LATE QUATERNARY VEGETATION AND CLIMATE CHANGE AT MORAINE BOG, TIEDEMANN GLACIER, COAST MOUNTAINS, BRITISH COLUMBIA, CANADA

by
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ABSTRACT

Moraine Bog lies outside a middle Neoglacial moraine at Tiedemann Glacier in the southern Coast Mountains, British Columbia. Palynology, magnetic susceptibility, loss on ignition, and radiocarbon dating were used to analyse the sediment core, with the objective of reconstructing changes in vegetation and climate during the late Holocene. There is little evidence of vegetation change prior to *ca.* 2400 ^{14}C yr BP. A period of disturbance, reflecting cooler moister conditions, coincides with the most extensive Tiedemann advance between 2530±50 and 2280±50 ^{14}C yr BP. A period of warm dry conditions, at *ca.* 1900-1500 ^{14}C yr BP, is marked by an increase in *Pseudotsuga* pollen and an increase in *Nuphar* sclereids, suggesting a fall in water levels. This period coincides with a time of drought and increased fire frequency in the southernmost Coast Mountains. By *ca.* 1300 ^{14}C yr BP, the forest acquires a more coastal composition, with abundant *Tsuga heterophylla* and *Abies*. An increase in *Tsuga mertensiana* pollen suggests the onset of cool and wet conditions by *ca.* 500 ^{14}C yr BP, coincident with the Little Ice Age. Changes in the intensity of North Pacific atmospheric circulation patterns may provide a forcing mechanism for changes in temperature and precipitation in the region.

QUOTATION

> A text is information stored through time. The stratigraphy of rocks, layers of pollen in a swamp, the outward expanding circles in the trunk of a tree, can be seen as texts. The calligraphy of rivers winding back and forth over the land leaving layer upon layer of traces of previous riverbeds is text.
>
> — Gary Snyder, "Tawny Grammar"

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CHAPTER ONE
INTRODUCTION

1.1 Background and objectives

An understanding of past environments is crucial for evaluating the impact of current and future climate change. The principle of uniformitarianism suggests that "the present is the key to the past", referring to the unchanging constancy of biological, chemical, and geological processes throughout Earth's history. The modern, large-scale, geographic distribution patterns of vegetation are directly influenced by climate, thus data provided by paleobotanical studies can be used to interpret past climate change (Webb 1986). Paleoecological studies, combined with stratigraphic and chronostratigraphic work, can thus be used to reconstruct past environments and offer perspectives on past and potential future environmental changes.

Pollen analysis has been used since the 1920s to reconstruct Holocene paleoenvironments (Delcourt and Delcourt 1991; Lowe and Walker 1997). The characteristics that allow palynology to be used to infer vegetation history are: (1) pollen and spores are produced in large quantities during the reproductive cycle of most plants;

(2) the proportion of pollen and spores depends, to a certain degree, on the number of parent plants, therefore reflecting vegetation composition; (3) pollen grains are extremely resilient and commonly persist in environments where other microfossils are destroyed; (4) few pollen grains fulfil their reproductive potential; some of those that do not are deposited in environments conducive to fossil preservation; (5) grains that are preserved can be extracted from the sediment and identified; and (6) comparison of pollen data from numerous sites provides information on differences in vegetation at these sites (Faegri and Iversen 1989b; MacDonald 1990).

The first paleoecological studies to provide information on past Holocene climate in the Pacific Northwest were made in the late 1930s by H.P. Hansen. His seminal studies on peat cores led him to suggest that a cool early postglacial period was succeeded by a period of warmer drier climate in the Pacific Northwest (Hansen 1947). He also inferred a return to cooler and moister conditions in the late Holocene (Hansen 1947).

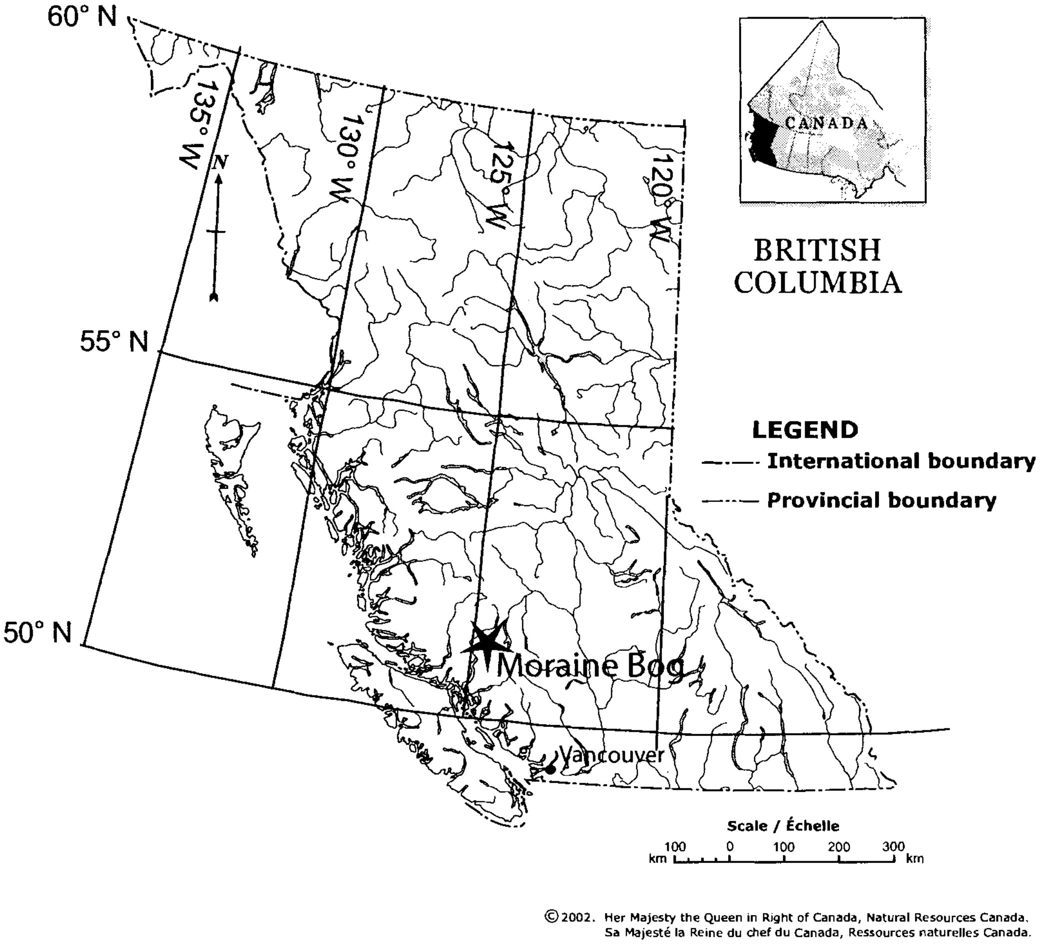
Much progress has been made since Hansen's early work. While the earlier studies (Hansen 1940, 1947, 1952, 1955) delimit broad changes in vegetation and climate, they lack detailed chronologies necessary for correlating sites. Radiocarbon dating, improved identifications (especially Cupressaceae pollen), and increased emphasis on the non-arboreal and deciduous pollen, have facilitated comparison and interpretation of pollen records (Mathewes 1985).

Quaternary mapping and stratigraphic studies have identified a period of increased glacial activity in the Coast Mountains from about 3300 to 1900 ^{14}C yr BP, termed the Tiedemann Advance by Ryder and Thomson (1986). This period of cool moist climate is now recognized throughout western North America. Records of increased sedimentation (Leonard 1986; Souch 1994; Clague and Mathewes 1996), decreased fire frequency (Hallett *et al.* 2003a), a shift to stenothermic (cold-indicator) chironomid species (Pellatt *et al.* 1998; Smith *et al.* 1998; Heinrichs *et al.* 2002b), and evidence of advancing glaciers (Crandell and Miller 1974; Osborn and Luckman 1988; Desloges and Ryder 1990; Luckman *et al.* 1993; Cashman *et al.* 2002; Larocque and Smith 2003) have shown that this is a regional event. There are few studies, however, that provide a record of how vegetation changed during this period.

This study was undertaken to establish a record of vegetation change during and following the Tiedemann Advance at its type section, Tiedemann Glacier (Fig. 1.1). Previous geological studies at Tiedemann Glacier (Fulton 1971; Ryder and Thomson 1986) provide a framework on which to establish a vegetation history.

Small peat bogs and lakes trap pollen, mostly from plants growing within 20 m of the edge of the sampling basin (Jacobsen and Bradshaw 1981). Moraine Bog (< 1 ha), located on the north side of Tiedemann Glacier, contains a 9000-year record of primarily local vegetation changes. Its open canopy, however, also allows for deposition of extra-local and, to a lesser degree, regional pollen (Jacobsen and Bradshaw 1981). Although the pollen record from Moraine Bog extends back to 8760 ^{14}C yr BP, the focus of this study is the last 4000 years, which includes the Tiedemann event.

The objectives of this study are to: (1) provide a reconstruction of mid-late Holocene environments for the Tiedemann Glacier area through analysis of pollen and sediment records; (2) examine the extent, timing, and nature of the Tiedemann Advance; and (3) compare the Moraine Bog record to other Holocene paleoecological records in the Canadian Cordillera.



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Sa Majesté la Reine du chef du Canada, Ressources naturelles Canada.

Figure 1.1: Map showing the general location of Moraine Bog and Tiedemann Glacier. This map was taken from The Atlas of Canada. http://atlas.gc.ca©2004. Reproduced with permission from Her Majesty the Queen in Right of Canada with permission of Natural Resources Canada.

1.2 Physiographic setting

Tiedemann Glacier is located in the southern Coast Mountains of British Columbia. The Coast Mountains extend in a northwest direction from southernmost British Columbia to Alaska and coincide with a belt of plutonic and metamorphic rocks (Tipper *et al.* 1981). The landscape of this region has been shaped by diastrophism, volcanism, subaerial erosion and deposition, and glaciation (Mathews 1989).

Tiedemann Glacier originates in an ice field on the east side of the Waddington Range and flows 24 km to the east to terminate in an extensive zone of stagnant ice at the head of Tiedemann Creek. Clear geomorphic evidence of Holocene glacier advances is provided by a suite of lateral moraines flanking the lower part of Tiedemann Glacier.

1.3 Bedrock geology

The Coast Belt, which forms the core of the Coast Mountains, formed during Late Cretaceous time through the accretion of several terranes to North America (Monger *et al.* 1982; Price and Monger 2003). It consists of Jurassic to Tertiary plutonic rocks, and Paleozoic to Tertiary metasedimentary and metavolcanic rocks. Thickening and tectonic overlap have been cited as the source of uplift (5-25 km) and erosion along the Coast Belt during the Cenozoic (Gabrielse and Yorath 1991). The study area lies within the Tatla Lake complex of gneisses and paragneisses (Tipper *et al.* 1981).

1.4 Quaternary climate history

The Cordilleran ice sheet covered British Columbia, southern Yukon Territory, and southern Alaska during numerous Pleistocene glaciations (Clague 1989). At its maximum extent, the Cordilleran Ice Sheet was up to 900 km wide and reached elevations of more than 2000 m over British Columbia's interior (Wilson *et al.* 1958). The last ice sheet began to develop around 30,000 – 25,000 ^{14}C yr BP (Clague and James 2002) and reached its maximum extent, in the south, about 14,000 ^{14}C yr BP (Porter and Swanson 1998). In the southern Coast Mountains, ice flowing down fjords and valleys coalesced with glaciers on Vancouver Island to produce a large piedmont lobe that flowed into the Puget Lowland in Washington (Armstrong *et al.* 1965; Waitt and Thorson 1983). Rapid retreat of the Puget lobe began before 13,000 ^{14}C yr BP (Clague and James 2002). By 10,000 ^{14}C yr BP, ice cover in the southern Coast Mountains was similar to that of today (Clague and James 2002).

Compared to the present, the coastal Pacific Northwest had a cooler and drier climate at the end of the last glaciation, prior to *ca.* 12,000 ^{14}C yr BP. From 12,000 to 10,500 ^{14}C yr BP, conditions were cool and relatively moist (Mathewes 1973; Mathewes and Rouse 1975; Mathewes and Heusser 1981; Heusser 1983; Mathewes 1991, 1993; Mathewes *et al.* 1993). Warming began before10,000 ^{14}C yr BP on the coast and culminated in a relatively warm and dry interval between *ca.* 10,000 and 7000 ^{14}C yr BP (Mathewes and Heusser 1981). The warm, dry climate was followed by gradual cooling during the mesothermic interval, from *ca.* 7000 to 4500 ^{14}C yr BP (Hebda 1995). The Garibaldi phase of glacier expansion (Ryder and Thomson 1986), from *ca.* 6000-5000

^{14}C yr BP, marks the beginning of a mid to late Holocene interval of recurrent glacier advances, termed Neoglaciation (Porter and Denton 1967).

During Neoglaciation, relatively temperate intervals (Mathewes 1985; Hebda 1995) were punctuated by periods of cooling and/or increased moisture and by periods of drought. One of the most significant of the cool periods, the Tiedemann Advance (3300 – 1900 ^{14}C yr BP) (Ryder and Thomson 1986), is documented at several sites in the Coast Mountains (Ryder and Thomson 1986; Ryder 1987; Desloges and Ryder 1990; Clague and Mathewes 1992, 1996; Koch *et al.* 2003; Reyes 2003).

A short-lived, pre-LIA advance around 1330 ^{14}C yr BP is recorded at Tiedemann Glacier (Ryder and Thomson 1986; Larocque and Smith 2003) and at Bridge and Lillooet Glaciers (Reyes 2003). Similar advances are recorded between 1500 and 1200 ^{14}C yr BP in the St. Elias Mountains, Yukon (Denton and Karlen 1977) and in the Kenai Mountains, Alaska (Wiles and Calkin 1990, 1993, 1994). This advance has been termed the Bridge Advance by Reyes (2003). It appears to overlap the Fraser Valley Fire Period (2400 – 1300 cal yr BP), an interval of seasonally warm, dry conditions in southwestern British Columbia (Hallett *et al.* 2003a, b).

The Little Ice Age (LIA), the last of the major Neoglacial cool intervals, is well documented in the western Canadian Cordillera (Clague and Rampton 1982; Ryder and Thomson 1986; Ryder 1987; Osborn and Luckman 1988; Desloges and Ryder 1990; Clague and Mathewes 1992, 1996; Smith and Desloges 2000). Radiocarbon ages from the southern Coast Mountains suggest that the LIA began about 900 ^{14}C yr BP and persisted until about 100 years ago (Mathews 1951; Ryder and Thomson 1986; Ryder

1989). Larocque and Smith (2003) provide a detailed review of LIA fluctuations in the Waddington Range and at Tiedemann Glacier.

1.5 Climatic setting

The Coast Mountains are a significant barrier to the easterly movement of moist Pacific air masses, creating a strong west-east environmental gradient across the range. The Aleutian Low and the Pacific High, two semi-permanent pressure systems centred over the Pacific Ocean (Burroughs 1999), are the primary controls on climate in the study area. Westerly winds, pushed by the jet stream, flow eastward across the region. During winter, the Aleutian Low intensifies, driving storm tracks onto the continent and delivering abundant snow at higher elevations. In spring, the Pacific High strengthens and extends north, blocking the Aleutian Low and generating warmer, drier conditions (Burroughs 1999).

Periods of enhanced and weakened Aleutian Low alternate on decadal timescales, with abrupt changes between the two states (Mantua *et al.* 1997; Gedalof and Smith 2001). This variability is referred to as the Pacific Decadal Oscillation (PDO) and is linked to changes in North Pacific sea surface temperature (Mantua *et al.* 1997; Mantua and Hare 2002). Water levels in Moraine Bog are potentially controlled by precipitation and summer temperatures, and are probably linked to PDO. During an intensified Aleutian Low, winter storms frequently track into Alaska (Wilson and Overland 1987). At these times, increased northward airflow creates warm, dry conditions in the Pacific Northwest (Emery and Hamilton 1985), thereby decreasing winter snow accumulation

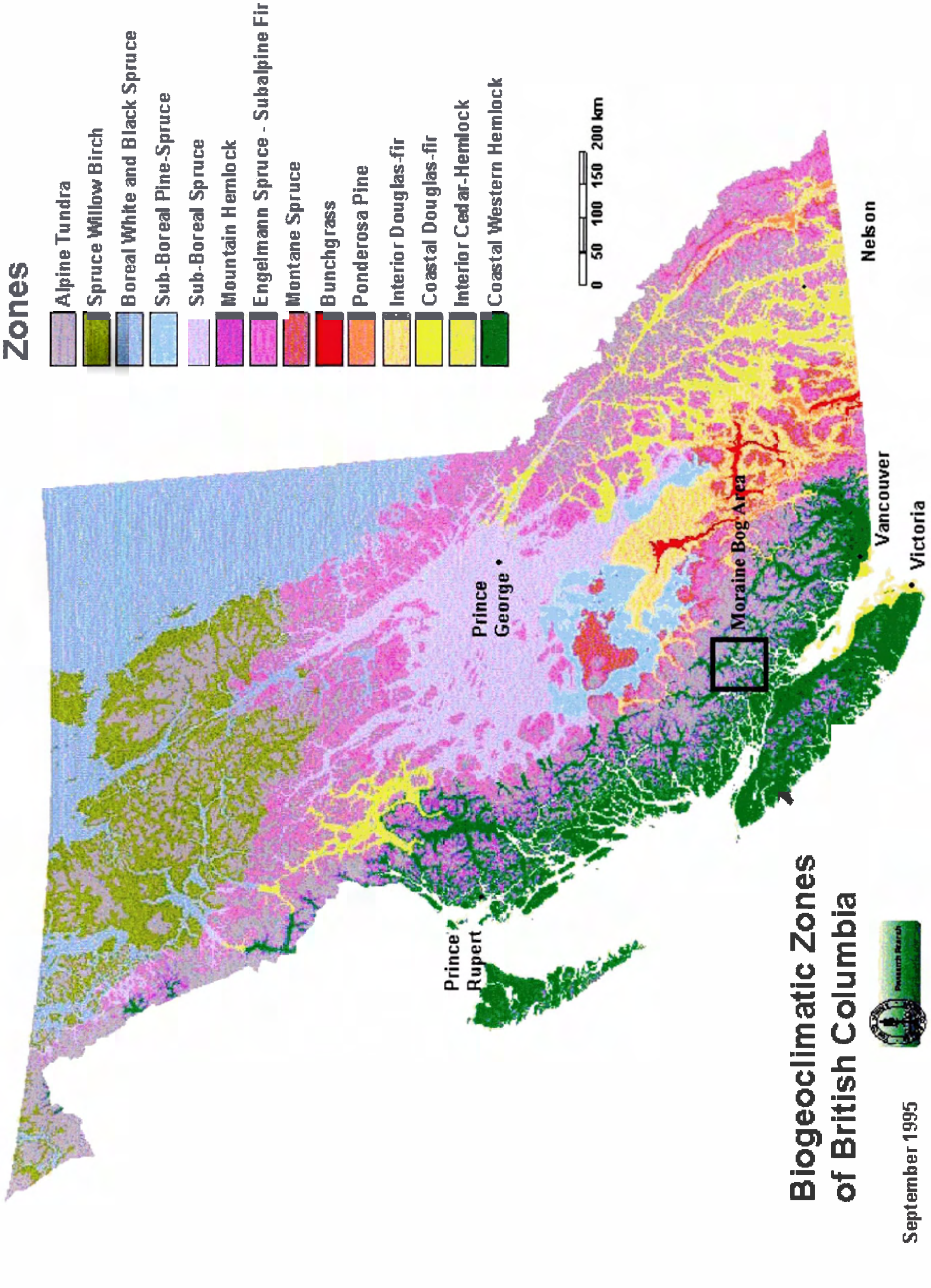
(Moore and McKendry 1996). An enhanced Aleutian Low also supports increased spring and summer temperatures (Ware 1995). In contrast, a weakened Aleutian Low promotes cool, wet winter and spring conditions and mild summers in the coastal Pacific Northwest (Moore and McKendry 1996).

The nearest Environment Canada weather station to Moraine Bog is at Tatlayoko Lake (870 m asl), 53 km to the northeast. Climate records spanning the last 30 years (Environment Canada 2003) indicate a daily mean January temperature of –6.8°C, with a mean minimum of –11.7°C and mean maximum of –1.8°C. January precipitation averages 42.0 mm, with 64.5% (25.8 mm) falling as snow. In July, mean daily temperature is 13.8°C, with a mean minimum of 5.3°C and a mean maximum of 22.3°C. On average, 36.8 mm of precipitation falls in July, all as rain. Although snow depth data are not available for this station, the influence of the Aleutian Low suggests that snowfall should be significant in the area. Tatlayoko Lake's easterly position relative to Moraine Bog implies that its precipitation levels are lower than those at the study site.

1.6 Biogeoclimatic setting

Ecosystems in British Columbia are characteristic of the regional climate (Pojar *et al.* 1991b). The British Columbia Ministry of Forests has subdivided the province into 14 biogeoclimatic zones (Fig. 1.2) based on general biological and climatic attributes (Meidinger and Pojar 1991). The 14 zones are further subdivided into subzones and variants to accommodate local variations (Pojar *et al.* 1991b).

Figure 1.2: Biogeoclimatic zones of British Columbia. Moraine Bog (darkened square) is located in the Mountain Hemlock zone transition with the Coastal Western Hemlock and Engelmann Spruce - Subalpine Fir zones. Reproduced with permission of the Province of British Columbia.


Biogeoclimatic Zones of British Columbia

September 1995

Plants[1] growing around Moraine Bog suggest that the site is in a transition zone. Moraine Bog displays characteristics of both coastal (Mountain Hemlock, MH) and interior (Engelmann Spruce – Subalpine Fir, ESSF) subalpine zones. The forest assemblage comprises *Abies amabilis*, *Tsuga mertensiana*, *Abies lasiocarpa*, *Picea engelmannii*, and *Tsuga heterophylla* (for common names refer to Table 1.1).

Tsuga mertensiana and *Abies amabilis* dominate the coastal zone and commonly occur with *Chamaecyparis nootkatensis*. These species are rare in the interior. *Tsuga mertensiana* and *Chamaecyparis nootkatensis* only occur where there is substantial winter snow accumulation, which prevents the ground from freezing. *Chamaecyparis nootkatensis* decreases with increasing continentality (Klinka and Chourmouzis 2002). *Picea engelmannii* and *Abies lasiocarpa* dominate the interior subalpine zone, and are commonly associated with *Pinus contorta* and *Pinus monticola* (Krajina 1975). *Tsuga heterophylla* is a lower-elevation coastal species that can occur at the montane-subalpine transition (Pojar *et al.* 1991a).

Krajina (1975) suggests that the subalpine transitional region occurs between 55° and 57° N latitude. Moraine Bog, at 51°2' N, is south of Krajina's transition area, but it displays similarities to it. The recently defined submaritime Lady Fern site association (Klinka and Chourmouzis 2002) provides the most apt ecological analogue for the site. Lady fern sites represent the ecological transition between ESSF and MH zones and support dominant or mixed-species stands of *Abies amabilis*, *Abies lasiocarpa*, *Tsuga*

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[1] Species names follow the Province of British Columbia plant species database (Meidinger *et al.* 2002)

mertensiana, and *Picea engelmannii* (Klinka and Chourmouzis 2002). Brief descriptions of the subalpine biogeoclimatic zones follow.

The Engelmann Spruce-Subalpine Fir zone occurs at mid to high elevations in the interior of the province, below the Alpine Tundra zone. A cold, moist climate provides a short growing season and a long winters with 1 to 4 m of snowfall (Coupe *et al.* 1991). *Picea engelmannii* and *Abies lasiocarpa* dominate the forest. The understorey is characterized by *Vaccinium membranaceum, Rhododendron albiflorum*, and *Menziesia ferruginea.*

The Mountain Hemlock zone occurs at subalpine elevations in coastal areas above the Coastal Western Hemlock zone. Proximity to the Pacific Ocean and rugged topography result in long, cool winters with high precipitation, a deep snow pack, and cool wet summers (Pojar *et al.* 1991a; Klinka and Chourmouzis 2002). The zone supports species dependent on unfrozen ground, including *Tsuga mertensiana*, *Abies amabilis*, and *Chamaecyparis nootkatensis.* Low-elevation species such as *Tsuga heterophylla*, *Thuja plicata*, *Picea sitchensis,* and *Pinus contorta* may occur near treeline along with typical subalpine species such as *Abies lasiocarpa* and *Pinus albicaulis* (Pojar *et al.* 1991a). At higher elevations the MH zone occurs as parkland, composed of tree islands within subalpine meadows.

Table 1.1: Latin and common names of FAMILIES, genera and species cited in the pollen diagram and text.

Latin Name	Common Name(s)
Abies	True fir or Balsam
Abies amabilis	Pacific silver fir
Abies lasiocarpa	Subalpine fir
Alnus incana - type	Mountain alder (m.c)
Alnus incana spp. tenuifolia	Mountain alder
Alnus rubra	Red alder
Alnus viridis - type	Sitka alder (m.c)
Alnus viridis spp. sinuata	Sitka alder
Ambrosia - type	Burweed
Arceuthobium	Dwarf mistletoe
Artemisia	Sagewort/mugwort
Betula	Birch
Botrychium	Grape ferns
Chamaecyparis nootkatensis	Yellow-cedar
CYPERACEAE	Sedge
Cystopteris fragilis	Fragile fern
Equisetum	Horsetail
ERICACEAE	Heath
FILICALES	Fern
Lycopodium	Clubmoss
Lycopodium dendroideum	Ground-pine
Menyanthes trifoliata	Buckbean
Menziesia ferruginea	False azalea
Nuphar lutea	Yellow waterlily
Picea	Spruce
Picea engelmannii	Engelmann spruce
Picea sitchensis	Sitka Spruce
Pinus	Pine
Pinus albicaulis	Whitebark pine
Pinus contorta	Lodgepole pine
Pinus monticola	Western white pine
POACEAE	Grass
Polypodium	Evergreen ferns
Potamogeton	Pondweed
Pseudotsuga menziesii	Douglas-fir
Pteridium aquilinum	Bracken fern
Rhododendron albiflorum	White-flowered rhododendron
Salix	Willow
Sphagnum	Peat moss
Thuja plicata	Western redcedar
Tsuga heterophylla	Western hemlock
Tsuga mertensiana	Mountain hemlock
Vaccinium membranaceum	Black huckleberry

m.c.: Most commonly present species of the 'type' designation

CHAPTER TWO
STUDY SITE

2.1 Site description

Moraine Bog is located north of Tiedemann Glacier (51°19.8' N, 124°55.7' W) (Figs. 1.1, 2.1, 2.2, 2.3, 2.4) at an elevation of 891 m above sea level in the southwestern Coast Mountains. It is a small ombrotrophic peat bog less than 1 hectare in area (Figs. 2.1, 2.3, 2.4). The ecohydrology of the bog is sensitive to climate change; shifts in the ratio of precipitation to evaporation cause significant changes in water level and vegetation (*cf.* Charman 2002; Committee on Abrupt Climate Change *et al.* 2002a).

Tsuga mertensiana and *Abies amabilis* dominate the surrounding forest (Fig. 2.1), and *Abies lasiocarpa*, *Picea engelmannii, Tsuga heterophylla,* and *Pinus monticola* are also present. The understorey consists mainly of *Alnus viridis* shrubs and various ferns. A typical sphagnum bog community covers the bog surface. Cyperaceae and *Menyanthes trifoliata* colonize small wet patches in the bog, and open shallow water supports *Nuphar lutea*. Maximum measured water depth in the open pool in the summer of 2002 was 39 cm.

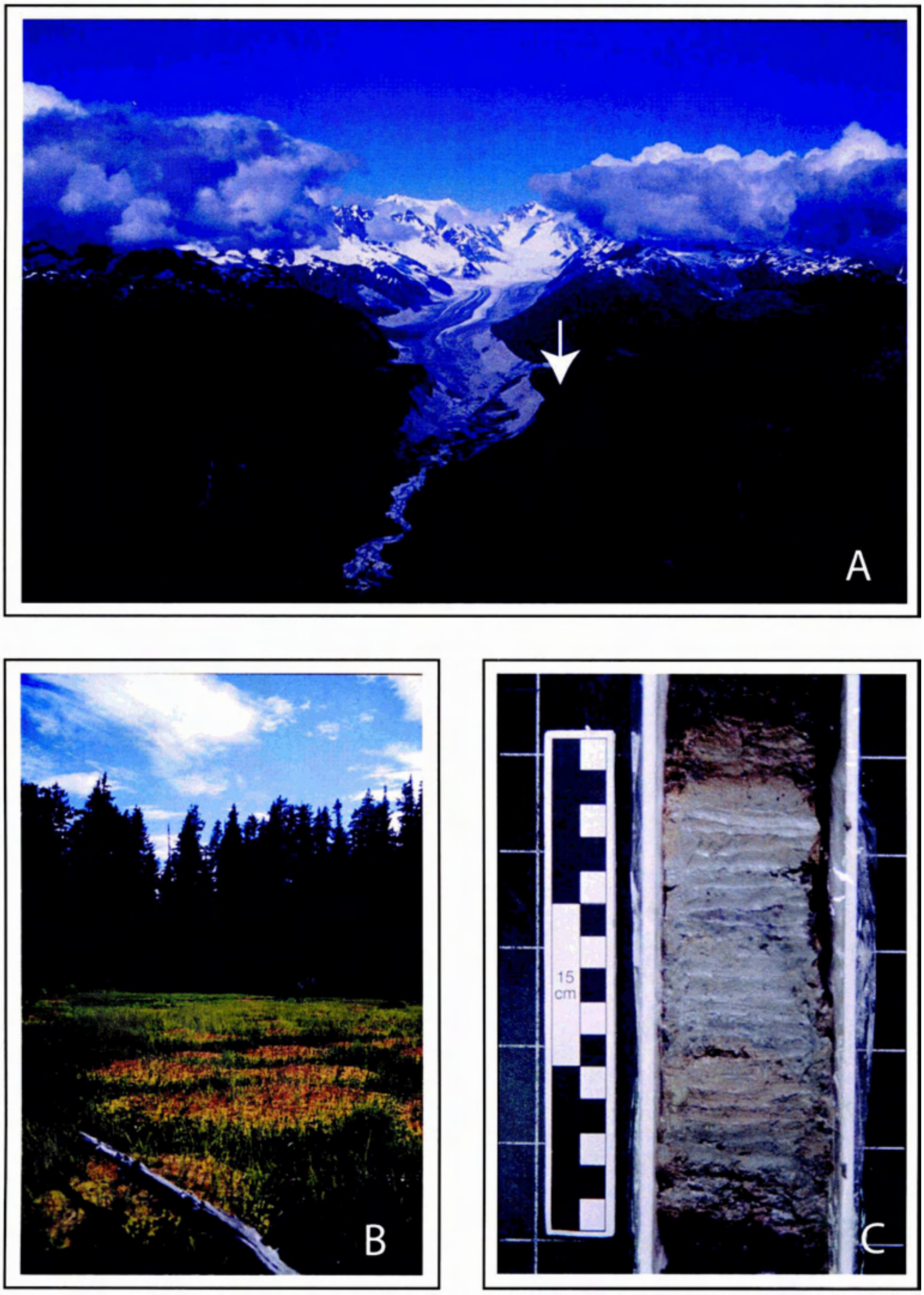


Figure 2.2: (A) Tiedemann Glacier, view west. Arrow indicates approximate location of Moraine Bog. (B) Moraine Bog. (C) Silty clay layer at 158-171 cm in the Moraine Bog core.

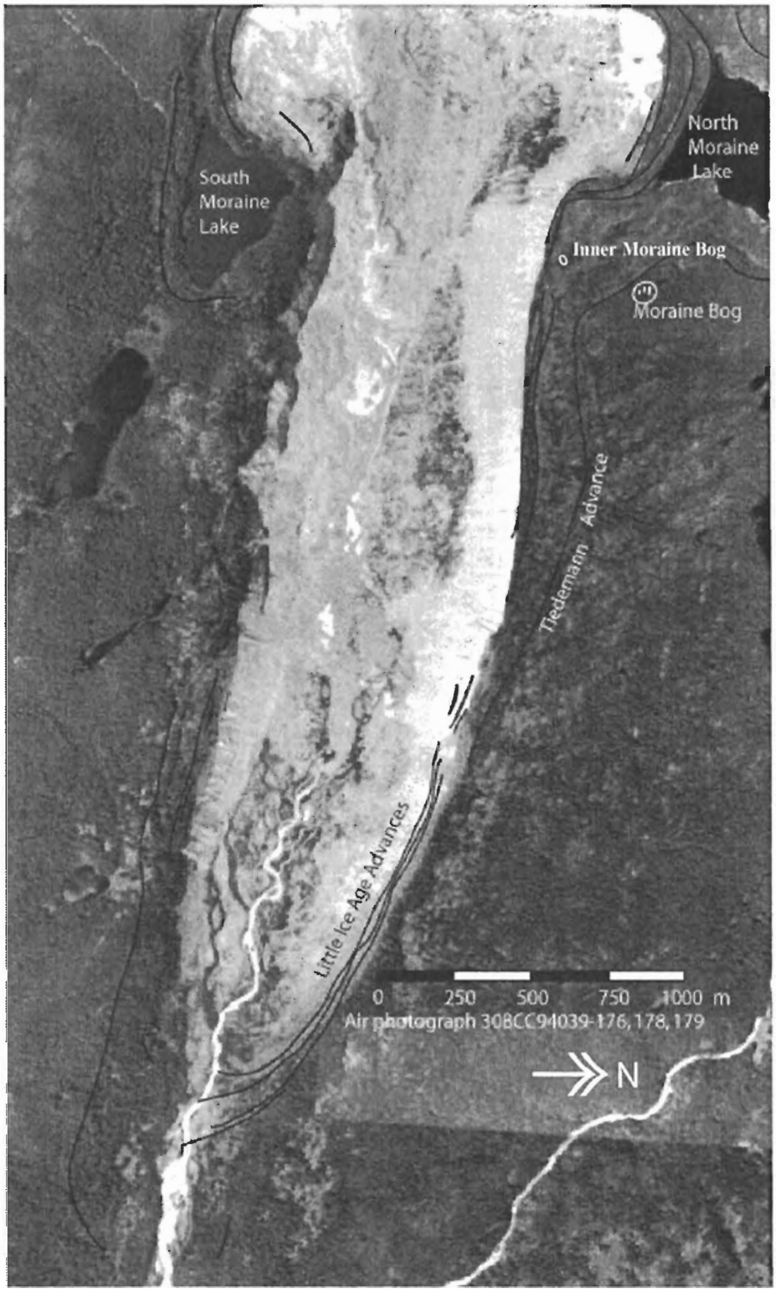


Figure 2.2: Aerial photograph of Tiedemann Glacier showing Neoglacial moraines (solid lines). Location of Moraine Bog is shown at upper right. Aerial photographs 30BCC94039-176, 178, 179. Reproduced with permission of the Province of British Columbia. Modified from Larocque and Smith (2003) with permission.

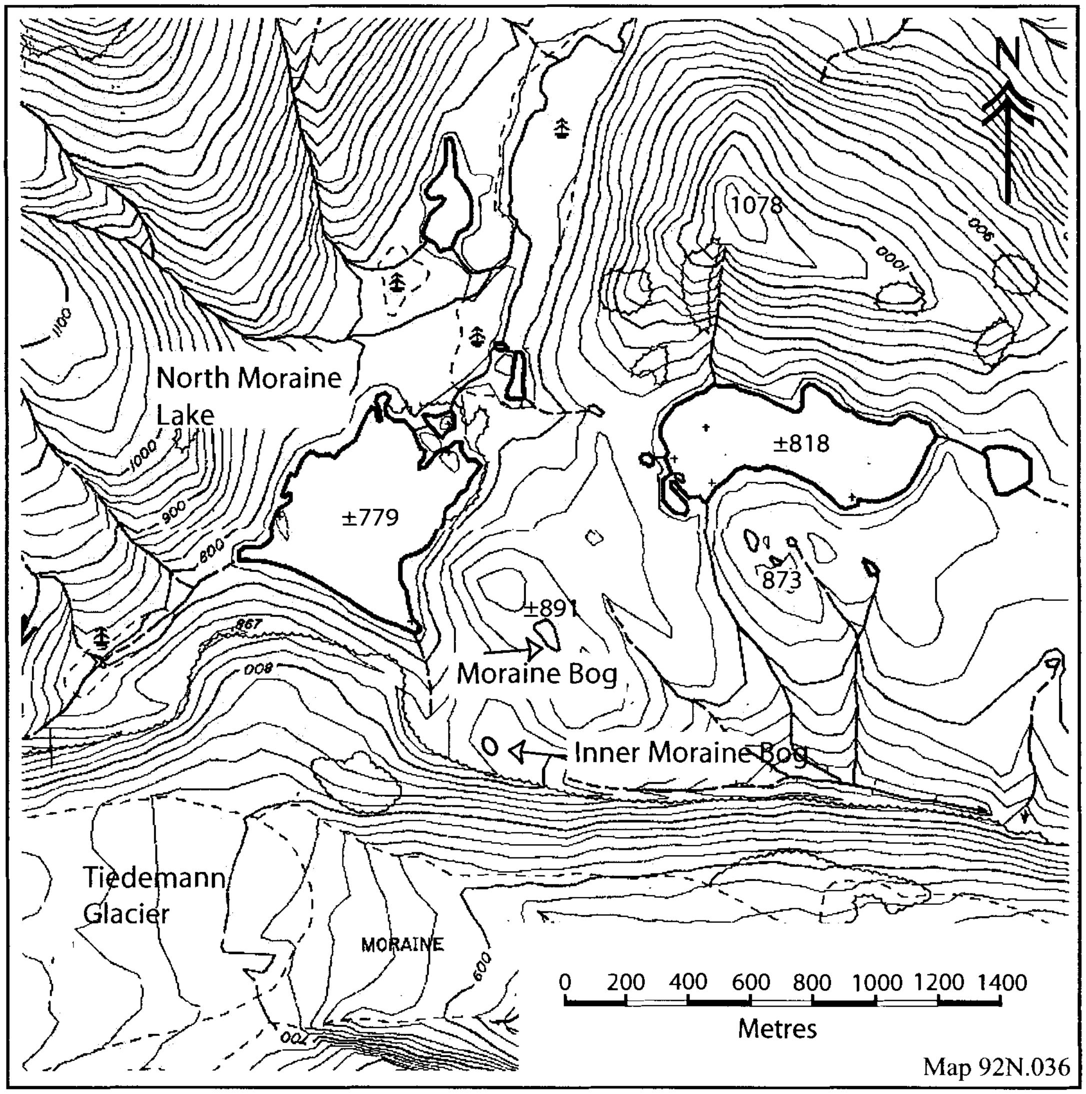


Figure 2.3: Topographic map of the area around Moraine Bog. Contour interval 20 m. Moraing Bog is located at 51°19.8' N, 124°55.7' W. Modified with permission of the Province of British Columbia.

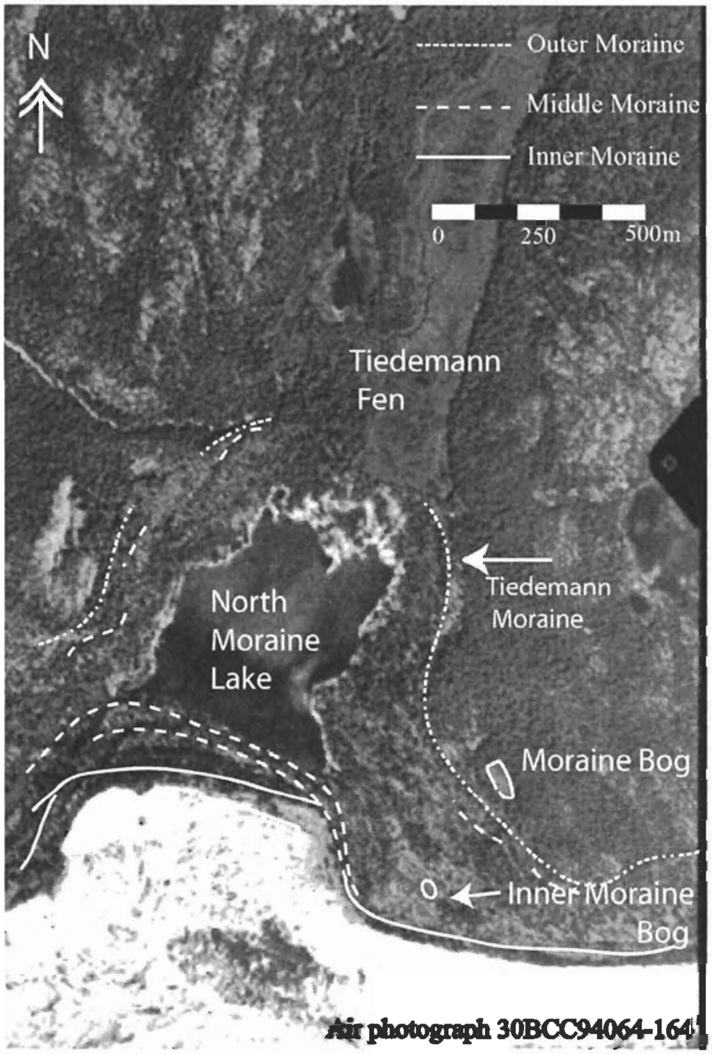


Figure 2.4: Aerial photograph of the area around Moraine Bog showing the outer,middle, and inner moraines. Aerial photograph 30BCC94064-164. Reproduced with permission of the Province of British Columbia.

Moraine Bog is bordered to the southwest by a series of moraines (Figs. 2.2, 2.4). Pre-Little Ice Age moraines have been grouped into outer, middle, and inner moraines (Ryder and Thomson 1986)(Fig. 2.4). The outer moraine is a well-defined blocky ridge that delimits the maximum Holocene extent of Tiedemann Glacier. The ridge is composed of angular to sub-rounded blocks that, on average, are greater than one metre across. It is continuous along the length of the glacier from the present glacier snout to where the inner and outer moraines converge (~7 km) up-valley. The inner moraine impounds both North and South Moraine lakes (previously termed Leak and Loop lakes by R.J. Fulton and also North Tiedemann and South Tiedemann lakes by Larocque and Smith 2003). It lies inside and is parallel to the outer moraine and, like the Little Ice Age lateral moraines, is sharp-crested. The moraine crest is vegetated with dense shrub alder (*A. viridis*). A series of at least three smaller, discontinuous blocky ridges, termed "middle moraines", lies between the inner and outer moraines (Fig. 2.4). Inner Moraine Bog lies within the series of middle moraines (Fig. 2.4).

2.2 Previous work at Moraine Bog

In 1967, R.J. Fulton collected two cores from Moraine Bog, and one core from Inner Moraine Bog. A silty clay layer, bracketed by radiocarbon ages of 2250±130 ^{14}C yr BP (GSC-948) and 2940±130 ^{14}C yr BP (GSC-938), occurred at a depth of 217-227 cm in the 280-cm-long Moraine Bog core (Fulton 1971). Fulton interpreted the silty clay layer as having been deposited when Tiedemann Glacier constructed the outer moraine. The age of basal peat from Moraine Bog, which Fulton interpreted to be a minimum age of deglaciation, is 9510±160 ^{14}C yr BP (GSC-939) (Fulton 1971). Basal peat from Inner

Moraine Bog core was dated at 1270±140 ^{14}C yr BP (GSC-977). Ryder and Thomson (1986) mapped the surficial geology of the study area through air photo interpretation, ground checking, and helicopter aerial observations. They also established a chronology of the Neoglacial advances of Tiedemann Glacier from radiocarbon ages obtained from moraines and soil pits. They described moraine stratigraphy at several locations along the glacier and recognized six units: three fluvial units (F1, F2, F3) separated by three tills (M1, M2, M3). A thick, stratified till (M1) exposed in the proximal flank of the inner moraine represents the earliest, undated advance of Tiedemann Glacier. A mature soil caps this till. M2, F1, and F2, are a middle till and two associated fluvial units. Deposition of these units began before *ca.* 3345 ^{14}C yr BP and culminated after *ca.* 2300 ^{14}C yr BP. During this advance, ice overrode a forested moraine and fluvial sediments (F1), reaching its maximum extent at the outermost moraine. Ryder and Thomson (1986) suggest that the glacier may have constructed the 'middle moraines' shortly before 1270 ^{14}C yr BP, which is the age of the base of Inner Moraine Bog. The amount of subsequent glacier recession prior to the first advance of the Little Ice Age is unknown. The date of initiation of the most recent advance, which left units M3 and F3, is also unknown.

Larocque and Smith (2003) attempted to date the "middle moraine" complex as well as the Little Ice Age moraines (Fig. 2.4) on the eastern side of Tiedemann Glacier using lichenometry. Dating was based on a lichen growth curve established for the Bella Coola area (Smith and Desloges 2000) and calibrated to the Mt. Waddington area. The lichen data suggest that the "middle moraines" were built during stillstands or minor re-advances after the Tiedemann advance. The oldest of the middle moraines was dated to

AD 620. The moraine that surrounds North Moraine Lake was constructed prior to AD 925 (Larocque and Smith 2003).

CHAPTER THREE
METHODS

3.1 Field methods

A trip was made to Tiedemann Glacier in the summer of 2002 to retrieve cores from Moraine Bog, field-check previously mapped moraines, and perform a brief qualitative description of the vegetation. Two sediment cores, 372 and 373 cm long, were collected from Moraine Bog with a 5-cm-diameter modified Livingstone piston sampler (Wright 1967). A 7-cm-diameter PVC casing helped maintain the borehole. The uppermost 42 cm of watery sediment were sampled using a Brown corer with a clear plastic tube. The loose sediments from the Brown core were siphoned into labelled plastic bags at 1 cm intervals. Segments of the Livingstone cores were extruded onto plastic wrap surrounded by aluminium foil, wrapped, labelled, and placed in a core box for transport to Simon Fraser University.

The cores were retrieved near the centre of a 39-cm-deep pool of open water in the bog. Both cores terminated in silt and sand. All cores were stored in a cold room at Simon Fraser University at 4°C until analysed.

Moraines bordering Tiedemann Glacier were mapped using air photos BCC94039-176, 178, 179, and a binocular scope. The mapping was checked in the field and compared to that of Larocque and Smith (2003). A brief survey was made of bog and woodland vegetation.

3.2 Stratigraphy and physical properties

Cores were split in the laboratory and photographed using colour slide film. One core was selected for further analysis. Sediments were described using a modified Troels-Smith system (Aaby and Berglund 1986). Notable changes in Munsell colour, texture, and sedimentary features were recorded. Wet mounts and grit tests established the type and texture of sediment. Organic content of the sediment was determined through loss on ignition (Bengtsson and Enell 1986). Changes in mineralogy were inferred through magnetic susceptibility analysis (King and Channell 1991).

3.2.1 Sedimentology

The Troels-Smith system classifies organic deposits on the basis of three descriptors: (1) physical properties, (2) humicity (degree of decomposition), and (3) deposit composition (Troels-Smith 1955; Aaby and Berglund 1986). A modified version of this classification scheme, primarily based on deposit composition, was used to describe the Moraine Bog sediment. Sediment was placed in four broad categories: (1) peat (humic organic sediment), (2) peaty gyttja (fragmented organic sediments of terrestrial and limnic origins), (3) gyttja (organic sediment of limnic origins), (4) silt and clay.

3.2.2 Magnetic susceptibility

Whole core magnetic susceptibility was performed at Western Washington University in Bellingham, WA. The magnetic strength of sediment depends on mineralogy, wet volume density, and total organic carbon (PALE Steering Committee 1993). Sediment provenance can be inferred from changes in magnetic susceptibility (Andrews and Jennings 1987). Measurements were taken at 2-cm intervals using a 60-mm-diameter loop connected to the Multisus system (King and Channell 1991; Bartington Instruments Ltd. 2002). They were recorded in SI units and plotted using PSIMPOLL (Bennett 2002).

3.2.3 Loss on ignition (LOI)

Loss on ignition (LOI) measurements were made to characterize the organic content of the core. The discovery that factors such as (1) exposure time, (2) position of crucibles relative to the furnace centre and (3) sample size can have an impact on results has led to recommendations to standardize LOI procedures (Heiri *et al.* 2001; Smith 2003). Researchers combust sediment for 1 to 4 hrs at a variety of temperatures, commonly without justification (Smith 2003). Heiri *et al.* (2001) recently recommended an exposure time of 4 hrs, but results from their study show that LOI is greatest in the first 2-2.5 hrs, after which weight loss decreases to 0.02% per hour at 2.5 hrs. The 2.5 hrs of exposure time suggested by Smith (2003) was thus used in this study.

General preparation procedures given by Bengtsson and Enell (1986) were followed, except for initial drying of ceramic crucibles (Heiri *et al.* 2001) and exposure time (Smith 2003). After each heating, crucibles were cooled in a dessicator to ensure that no additional moisture affected the dry weight measurements. Ceramic crucibles were dried for 12 hrs at 105°C in a Fisher Isotemp oven and weighed to determine dry crucible weight (DCW). One cm^3 samples were taken at 2 cm intervals using a calibrated brass sampler, placed in the crucibles, weighed, dried at 105°C overnight (~12 hrs), and weighed again, giving the dry crucible + dry sample weight (DCSW). The value obtained for the dry sample weight (DW_{105}) was then calculated as: DCSW - DCW = DW_{105}. Samples were then placed into a digital Themolyne 48000 Furnace at 550°C for 2.5 hrs, cooled, and weighed giving a value for the dry crucible + ash weight (DAW). Dry weight after ignition at 550°C (DW_{550}) was calculated as DAW – DCW. Loss on ignition (LOI_{550}) was calculated as a percentage of dry weight as: $((DW_{105} - DW_{550})/DW_{105})*100$.

3.2.4 Sedimentation and influx rates

Sedimentation rates were determined using the age-depth modelling function in PSIMPOLL (Bennett 2002). The age-depth model for Moraine Bog is a three-term polynomial curve fitted by least squares using an equation of the type $y = a + bx + cx^2$, where x is the sediment depth, y is the calculated radiocarbon age for depth x, and a, b, and c are constants. The chi-squared and goodness-of-fit are given for the equation in the results. Bennett (2002) suggests that chi-squared goodness-of-fit values that exceed 0.05 are acceptable. Sedimentation rates were calculated as the reciprocal of the difference in estimated age between the centre of the interval under examination and that immediately below it (Maher 1992). Sedimentation rates (cm/yr) were multiplied by concentrations (grains/cm^3) to obtain pollen influx values (grains/cm^2/yr). Average values for each pollen assemblage zone are presented in Table 4.2.

3.3 Pollen analysis

The core was scraped with a clean spatula to remove possible surface contamination and sectioned into 1 cm slices. Volumetric subsamples of 1 cm^3 were taken from the core at 2 cm intervals from 0-220 cm with a calibrated brass sampler (Birks 1976). Samples were placed in labelled, sealed glass vials, and the remaining core was stored in a cold room at 4°C for later use.

A known concentration of exotic *Lycopodium* marker spores (11,300 ± 400, Batch # 201890) was added to each sample prior to processing (Stockmarr 1971). A modification of standard procedures, following Faegri and Iversen (1989a), included treatment in 10% HCl, 10% KOH in a hot water bath for 10 minutes, concentrated HF in a hot water bath for 12 minutes, followed by acetolysis (9:1 acetic anhydride: sulphuric acid). All treated samples were then screened through a 500 μm sieve. Mineral-rich samples were filtered through a 7 μm Nitex screen to remove clay (Cwynar 1978). Residues were dehydrated with ethanol, stained with saffranin, and stored in silicone oil (2000 cs) in 1ml plastic vials. Slides were prepared using a drop of concentrate, smeared with a toothpick to cover an area slightly smaller than the cover slip. Clear nail polish was applied to the edges of the cover slip to seal it.

Pollen identification and counting were performed at 400x magnification. Critical identifications were made under oil immersion at 1000x magnification using a Zeiss binocular microscope (Model 46 0100-9904). A minimum of 500 terrestrial pollen grains were counted per sample, along regularly spaced traverses. Counts were terminated at 300 terrestrial grains for samples with low concentrations (< 30,000 grains/cm^3) and poor preservation. The first group of counts for samples between 155-175 cm involved 300 grains, but the number was subsequently raised to 500 to verify counting accuracy.

Identifications were made using Richard (1970), McAndrews *et al.* (1973), and Kapp (2000) and by comparison with the reference collection at Simon Fraser University from British Columbia. Some non-pollen fossils were identified using Warner (1990) and plotted as concentrations. Species-level identifications were made where the genus is represented by only one species within the study area. Latin and common names of plants are given in Table 1.1. 'Unknown' refers to pollen and spores not identifiable to a known taxon. Numerous grains of the same 'type' appear in this category if they have not been identified with the aid of the reference collection. Data were processed and the pollen diagram plotted using PSIMPOLL (Bennett 2002).

Zonation of pollen diagrams was done using both constrained cluster analysis by sum-of-squares (CONISS) and optimal splitting by information content in order to test the robustness of the zonation proposed by each method. Pollen grains were divided into trees and shrubs, herbs, aquatics, and spores for graphing and discussion. The terrestrial sum includes trees, shrubs, and herbs. Aquatics and spores form a separate sum. Species with over 2% representation are included in the pollen diagram.

3.3.1 *Alnus* species

Two species of alder (mountains alder and sitka alder) occur in the study area. Both are indicators of disturbed environments (Pojar and MacKinnon 1994). Pollen of both types have a scabrate surface and are characterized by four to six pores (Richard 1970) (Fig. 3.1). *Alnus viridis*-type (sitka alder) generally has five evenly spaced pores, connected by weak arci ~1.8 μm thick (Richard 1970). Grains have concave indentations between pores, are approximately circular in polar view, and are irregularly elliptical in equatorial view. Pores are subtle in equatorial view, have a distinct annulus, and are 5-6 μm in diameter. Average dimensions of *Alnus viridis*-type pollen grains are 18.1 ± 0.9 μm (polar view) and 21.5 ± 0.6 μm (equatorial view) (Richard 1970). *Alnus viridis*-type likely represents *Alnus viridis spp. sinuata*, sitka alder.

Alnus incana-type (mountain alder) pollen grains typically have four or five pores (Richard 1970). Pores are surrounded by an annulus 8 μm in diameter (Richard 1970). Arci, 3-4 μm in width, connect the pores (Richard 1970). The grains commonly have an irregular circular outline in polar view but are strongly elliptical in equatorial view. Protruding pores punctuate the rounded elliptical shape. Dimensions of *Alnus incana*-type pollen grains are 20.7 ± 1.6 μm (polar view) and 28.4 ± 3.7 μm (equatorial view) (Richard 1970). *Alnus incana*-type is likely derived from mountain alder.

Pollen of *Alnus incana* and *Alnus rubra* (red alder) have similar characteristics, but the number of pores distinguish the two species. *Alnus incana* has up to 50% four-pored grains, whereas *A. rubra* has only ~ 10% four-pored grains (R.W. Mathewes, personal communication, 2003). A count of specimens from Moraine Bog revealed that 42% of the alder grains are four-pored, suggesting that mountain alder is dominant. While postdepositional deformation commonly alters the shape of grains, few alder grains are broken or fragmented, making identification straightforward. Emphasis was placed on the equatorial dimensions of the grain, the depth, visibility, and concavity of arcs, and the size and number of pores.

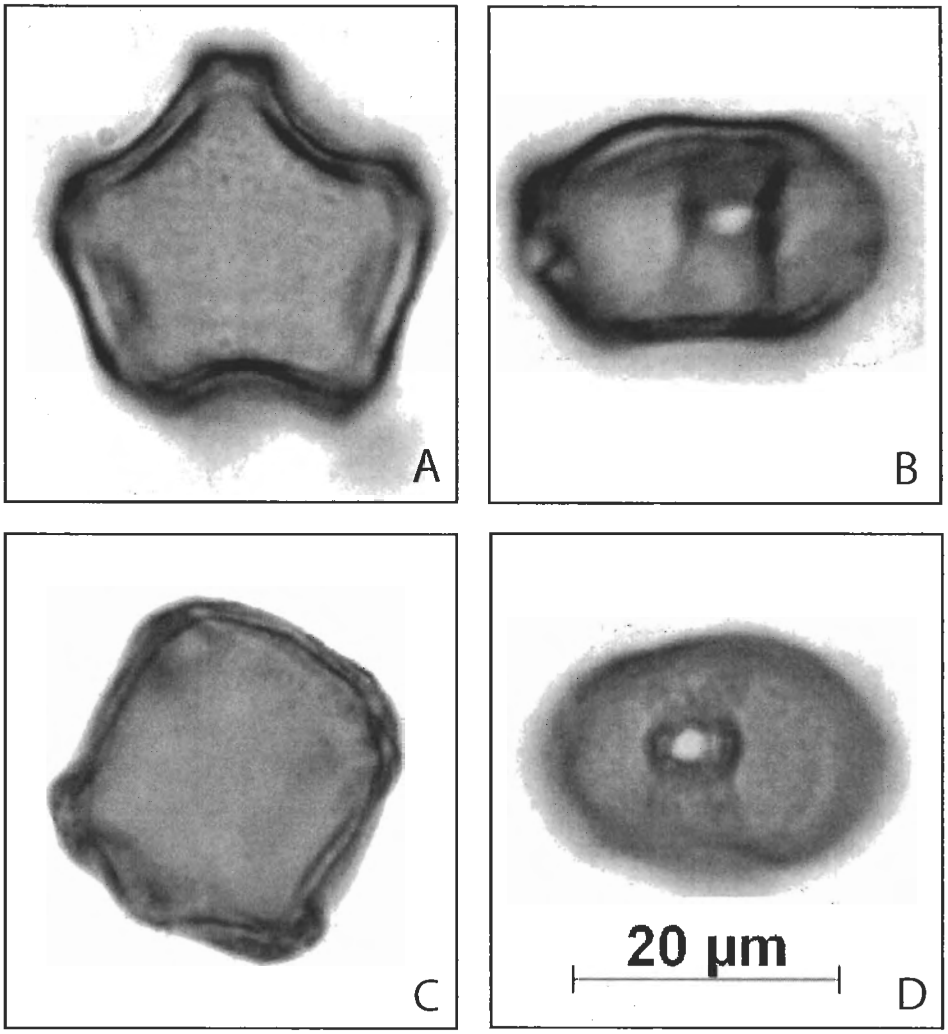


Figure 3.1: ***Alnus viridis*** **in (A) polar view and (B) equatorial view.** ***Alnus incana*** **in (C) polar view, (D) equatorial view. All grains taken from Moraine Bog core. All images taken at 1000x magnification under oil immersion.**

3.3.2 Abies species

Abies amabilis (Pacific silver fir) is common in the forest around Moraine Bog and *Abies lasiocarpa* (subalpine fir) is also present. Studies in the Coast Mountains have shown that *Abies* is underrepresented in pollen records despite being a major component of mid and high elevation forests (Hebda and Allen 1993; Pellatt 1996; Evans 1997; Heinrichs *et al.* 2002a). Low pollen production may explain the low representation relative to other tree species (Heusser 1973; Alley 1976; Macdonald 1987; Hebda and Allen 1993; Pellatt *et al.* 1997; Heinrichs *et al.* 2002b).

Abies amabilis and *Abies lasiocarpa* are infrequently found together. *Abies lasiocarpa* is the most widespread of the true firs in North America (Heinrichs 2002). It occurs throughout the Coast Mountains, extends north to the Yukon, south to New Mexico, and east to the Rocky Mountains (Alexander *et al.* 1990). It is a moderately shade-tolerant species, but also occurs as a colonizer in harsh environments such as talus slopes, avalanche tracks, and tundra (Alexander *et al.* 1990). It tolerates a wide range of summer and winter temperatures (Woodward *et al.* 1994), but is more likely to occur at higher elevations and at colder and drier sites than *A. amabilis* (Thompson *et al.* 1999). *Abies amabilis* is a shade-tolerant species (Alexander 1990) that thrives at lower elevations and at slightly warmer and wetter sites than *A. lasiocarpa* (Thompson *et al.* 1999). In particular, *A. amabilis* requires warmer winters than *A. lasiocarpa.*

Abies is an important component of the fossil pollen record in Moraine Bog. Attempts have been made to separate *Abies* pollen types in the Pacific Northwest

(Wodehouse 1935; Erdtman 1965; Bagnell 1975), but no consistent separation was possible in this study. *Abies* pollen grains are simply referred to by genus in this study.

3.3.3 *Tsuga* species

Tsuga heterophylla (western hemlock) grows in cool temperate and mesothermal climates. It increases in abundance as precipitation increases and decreases with increased continentality and elevation (Klinka *et al.* 1989). *Tsuga mertensiana* (mountain hemlock) also decreases in abundance with increasing precipitation and continentality and is most common in maritime subalpine forests (Klinka *et al.* 1989). *Tsuga mertensiana* pollen is bisaccate with small bladders wheras *T. heterophylla* lacks air sacs.

3.3.4 *Picea* species

Picea engelmannii (engelmann spruce) occurs most commonly in continental subalpine forests, particularly in the coast-interior transition zone. *Picea engelmannii* and *P. sitchensis* (sitka spruce) commonly hybridise (Klinka *et al.* 1989), therefore no attempt was made to separate the two pollen types, which are all listed as *Picea*.

3.3.5 *Pinus* species

Several species of *Pinus* occur in British Columbia. Trees are easily distinguished on the basis of physical characteristics such as needle length, cone size, and differences in bark texture. Distinguishing species on the basis of pollen is, however, more difficult. in this study An attempt was made in this study to classify each grain as either diploxylon or haploxylon type based on the presence or absence of distal membrane verrucaea (Ueno 1958; Bagnell 1975; Jacobs 1985). However, the preservation of *Pinus* pollen in the core is such that very few grains have an intact distal membrane. Other characteristics were examined, such as bladder and grain shape, presence or absence of a marginal frill and bladder blisters, and the degree of bladder constriction (Ueno 1958; Hansen and Cushing 1973; Bagnell 1975; Jacobs 1985), but the majority of grains could still not be identified to species level. In view of the large quantity of 'unknown' *Pinus* grains at some levels, the *Pinus* sum is referred to as '*Pinus*' and incorporates all pine pollen types.

3.4 Other microfossils

Entomophilous (insect-pollinated) plants are common in wetlands, but their pollen is rare due to directed dispersal (Faegri and Iversen 1989c). Little if any pollen from such plants is deposited in basins such as Moraine Bog. The presence of entomophilous species is better indicated through the use of other preserved organic components. Microscopic sclereids of *Nuphar lutea*, for example, can be used to estimate the past abundance of this aquatic plant. Sclereids are branched support cells located in the petiole and peduncle of species of the Nymphaeaceae family (Ogden 1974). The sclereids are stellate (star-shaped) and range in size from 100 to 400 µm (Fig. 3.2). They are composed of complex polymers of hardened lignin and cellulose, and thus survive standard pollen chemical treatments, are highly resistant to decomposition and decay, and can be easily identified under the microscope (Warner 1990).

Nuphar lutea spp. polysepalum (also known as *Nuphar polysepalum)* is an aquatic macrophyte with floating leaves, found throughout coastal British Columbia at all elevations (Pojar and MacKinnon 1994). It generally occurs in ponds and lakes less than

2 m deep, slow streams, and ditches (Warrington 1980). Large rhizomes, which anchor the plant to the substrate, produce floating leaves up to 45 cm long, and smaller submerged leaves. Dense colonies can produce enough floating leaves to cover the surface of the water (Warrington 1980).

Application of previous research on eutrophication and biomass suggests that *Nuphar lutea* is a good indicator of changing water depth at Moraine Bog. Firstly, researchers have suggested that floating-leaved plants, including *Nuphar*, become more prevalent with increasing eutrophication (US Environmental Protection Agency 2003). Concentration of phosphorous, nitrogen, and other nutrients commonly increase as water levels decrease (Charman 2002). Secondly, the sensitivity of *Nuphar* to water level is indicated by the following two-year study from Finland. In 1998, Lake Kevätön (mean depth of 2.3 m) received 1.5 times its average annual precipitation, with an effective growing season temperature sum of 1083 degree-days (Larmola *et al.* 2003). In 1999, it received 0.8 times the average precipitation and experienced 1309 degree-days, a total difference of 5°C during the growing season. *Nuphar* biomass increased approximately four times in 1999, the warmer and drier of the two years, when the water level was 39 cm lower than in the previous year (Larmola *et al.* 2003). These results suggest that the concentration of sclereids derived from the petiole and peduncles of *Nuphar* and other aquatic macrophytes could be a proxy for water level in Moraine Bog.

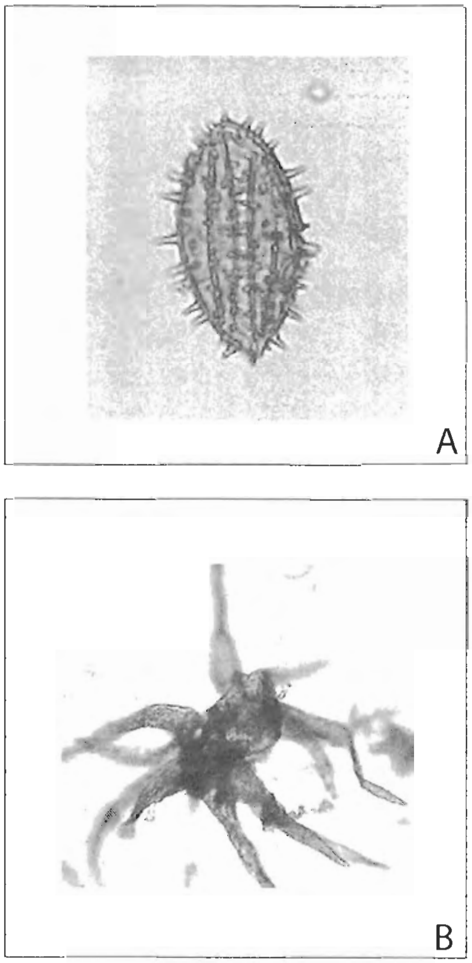


Figure 3.2: (A) *Nuphar* pollen (~45 μm in length). (B) *Nuphar* sclereid (~200 μm in diameter).

3.5 Radiocarbon dating

Well-preserved terrestrial macrofossils at six levels in the Moraine Bog core were dated by accelerator mass spectrometry (AMS) radiocarbon dating at IsoTrace Laboratory (TO) and Lawrence Livermore (CAMS). The dated macrofossils were whole needles and wood fragments. Two samples at 138-139 cm were dated by CAMS to give an indication of the precision of the laboratory. Uncalibrated radiocarbon ages are expressed as ^{14}C yr BP. Radiocarbon ages were calibrated using CALIB 4.3 (Stuiver and Braziunas 1993; Stuiver *et al.* 1998a, b) and are expressed as cal yr BP.

3.6 Statistical zonation

The Moraine Bog pollen sequence was subdivided into "pollen assemblage zones", defined by Birks (1972) as a body of sediment with particular fossil pollen and spore content that can be distinguished from other adjacent sediment based on the frequency of pollen and spores. Pollen zones are biostratigraphic units based entirely on fossil pollen and spores (Janssen 1980). As early as the 1970s, researchers began placing emphasis on using numerical methods, as opposed to visual inspection, to define pollen zones (Gordon and Birks 1972).

Numerical methods permit identification of zones that are not biased by sediment lithology, chronology, past vegetation, or inferred climate change. The Moraine Bog diagram was zoned through constrained cluster analysis (CONISS) (Grimm 1987) of percentage data. Samples were grouped into clusters based on their similarity to adjacent samples. The squared Euclidian distance is the measure of dissimilarity used to create the initial matrix. One drawback of the method is that squared Euclidian distances overemphasize the degree of dissimilarity of more abundant taxa (Birks and Gordon 1985). An indication of the robustness of zonation was achieved by reprocessing the data using optimal splitting by information content (Prentice 1980), which applies a different dissimilarity matrix. Zonation results are presented as a dendrogram in the pollen diagram.

Although determining zones is relatively straightforward and objective, establishing the number of zones that are statistically significantly different and can be reasonably recognized in a sequence remains subjective. The 'broken-stick' model (MacArthur 1957) was applied to objectively determine the number of numerically recognizable zones in the Moraine Bog sequence (Bennett 1996). This number is based on the variance associated with each successive CONISS cluster (Bennett 2002).

CHAPTER FOUR
RESULTS

4.1 Stratigraphy

The 3.7-m-long core consists primarily of dark brown gyttja intercalated with brown, rooty, decomposed peat. Coarse detritus and macrofossils are abundant throughout the core. A silty clay layer is present at 158-171 cm (Figs. 2.1, 4.1, 4.2). A silt and sand layer occurs at the base of the core and lies on an impenetrable material, thought to be late Pleistocene till (Fig. 4.1). The stratigraphy of the upper 220 cm of the core, which is the focus of the study, is shown in Figure 4.2. Radiocarbon ages are presented in Table 4.1. The radiocarbon age ranges from the two samples at 138-139 cm (1880±40 ^{14}C yr BP and 1850±35 ^{14}C yr BP) overlap at 2-sigma, indicating good laboratory precision.

Loss on ignition (Fig. 4.2) is high (> 90% organic content) for most of the record. Lower organic values occur between 0 and 10 cm (75% organics), 154 and 174 cm (~6% organics), 188 and 194 cm (~62% organics), and 210 and 220 cm (75% organics). Magnetic susceptibility values (Fig. 4.2) are low throughout the core, except from 158 to 172 cm where they reach 10 SI (metres-kilograms-seconds).

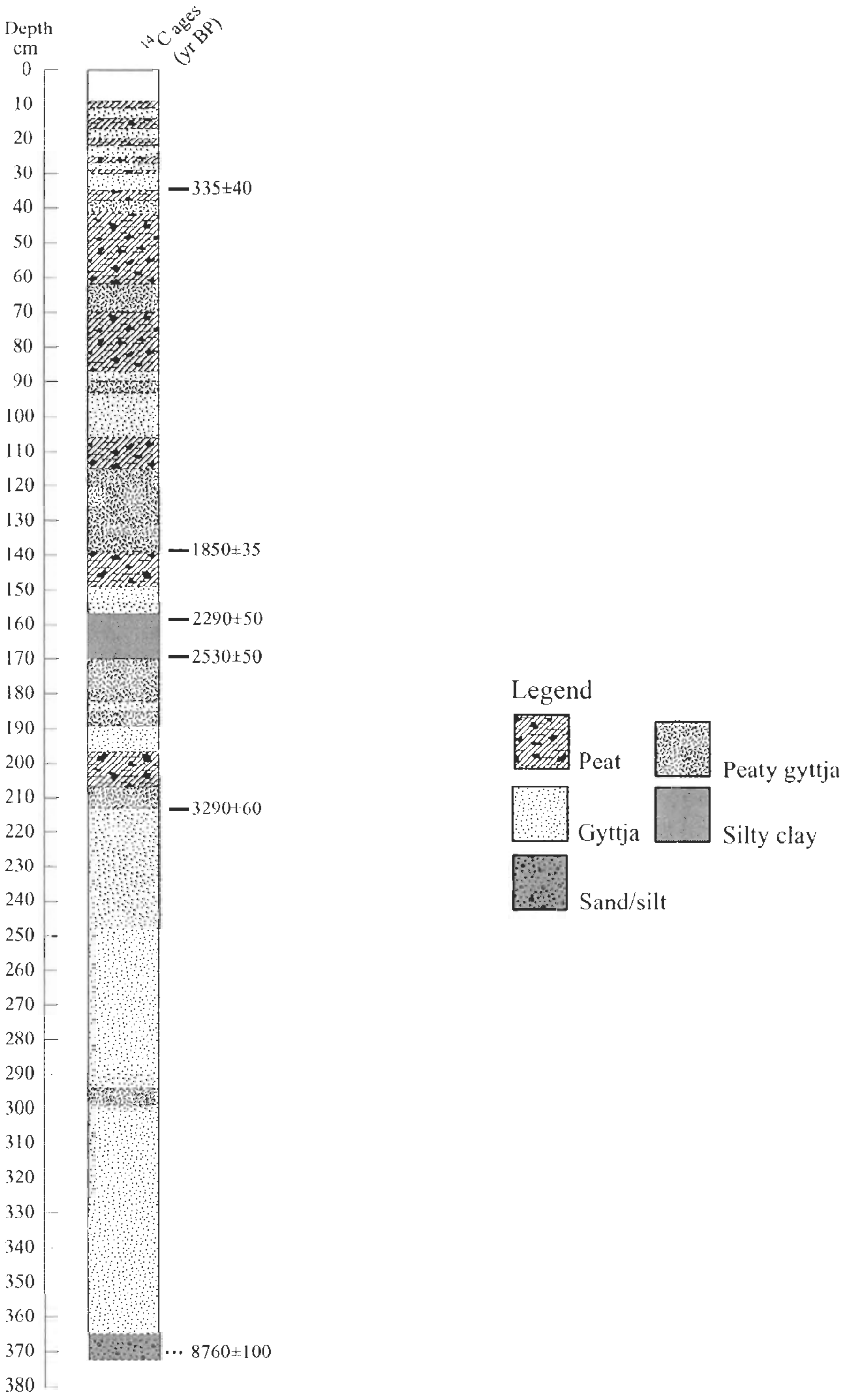


Figure 4.1: Simplified stratigraphy of the Moraine Bog core.

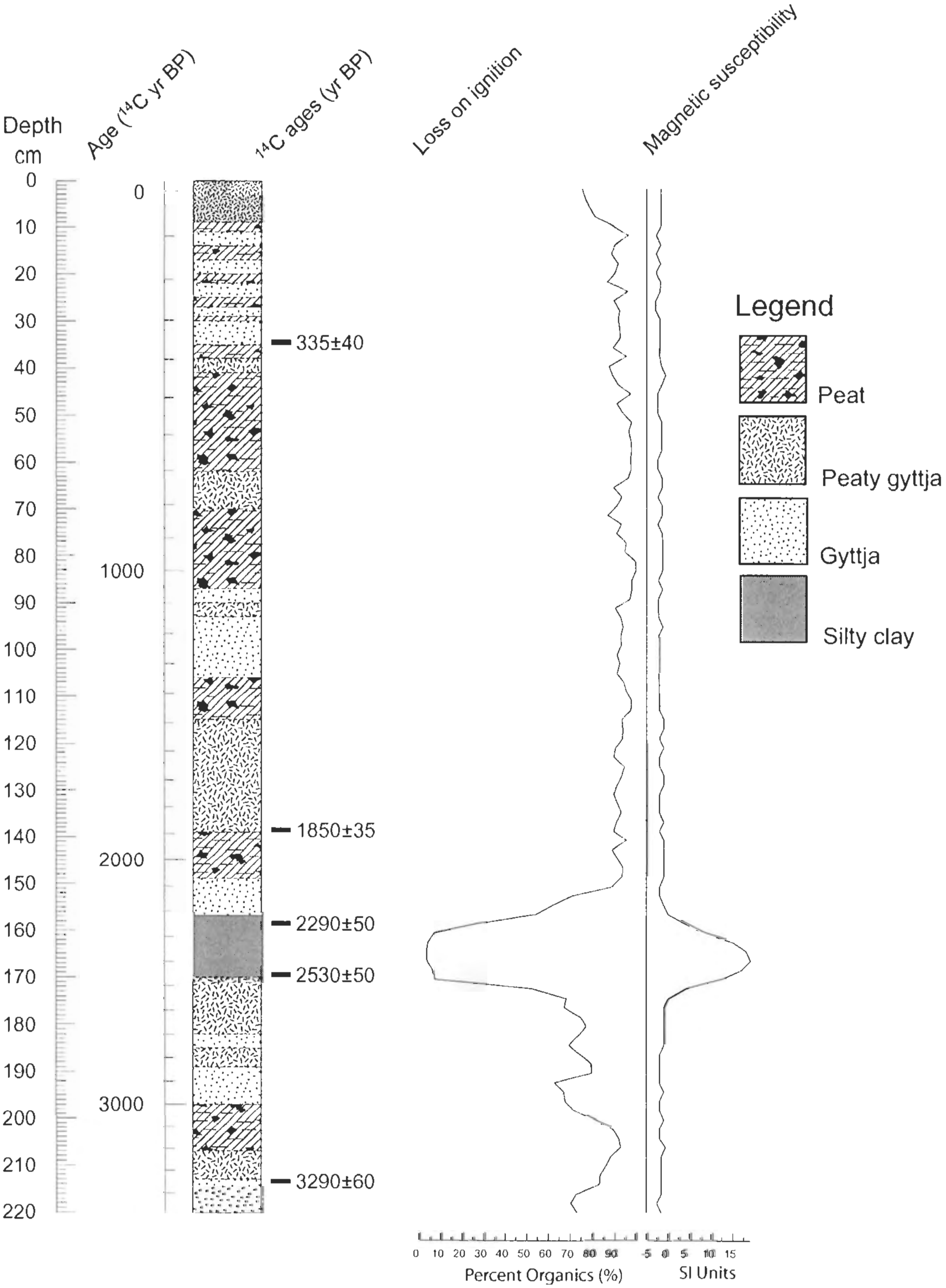


Figure 4.2: Stratigraphy of the upper 220 cm of the Moraine Bog core.

4.2 Chronology

An age-depth model (Fig. 4.3) for the last 3500 years is based on five radiocarbon ages (Table 4.1) from the upper 220 cm of sediment. The age-depth curve (Fig. 4.2) was constructed using a three-term polynomial ($y=-61.58 + 10.73x + 0.024x^2$). The R^2 value is 99.87% and the $\chi 2$ value is 4.872. The goodness-of-fit value for the chi-squared term is 0.181, indicating that the model is suitable. If compaction is considered, the sedimentation rate over the last 3500 years appears to be constant.

Table 1: AMS^{14}C ages on macrofossils from Moraine Bog.

Laboratory number	Depth below surface (cm)	Sample description	^{14}C age (^{14}C yr BP)[a]	Calibrated age with 2-sigma age range (calendar yr BP)[b,c]
CAMS-100583	34-35	Needles, in Trichoptera case	335±40	501 (430, 363, 325) 299
CAMS-100584[d]	138-139	Needles, *Abies amabilis*	1880±40	1920 (1822) 1711
TO-10755	158-159	Needles	2290±50	2355 (2336) 2152
TO-10756	169-170	Needles	2530±50	2752 (2713) 2361
CAMS-100585	213-214	Needles, joined pair, *Pinus contorta*	3290±60	3686 (3545, 3541, 3474) 3381
TO-10757	370-371	Wood	8760±100	10190 (9724, 9714) 9534

a ^{13}C = -25% (assumed values according to Stuiver and Polach 1977).

b Intercept ages in parentheses with upper and lower age range. Calibrated using CALIB 4.3 (Stuiveet *al.* 1998).

c Calendar yr BP denotes years before 1950.

d A second age of 1850±35 ^{14}C yr BP (CAMS 101001) was obtained on needles from the same depth.

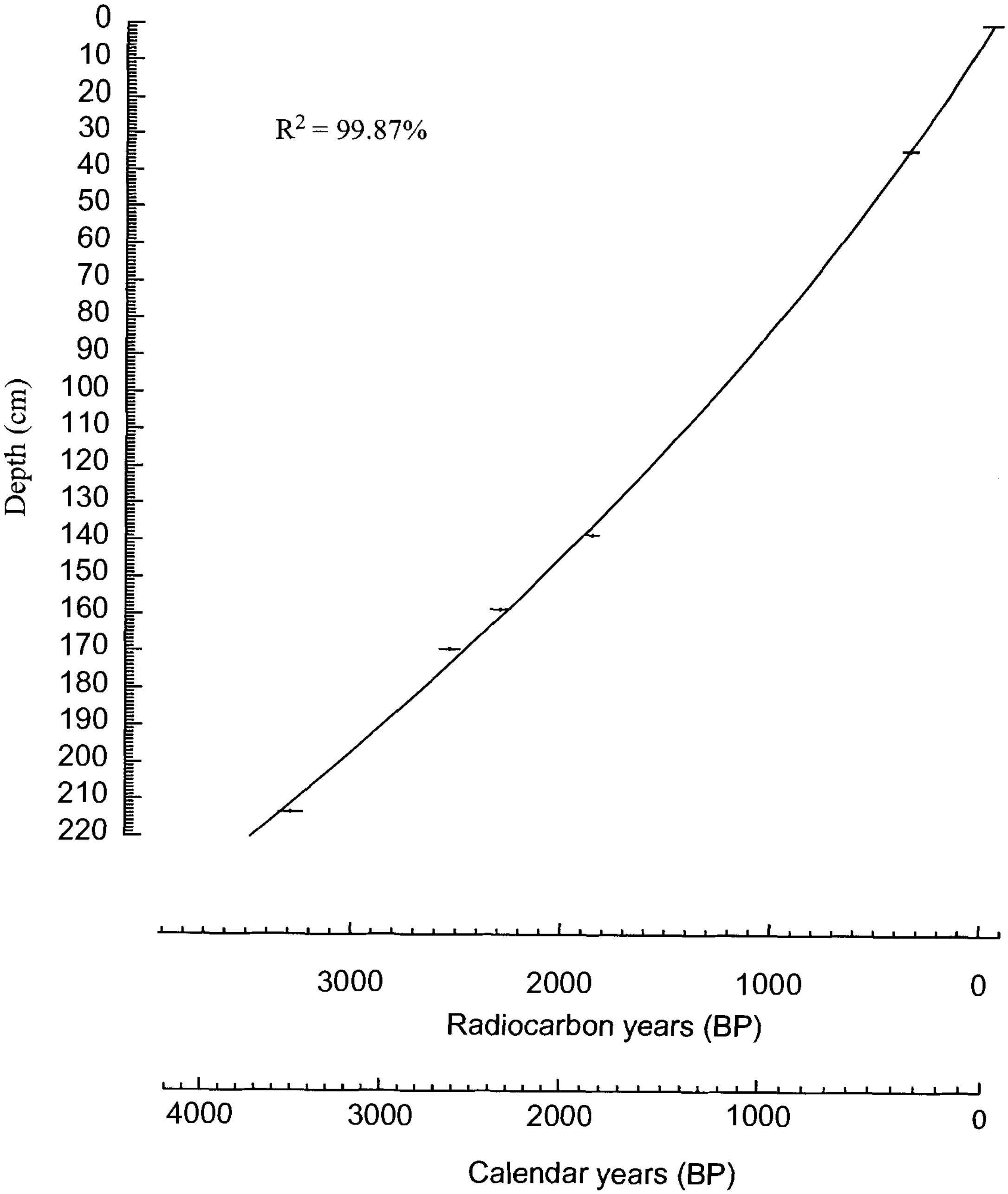


Figure 4.3: Age-depth plot for sediment core from Moraine Bog. A three-term polynomial equation ($y=-61.58 + 10.73x + 0.024x^2$) was used to construct the curve.

4.3 Pollen zonation

Five local pollen assemblage zones are defined for Moraine Bog (Table 4.2, Figs. 4.4, 4.5). Average sedimentation rates, pollen percentages, pollen concentration, and pollen influx rate are presented for each assemblage zone in Table 4.2, and pollen percentage data are summarized in Figure 4.5. *Nuphar* sclereid data are summarized in Figure 4.6. Zonation patterns produced by CONISS and optimal splitting by information content are very similar, with only the MB-2 lower boundary differing by several centimetres. Pollen from Moraine Bog is generally well preserved, although pollen preservation in some intervals is poor to extremely poor.

Zone MB-1:

(Abies – Tsuga heterophylla, Tsuga mertensiana, 220-165 cm, *ca.* 3500 – 2400 ^{14}C yr BP, *ca.* 3750-2425 cal yr BP)

Alnus viridis (~30%) dominates the base of zone MB-1 and likely formed the forest understorey around the bog. The forest cover is mainly *Abies* (~17%) and *Tsuga heterophylla* (15%). *Pinus* (26%) is also a major component of the forest, but shows fluctuates significantly during this zone. *Tsuga mertensiana* briefly achieves its highest percentages (14%) in this zone. The assemblage suggests a local mixed-species conifer forest. Pollen influx rates (2640 grains/cm^2/yr) are low compared to the other zones. *Nuphar* pollen values remain around 1% throughout the zone whereas sclereid values fluctuate, but are generally between 15,000 and 40,000 sclereids/cm^3.

Zone MB-2:

(*Alnus viridis – Alnus incana – Picea – Lycopodium,* 165 – 149 cm, *ca.* 2400-2100 ^{14}C yr BP, *ca.* 2425–2100 cal yr BP)

Zone MB-2 exhibits the largest changes in pollen percentages in the Moraine Bog record. *Alnus viridis* continues to dominate, increasing to a mid-late Holocene maximum (~45%). *Alnus incana* increases to about 10%, whereas *Abies*, *T. mertensiana*, *T. heterophylla*, and *Pinus* decrease rapidly in abundance at the beginning of the zone. *Abies* increases midway through the zone. *Tsuga heterophylla* and T. *mertensiana* show more gradual, but simultaneous increases. *Picea* increases slightly, reaching its highest values (~ 12%) in the lower half of the zone, before declining to about 1% at the top. Monolete fern spores, *Lycopodium* spores, and *Equisetum* spores reach their highest levels in this zone whereas N*uphar* pollen decreases and *Nuphar* sclereids reach their lowest values. Influx rates are low, averaging 1760 grains/cm^2/yr in this zone and dropping to 840 grains/cm^2/yr during deposition of silty clay layer between 171-158 cm.

Zone MB-3:

(*Abies – Tsuga heterophylla – Pseudotsuga*, 149-101 cm, *ca.* 2100 – 1300 ^{14}C yr BP, *ca.* 2100-1250 cal yr BP)

Abies and *T. heterophylla* increase to about 24% and 18%, respectively, in zone MB-3. The percentages of the two species in the lower part of this zone are higher than in zone MB-1. *Cystopteris fragilis* spores increase in abundance. This fern occurs at all elevations in cool, moist to dry environments, including rocky forests, rock cliffs, crevices, ledges, talus slopes (Pojar and MacKinnon 1994), and moraines. Trace amounts of *Pseudotsuga* occur in the lower part of the zone and exceed 10% by the middle of the zone (*ca.* 1800 ^{14}C yr BP). *Nuphar* sclereids and pollen fluctuate, but remain high (~ 40,000 sclereids/cm^3), throughout the zone. Pollen influx rates (2550 grains/cm^2/yr) are higher than in zone MB-3.

Zone MB-4:

(*Tsuga heterophylla – Abies – Alnus viridis*, 101- 45 cm, *ca.* 1300 – 500 ^{14}C yr BP, *ca.* 1250-550 cal yr BP)

Abies and *A. viridis* percentages (20%) are constant in zone MB-4, and *Pinus* increases slightly to 23%. *Cystopteris fragilis* values decrease to about 2%. *Pseudotsuga* decreases to 4% and *T. heterophylla* increases to 23%. Pollen influx values increase to 3180 grains/cm^2/yr. *Nuphar* sclereids and pollen decrease at two times in zone MB-4. Values drop to almost zero in the lower part of the zone, followed by an increase to about 30,000 sclereids/cm^3 in the middle, and a subsequent decrease to about 5000 sclereids/cm^3 near the top.

Zone MB-5:

(*Abies – Tsuga heterophylla – Pinus – Tsuga mertensiana*, 45-0 cm, *ca.* 500 ^{14}C yr BP – present, *ca.* 525-0 cal yr BP)

Pinus is abundant (30%) in the middle of zone MB-5 and declines slowly to about 20% by the top. *Tsuga mertensiana* increases to about 6% in this zone. *Abies* and *Alnus viridis* remain constant at about 20%. *Nuphar* sclereid concentrations remain around 30,000 scleirids/cm^3 throughout the zone. Influx values (4390 grains/cm^2/yr) are the highest of the last 3500 years.

Table 4.2: Zone characteristics, summary of pollen and spore percentages, sedimentation rates, pollen concentration, and pollen influx rates for the Moraine Bog core.

Zone description	Depth (cm)	Age (*ca.* cal BP)	Pollen and spore percentages	Sedimentation rate (cm/yr) and pollen concentration (grains/cm3)	Pollen influx (grains/cm^2/yr)
MB-1: *Abies – Tsuga heterophylla – Tsuga mertensiana*	220-165	3750-2425	*Alnus viridis-type* 27%; *Pinus* 26%; *Abies* 17%; *Tsuga heterophylla* 15%; *Tsuga mertensiana* 6%; *Alnus incana-type* 3%; *Picea* 2%	0.050^{s}, 63,600^{c}	2640
MB-2: *Alnus viridis – Alnus incana – Picea – Lycopodium*	165-149	2425-2100	*Alnus viridis-type* 41%; *Pinus* 19%; *Abies* 13%; *Tsuga heterophylla* 10%; *Alnus incana-type* 7%; *Lycopodium* 4%; *Picea* 3%; *Tsuga mertensiana* 2%;	0.055^{s}, 37,200^{c}	1760
MB-3: *Abies – Tsuga heterophylla – Pseudotsuga – Cystopteris fragilis*	149-101	2100-1250	*Alnus viridis-type* 26%; *Abies* 24%; *Tsuga heterophylla* 18%; *Pinus* 17%; *Cystopteris fragilis* 7%; *Tsuga mertensiana* 4%; *Pseudotsuga* 4%; *Alnus incana-type* 3%; *Picea* 2%	0.060^{s}, 46,900^{c}	2550
MB-4: *Tsuga heterophylla – Abies – Alnus viridis*	101-45	1250-550	*Tsuga heterophylla* 24%; *Pinus* 23%; *Abies* 21%; *Alnus viridis-type* 20%; *Tsuga mertensiana* 4%; *Pseudotsuga* 4%;	0.070^{s}, 46,300^{c}	3180
MB-5: *Tsuga heterophylla – Pinus – Tsuga mertensiana*	45-0	525-0	*Pinus 30%; Alnus viridis-type 21%; Tsuga heterophylla 14%; Tsuga mertensiana 7%; Cystopteris fragilis 4%; Pseudotsuga 3%; Picea 2%*	0.085^{s}, 52,700^{c}	4390

^{s}Sedimentation rate.
^{c}Pollen concentration.

Figure 4.4: Moraine Bog summary diagram. Pollen percentages (>5%), loss on ignition (LOI), magnetic susceptibility, and concentration (sclereids/cm^3) of *Nuphar* sclereids are shown. Unfilled curves are percentages at 10x exaggeration. Lithology and radiocarbon ages are shown at left. Pollen zones and CONISS dendrogram are shown on the right. Horizontal lines in the *Nuphar* plot indicate sample depths.

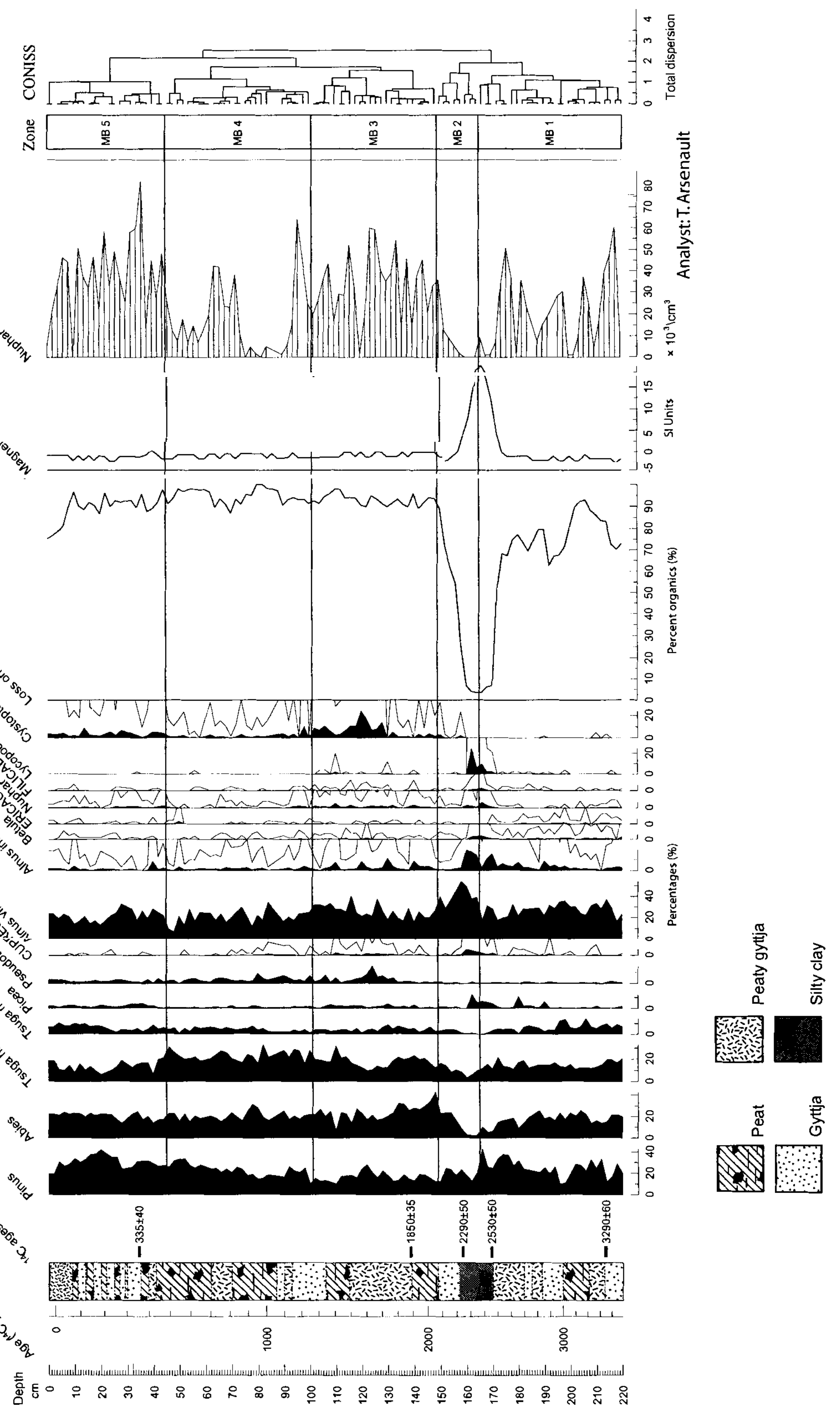
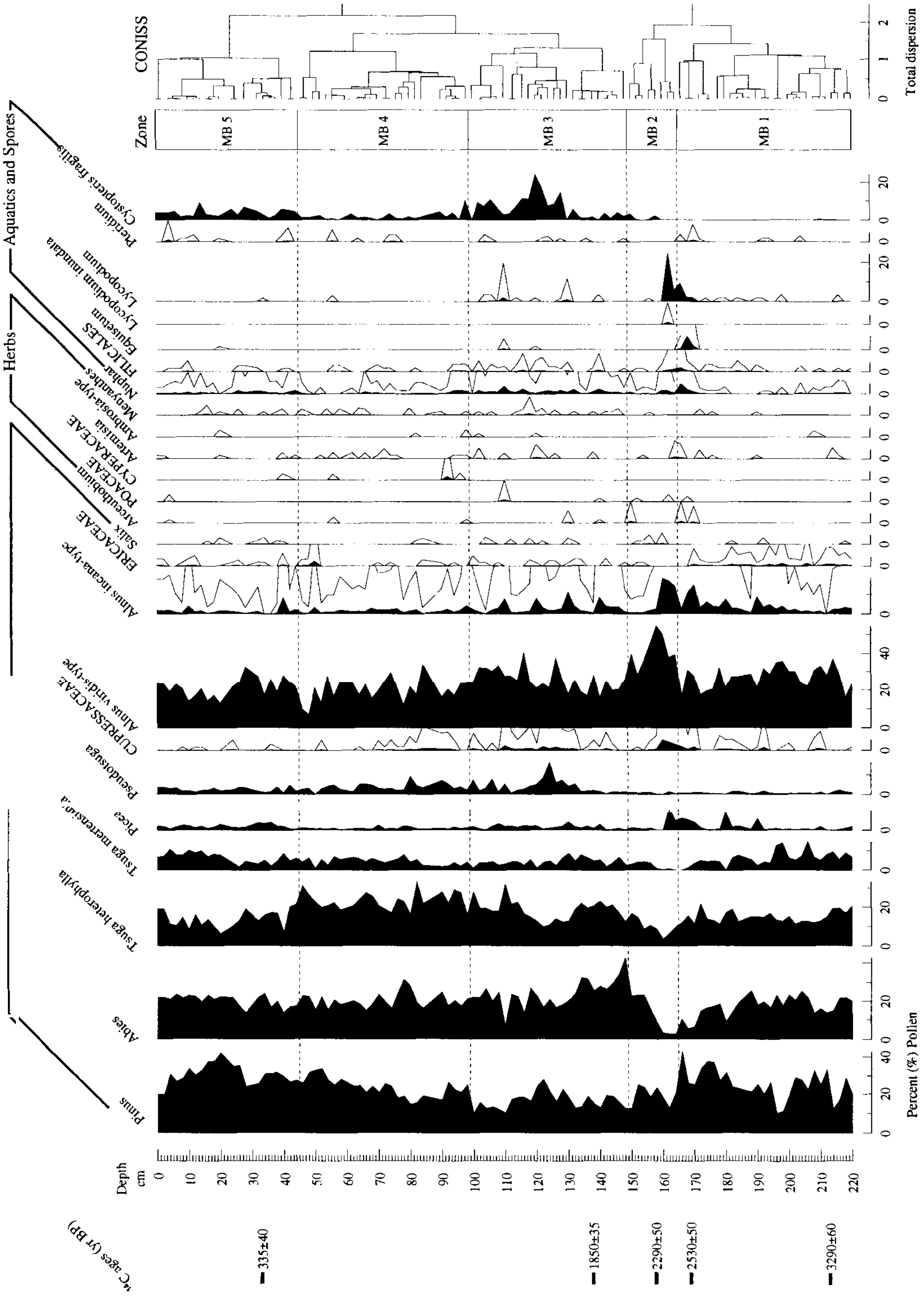

Depth cm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
Age (¹⁴C yr BP)
0
1000
2000
3000
¹⁴C ages (yr BP)
335±40
1850±35
2290±50
2530±50
3290±60
Pinus
Abies
Tsuga heterophylla
Tsuga mertensiana
Picea
Pseudotsuga
CUPRESSACEAE
Alnus viridis type
Alnus incana type
Betula
ERICACEAE
Nuphar
FILICALES
Lycopodium
Cystopteris fragilis
Loss on ignition
Magnetic susceptibility
Nuphar sclereids
Percentages (%)
Percent organics (%)
SI Units
x 10³\cm³
Zone
MB 1
MB 2
MB 3
MB 4
MB 5
CONISS
Total dispersion
Analyst: T. Arsenault
Peat
Peaty gyttja
Gyttja
Silty clay

Figure 4.5: Pollen percentage diagram for Moraine Bog core. Only values of 2% or greater are included. Unfilled curves represent 10x exaggeration of real values (black).



Pinus
Abies
Tsuga heterophylla
Tsuga mertensiana
Picea
Pseudotsuga
CUPRESSACEAE
Alnus viridis-type
Alnus incana-type
ERICACEAE
Salix
Arceuthobium
POACEAE
CYPERACEAE
Artemisia
Ambrosia-type
Menyanthes
Nuphar
FILICALES
Equisetum
Lycopodium
Lycopodium inundata
Pteridium
Cystopteris fragilis
Herbs
Aquatics and Spores
Zone
MB 5
MB 4
MB 3
MB 2
MB 1
CONISS
Total dispersion
0
1
2
Percent (%) Pollen
0
20
40
Depth cm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
210
220
¹⁴C ages (yr BP)
335±40
1850±35
2290±50
2530±50
3290±60

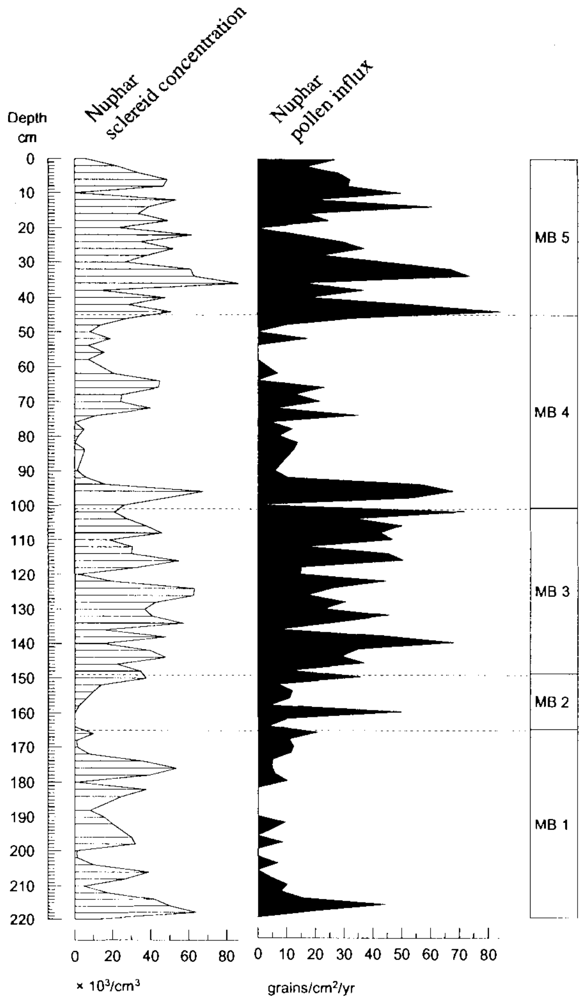


Figure 4.6: ***Nuphar*** **sclereid concentration and pollen influx diagram. Pollen assemblage zones are indicated.**

CHAPTER FIVE
DISCUSSION

5.1 Regional synthesis

This study provides palynological evidence for vegetation change in the central Coast Mountains of British Columbia over the last 3500 years. The vegetation and climate records developed for the Tiedemann Glacier study site corresponds well with other mid- and late-Holocene records for the coastal Pacific Northwest. There are several previously reported climatic events in the Coast Mountains (Fig. 5.1) Most published studies report establishment of modern climatic conditions in southern British Columbia around 3000 yr BP (Mathewes and Heusser 1981; Mathewes 1985; Wainman and Mathewes 1987; Mathewes and King 1989; Hebda 1995; Pellatt and Mathewes 1997; Pellatt *et al.* 1998, 2000, 2001; Gavin *et al.* 2001). These studies, however, are based on relatively coarse sampling, and some of the study sites are insensitive to minor changes in climate. Some recent paleoecological studies suggest that there was an interval of seasonably warmer and drier climate within the last 3000 years (Hallett *et al.* 2003a, b). This interval, from 2400 – 1300 cal yr BP (Hallett *et al.* 2003a, b) was followed by episodic cooling and glacier advance in the Coast Mountains (Larocque and Smith 2003; Reyes 2003). The Moraine Bog core provides evidence for a period of cooler and wetter climate *ca.* 3200-1900 ^{14}C yr BP, followed by warmer, drier conditions between *ca.* 1900 and 1500 ^{14}C yr BP, before the onset of modern conditions.

5.1.1 Tiedemann Advance

Ryder and Thomson (1986) defined the Tiedemann Advance as a period of glacier expansion between *ca.* 3300 and 1900 ^{14}C yr BP based on their work at Tiedemann Glacier (Fig. 5.1). This work indicates that Tiedemann Glacier constructed its outermost moraine between *ca.* 2500 and 2200 ^{14}C yr BP (ca. 2300 – 2700 cal yr BP) (Fig. 4.2). Earlier and later glacier advances were less extensive. Thus, the term "Tiedemann Advance" is somewhat of a misnomer, and should refer to the period of cool, wet climate from *ca.* 3300 to 1900 ^{14}C yr BP, not simply the glacier advance.

Several researchers have advocated using *Alnus* as an indicator taxon for the onset of environmental conditions associated with cooler climate and glacier advance (Heusser 1985; Mayle *et al.* 1993; Brown and Hebda 2003). Others have also noted dramatic increases in alder pollen concentrations during periods of disturbance (Walker 2003). Expansion of *Alnus incana* in the Pacific Northwest has been attributed to increased avalanche activity associated with cooler wetter climates (Gavin *et al.* 2001). The largest increase in *Alnus* at Moraine Bog is occurred during deposition of the silty clay layer. Newly exposed minerogenic soils would have provided habitat for *Alnus*, a pioneer genus in the Pacific Northwest. The soils were likely exposed due to glacier advance and increased avalanche activity in the area. Both *Alnus viridis* and *Alnus incana* are indicators of disturbed environments (Pojar and MacKinnon 1994). The abundance of

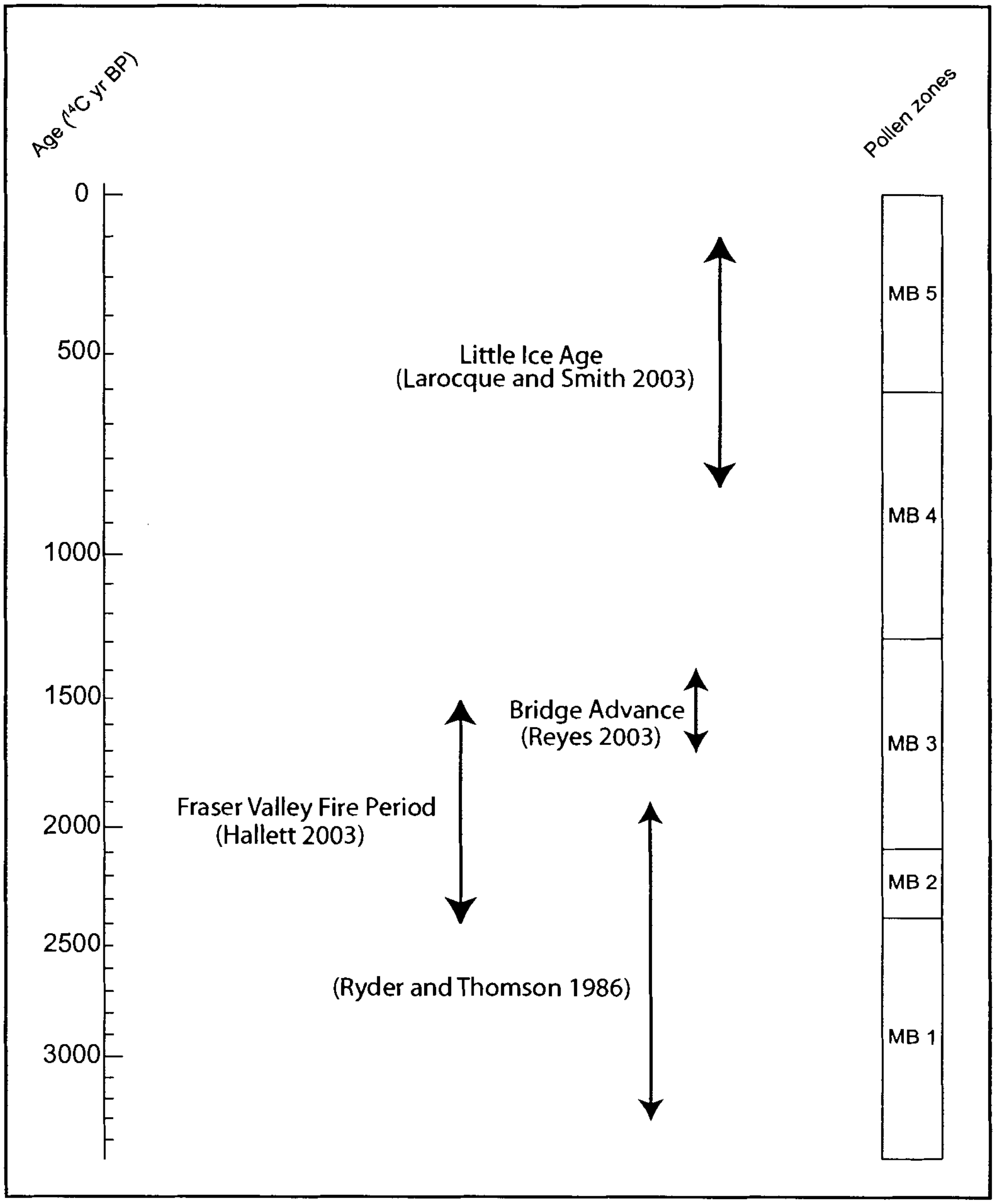


Figure 5.1: Summary of previously reported climate events during the last *ca.* 3500 ^{14}C yr BP in the Coast Mountains. Moraine Bog pollen zones indicated on the right.

Alnus viridis throughout the core suggests that a disturbed environment persisted throughout the late Holocene, likely at the edges of the bog, in the understorey, and on nearby rocky substrates.

Loss on ignition and pollen records indicate a shift to disturbed conditions at *ca.* 3200 ^{14}C yr BP, well before the Tiedemann maximum. Loss on ignition values reach 60% and *A. viridis* and *A. incana* pollen increase prior to the deposition of the silty clay layer. The increase in alder may reflect a vegetation response to glacier advance at 3345 ± 115 ^{14}C yr BP, inferred by Ryder and Thomson (1986). A coeval advance (3034 ±42 ^{14}C yr BP) has been inferred at Lillooet Glacier, 115 km to the southeast of Tiedemann Glacier (Reyes 2003). The decrease in *Abies* pollen and increases in fern and clubmoss spores likely result from inwash of soil during construction of the outermost Tiedemann moraine. Elevated fern spore abundances due to increased soil erosion have been noted at Marion Lake in the southern Coast Mountains (Mathewes 1973, 1985). The period of cool, wet climate, evident in the vegetation and water level records, persists until *ca.* 1900 ^{14}C yr BP.

Tiedemann-age glacier advances have been documented elsewhere in western North America, for example at Berendon and Frank Mackie glaciers in the Boundary Ranges (2870 - 2220 ^{14}C yr BP) (Clague and Mathewes 1996), Gilbert Glacier in the middle Coast Mountains (2200 – 1900 ^{14}C yr BP) (Ryder and Thomson 1986), Jacobsen Glacier near Bella Coola (2500 ^{14}C yr BP) (Desloges and Ryder 1990), and at Mount Rainier in the Cascade Ranges (2980 ^{14}C yr BP) (Crandell 1965; Crandell and Miller 1974). Two separate advances are recorded at Lillooet Glacier, one at *ca.* 3000 ^{14}C yr BP and another at *ca.* 2500 ^{14}C yr BP (Reyes 2003). Sediment records from Black Tusk Lake in Garibaldi Provincial Park, southern Coast Mountains, suggest a glacier advance beginning approximately 2750 cal yr BP (ca. 2650 ^{14}C yr BP) (Cashman *et al.* 2002). A correlative glacier advance, termed the Peyto Advance, has also been documented in the Canadian Rocky Mountains at Peyto and Robson glaciers (Luckman *et al.* 1993), Saskatchewan Glacier (Smith and Wood 2000), and Yoho Glacier (Luckman *et al.* 1993). It occurred between 3300 and 2500 ^{14}C years BP (Luckman *et al.* 1993). The Peyto Advance culminated at Stutfield Glacier prior to the deposition of the Bridge River tephra 2400 cal yr ago (ca. 2400 ^{14}C yr BP) (Osborn *et al.* 2001). High sedimentation records in lakes in Banff National Park between 3000 and 2350 ^{14}C years BP have also been interpreted as indicating glacier advance at this time (Leonard 1986).

5.1.2 Fraser Valley Fire Period

Several independent lines of evidence suggest that the Tiedemann Advance was followed by dry warmer conditions from *ca.* 1900 to 1500 ^{14}C yr BP (*ca.* 1800 – 1350 cal yr BP). This interval has been termed the Fraser Valley Fire Period (FVFP), has been documented in mountain hemlock forests 300 km southeast of Moraine Bog, based on an increase in macroscopic charcoal accumulation rates in high-elevation lake between 2400 and 1300 cal yr BP (Hallett *et al.* 2003a, b)(Fig. 5.1).

The increase in *Pseudotsuga* pollen and decrease in *Tsuga heterophylla* pollen in Moraine Bog zone MB-3 suggests a period of lower precipitation, drought, and increased fire frequency between about 1900 and 1500 ^{14}C yr BP (ca.. *Tsuga heterophylla* typically occurs in mesic areas in the Coast Mountains, but is replaced by *Pseudotsuga* on dry, rocky sites or in areas subject to fire disturbance (Pojar and MacKinnon 1994).

Pseudotsuga pollen grains are relatively large and do not disperse far from their source (McLennan and Mathewes 1984). Values as low as 10% have been recorded within *Pseudotsuga* stands in British Columbia (Mathewes and King 1989). *Pseudotsuga* pollen percentages briefly exceed 10% at Moraine Bog suggesting that the taxon was common at Moraine Bog during this period. Once established, stands of *Pseudotsuga* commonly persist for 800 to 1300 years (Franklin *et al.* 2002).

The *Nuphar* sclereid record provides additional evidence for a dry period at Moraine Bog during the late Holocene. Sclereids are abundant from *ca.* 1900 to 1600 ^{14}C yr BP, suggesting lower water levels. Sediment deposited in the bog during this interval is peat and peaty gyttja, which is consistent with low water levels. Increases in *Cystopteris fragilis* may reflect colonization of exposed rocky substrates (Pojar and MacKinnon 1994), such as the nearby blocky moraine, which may have been subject to fire.

Larocque and Smith (2003) found no evidence for a readvance of Tiedemann Glacier until the end of the Fraser Valley Fire Period (*ca.* 1300 cal yr BP), but Reyes (2003) suggests that Lillooet Glacier and other glaciers in the Coast Mountains expanded between about 1700 and 1400 ^{14}C yr BP (Fig. 5.1). This advance occurred late during the Fraser Valley Fire Period. Reyes (2003) invokes intensification of the Aleutian Low during the winter months to explain the Bridge Advance.

Water-level changes in lakes throughout North America suggest that present-day atmospheric circulation and storm trajectory patterns in the Pacific Northwest became established around 3000 yr BP (Harrison and Metcalfe 1985). Two patterns exist today. One pattern is characterized by intensified highs and lows and strong atmospheric circulation, with storms tracking across the Pacific Northwest (Burroughs 1999). The other exhibits reduced atmospheric circulation due to more subtle differences in highs and lows (Committee on Abrupt Climate Change *et al.* 2002b). In the latter state, winter storms track to the north and are directed onto the coast of Alaska (Wilson and Overland 1987). Penetration of the Pacific High during the summer brings warm dry conditions to the Pacific Northwest (Mantua *et al.* 1997).

Hallett (2003a) proposed a long-term increase in the intensity of the Pacific High as the cause of drought during the Fraser Valley Fire Period. Evidence for similar drought at Tiedemann Glacier suggests that an intensified Pacific High affected latitudes up to at least 51° N, more northerly than previously observed. Drought likely set in at higher latitudes due to poleward migration of the Pacific High. An intensified Pacific High may also have reduced continental penetration of the Aleutian Low, resulting in a westerly shift in the boundary of the coastal rainshadow. Sites farther north in the Coast Mountains likely experienced briefer droughts than southern sites.

Although sparse, the evidence supports the hypothesis that the Pacific High retreated as the Aleutian Low pushed south about 1500 ^{14}C yr BP (Hallett *et al.* 2003a, b; Reyes 2003). drought likely ended at Tiedemann Glacier *ca.* 1500 ^{14}C yr BP. Bridge Glacier was advancing 1500 ^{14}C yr BP suggesting an end of dry conditions by that time (Reyes 2003). Farther south, and east, increased fire frequency persisted until *ca.* 1300 cal yr BP at Frozen Lake and Mt. Barr Cirque, (Hallett *et al.* 2003a).

Tiedemann Glacier retreated during the Fraser Valley Fire Period, interrupted by still-stands or minor readvances (Ryder and Thomson 1986). The retreat indicates ablation due to higher summer temperatures and/or decreased winter precipitation. The fragmented middle moraines (Fig. 2.4) were deposited during slow and pulsatory recession between about 2300 ^{14}C yr BP and 1300 ^{14}C yr BP (Ryder and Thomson 1986).

5.1.3 Bridge Advance

About *ca.* 1350 ^{14}C yr BP (*ca.* 1250 cal yr BP), cooler, wetter conditions returned to Moraine Bog, likely due to intensification of Aleutian Low. *Pseudotsuga* decreases, and *T. heterophylla* increases to its highest late Holocene level, at this time. These changes occur at the transition between zones MB-4 and MB-3. A decrease in *Nuphar lutea* sclereids and a shift from peaty vegetation to gyttja support a return to wetter conditions and higher water levels. The first wet period commences prior to *ca.* 1300 ^{14}C yr BP (*ca.* 1260 cal yr BP). A similar period begins prior to *ca.* 700 ^{14}C yr BP (*ca.* 650 cal yr BP) and lasts about 200 years.

Tiedemann Glacier moraines provide evidence for glacier fluctuations during this time. Larocque and Smith (2003) present lichenometric evidence for two pre-LIA advances, the first prior to 1330 cal yr BP (AD 620) and a second prior to 1025 cal yr BP (AD 925), which built the moraine impounding North Moraine Lake. A basal radiocarbon age of 1270±140 ^{14}C yr BP from Inner Moraine Bog, is consistent with formation of North Moraine Lake around this time (Ryder and Thomson 1986).

5.1.4 Little Ice Age

Research in the Mount Waddington area indicates that glacier advances occurred, on average, every 65 years over the past 500 years (Larocque and Smith 2003). An early LIA advance around *ca.* 800 cal yr BP (1118 AD) delimits the maximum LIA extent of the Tiedemann Glacier (Larocque and Smith 2003). The rhythmic behaviour of these fluctuations is likely related to large-scale climate forcing (Bitz and Battisti 1999; Larocque and Smith 2003). Differences in mass balance, aspect, and local climate may account for different responses of glaciers sourcing from the same ice fields (Larocque and Smith 2003).

Although the Moraine Bog core establishes a cooler, wetter climate for the late Holocene, its chronological resolution is too poor to constrain individual LIA events. Increases in *Picea* and *T. mertensiana* pollen and decreases in *T. heterophylla* during the last *ca.* 500 years are likely the result of increased winter snowpacks and decreased summer temperatures (Gagan *et al.* 1998). The cooling may have triggered the establishment of a Mountain Hemlock Zone forest at Moraine Bog.

5.2 Ecosystem dynamics

Plant succession is a directional change in community composition and structure over time (Franklin *et al.* 2002; Gurevitch *et al.* 2002). Disturbances, such as glacier advances and forest fires, cause abrupt changes in the ecosystem and play a critical role in community ecology. Changes in the forest surrounding Moraine Bog are suggested in the pollen assemblage zones.

The microfossil record from Moraine Bog suggests that changes in precipitation, temperature and water levels are correlative with fluctuations of the Tiedemann Glacier. Pollen and *Nuphar* sclereids indicate several shifts in precipitation and, most likely, temperature during the last 3500 years. Although the proximity of the glacier to Moraine Bog during the maximum extent of the Tiedemann Advance (*ca.* 2500 – 2200 ^{14}C yr BP) likely had an impact on the micro-climate and vegetation record, changes in precipitation during and following this period are unaffected by the presence of the glacier. It is therefore likely that regional climate change triggered co-eval, but independent, responses by Tiedemann Glacier and the vegetation surrounding Moraine Bog during most of the late Holocene.

The forest surrounding Moraine Bog has yet to reach the climax stage (Braun-Blanquet 1932; Krajina 1959) expected of the Mountain Hemlock (MH) zone (Pojar *et al.* 1991a). Species such as *Pseudotsuga* and *Tsuga heterophylla* may be remnants of a previous community. Alternatively, the mixed assemblage may also be a unique mid-elevation climax forest adapted to a transitional coastal-interior climate. The greater abundance of *Tsuga heterophylla* at Moraine Bog during the Neoglacial period indicates a CWH ecosystem zone as opposed to the present MH zone. The greater abundance of *Pseudotsuga* between ca. 1900 and 1500 ^{14}C yr BP suggests drier conditions than today. This may indicate that one or both of the elevational and coast-interior (longitudinal) ecotones have shifted; elevationally with changing temperature or longitudinally with changing precipitation. Further analysis and comparison of samples with the modern palynology database for British Columbia is necessary to verify this hypothesis.

The lithological record from Moraine Bog suggests that sphagnum was important in the development of the bog, but the overall lack of *Sphagnum* spores in the fossil record is puzzling and largely unexplained. Although over forty species of *Sphagnum* have been identified in British Columbia (Pojar and MacKinnon 1994; Meidinger *et al.* 2002), little is known about the range and reproductive history of most species (Schofield 1990). Environmental stress experienced by bryophyte communities near their range limits has been related to a decrease in frequency of spore production and a dependence on asexual (vegetative) reproduction (Hill 1978; Ryan 1996; Sundberg 2002). There is no evidence suggesting Moraine Bog is at the limit of the sphagnum range, but I believe the limited presence of *Sphagnum* spores in the core is may be due to a lack of sexual reproduction.

CHAPTER SIX
SUMMARY

Results of palynological and lithological analyses of a core from Moraine Bog reveal the history of late Holocene vegetation and climate change at Tiedemann Glacier in the Coast Mountains of British Columbia. Several conclusions follow from the main objectives of this study: (1) a reconstruction of mid-late Holocene environments was made through analysis of pollen and sediment records. Four distinct, centennial-scale climate phases are evident over the last 3500 years. The Tiedemann Advance, a period of cool, wet climate and glacier advance occurred from *ca.* 3300 to 1900 ^{14}C yr BP. A warm, dry interval from *ca.* 1900 to 1500 ^{14}C yr BP is inferred from high *Nuphar* sclereid abundance and an increase in *Pseudotsuga* pollen at the site. A return to cool wet conditions around 1350 ^{14}C yr BP is coeval with the Bridge Advance documented at Lillooet Glacier. Cool, moist conditions characterize the Little Ice Age.

(2) The extent, time and nature of the Tiedemann Advance were established in this study. Results from Moraine Bog suggest the Tiedemann Glacier achieved its maximum Holocene extent between *ca.* 2500 and 2200 yr ^{14}C BP. Several advances

between *ca.* 3300 and 1900 ^{14}C yr BP are evident in Tiedemann Glacier moraines, but are not clearly recorded in the Moraine Bog vegetation record. Changes in vegetation lag changes in lithology in the Moraine Bog core, suggesting that vegetation responds slowly to the disturbances induced by the advancing glacier and cooling climate. Changes in climate are governed by intensification and weakening of the Aleutian Low and Pacific High systems. These changes likely caused elevational and coastal-interior ecotones to shift.

(3) The record of inferred climate change at Moraine Bog is generally consistent with paleoecological and paleoclimate records from other parts of the Coast Mountains, but it is unique in one important respect. Most previous palynological studies in the Coast Mountains establish the onset of modern conditions around 3000 ^{14}C yr BP and show little if any vegetation change after that. The Moraine Bog record provides more detail on the last 3500 years and highlights the importance of a fine sampling interval and selection of a site that is sensitive to climate change. Shifts in vegetation, hydrology, and inferred climate coincide with periods of increased fire frequency and mid-late Holocene glacier advances.

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APPENDIX A

Appendix A: Palynological percentage data

DEPTH (cm)	0	2	4	6	8	10	12	14	16	18
TAXON										
Pinus	19.86	19.86	30.83	26.92	28.73	33.78	30.31	32.89	37.50	37.77
CUPRESSACEAE	0.00	0.00	0.00	0.00	0.19	0.00	0.18	0.19	0.00	0.00
Pseudotsuga	4.84	3.79	3.12	3.58	1.89	2.11	1.45	1.88	2.11	3.18
Tsuga heterophylla	19.19	19.13	11.38	10.56	14.74	8.64	16.15	10.71	13.73	9.94
Tsuga mertensiana	7.04	7.04	10.64	7.84	7.75	10.17	8.89	9.77	6.87	8.15
Picea	3.68	2.35	0.92	2.21	2.84	2.69	1.45	2.26	1.06	1.79
Abies	16.47	22.20	21.28	24.02	21.93	23.42	22.87	19.74	23.24	21.07
Alnus incana-type	1.16	1.81	2.02	1.02	0.57	4.22	1.09	1.50	0.35	0.60
Alnus viridis-type	25.58	23.29	19.08	23.00	20.79	14.01	16.88	20.68	14.26	17.10
Betula	1.16	0.00	0.18	0.85	0.38	0.58	0.18	0.19	0.18	0.20
ERICACEAE	0.36	0.36	0.00	0.00	0.19	0.38	0.54	0.00	0.00	0.00
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20
Arceuthobium	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauria/Menyanthes	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.53	0.00
Nuphar	0.58	0.36	0.55	0.68	0.57	1.15	0.36	1.13	0.35	0.60
Potamogeton	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.40
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.97	0.00	0.18	0.17	0.19	0.58	0.00	0.00	0.00	0.00
Equisetum	1.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.34	0.00	0.00	0.00	0.00	0.18	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Polypodium	0.19	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	1.10	0.00	0.19	0.19	0.36	0.00	0.00	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	5.04	3.97	3.85	4.77	1.89	2.50	1.81	9.21	2.82	2.39

DEPTH (cm)	20	24	26	28	32	34	36	38	40	42
TAXON										
Pinus	41.95	35.24	35.51	24.22	25.90	31.15	31.35	31.71	29.28	26.39
CUPRESSACEAE	0.00	0.55	0.00	0.00	0.00	0.00	0.33	0.17	0.00	0.00
Pseudotsuga	1.77	2.40	3.74	3.42	1.59	1.09	1.32	3.83	0.66	4.67
Tsuga heterophylla	6.55	10.33	13.40	19.25	12.95	16.03	17.16	17.07	7.24	20.11
Tsuga mertensiana	7.79	3.87	1.87	4.66	3.39	5.28	2.31	4.70	8.39	4.67
Picea	3.36	1.66	1.56	1.86	4.38	4.01	4.62	2.44	2.30	1.08
Abies	22.48	21.96	17.45	13.66	22.11	24.23	16.83	20.03	13.65	17.06
Alnus incana-type	1.77	1.29	0.93	0.31	1.39	0.00	0.00	0.52	8.39	1.26
Alnus viridis-type	13.10	21.96	24.30	32.61	27.69	17.30	26.07	18.99	27.96	24.60
Betula	0.18	0.55	0.62	0.00	0.20	0.18	0.00	0.17	0.33	0.00
ERICACEAE	0.00	0.18	0.31	0.00	0.20	0.18	0.00	0.00	0.66	0.00
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.35	0.00	0.00	0.00	0.20	0.36	0.00	0.17	0.16	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.18
Artemisia	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.00
Ambrosia-type	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauria/Menyanthes	0.18	0.00	0.31	0.00	0.00	0.18	0.00	0.17	0.33	0.00
Nuphar	0.00	0.37	1.87	0.93	1.79	1.46	0.66	0.70	0.33	1.26
Potamogeton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.00	0.31	0.31	0.20	0.00	0.00	0.00	0.16	0.18
Equisetum	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
Polypodium	0.00	0.00	0.62	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.33	0.72
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	1.95	5.72	2.49	6.83	4.78	2.91	0.99	2.44	5.76	5.39

DEPTH (cm)	44	46	48	50	52	54	56	58	62	64
TAXON										
Pinus	27.64	25.88	31.80	33.05	33.76	27.42	25.00	28.06	24.44	24.72
CUPRESSACEAE	0.00	0.00	0.00	0.00	0.54	0.00	0.00	0.00	0.00	0.18
Pseudotsuga	1.73	2.86	3.31	0.00	2.90	4.19	4.75	2.58	1.29	5.17
Tsuga heterophylla	21.69	31.43	26.65	22.88	19.96	20.97	22.47	18.71	20.90	24.35
Tsuga mertensiana	6.14	4.20	6.25	0.85	5.44	2.58	6.96	5.48	6.75	5.90
Picea	0.77	1.34	1.10	0.85	0.91	0.65	1.27	0.32	0.96	1.29
Abies	17.66	23.19	22.79	15.25	22.32	15.16	20.57	18.06	20.26	18.45
Alnus incana-type	2.50	0.67	0.37	3.39	0.54	0.97	0.95	1.94	1.29	1.48
Alnus viridis-type	21.69	9.75	7.17	21.19	13.25	27.74	16.77	24.52	23.79	17.53
Betula	0.00	0.00	0.00	0.00	0.18	0.00	0.32	0.00	0.00	0.37
ERICACEAE	0.00	0.34	0.37	2.54	0.00	0.00	0.00	0.00	0.00	0.00
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00
Artemisia	0.19	0.00	0.00	0.00	0.18	0.00	0.32	0.00	0.32	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Faurial Menyanthes	0.00	0.34	0.18	0.00	0.00	0.32	0.00	0.32	0.00	0.37
Nuphar	2.11	0.67	0.18	0.00	0.36	0.00	0.00	0.00	0.32	0.00
Potamogeton	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.32	0.00	0.00
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.00	0.00	0.18
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	4.61	1.68	1.10	1.69	2.36	0.32	0.63	0.00	3.22	1.11

DEPTH (cm)	66	68	70	72	74	76	78	80	82	84
TAXON										
Pinus	20.89	24.16	20.96	25.77	24.14	17.94	18.92	14.53	15.59	19.05
CUPRESSACEAE	0.00	0.00	0.53	0.18	0.57	0.19	0.18	0.74	0.40	1.27
Pseudotsuga	5.38	4.83	3.20	2.88	3.23	2.10	2.52	9.31	4.66	3.49
Tsuga heterophylla	27.85	26.21	20.78	18.92	17.11	24.43	22.88	16.39	33.40	21.90
Tsuga mertensiana	4.43	6.13	4.97	3.96	4.94	5.73	7.93	4.10	5.47	2.54
Picea	0.95	0.74	3.02	0.90	1.14	0.95	2.70	2.23	0.81	0.63
Abies	14.87	18.77	23.80	19.82	16.16	24.81	31.53	28.12	19.23	16.19
Alnus incana-type	1.27	2.97	2.13	2.16	2.28	2.86	0.72	1.68	2.23	0.32
Alnus viridis-type	23.10	15.61	19.89	24.86	29.66	20.80	12.07	21.79	17.61	33.97
Betula	0.63	0.56	0.18	0.00	0.38	0.00	0.54	0.74	0.20	0.00
ERICACEAE	0.00	0.00	0.18	0.00	0.19	0.00	0.00	0.00	0.00	0.32
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.32
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.32	0.00	0.18	0.54	0.19	0.19	0.00	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauria/Menyanthes	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.37	0.00	0.00
Nuphar	1.27	0.56	0.71	0.18	0.57	0.19	0.18	0.19	0.61	0.63
Potamogeton	0.00	0.00	0.00	0.00	0.57	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.19	0.36	0.18	0.19	0.00	0.00	0.00	0.20	0.00
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.00	0.38	0.38	0.00	0.00	0.00	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	1.58	1.12	0.18	1.26	3.42	1.15	0.72	1.86	1.01	1.59

DEPTH (cm)	90	92	94	96	98	100	102	104	106	108
TAXON										
Pinus	16.91	26.42	22.45	21.00	25.10	10.14	15.70	12.74	13.50	11.88
CUPRESSACEAE	0.93	0.98	0.56	0.00	0.00	0.89	0.37	0.00	0.38	0.00
Pseudotsuga	7.25	5.48	2.97	3.90	2.30	7.47	1.87	3.42	7.79	1.34
Tsuga heterophylla	28.07	22.11	29.13	27.70	16.09	28.11	19.81	19.39	17.87	18.01
Tsuga mertensiana	2.04	2.15	3.90	2.23	4.21	1.25	4.11	3.99	4.56	2.87
Picea	1.12	0.59	1.86	0.93	1.53	2.14	0.93	0.38	2.47	3.83
Abies	25.09	17.42	20.41	17.47	21.26	22.24	22.06	26.81	19.96	24.90
Alnus incana-type	1.30	2.35	0.93	1.86	4.21	2.31	1.12	0.19	2.09	3.07
Alnus viridis-type	16.36	20.35	17.25	23.42	23.75	24.73	32.34	32.13	30.42	33.33
Betula	0.37	0.20	0.19	0.93	0.57	0.00	0.56	0.38	0.57	0.57
ERICACEAE	0.19	0.00	0.19	0.00	0.00	0.53	0.19	0.19	0.00	0.19
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.19	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	1.96	0.00	0.37	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.00	0.19	0.19	0.19	0.00	0.56	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.38	0.00	0.19	0.00	0.00	0.00
CHENOPODIACEAE	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Faurial/Menyanthes	0.19	0.00	0.00	0.00	0.19	0.00	0.19	0.00	0.19	0.00
Nuphar	0.19	0.39	1.67	1.86	1.72	0.00	1.87	0.95	1.52	1.15
Potamogeton	0.00	0.00	0.00	0.00	0.00	0.89	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.20	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.00	0.37	0.37	0.38	0.00	0.56	0.00	0.38	0.19
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.19	0.00	0.19	0.00	0.19	0.00	0.37	0.00	0.00	0.19
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.38	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.53	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.19	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	4.28	1.57	3.71	0.00	10.54	0.00	9.16	7.22	10.84	6.70

DEPTH (cm)	110	112	114	116	118	120	122	124	126	128
TAXON										
Pinus	10.17	17.14	18.18	18.27	16.24	24.48	28.12	21.08	16.07	22.62
CUPRESSACEAE	2.54	1.02	0.57	0.93	1.27	0.38	2.23	1.14	1.94	1.13
Pseudotsuga	5.37	0.77	2.27	2.79	4.46	5.27	8.75	16.52	6.37	7.27
Tsuga heterophylla	32.20	21.48	22.54	16.72	14.97	12.81	10.06	10.83	14.13	12.60
Tsuga mertensiana	3.39	4.35	4.36	2.48	5.41	1.13	3.91	4.84	2.49	6.30
Picea	2.26	2.56	1.89	2.79	2.55	2.45	0.74	1.14	1.66	2.26
Abies	6.78	23.79	22.54	13.62	27.07	22.98	16.76	21.08	16.62	17.93
Alnus incana-type	7.91	1.02	0.95	1.24	1.59	8.10	3.35	1.71	1.94	2.75
Alnus viridis-type	27.68	27.62	25.38	40.25	24.20	21.09	23.28	21.37	37.40	26.49
Betula	0.28	0.00	1.14	0.62	0.64	0.00	1.86	0.00	0.55	0.65
ERICACEAE	0.00	0.00	0.00	0.00	0.32	0.19	0.00	0.28	0.28	0.00
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.26	0.00	0.00	0.32	0.00	0.19	0.00	0.00	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.28	0.00	0.00	0.00	0.00	0.75	0.37	0.00	0.28	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FaurialMenyanthes	0.00	0.00	0.19	0.31	0.96	0.19	0.37	0.00	0.28	0.00
Nuphar	4.24	1.28	1.14	2.79	0.96	0.56	1.30	1.99	1.39	1.78
Potamogeton	0.28	0.00	0.00	0.00	0.00	0.56	0.37	0.00	0.83	1.29
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
FILICALES	0.28	0.00	0.38	0.93	0.00	0.56	0.74	0.28	0.28	0.16
Equisetum	0.56	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.16
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	1.98	0.00	0.19	0.00	0.00	0.19	0.00	0.00	0.00	0.16
Polypodium	0.00	0.00	0.00	0.00	0.00	0.56	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.00	0.00	0.00	0.19	0.28	0.00	0.16
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.32	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	2.82	3.32	7.01	11.46	11.15	24.29	17.50	7.41	8.31	14.38

DEPTH (cm)	130	132	134	136	138	140	142	144	146	148
TAXON										
Pinus	17.80	12.79	13.57	18.72	14.93	13.04	19.37	18.86	15.77	12.50
CUPRESSACEAE	1.00	1.15	0.00	0.18	0.56	0.19	0.98	0.36	0.00	0.00
Pseudotsuga	4.16	5.34	1.37	1.83	2.05	1.49	0.39	1.42	1.17	1.25
Tsuga heterophylla	12.81	19.08	22.16	19.82	20.90	23.28	19.96	21.17	16.95	12.50
Tsuga mertensiana	8.65	4.77	7.90	6.42	4.85	5.40	1.96	3.74	6.71	3.04
Picea	4.66	2.10	1.37	2.39	1.12	3.35	0.39	0.71	1.17	0.36
Abies	20.30	23.85	32.47	31.93	25.75	28.12	26.61	29.72	34.06	42.50
Alnus incana-type	11.31	4.20	1.72	1.28	0.56	8.57	4.11	3.56	3.69	1.25
Alnus viridis-type	17.97	25.76	19.07	17.25	28.36	16.01	25.24	19.93	20.13	26.07
Betula	0.17	0.19	0.00	0.18	0.37	0.19	0.39	0.18	0.00	0.36
ERICACEAE	0.17	0.38	0.34	0.00	0.00	0.00	0.39	0.00	0.00	0.18
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.18	0.00	0.00
Salix	0.33	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.67	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.00	0.00	0.00	0.37	0.00	0.00	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FaurialMenyanthes	0.00	0.19	0.00	0.00	0.19	0.00	0.20	0.18	0.34	0.00
Nuphar	1.00	2.48	0.52	0.18	1.31	2.79	1.37	0.89	1.01	0.36
Potamogeton	0.17	0.00	0.00	0.00	0.75	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.50	0.00	0.00	0.00	0.19	0.93	0.00	0.00	0.00	0.18
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	1.16	0.00	0.00	0.00	0.00	0.37	0.00	0.00	0.00	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.18
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	0.00	5.53	1.55	0.92	1.68	0.00	3.52	0.89	4.03	1.96

DEPTH (cm)	150	152	154	156	158	160	162	164	166
TAXON									
Pinus	12.67	25.14	23.60	18.39	23.48	18.06	12.74	20.56	42.70
CUPRESSACEAE	0.00	0.18	0.00	0.50	0.78	5.75	4.63	3.43	2.25
Pseudotsuga	1.13	0.90	0.94	1.17	0.20	0.00	1.54	0.31	0.75
Tsuga heterophylla	16.64	14.65	8.80	10.70	8.81	3.57	6.56	9.97	11.99
Tsuga mertensiana	3.02	4.16	4.31	3.85	0.98	0.20	0.77	0.00	0.00
Picea	1.51	1.27	0.75	1.34	0.00	0.00	12.74	5.30	6.74
Abies	22.87	23.33	23.41	15.89	8.61	2.98	2.70	2.49	10.11
Alnus incana-type	0.76	0.90	0.94	2.01	2.74	18.65	17.37	14.33	2.62
Alnus viridis-type	39.51	28.39	36.14	45.15	54.40	50.00	37.84	39.25	17.23
Betula	0.76	0.54	0.56	0.33	0.00	0.20	2.70	3.43	3.37
ERICACEAE	0.00	0.18	0.19	0.00	0.00	0.00	0.00	0.00	0.00
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.18	0.19	0.50	0.00	0.60	0.00	0.00	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	1.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.12
POACEAE	0.00	0.18	0.00	0.00	0.00	0.00	0.39	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.93	0.75
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37
Faurial Menyanthes	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.00	0.00
Nuphar	1.13	0.18	0.37	0.33	0.20	2.18	1.93	0.62	5.62
Potamogeton	0.00	0.18	0.00	0.17	0.00	0.60	2.32	1.56	1.50
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.18	0.19	0.00	0.00	0.40	1.16	1.56	2.25
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75
Botrychium	0.00	0.00	0.00	0.17	0.00	0.00	0.00	0.62	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	1.16	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.17	0.00	0.00	24.71	5.92	9.36
Polypodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.37
Selaginella	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.20	0.00	0.00	0.00
Cystopteris fragilis	3.21	0.36	0.00	0.33	2.35	0.00	0.00	0.00	0.00

DEPTH (cm)	168	170	172	174	176	178	180	182	184
TAXON									
Pinus	25.91	25.23	33.75	37.76	37.27	27.38	31.83	24.06	23.29
CUPRESSACEAE	0.84	2.10	0.00	0.00	0.00	0.78	0.56	0.59	0.39
Pseudotsuga	0.56	0.90	0.95	0.57	0.55	0.39	0.19	1.58	1.76
Tsuga heterophylla	15.60	11.41	21.77	14.04	13.28	11.26	17.33	18.93	12.52
Tsuga mertensiana	1.39	3.60	5.05	4.55	4.98	4.47	0.38	6.51	7.83
Picea	5.85	4.50	1.42	0.38	0.37	0.97	10.55	1.97	2.54
Abies	5.29	6.31	14.51	16.32	17.16	18.45	9.04	14.00	19.37
Alnus incana-type	11.14	15.02	3.31	6.26	4.06	3.69	7.72	3.16	2.94
Alnus viridis-type	30.92	27.93	17.51	19.54	20.66	32.23	21.28	27.81	27.79
Betula	1.95	0.90	0.63	0.38	1.11	0.19	0.75	0.20	0.98
ERICACEAE	0.00	0.90	0.32	0.19	0.18	0.19	0.38	0.99	0.59
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.00	0.47	0.00	0.18	0.00	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Faurial/Menyanthes	0.00	0.00	0.32	0.00	0.18	0.00	0.00	0.00	0.00
Nuphar	2.51	1.20	0.32	0.19	0.18	0.19	0.38	0.00	0.00
Potamogeton	2.51	0.90	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.56	0.30	0.00	0.38	0.37	0.19	0.19	0.20	0.59
Equisetum	6.96	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.19	0.00	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	2.51	2.10	0.00	0.19	0.00	0.19	0.19	0.00	0.20
Polypodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.00	0.90	0.16	0.00	0.00	0.00	0.00	0.00	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

DEPTH (cm)	188	190	192	194	196	198	200	202	204	206
TAXON										
Pinus	21.12	25.27	20.03	26.19	10.00	11.17	19.77	28.92	27.61	22.51
CUPRESSACEAE	0.00	0.18	1.73	0.00	0.00	0.18	0.39	0.00	0.00	0.00
Pseudotsuga	0.36	0.72	1.90	0.88	0.56	0.73	0.58	0.38	0.61	0.64
Tsuga heterophylla	15.16	14.98	14.85	16.81	13.52	12.82	15.31	11.34	12.88	12.86
Tsuga mertensiana	5.60	2.53	4.15	3.89	12.59	13.92	6.40	5.29	7.06	14.47
Picea	0.72	6.50	0.69	0.53	0.93	0.37	0.58	0.19	0.61	0.64
Abies	25.63	18.05	19.69	16.46	23.33	17.58	23.45	20.60	25.46	21.86
Alnus incana-type	0.72	8.84	3.63	4.96	2.59	4.21	1.55	2.46	1.23	1.61
Alnus viridis-type	28.70	21.48	31.61	28.67	34.81	35.71	30.23	30.06	23.62	22.19
Betula	1.26	0.54	1.04	0.53	1.11	1.65	1.36	0.38	0.61	1.61
ERICACEAE	0.72	0.18	0.35	1.06	0.56	1.65	0.39	0.38	0.31	1.61
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.35	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ambrosia-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fauria/Menyanthes	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nuphar	0.00	0.00	0.17	0.18	0.00	0.37	0.00	0.00	0.61	0.00
Potamogeton	0.00	0.36	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.36	0.17	0.00	0.00	0.00	0.00	0.00	0.31	0.00
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.00	0.00	0.55	0.00	0.00	0.00	0.00
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.18	0.17	0.00	0.00	0.37	0.00	0.00	0.00	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Pteridium	0.00	0.00	0.17	0.18	0.00	0.00	0.00	0.00	0.31	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

DEPTH (cm)	208	210	212	214	216	218	220
TAXON							
Pinus	32.79	24.91	33.15	12.38	17.00	28.72	20.25
CUPRESSACEAE	0.66	1.02	0.00	0.00	0.00	0.00	0.18
Pseudotsuga	0.33	1.19	0.00	1.35	2.35	1.40	0.90
Tsuga heterophylla	12.13	13.14	15.07	19.73	19.71	16.99	20.61
Tsuga mertensiana	6.89	5.12	8.10	9.48	5.61	8.93	6.99
Picea	0.33	2.05	0.19	0.00	0.54	1.23	2.15
Abies	13.44	15.87	13.56	14.89	21.70	22.07	20.07
Alnus incana-type	0.98	1.54	0.00	2.32	2.53	3.50	2.87
Alnus viridis-type	30.82	33.11	28.25	36.94	28.75	16.29	23.12
Betula	1.31	1.54	0.75	1.35	1.08	0.00	2.51
ERICACEAE	0.00	0.34	0.94	0.97	0.54	0.70	0.36
Empetrum-type	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Salix	0.00	0.00	0.00	0.00	0.00	0.18	0.00
Shepherdia canadensis	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ROSACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Arceuthobium	0.00	0.00	0.00	0.00	0.00	0.00	0.00
POACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CYPERACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Artemisia	0.00	0.00	0.00	0.58	0.18	0.00	0.00
Ambrosia-type	0.33	0.17	0.00	0.00	0.00	0.00	0.00
CHENOPODIACEAE	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ranunculus	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Thalictrum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Faurial/Menyanthes	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nuphar	0.33	0.17	0.38	0.39	0.72	0.70	0.00
Potamogeton	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Typha latifolia	0.00	0.17	0.00	0.00	0.00	0.00	0.00
FILICALES	0.00	0.17	0.00	0.00	0.18	0.00	0.18
Equisetum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Botrychium	0.00	0.00	0.00	0.00	0.00	0.18	0.18
Lycopodium inundata	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lycopodium	0.00	0.00	0.00	0.00	0.36	0.00	0.00
Polypodium	0.00	0.00	0.00	0.00	0.00	0.18	0.00
Pteridium	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Selaginella	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sphagnum	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Liverwort	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cystopteris fragilis	0.00	0.51	0.00	0.39	0.00	0.00	0.00