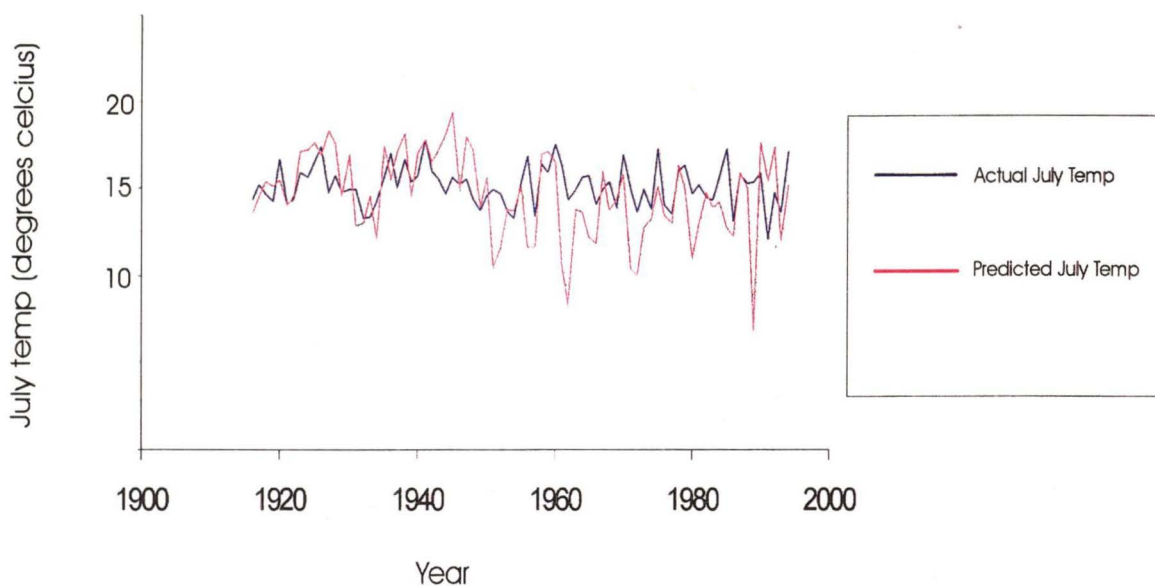
#### 4.6 Reconstructed July Temperatures during the Neoglacial Onset

The results of the response function analysis were used to develop an annually-resolved record of average July temperature conditions recorded by the floating subalpine fir chronology. The response function derived from PRECON through the bootstrapping process is presented as a simple linear regression with a predictive capability of 37 percent. This relationship is represented by *Equation 1* and provides an opportunity to predict July temperatures based upon annual tree ring variation.

$$\text{July temperature} = (\text{RW} - 0.066) / 0.051$$

*Equation 1.* Transfer function for predicting July temperature

The robustness of the transfer function is evaluated by comparing the predicted July temperatures (measured ringwidths [RW]) to the recorded July temperatures from 1916 to 1994. A simple visual examination of Figure 4.7, clearly demonstrates a high degree of commonality between the records. Although years with extremely cold or warm July temperatures are underestimated, the predictive model appears to capture decadal length trends. Based upon the recognition that July temperatures influence subalpine fir growth over a wide geographical range and the strength of the predictive model, *Equation 1* was used to reconstruct the July temperatures implicit in the annual tree ring variability measured within the floating subalpine fir chronology.

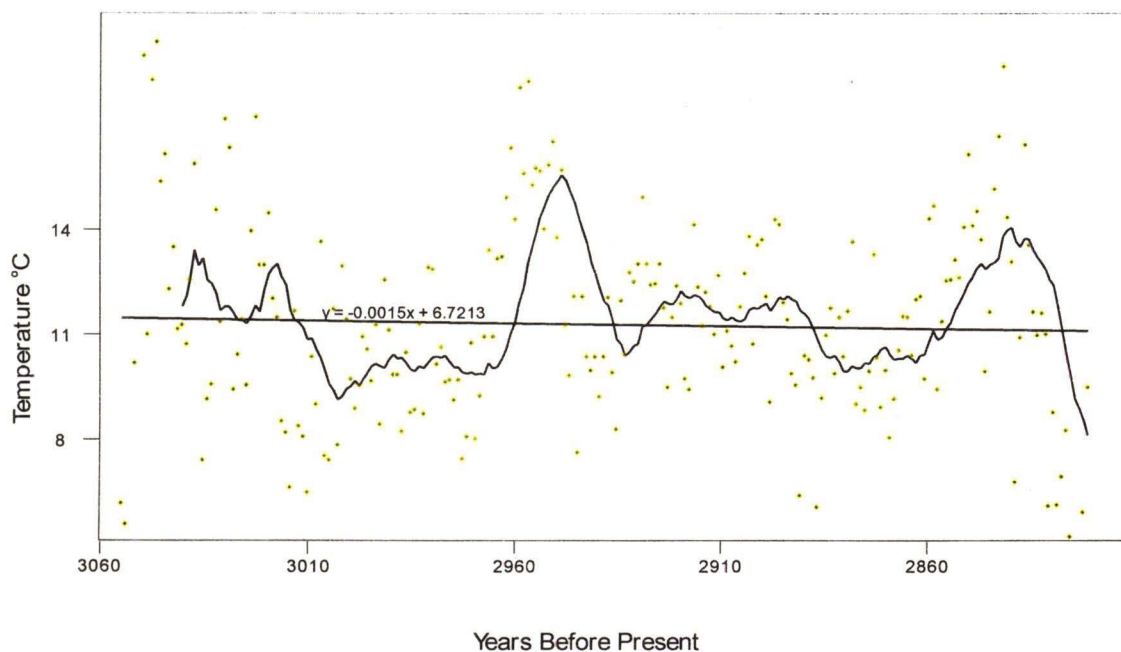


**Figure 4.7** Comparison of predicted to recorded July temperatures, Jasper townsite (1916-1994).

Figure 4.8 illustrates the reconstructed July temperatures at the Saskatchewan Glacier between 3055 and 2830  $^{14}\text{C}$  yr BP. In order to correct cooler temperatures related to altitude at the Saskatchewan Glacier (1700 m asl), a lapse rate correction factor was established based upon average July temperatures recorded on Parkers Ridge (2000 m asl) and Jasper townsite (elevation 980 m asl) between 1978 and 1982. Based on this assessment, the mean July temperature at the Saskatchewan Glacier over the 225 years of the floating chronology is *ca.* 11.2  $^{\circ}\text{C}$ .

The reconstructed July temperatures shown in Figure 4.8 suggest a high degree of annual variability at the site. Nevertheless, there is a clear indication that the long-term average July temperature did decrease by *ca.* 0.6  $^{\circ}\text{C}$  prior to the glacier killing these trees. Unfortunately, there is little to indicate whether this decline in temperature was due to the increasing proximity of the glacier or is merely a reflection of the same climatic changes

that resulted in advance of the Saskatchewan Glacier. Nevertheless, it is likely that the cool temperature recorded in the ten years immediately prior to the destruction of the trees is an indication of ice proximal frigid conditions.



**Figure 4.8.** Reconstructed annual July air temperatures at the Saskatchewan Glacier between 3055 and 2830  $^{14}\text{C}$  yr BP. A 15-year moving average is used to emphasize the climate trends

#### 4.7 Summary

The growth response of the subalpine fir to July temperatures at the Columbia Icefield corresponds to the work of other researchers examining growth/climate response of subalpine fir. Through this single variable response function, July temperatures can be predicted with an acceptable degree of precision by accurately demonstrating both climate trends and significant years of warm or cold temperatures. By applying this response function to the floating chronology, a proxy record of July temperatures during the two centuries prior to forest destruction can be observed. The predicted July

temperatures demonstrate a gradual decrease in air temperature of more than half a degree during that time period and provide evidence for the cause of the Neoglacial Advance in the Canadian Rocky Mountains.

## Chapter 5 Summary

This thesis documents the discovery and interpretation of a recently exposed stand of subfossil trees in the Canadian Rocky Mountains. The rooted subfossil forest stand found at the terminus of the Saskatchewan Glacier site in September, 1999, was destroyed some 3000 years ago during a Neoglacial advance of the glacier. Consisting of a collection of sheared 125 to 225 year old subalpine fir, englemann spruce and whitebark pine stumps, the trees lay buried beneath over 5 m of glacial sediment until historical ice recession and stream incision exposed the site.

The research had three basic objectives: to complete an assessment of the Saskatchewan Glacier subfossil forest site; to describe the glaciological events that led to the preservation of the site; and to complete a dendroclimatological analysis of environmental conditions at the time of this event. The major findings of these investigations are summarized below:

- The *in-situ* subfossil forest site found adjacent to the Saskatchewan Glacier confirms that the glacier was actively advancing down the Saskatchewan River valley 2823  $^{14}\text{C}$  yrs BP. This evidence and previous findings in the Canadian Rocky Mountains confirm the significance of the 'Peyto Advance' as a regional glaciological response to changing mass balance conditions.
- The research indicates that the glaciological response of large glaciers to Neoglacial climate changes in the region lagged behind the attendant mass balance changes by as much as 1000 years.

- The presence of a deeply-weathered buried soil horizon at the site confirms that the Peyto Advance at the Saskatchewan Glacier was the most extensive since the retreat of the ancestral Late Wisconsinan / Younger Dryas Saskatchewan Glacier.
- Initially it was assumed that the sediment overlying the site was deposited by a succession of Neoglacial and Little Ice Age glacial advances and retreats. However, radiocarbon dating and cross-dating of wood samples from the deposit showed that it was the same age as the radiocarbon controlled *in-situ* stumps. Subsequent cross-dating of a large collection of woody detritus and *in-situ* stumps into species-specific tree-ring chronologies further supported this finding, and showed that the majority of glacial sediments exposed at the subfossil forest site are Neoglacial in age.
- Sufficient subfossil wood was collected to permit the development of : a) a 262 year long floating whitebark pine tree-ring chronology extending from 3174 to 2912 <sup>14</sup>C yrs BP; and, b) a 225 year long floating subalpine fir chronology extending from 3047 to 2823 <sup>14</sup>C yrs BP.
- An analysis of the climate-radial growth response of living subalpine fir trees in the vicinity of the Saskatchewan Glacier showed there was a correlation between July air temperature and ring-growth (0.316 at  $\alpha=95\%$ ).
- The results of the climate-radial growth analysis were used to develop an annually-resolved proxy record of average July temperature conditions between 3055 and 2830 <sup>14</sup>C yr BP.
- The reconstructed July temperatures suggest a high degree of annual variability characterized environmental conditions at the site. In addition, there is sufficient

evidence in the tree-ring record to suggest that the long-term average July temperature at the site decreased by *ca.* 0.6 °C over the 200 years prior to the glacier killing these trees.

The sub-fossil forest investigated for this thesis had been entombed and preserved beneath the Saskatchewan Glacier since its destruction. Buried among ice and rock and left virtually unaltered for the entire duration of the late Holocene, a rare glimpse of early Neoglacial conditions has arisen.

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## Appendices

### Appendix A: Standardised master chronology for subalpine fir series

Year	Ring-width	Year	Ring-width	Year	Ring-width
-3055	0.928	-3014	1.043	-2973	1.024
-3054	0.896	-3013	1.027	-2972	1.089
-3053	0.77	-3012	0.944	-2971	1.178
-3052	1.138	-3011	1.147	-2970	1.307
-3051	0.828	-3010	1.077	-2969	1.178
-3050	1.597	-3009	1.32	-2968	1.294
-3049	1.181	-3008	0.999	-2967	1.298
-3048	1.561	-3007	0.992	-2966	1.386
-3047	1.618	-3006	1.218	-2965	1.46
-3046	1.41	-3005	1.015	-2964	1.352
-3045	1.451	-3004	1.283	-2963	1.55
-3044	1.249	-3003	1.203	-2962	1.422
-3043	1.312	-3002	1.114	-2961	1.559
-3042	1.188	-3001	1.07	-2960	1.405
-3041	1.195	-3000	1.105	-2959	1.43
-3040	1.166	-2999	1.177	-2958	1.426
-3039	1.263	-2998	1.158	-2957	1.338
-3038	1.437	-2997	1.111	-2956	1.434
-3037	0.801	-2996	1.195	-2955	1.469
-3036	0.993	-2995	1.046	-2954	1.325
-3035	1.084	-2994	1.263	-2953	1.427
-3034	1.106	-2993	1.187	-2952	1.194
-3033	1.367	-2992	1.121	-2951	1.119
-3032	1.2	-2991	1.121	-2950	1.237
-3031	1.503	-2990	1.035	-2949	1.004
-3030	1.46	-2989	1.153	-2948	1.237
-3029	1.099	-2988	1.063	-2947	1.147
-3028	1.15	-2987	1.069	-2946	1.127
-3027	1.202	-2986	1.197	-2945	1.147
-3026	1.105	-2985	1.062	-2944	1.087
-3025	1.336	-2984	1.282	-2943	1.147
-3024	1.505	-2983	1.279	-2942	1.235
-3023	1.285	-2982	1.136	-2941	1.124
-3022	1.284	-2981	1.162	-2940	1.039
-3021	1.362	-2980	1.109	-2939	1.231
-3020	1.234	-2979	1.112	-2938	1.151
-3019	1.206	-2978	1.083	-2937	1.273
-3018	1.051	-2977	1.112	-2936	1.259
-3017	1.033	-2976	0.994	-2935	1.287
-3016	0.951	-2975	1.027	-2934	1.386
-3015	1.216	-2974	1.168	-2933	1.287

Year	Ring-width	Year	Ring-width	Year	Ring-width
-2932	1.254	-2898	1.105	-2864	1.2
-2931	1.257	-2897	0.939	-2863	1.261
-2930	1.286	-2896	1.149	-2862	1.263
-2929	1.22	-2895	1.142	-2861	1.293
-2928	1.101	-2894	1.116	-2860	1.266
-2927	1.205	-2893	0.922	-2859	1.342
-2926	1.253	-2892	1.086	-2858	1.45
-2925	1.227	-2891	1.179	-2857	1.343
-2924	1.114	-2890	1.22	-2856	1.366
-2923	1.098	-2889	1.122	-2855	1.322
-2922	1.344	-2888	1.206	-2854	1.126
-2921	1.252	-2887	1.147	-2853	1.214
-2920	1.193	-2886	1.215	-2852	1.399
-2919	1.244	-2885	1.32	-2851	1.478
-2918	1.221	-2884	1.076	-2850	1.582
-2917	1.181	-2883	1.102	-2849	1.355
-2916	1.269	-2882	1.066	-2848	1.29
-2915	1.131	-2881	1.125	-2847	0.96
-2914	1.186	-2880	1.301	-2846	1.175
-2913	1.163	-2879	1.145	-2845	1.465
-2912	1.139	-2878	1.071	-2844	1.314
-2911	1.221	-2877	1.127	-2843	1.213
-2910	1.272	-2876	1.025	-2842	1.179
-2909	1.328	-2875	1.084	-2841	1.212
-2908	1.167	-2874	1.157	-2840	1.18
-2907	1.314	-2873	1.208	-2839	0.923
-2906	1.323	-2872	1.205	-2838	1.063
-2905	1.238	-2871	1.149	-2837	0.925
-2904	1.079	-2870	1.232	-2836	0.968
-2903	1.353	-2869	1.237	-2835	1.036
-2902	1.344	-2868	1.114	-2834	0.877
-2901	1.228	-2867	1.354	-2833	0.761
-2900	1.203	-2866	1.373	-2832	0.769
-2899	1.122	-2865	1.099	-2831	0.913

**Appendix B: Uncorrected raw data for floating whitebark pine series**

00Abc10a1900	274	206	190	174	168	185	180	174	182	147
00Abc10a1910	158	161	166	146	131	122	140	115	102	114
00Abc10a1920	120	94	106	80	89	97	91	101	106	104
00Abc10a1930	83	124	111	99	79	103	107	85	96	93
00Abc10a1940	79	78	94	81	98	67	64	84	82	86
00Abc10a1950	107	77	69	80	66	61	72	66	79	48
00Abc10a1960	62	67	53	54	50	59	43	40	59	65
00Abc10a1970	47	71	69	64	75	69	75	67	47	66
00Abc10a1980	53	60	59	58	56	47	65	64	61	999
00Abc10b1900	247	202	223	236	235	217	215	189	186	205
00Abc10b1910	172	198	201	176	157	152	157	152	137	143
00Abc10b1920	161	132	154	110	132	122	117	120	141	149
00Abc10b1930	109	157	132	151	114	126	126	111	119	119
00Abc10b1940	101	88	108	91	101	71	83	106	105	101
00Abc10b1950	93	91	96	78	75	69	69	76	98	79
00Abc10b1960	63	73	55	61	56	63	75	82	63	86
00Abc10b1970	66	77	78	50	91	80	72	65	67	72
00Abc10b1980	78	71	73	66	60	58	74	79	82	70
00Abc10b1990	52	999								
99W31B 1833	17	19	19	23	14	19	17			
99W31B 1840	15	12	16	12	22	20	13	13	17	19
99W31B 1850	20	12	11	17	29	29	22	50	53	61
99W31B 1860	68	73	25	13	19	22	16	14	20	17
99W31B 1870	35	21	29	29	38	40	37	43	49	29
99W31B 1880	32	25	24	30	18	18	19	13	31	26
99W31B 1890	34	29	35	44	36	39	62	53	80	90
99W31B 1900	122	100	76	114	109	100	105	76	80	60
99W31B 1910	57	67	95	95	78	97	97	143	108	77
99W31B 1920	87	69	94	81	63	57	47	49	44	32
99W31B 1930	32	34	39	59	63	64	55	55	44	41
99W31B 1940	38	53	45	55	62	19	23	19	26	15
99W31B 1950	22	999								
99W12B 1821	33	264	127	101	83	109	123	144	156	
99W12B 1830	126	128	137	132	122	136	180	123	150	176
99W12B 1840	157	170	165	127	160	162	139	136	122	118
99W12B 1850	108	117	154	119	144	147	146	130	144	141
99W12B 1860	164	154	169	186	181	170	151	181	188	141
99W12B 1870	177	210	171	209	212	229	235	202	168	184
99W12B 1880	174	138	140	149	122	134	109	87	120	131
99W12B 1890	123	112	136	116	119	124	108	112	110	127
99W12B 1900	79	90	95	93	88	80	68	57	62	61
99W12B 1910	47	44	59	47	47	35	42	33	38	29
99W12B 1920	36	37	41	35	31	49	34	54	60	53
99W12B 1930	58	66	55	47	56	36	49	40	37	21
99W12B 1940	19	16	19	22	33	21	24	27	19	30
99W12B 1950	25	23	20	31	26	22	23	25	21	21



00AA11b 1820	118	96	94	79	81	72	85	68	66	58
00AA11b 1830	45	55	42	52	37	47	39	36	63	53
00AA11b 1840	58	54	65	46	52	52	58	53	40	42
00AA11b 1850	32	41	42	38	37	48	42	32	44	43
00AA11b 1860	40	38	33	26	31	29	31	32	32	24
00AA11b 1870	24	26	21	33	27	30	36	40	25	24
00AA11b 1880	28	17	20	17	14	23	20	25	26	19
00AA11b 1890	19	19	17	16	28	19	25	19	22	18
00AA11b 1900	23	26	28	20	999					
00AA11a 1780	374	220	241	197	248	251	207	243	203	202
00AA11a 1790	166	157	146	127	188	200	164	145	161	191
00AA11a 1800	191	174	147	119	119	111	136	141	129	107
00AA11a 1810	124	111	104	117	140	106	98	68	69	74
00AA11a 1820	71	50	58	60	46	46	53	46	44	35
00AA11a 1830	40	64	75	74	61	36	44	27	41	39
00AA11a 1840	35	42	38	30	32	40	37	38	40	41
00AA11a 1850	35	36	28	25	35	26	34	32	40	36
00AA11a 1860	45	33	28	22	30	34	26	29	36	28
00AA11a 1870	21	29	31	27	26	45	36	42	27	36
00AA11a 1880	21	28	21	15	11	999				
00x21b 1871	178	67	66	45	217	148	109	86	76	
00x21b 1880	88	81	90	65	51	78	75	74	75	86
00x21b 1890	90	84	91	91	145	131	142	149	133	113
00x21b 1900	115	132	111	126	110	109	127	106	114	109
00x21b 1910	109	95	119	122	82	79	88	85	94	78
00x21b 1920	78	78	70	72	72	84	73	67	59	73
00x21b 1930	59	60	57	65	70	70	63	56	52	49
00x21b 1940	54	47	49	38	43	33	25	49	39	51
00x21b 1950	39	43	34	36	46	44	43	39	43	44
00x21b 1960	46	38	30	56	40	32	43	46	40	34
00x21b 1970	35	42	34	55	39	44	41	39	38	38
00x21b 1980	32	999								
00aa13a 1739	222									
00aa13a 1740	92	85	98	79	85	80	77	71	91	65
00aa13a 1750	115	72	56	139	143	58	53	51	89	91
00aa13a 1760	88	126	114	153	79	183	113	100	122	160
00aa13a 1770	148	130	81	90	124	85	115	133	132	121
00aa13a 1780	85	50	66	43	52	59	55	79	99	110
00aa13a 1790	126	121	135	121	127	157	113	94	104	105
00aa13a 1800	117	82	92	76	100	122	167	201	192	161
00aa13a 1810	194	197	136	173	180	132	180	174	156	153
00aa13a 1820	146	126	181	134	134	179	161	152	119	85
00aa13a 1830	60	88	62	57	47	48	71	35	29	39
00aa13a 1840	31	51	43	39	56	60	59	33	41	27
00aa13a 1850	26	34	36	33	34	63	78	63	52	51
00aa13a 1860	50	87	95	94	60	68	77	37	24	20
00aa13a 1870	17	23	23	27	26	30	25	39	28	22
00aa13a 1880	24	17	21	15	999					

00flute 1760	10	15	19	13	7	12	12	13	9	9
00flute 1770	18	13	10	10	9	13	13	9	5	8
00flute 1780	5	10	11	17	18	13	21	18	11	11
00flute 1790	4	7	11	14	25	28	13	11	13	14
00flute 1800	16	19	21	15	21	27	21	25	21	15
00flute 1810	19	20	25	21	39	20	27	23	44	49
00flute 1820	59	49	66	87	102	68	109	103	74	68
00flute 1830	85	88	91	98	110	76	119	79	119	109
00flute 1840	103	81	113	120	95	134	157	183	223	165
00flute 1850	118	78	54	55	106	161	197	186	242	193
00flute 1860	212	204	197	169	180	167	159	190	204	192
00flute 1870	160	147	158	171	142	158	141	194	255	226
00flute 1880	203	201	174	181	221	211	155	163	111	999

## Appendix C: Homogenised climate data for Jasper Townsite from 1916-1994

### Temperature

1916	-318	-98	-31	47	75	132	143	148	108	56	-46	-142
1917	-159	-102	-71	17	73	104	152	130	95	42	29	-164
1918	-98	-98	-46	20	58	118	147	140	111	57	-37	-57
1919	-48	-114	-80	27	75	116	142	145	97	5	-83	-103
1920	-115	-32	-34	-8	67	107	167	149	90	41	-14	-66
1921	-113	-56	-36	39	87	130	141	137	81	62	-44	-110
1922	-107	-165	-44	34	79	130	144	150	114	61	-21	-123
1923	-117	-66	-19	38	66	133	159	141	107	62	12	-70
1924	-117	-22	-26	23	90	116	156	128	107	49	-53	-151
1925	-92	-72	-24	49	103	136	165	127	92	27	-6	-9
1926	-50	-8	22	48	92	124	174	142	52	48	-32	-87
1927	-115	-68	-21	27	77	128	148	153	102	51	-96	-162
1928	-60	-28	9	24	103	118	157	131	101	33	-2	-62
1929	-153	-89	-12	18	73	130	148	153	96	67	-11	-105
1930	-172	-27	-19	55	71	119	149	156	104	19	-4	-17
1931	-25	-17	-29	49	92	125	149	137	90	46	-64	-81
1932	-106	-80	-46	48	86	127	133	150	104	34	-27	-102
1933	-87	-92	-42	24	75	109	134	152	82	23	17	-193
1934	-56	-23	-7	68	46	123	142	153	81	60	0	-82
1935	-141	-16	-53	6	89	132	156	135	113	40	-41	-37
1936	-108	-198	-22	31	121	137	170	150	100	69	7	-107
1937	-192	-123	-4	39	84	126	150	118	113	65	-55	-99
1938	-76	-125	-11	44	84	139	167	127	144	63	-34	-78
1939	-47	-101	-17	56	103	114	154	153	101	41	41	-16
1940	-137	-81	-10	44	100	118	157	143	132	62	-69	-47
1941	-60	-55	22	78	99	150	178	154	77	61	-10	-78
1942	-71	-75	-22	44	89	125	160	150	106	57	-67	-99
1943	-169	-37	-57	55	73	109	155	135	111	59	12	-50
1944	-58	-72	-38	56	93	133	147	135	105	80	-24	-102
1945	-74	-66	-11	5	88	120	156	148	93	54	-77	-81
1946	-58	-50	9	42	97	120	152	148	105	30	-70	-93
1947	-97	-60	-12	53	98	119	155	127	98	44	-44	-54
1948	-62	-132	-57	-4	94	144	144	132	99	50	-23	-139
1949	-145	-137	-25	60	90	113	137	139	104	28	18	-143
1950	-275	-67	-52	17	71	131	146	133	115	25	-91	-69
1951	-157	-97	-75	27	89	105	149	122	85	11	-38	-146
1952	-159	-57	-33	46	91	118	147	143	113	71	-30	-63
1953	-134	-39	-15	14	91	118	137	139	96	68	5	-48
1954	-192	-24	-52	-35	73	104	133	129	90	35	16	-45
1955	-74	-90	-81	27	73	128	154	136	95	46	-147	-159
1956	-154	-113	-35	32	96	121	168	155	98	31	-24	-87
1957	-172	-106	-21	40	106	122	134	122	112	18	-11	-55
1958	-41	-80	-37	42	118	147	164	159	94	61	-55	-67
1959	-151	-86	0	33	74	118	159	118	90	36	-55	-47
1960	-115	-61	-29	45	70	113	175	137	99	72	-44	-72
1961	-60	-30	1	31	102	155	163	168	80	34	-58	-117

1962	-107	-83	-42	55	76	118	143	131	97	62	3	-60
1963	-132	-11	-2	38	79	121	149	153	140	62	-50	-89
1964	-74	-21	-39	26	79	124	156	127	76	61	-62	-173
1965	-119	-79	-59	39	75	123	157	162	65	65	-46	-103
1966	-152	-47	-9	8	94	113	141	136	121	43	-65	-81
1967	-104	-37	-55	22	78	133	149	166	143	48	-20	-81
1968	-103	-56	16	25	80	111	154	125	101	44	-22	-146
1969	-250	-81	-5	63	99	152	139	132	92	33	1	-60
1970	-136	-27	-12	21	85	150	169	163	86	41	-61	-134
1971	-132	-47	-50	43	104	121	149	180	83	36	-14	-147
1972	-171	-115	-13	19	95	130	136	158	65	26	-26	-127
1973	-96	-65	3	32	90	117	149	142	107	36	-113	-75
1974	-151	-38	-46	51	70	132	138	144	98	63	-34	-40
1975	-106	-133	-47	19	82	113	173	122	115	36	-40	-83
1976	-71	-57	-36	46	91	105	141	141	115	43	-19	-45
1977	-84	2	-14	53	82	131	135	140	82	42	-59	-150
1978	-143	-66	2	46	79	133	160	137	88	58	-54	-102
1979	-160	-141	1	25	75	121	163	157	117	65	-44	-73
1980	-143	-53	-29	71	103	129	147	120	96	64	-9	-95
1981	-34	-39	12	37	99	113	152	174	111	44	8	-101
1982	-181	-114	-45	2	79	147	145	128	106	51	-63	-76
1983	-59	-19	-10	43	102	123	143	160	79	48	-14	-172
1984	-53	-6	9	39	68	120	156	149	70	20	-57	-161
1985	-85	-80	-8	41	100	116	173	136	63	27	-148	-71
1986	-31	-83	23	36	93	136	131	137	78	69	-60	-67
1987	-47	-13	-4	61	95	147	158	120	127	62	6	-68
1988	-111	-51	16	60	97	138	153	143	99	68	-22	-73
1989	-84	-132	-45	46	87	136	154	139	103	43	-17	-53
1990	-66	-78	-5	48	89	127	159	159	119	26	-50	-131
1991	-117	12	-33	51	88	121	121	161	111	20	-23	-28
1992	-29	-23	33	50	92	155	148	138	87	39	-28	-133
1993	-132	-69	-13	53	120	125	136	135	101	56	-44	-58
1994	-82	-128	18	59	96	126	171	147	126	38	-30	-82

## Precipitation

1916	396	147	389	268	13	142	58	216	508	762	10	13
1917	79	246	51	40	227	297	180	152	417	178	312	577
1918	241	168	315	48	335	445	216	216	124	225	112	276
1919	508	127	84	256	655	267	58	61	48	142	218	206
1920	454	52	231	107	8	119	30	414	71	351	316	137
1921	660	282	159	282	221	135	465	277	472	470	371	147
1922	254	127	368	178	200	295	386	505	262	716	104	81
1923	99	130	89	356	211	716	511	399	399	94	51	650
1924	701	229	28	323	197	455	457	627	175	216	84	335
1925	478	325	79	53	124	269	216	874	241	137	224	305
1926	290	58	97	99	170	191	302	198	315	165	257	173
1927	58	135	109	211	119	188	640	442	503	361	218	198
1928	301	80	615	142	114	453	589	268	32	330	294	113

1929	165	48	221	110	434	234	300	399	602	127	89	229
1930	198	564	163	147	401	274	279	183	465	201	51	3
1931	356	86	528	165	351	791	663	378	445	297	442	232
1932	229	1247	81	117	221	442	323	782	69	345	307	198
1933	30	33	28	43	432	302	480	536	668	222	286	1070
1934	386	107	125	229	422	502	490	232	404	450	358	56
1935	503	25	119	66	160	714	1854	276	216	132	167	66
1936	104	127	160	149	198	417	415	331	294	154	205	372
1937	391	114	20	104	188	300	427	605	208	424	307	330
1938	48	38	94	81	142	775	493	1168	518	163	46	495
1939	290	36	135	320	363	653	411	147	452	330	269	152
1940	102	248	360	241	244	503	330	269	381	325	368	254
1941	254	112	127	86	168	234	86	277	157	152	295	241
1942	18	231	259	117	249	328	302	343	180	246	404	196
1943	114	165	152	135	239	287	376	297	145	150	206	218
1944	127	198	165	132	1082	640	770	401	523	127	216	94
1945	224	114	91	160	127	363	503	409	483	218	455	137
1946	198	99	279	168	254	389	368	368	290	224	259	450
1947	206	191	76	86	325	706	373	478	269	620	386	521
1948	180	919	196	396	208	582	483	1247	996	142	231	206
1949	140	455	23	152	208	503	554	320	236	498	315	914
1950	536	437	137	323	429	594	582	785	58	511	561	307
1951	505	127	114	23	429	300	437	457	163	135	173	277
1952	165	140	112	401	236	963	676	272	483	91	51	145
1953	1394	43	168	71	488	696	737	673	587	277	218	361
1954	384	488	300	505	389	892	450	813	236	142	292	165
1955	130	163	132	91	818	312	1008	330	142	310	917	627
1956	460	102	224	64	15	465	107	457	290	610	229	808
1957	157	597	30	76	211	505	582	386	470	150	183	478
1958	163	328	300	447	86	579	229	343	513	310	419	368
1959	411	173	257	396	315	737	254	711	470	343	396	384
1960	79	140	218	218	935	826	58	597	577	272	229	160
1961	386	262	64	239	196	424	892	163	305	676	300	371
1962	411	76	66	272	452	137	343	445	224	236	437	503
1963	254	224	155	391	76	399	663	236	127	544	485	282
1964	254	160	84	269	290	584	345	269	688	208	434	117
1965	452	503	53	302	546	432	678	419	488	287	363	351
1966	356	71	198	376	452	239	572	643	241	450	335	361
1967	427	353	160	33	206	559	546	295	208	579	117	358
1968	318	163	99	340	381	526	404	564	333	185	267	218
1969	251	112	43	246	292	262	483	1242	279	234	264	53
1970	130	107	165	282	343	500	363	132	312	107	305	251
1971	833	163	292	224	104	917	843	206	409	152	160	254
1972	391	523	376	142	259	1039	533	434	564	180	91	348
1973	234	97	180	229	249	315	152	384	224	399	503	109
1974	879	97	221	160	251	325	544	251	287	249	345	155
1975	117	180	89	41	310	724	218	767	180	368	470	422
1976	274	127	117	130	185	302	452	904	419	290	142	282
1977	75	113	205	111	509	340	885	574	543	265	300	243
1978	124	10	140	413	407	662	964	342	1076	332	217	103

1979	81	411	80	222	280	426	292	604	194	208	52	724
1980	192	128	172	75	264	1054	214	647	364	164	182	557
1981	24	52	66	286	244	196	1068	316	338	198	210	201
1982	698	338	231	122	296	286	1350	564	284	271	46	66
1983	141	56	215	90	86	738	542	234	294	530	146	188
1984	384	74	66	274	282	594	234	516	628	270	200	316
1985	70	156	18	266	242	540	74	528	450	526	141	72
1986	126	201	444	78	166	278	1154	166	434	102	268	88
1987	292	58	176	228	254	264	672	704	264	84	182	210
1988	208	170	240	275	100	564	252	840	272	196	264	256
1989	726	32	102	154	344	552	420	1222	386	362	448	220
1990	323	224	154	162	1306	828	806	392	91	807	846	343
1991	25	278	176	300	642	314	314	1092	220	318	244	172
1992	282	10	40	372	416	230	692	258	662	172	206	168
1993	48	1	268	94	452	798	760	1158	314	160	180	252
1994	254	226	200	212	458	938	202	712	180	258	110	206

## VITA

Surname: Wood

Place of Birth: Salmon Arm, British Columbia, Canada

### Educational Institutions Attended

Okanagan University College, Salmon Arm Campus	1993-1995
University of Victoria	1995-2002

### Degrees Awarded

B.Sc. University of Victoria	1999
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### Honours and Awards

NSERC Undergraduate Student Research Award	1999
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### Publications

Smith, D.J. and Wood, C. (2000) Neoglaciation at Saskatchewan Glacier, Banff National Park, Canada. Annual Meeting, Canadian Association of Geographers, Brock University, St. Catharines, Ontario, May 31 - June 3, 2000.

Smith, D.J. and Wood, C.; Luckman, B.H.; and Robinson, B.J. (2000) Dendroglaciology at Saskatchewan Glacier, Banff National Park, Canada. International Conference on Dendrochronology for the Third Millennium, 2-7 April, 2000 Mendoza, Argentina.

Wood, C. and Smith, D.J. (2001). Evidence for early Neoglacial onset in the Canadian Rocky Mountains. Annual Meeting of the Western Division, Canadian Association of Geographers. March 8 - June 10, 2001. University of Calgary, Alberta.


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Title of Thesis:

Neoglaciation and Dendroglaciology at the Saskatchewan Glacier, Banff National Park, Canadian Rocky Mountains

Author

  
Christopher Andrew Wood  
June 24, 2002