Late Quaternary Vegetation, Climate, Fire History, and GIS Mapping of Holocene Climates on Southern Vancouver Island, British Columbia, Canada

by

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

DOCTOR OF PHILOSOPHY

in the School of Earth and Ocean Sciences

We accept this dissertation as conforming
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Abstract

Pollen and microscopic charcoal fragments from seven sites (East Sooke Fen and Pixie, Whyac, Porphyry, Walker, Enos, and Boomerang lakes) were used to reconstruct the post-glacial vegetation, climate, and fire disturbance history on southern Vancouver Island, British Columbia, Canada. A non-arboreal pollen and spore zone occurs in the basal clays at Porphyry Lake and likely represents a tundra or tundra-steppe ecosystem. This zone precedes the *Pinus contorta* (lodgepole pine) biogeochron that is generally considered to have colonised deglaciated landscapes and may represent a late Wisconsinan glacial refugium. An open *Pinus contorta* woodland characterised the landscape in the late-glacial interval. Fires were rare or absent and a cool and dry climate influenced by "continental-scale katabatic" easterly winds dominated. Closed lowland forests consisting of *Picea* (spruce), *Abies* (fir), *Tsuga heterophylla* (western hemlock), and *Tsuga mertensiana* (mountain hemlock) with *P. contorta* and *Alnus* (alder) and sub-alpine forests containing *Picea*, *Abies*, and *T. mertensiana* with *P. contorta* replaced the *P. contorta* biogeochron in the late Pleistocene. Fires became more common during this interval even though climate seems to have been cool and moist. Open *Pseudotsuga menziesii* (Douglas-fir) forests with *Pteridium* (bracken fern) in the understory and *Alnus* in moist and disturbed sites expanded westward during the warm dry early Holocene. At this time closed *Picea*, *T. heterophylla*, and possibly *Alnus* forests grew in the wettest part of southern Vancouver Island at Whyac Lake. At high elevations, forests consisting of *T. heterophylla* and *Pseudotsuga* coupled with *Alnus* expanded during the early Holocene.

Fires occurred frequently in lowland forested ecosystems during this interval, although East Sooke Fen in a dry, open region experienced less fire. At high elevations, charcoal increased somewhat from the late Pleistocene, indicating slightly more fires and reflecting continued moist conditions at high elevations. The mid and late Holocene was characterized by increasing precipitation and decreasing temperature respectively. Mid Holocene lowland forests were dominated by *Pseudotsuga* with *T. heterophylla* and *Alnus* in southeastern regions, *T. heterophylla* and *Thuja plicata* (western red-cedar) in southern regions, and *T. heterophylla* and *Picea* in southwestern regions. An overall decrease in charcoal influx suggests a decrease in lowland fires, although locally isolated fire events are evident in most sites. *Quercus garryana* (Garry oak) stands spread westward during the mid Holocene, attaining maximum extent between East Sooke Fen and Pixie Lake, approximately 50 km beyond their modern limit. Lowland sites record a general decrease in fires at this time. At high elevation, mid Holocene forests were dominated by *T. heterophylla*, *Picea*, and *Abies* with *Alnus*. An overall increase in charcoal influx at high elevations may reflect an increase in the number of charcoal fragments entering the basins by overland flow as opposed to an increase in fire incidence because climate was moister. In the late Holocene, closed *T. heterophylla* and *T. plicata* forests became established in wetter western regions, *Pseudotsuga* forests occupied drier eastern portions, and *T. mertensiana* and *Cupressaceae*, likely *Chamaecyparis nootkatensis* (Alaska yellow cedar), forests were established in sub-alpine sites. Lowland fires were infrequent in wet western regions but frequent in drier eastern regions. A slight reduction in charcoal influx generally occurs at high elevations, implying fewer fires. A

recent increase in charcoal influx at East Sooke Fen and Whyac, Walker, Enos, and Boomerang lakes may reflect anthropogenic burning. Holocene paleoclimates were reconstructed at 1,000 year intervals through a geographic information system (GIS) using contemporary climate data and surface and fossil pollen assemblages by establishing empirical regression equations that calibrated contemporary precipitation and temperatures to present day Douglas-fir-western hemlock (DWHI) and *T. heterophylla-T. mertensiana* (THMI) pollen ratios.

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ACKNOWLEDGEMENTS

Many thanks are due to the various organizations and individuals that contributed to the completion of this work. The University of Victoria provided general funding in the form of a Graduate Student Fellowship. The Natural Sciences and Engineering Research Council provided research funding through grant no. OGP0090581 to Dr. R. J. Hebda. The Royal British Columbia Museum provided office space, laboratory facilities, field equipment, and access to collections. Ross Benton and the Pacific Forestry Center allowed use of GIS facilities and related hardware and software.

I would like to thank all those who contributed their time and energy, especially Dave Gillan and Qi-bin Zhang for their assistance in all aspects of the research including field work and laboratory analyses and for their thoughts, discussion, and friendship. I would also like to thank my other lab colleagues, namely Greg Allen and Markus Heinrichs for their contributions.

I would like to thank Karen Golinski for her support, encouragement, friendship, and perhaps most importantly, for lending me a poncho in Burns Bog and Brenda Beckwith for her friendship and fire discussions. I am grateful to my friend, Rob Hewlett, for his expert help with GIS issues and for his willingness to always provide assistance when needed. I would like to express my gratitude to Karen Drysdale for always ensuring a TAship was available and for her thoughts and friendship. I am grateful to Ze'ev Gedalof for his friendship and for the field experiences. I would like to express my gratitude to Rob Diaz for friendship and keeping the research in focus and to my friends Meredith, Jackie, Brian, Ed, and Bob Holm for helping to maintain a well-balanced life. Thanks to my occasional jogging partner, Brent Carbno, for his support and friendship and to Neil Banerjee for his friendship and forwarding of PDF and faculty position advertisements. I would also like to thank all of the other friends that I have made along the way for their contributions and the memories. Many thanks to Dr. Dave Scott for preparing me for graduate studies and to my committee for their support and guidance. Thank you to anybody else that I have unintentionally missed.

I am indebted to my supervisor, Dr. Richard Hebda, for his encouragement, enthusiasm, and willingness to discuss ideas. His support and guidance while venturing into new areas and different venues of research is greatly appreciated.

Most of all I thank Mom, Dad, Ben, Per, Man and Nana, Auntie, Blackie, and Bear for a lifetime of love, support, and devotion.

DEDICATION

To my family

QUOTE

"The laws of nature are written deep in the folds and faults of the earth…"

-John Lynch

CHAPTER 1: INTRODUCTION

Introduction

Climate change poses a serious global environmental threat and changes in forests and biodiversity can be expected (Burton and Cumming, 1995; Kerr, 1995; Hebda, 1998). Two common techniques used to examine the possible impacts of climate change include paleoecological research (Hebda, 1994; 1997a; 1998; 1999) and computer modeling (Thompson et al., 1998). To gain a greater appreciation of the paleoecological approach, it is necessary to examine the pros and cons of the technique.

In terms of predicting ecosystem response to climate change, the paleoecological approach is in some ways better suited than the application of global climate models. Global climate models can only suggest what did or could happen with climate under certain specified conditions (Dotto, 1999). Combining climate models with ecological data can reveal some of the possible ecosystem changes manifest under specified conditions (Hebda, 1997a; Thompson et al, 1998). Paleoecology, on the other hand, can reveal how past ecosystems in fact responded to changes in past climates and thus provide insight into future ecosystem response to global climate warming.

Hebda (1998) described many of the advantages of using a paleoecological approach to probe the relationship between climate change and ecosystem response. The paleoecological approach can (1) be used to reconstruct past vegetation and climate; (2) provide an actual (ecosystem) final state scenario; (3) determine the rate of change; (4) provide local, extra-local, and regional examples of ecosystem response; and (5) examine the response of individual species. The paleoecological approach can also (6) characterise the (fire) disturbance regimes under different climatic conditions; (7)

examine vegetation inertia and resilience; (8) identify sites or areas that are particularly sensitive to climate change; and (9) identify critical (climate) thresholds that separate one ecological state from another (Hebda, 1995). Recently, paleoecological analysis has focused on (10) predicting future environmental response to forecasted climate warming (Burton and Cumming; 1995; Kerr, 1995; Hebda, 1997a; 1998). For example, examining the response of vegetation, water-levels, and fire to early Holocene warming and drying (Mathewes, 1985) 10,000-7,000 years before present (ybp) may provide useful data for assessing the impacts of future global warming and aid effective environmental management.

Hebda (1998) points out that the paleoecological approach has several shortcomings, namely (1) the fossil record is incomplete and can contain reworked pollen and spores; (2) relies on modern knowledge of ecosystems and species; and (3) cannot provide exact replicas of future conditions because the cause of change and the initial landscape conditions are likely different. These issues constrain the strict application of using paleoecological investigations for forecasting potential impacts at specific sites (Hebda, 1997a; 1998).

In response to paleoecological investigations that are oriented toward predicting future landscape conditions resulting from global climate change, Crowley (1990) argues that application of a paleoanalogue is not a satisfactory approach because the future "globally warmed" climate will represent a unique climatic interval unlike other post-glacial periods that were seasonally warmer/cooler. Some of the limitations hindering the paleoanolgue approach for predicting future landscapes include (1) differences in initial environmental (e.g. climatic, edaphic, and disturbance) conditions; (2) differences in rates of change; (3) individual species response may produce new combinations of plants unlike those in the past; (4) predicted warming may exceed early Holocene temperatures creating non-analogous conditions; and (5) human induced landscape fragmentation may prevent plant migration (Franklin et al., 1991; Hebda, 1998).

Paleoecological investigations have revealed that the post Wisconsinan climate in the Pacific Northwest has fluctuated from cold dry in the late glacial to cold wet in the late Pleistocene to warm dry in the early Holocene to present day cool wet conditions (Heusser, 1983; Mathewes, 1985; Barnosky et al., 1987; Hebda, 1995). The landscape and climatic conditions during each of these intervals can be examined and reconstructed using several different chemical, physical, or biological techniques. One of the most widely applied paleoecological techniques is palynology (pollen and spore analysis), the discipline of examining fossilised pollen and spores to reconstruct past vegetation and climate.

Pollen grains and spores consist of two general layers, an inner intine and an outer exine (Moore et al., 1991). The intine is composed of cellulose and is rarely preserved, whereas the exine consists of sporopollenin, a durable substance that is frequently fossilised. Sculptures and aperatures (pori and colpi) are surface features that are used for identification purposes. It is because of the durable nature of sporopollenin coupled with surface sculptures and aperatures that fossil pollen and spores can be collected, identified, and interpreted.

Several authors (Heusser, 1960; Mathewes and Heusser, 1981; Mathewes, 1973; 1985; Hebda, 1983; 1995; 1997b; Allen, 1995; Pellatt, 1996) have examined the post-glacial vegetation and climate history of coastal British Columbia using pollen and spore analysis. Many of these studies are restricted to lowland or montane sites (Mathewes, 1973; 1989; Mathewes and Clague, 1982; Hebda, 1983; 1995; 1997b; Barnosky, 1985a,b; Allen, 1995). In contrast, relatively few sub-alpine or alpine areas have been examined (Sea and Whitlock, 1995; Pellatt and Mathewes, 1994; Pellatt, 1996). Coupled vegetation and fire history studies are even fewer (Mathewes and Rouse, 1975; Sugita, and Tsukada, 1982; Mathewes, 1985; Cywnar, 1987; Brown and Hebda, 1998a,b).

Palynological investigations on southern Vancouver Island have largely been confined to lowland southeastern sites and show that post-glacial vegetation composition, distribution, and dynamics have varied in response to changing paleoclimates (Heusser, 1960; 1985; Allen, 1995; Hebda, 1995; Brown and Hebda, 1998a,b). In contrast, the history and dynamics of forests on southwestern Vancouver Island and at high elevations are not known. Southwestern Vancouver Island is particularly interesting because it occupies the transition from relatively dry warm climates of southeastern Vancouver Island to typical moist and mild climates of west and south Vancouver Island. High elevation sites are interesting because they potentially contain post-glacial temperature records that have generally been unrealised from low elevation sites.

Purpose

The purpose of this research is to reconstruct the vegetation, climate, and fire history on southern Vancouver Island to reveal how the landscape, vegetation, and ecological processes have changed through time and to examine some of the possible causes for the observed changes. This research will also provide insight into some of the possible landscape changes in the region to be expected because of global climate change.

In this study, the history of coastal forests on southern Vancouver Island is examined using paleoecological techniques to provide insight into the relationship between species dynamics, forest composition, and climate change. This study seeks answers to the following questions: (1) Have the forests on southern Vancouver Island been unchanging and therefore of a relatively ancient age or do these forests have a relatively recent origin? (2) What major disturbances have affected the forests and what is the relationship between these disturbances, climate change, and forest composition? (3) If forest composition and structure have changed, were the changes sudden or gradual? (4) How have individual species responded to climate change and other disturbances? (5) What impact, if any, did First Peoples and European settlers have on local ecosystems? (6) Having established the (past) dynamics of forests, to what extent and in what way might forests on southern Vancouver Island change in response to future climatic conditions?

Approach: Cores, Surface Samples, and Geographic Information Systems

The approach used in this study is to measure the frequency distribution of pollen and spores from 5 sediment cores (Figure 1), to evaluate the frequencies obtained, and to determine age by radiocarbon-14 (^{14}C) dating (Gillespie, 1986) of selected samples. These analyses are used to reconstruct post-glacial vegetation cover, using the pollen and spore assemblages to represent the paleovegetation and ^{14}C dates to establish chronology. The concept of a biogeochron (Hebda and Whitlock, 1997) is used during the reconstruction of paleovegetation when discussing the persistence of relatively coherent ecosystems through time. Surface sample analyses are used to help in the

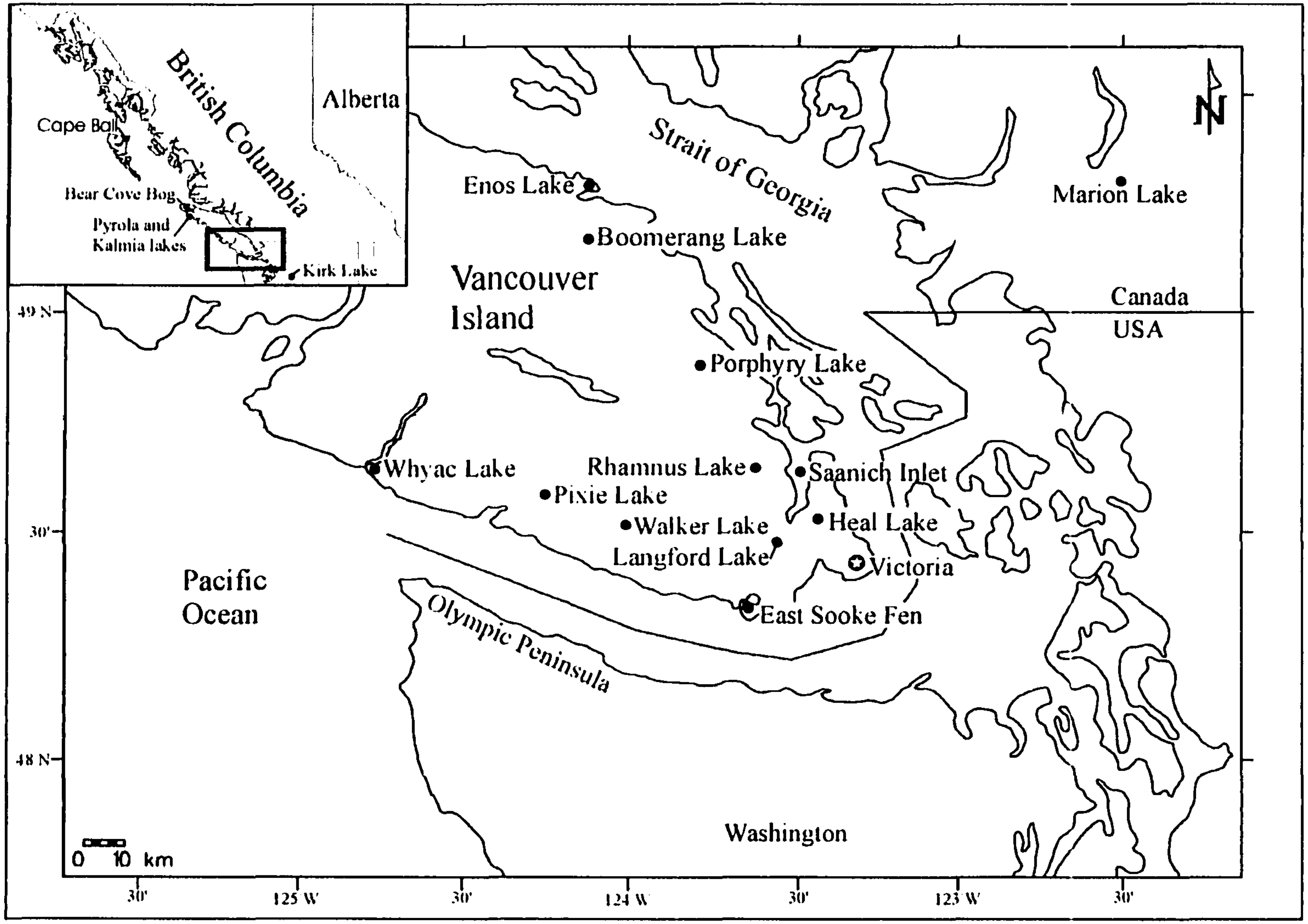


Figure 1a. Regional location map and map showing sediment core sites (•) mentioned in text.

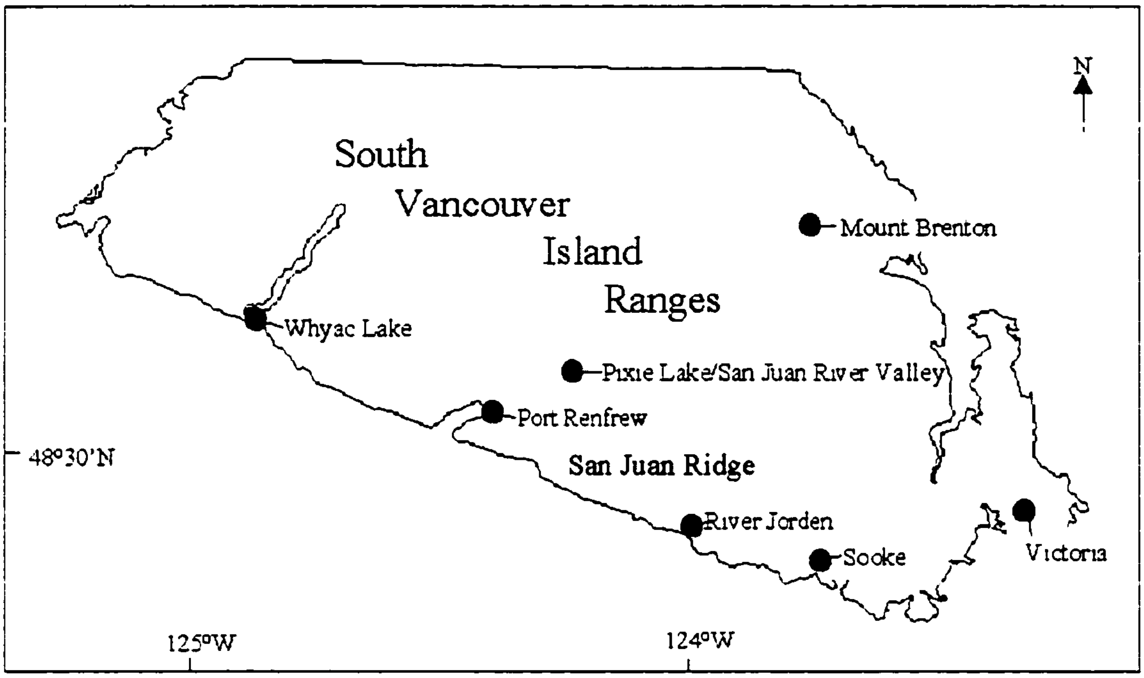


Figure 1b. Reference sites and areas on southern Vancouver Island cited in text.

reconstruction and interpretation of past landscapes (Figure 2). Microscopic charcoal influx from 7 sediment cores is used to reconstruct and interpret past fire history (Figure 1), whereas sedimentological analyses of cores coupled with aquatic pollen evidence will be used to examine fluctuations in water levels. Holocene climate maps will be generated using a geographic information system (GIS), pollen data from surface samples and sediment cores, and contemporary climate (temperature and precipitation) data.

Core sites are selected from lowland sites across a general east-west transect of southern Vancouver Island and from high elevation sites to reveal how past vegetation (composition and structure) responded to past changes in climate across two different gradients in the same region. In doing so and by comparison to other nearby sites on Vancouver Island and the adjacent mainland, these analyses will (1) determine when climatic gradients were established and how they changed with time on southern Vancouver Island; (2) reveal post-glacial temperature and precipitation fluctuations; (3) show the positions of paleoecotones; (4) and identify sites particularly sensitive to future climate change (Hebda 1994; 1997a; 1998). Microscopic charcoal fragments will be used to reconstruct post-glacial fire incidence and establish the relationship between fire disturbance, vegetation, and climate (Whitlock and Millspaugh, 1996) as another way of looking at climate change. This research will also (5) monitor how rapidly vegetation responded to changes in climate; and (6) examine the distribution, composition, and structure of forests during unique climatic intervals. There is particular focus on the rate of vegetation and species response to changes in climate and to the distribution, composition, and structure of forests during the regionally warm dry early Holocene

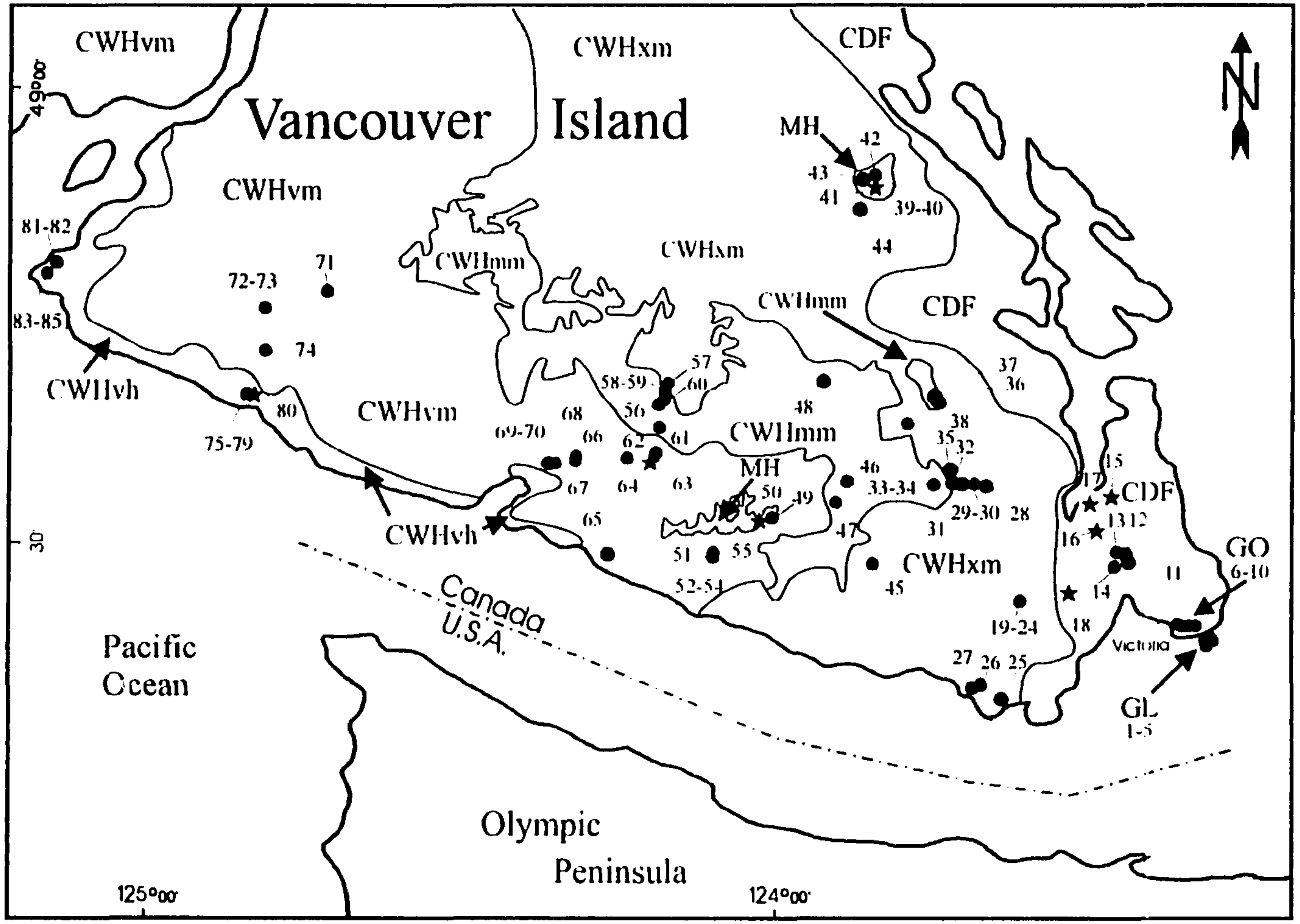


Figure 2. Biogeoclimatic designations on southern Vancouver Island, where GL=grassland; GO=Garry oak; CDF=Coastal Douglas-fir; CWH=Coastal Western Heml ock; MH=Mountain Hemlock; xm=dry maritime; mm=moist maritime; vm=very wet maritime; and vh=very wet hypermaritime. Surface sample sites are shown by a ●, whereas lake sample sites are shown with a ★. The surface sample numbers correlate with the ID numbers in Table 1.

xerothermic interval (Mathewes, 1985), a possible analogue to conditions resulting from future climate change (Hebda, 1998).

Surface samples collected from various sites around southern Vancouver Island (Figure 2) will be used to reveal the characteristic pollen signal of the different biogeoclimatic zones, subzones and variants (Meidinger and Pojar, 1991) and to show the relationship between vegetation cover and the over- and underrepresentation of different pollen types.

CHAPTER 2: SETTING

Introduction

The Pacific Northwest coastal region has a maritime climate that is influenced by the Aleutian Low during the winter and the North Pacific High during the summer, making winters stormy with abundant precipitation and summers warm and clear (Schoonmaker et al., 1997; Salmon, 1997). This climate has fostered the development of the largest area of coastal temperate rainforests on earth, occupying a narrow coastal zone from Alaska to California. The coastal topography is mountainous, although floodplains, basins, and fjords occur along the coast. Mountain systems result in rainshadows on their eastern flanks. The dominant disturbance agent is wind (Redmond and Taylor, 1997). The general characteristics of the Pacific Northwest region are manifest on Vancouver Island, including the study area (Figure 1).

Geology

Vancouver Island is situated within the Insular Belt of the Canadian Cordillera and consists primarily of the Wrangellia terrane (Gabrielse et al. 1991; B.C. Ministry of Energy, Mines, and Petroleum Resources 1995; Yorath and Nasmith, 1995). Sections of the Pacific Rim and Cresent terranes have been added to Wrangellia in the western and southern portions of Vancouver Island. In general, Vancouver Island is composed of Paleozoic, Mesozoic, and Cenozoic island arc, oceanic, and sedimentary wedge deposits.

According to B.C. Ministry of Energy, Mines, and Petroleum Resources (1995) and Yorath and Nasmith (1995), the oldest lithostratigraphic unit on Vancouver Island is the Sicker Group, containing Devonian rhyolites, coarse grained sandstones interbedded with cherty tuffs, amygdule basalts, and tuffs. During the Carboniferous and Permian periods, fossiliferous limestone that now forms part of the Buttle Lake Group was deposited on a shallow submarine platform.

Volcanic activity, specifically extensive deposition of basalt, recurred during the Triassic Period (Yorath and Nasmith, 1995). Volcanic deposition was accompanied by accumulation of limestone and other sedimentary deposits such as shales of the Vancouver Group. Formation of an island arc system during the Jurassic period resulted in the deposition of the Bonanza Group, consisting of volcanic rocks such as andesite and rhyolite. Concurrently, large volumes of magma were intruded, forming granitic batholiths and metamorphosing Sicker Group volcanics. Subsequent widescale erosion of these deposits during the Cretaceous resulted in the deposition of the Coal Harbour conglomerates, sandstones, and shales in the Quatsino Sound region and Nanaimo Group sandstones, shales, and coal deposits in the Strait of Georgia basin.

During the Tertiary, the Pacific Rim terrane was added to Wrangellia. This terrane consists of sedimentary slope deposits belonging to the Pacific Rim and Leech River complexes. Next, the Cresent terrane, consisting of volcanic rocks belonging to the Metchosin Igneous Complex, was added. These accretionary episodes culminated in the uplift of Vancouver Island, erosion, and the exposure of the Wark and Colquitz gneissic complexes. The Tertiary ended with the accumulation of Carmanah Group sandstones, conglomerates, and shales along western Vancouver Island (Yorath and Nasmith, 1995).

Physiography

Southern Vancouver Island consists of several physiographic units (Holland, 1976; Yorath and Nasmith, 1995). The South Vancouver Island Ranges occupy the south central portion of the island and are surrounded by the Nanaimo Lakes Highland, Nanaimo Lowland, and the Victoria Highland in the east and south and by the Estevan Lowland in the west. The South Vancouver Island Ranges consist of rugged mountains attaining elevations between 900-1,800 m above sea level (asl). The Nanaimo Lakes Highland is transitional between the South Vancouver Island Ranges and the Nanaimo Lowland and consists of hills and low mountains between 200-1,000 m asl. The Victoria Highland is similar to the Nanaimo Lakes Highland, consisting of hills and low mountains between 200-500 m asl. The Nanaimo Lowland occupies the coastal region on east Vancouver Island and consists of rolling hills with elevations of approximately 200 m asl and flat plains. The Estevan Lowlands include the flat coastal regions north and south of Barkley Sound and are dissected by numerous inlets and fiords. Elevations are typically less than 50 m asl but some hills may reach 100 m asl.

Climate

Southern Vancouver Island is generally characterised by cool, wet winters and warm, dry summers. However, changes in elevation, rainshadow effects, and proximity to the ocean result in local and regional climatic variations (Gullett and Skinner, 1992). Climatic data from two stations illustrate the regional climatic variability. At Victoria International Airport, located on the Saanich Peninsula and in a rainshadow on the eastern side of southern Vancouver Island, the mean annual precipitation (MAP) is 858 mm and mean annual temperature (MAT) is 9.5 °C. Mean monthly precipitation ranges from a low in July of 18 mm to a December high of 152 mm. Mean monthly temperatures vary from 3.4 °C in January to 16.2 °C in both July and August. In contrast, Bamfield on the west side of Vancouver Island approximately 140 km west of Victoria records 2876 mm MAP and 9.1 °C MAT. Mean monthly precipitation ranges from 62 mm in July to 413 mm in November. Mean monthly temperatures range from a low of 4.4 °C in January to 14.5 °C in August. In general, frost can occur between September-May. The winds that influence southern Vancouver Island vary with the seasons. During the winter, gusty westerly winds associated with cyclonal storms dominate, whereas during the summer storms are less common and land/sea breezes characterise the region (Redmond and Taylor, 1997).

Vegetation and Soils

Meidinger and Pojar (1991) summarize the biogeoclimatic ecological classification (BEC) system used to classify forests and range lands in British Columbia. The most general BEC unit is a zone, which groups ecosystems on the basis of regional climate. The basic working unit, the subzone, classifies ecosystems according to their distinct climax associations. BEC variants are based on the climatic differences within subzones that cause local changes in vegetation, soils, and productivity.

Three biogeoclimatic zones, distributed along precipitation and continentality gradients, are present on southern Vancouver Island (Meidinger and Pojar, 1991). The Coastal Douglas Fir (CDF) zone is restricted to elevations below 150 m asl in the southeastern portion of Vancouver Island and to the Gulf Islands in the Strait of Georgia

(Figure 2). The CDF is characterised by warm, dry summers and wet, mild winters. Both brunisols and podsols occur within the CDF zone (Meidinger and Pojar, 1991). MAP and MAT range between 648-1263 mm and 9.2-10.5 °C respectively. Typically, July is the driest month and receives 13-39 mm of precipitation, whereas December is the wettest month and receives 119-233 mm of precipitation. Mean monthly temperatures vary from 15.4-18 °C during the warm summer months to 1.8-4.1 °C during the cold winter months.

The composition of CDF forests depends on site moisture and nutrient availability. Typical CDF plant associations include *Pseudotsuga menziesii* (Mirb.) Franco (Douglas-fir), *Thuja plicata* Donn. (western red cedar), *Abies grandis* (Dougl.) Lindl. (grand fir), *Arbutus menziesii* Prush. (arbutus), and *Alnus rubra* Bong. (red alder) (Note: scientific nomenclature follows that of Douglas et al. (1989) and Hitchcock and Cronquist (1991)). Distinctive *Quercus garryana* Dougl. (Garry oak) and grassland associations are present in the CDF (Meidinger and Pojar, 1991).

The Coastal Western Hemlock (CWH) zone is juxtaposed to the west of the CDF and occurs at low to middle elevations ranging between 0-1,000 m asl. The CWH receives abundant precipitation and is characterised by cool summers and wet, mild winters. MAP and MAT range between 990-4,390 mm and 4.5-10.5 °C respectively. Mean monthly precipitation varies from 17-151 mm during July to 146-625 mm during December. Temperature also varies from summer highs of 13.1-18.7 °C to winter lows of -6.6 to 4.7 °C. The CWH is divided into several subzones ranging from a very dry maritime coastal western hemlock (CWHxm) subzone in the east to moist maritime coastal western hemlock (CWHmm) to very wet hypermaritime coastal western hemlock (CWHvh) subzone in the west (Figure 2). CWH soils are characteristically podzols.

Tsuga heterophylla (Raf.) Sarg. (western hemlock) and *T. plicata* are the most common trees in the CWH. *P. menziesii* occurs in drier parts of the zone, whereas *Abies amabilis* (Dougl.) Forbes (amabilis fir) and *Chamaecyparis nootkatensis* (D.Don) Spach (yellow-cedar) occupy wetter parts. *Pinus contorta* Dougl. (lodgepole pine), *A. rubra*, and *Picea sitchensis* (Bong.) Carr. (Sitka spruce) also occur within the CWH.

The Mountain Hemlock zone (MH) is restricted to elevations greater than 900 m asl and is characterised by short, cool summers and long, cool, wet winters. MAP and MAT are approximately 2,954 mm and 5 °C respectively with approximately 30% of annual precipitation falling as snow. Mean monthly precipitation varies between 107 mm in July to 435 mm in December, whereas the mean monthly temperature varies between 13.2 °C in the summer to -2.3 °C during the winter. Podzols are a common soil in the MH zone.

The most common trees in the MH are *Tsuga mertensiana* (Bong.) Carr. (mountain hemlock), *A. amabilis*, and *C. nootkatensis*. Other trees occurring in the MH zone include *T. heterophylla*, *T. plicata*, and *Pinus monticola* Dougl. (western white pine).

Site Selection

The sediment core sites and surface sample sites are all obtained from southern Vancouver Island (Figures 1 and 2). Whyac Lake, Pixie Lake, and East Sooke Park are located at low elevations in the CWH zone, whereas Walker Lake and Porphyry Lake are located in the MH zone. Enos Lake and Boomerang Lake are two additional sites located at low elevations in the CDF and CWH zones respectively that were analysed for charcoal only.

The sites were selected because (1) they represent areas that have not been previously studied; (2) they are near the southern limits of the Fraser glaciation and can be used to examine species migration during colonisation after ice retreat; (3) are located along a steep precipitation gradient and could record changes in past precipitation; (4) represent different elevations and could record changes in past temperatures; and (5) are located close to the Pacific Ocean and may record terrestrial responses to coupled oceanic/atmospheric changes generated in the Pacific Ocean (Weaver and Hughes, 1992).

CHAPTER 3: BACKGROUND STUDIES

Introduction

Paleoecological research can be used to reveal how landscapes and processes have changed through time. In British Columbia, most paleoecological records represent the post-glacial time interval (Hebda, 1995), with occasional records extending into full- and pre-glacial intervals (Alley and Chatwin, 1979; Armstrong et al., 1985; Alley and Hicock, 1986; Mathewes, 1989). This chapter reviews research related to paleoecological investigations to provide a framework for this study.

Cordilleran Glaciation

Stratigraphic and geomorphologic evidence such as an extensive network of fjords, U-shaped river valleys, widespread diamictons and glacial outwash deposits, and glacial grooves and striations embedded in bedrock show that several episodes of Cordilleran glaciation spanning from before 128,000 ybp to 13,000 ybp occurred in British Columbia (Clague, 1976; 1991). Clark et al. (1993) identify glaciations as diachronic systems that show time-space variations and review oxygen-isotope records in order to temporally constrain the last northern hemispheric glaciation between 116,000-12,000 ybp. During the Late Wisconsinan, the Fraser glacial episode commenced between 30,000-25,000 ybp, attained glacial maximum during the Vashon stade after 20,000 ybp, and experienced initial deglaciation between 14,000-13,000 ybp (Alley and Chatwin, 1979; Howes, 1981; Clague 1991). Blaise et al. (1990) indicate that more northern regions such as the Queen Charlotte Sound, Hecate Strait, and adjacent land areas experienced deglaciation before 15,000 ybp and were ice-free by 13,000 ybp.

During the Fraser glacial maximum ice cover appears to have been extensive, although areas such as Beringia, parts of the Queen Charlotte Islands and western Vancouver Island, isolated coastal refugia, and nunataks remained ice-free (Mathewes, 1989; Clague, 1991; Pielou, 1991; Hebda, 1997b).

During the Vashon stade of Fraser glaciation, glaciers radiating from the Vancouver Island Mountains and the Coastal Mountains, flowed south down the Strait of Georgia after 19,000 ybp and diverged into the Puget and Juan du Fuca lobes (Halstead, 1968; Alley and Chatwin, 1979). Drift associated with the Fraser glaciation is present on southern Vancouver Island and the adjacent continental shelf and in decreasing order of age consists of the Quadra Sand stratified outwash sand and gravel deposits, Vashon Till, and Capilano Sediments containing glaciomarine, marine, and fluvioglacial or fluvial deposits (Clague, 1976; Howes, 1981; Herzer and Bornhold, 1982).

Paleovegetation

Many paleoecological records have been collected from the Pacific Northwest region (Barnosky et al., 1987; Hebda, 1995) and a general picture of the regions history is starting to emerge. This section examines the basic concepts of pollen and spore analysis and outlines the paleovegetation history of coastal British Columbia and Washington State as evidenced by previous research.

Basic Concepts

Pollen and spore analyses are based on four basic principles (Hebda, 1981; MacDonald, 1987). First, pollen and spores are produced during reproductive cycles in vast quantities. The number of pollen and spores released during these cycles reflects the vegetation composition of the ecosystem in which they are produced. Second, most of the pollen and spores produced do not fulfil their reproductive potential and many of these are deposited in environments where they are fossilised. Third, the grains can be recovered by a variety of sampling and coring techniques. Fourth, the pollen and spores can be extracted from sediment, then identified, and the results interpreted.

Several authors have examined post-glacial vegetation in the Pacific Northwest coast (Heusser, 1960; Mathewes, 1973; 1993; Hebda and Rouse, 1979; Sugita and Tsukada, 1982; Hebda, 1983; 1995; Heusser, 1983; Barnosky, 1985a,b; Ritchie, 1987; Wainman and Mathewes, 1987; Barnosky et al., 1987; Anderson, 1988; Mathewes and King, 1989; Allen, 1995; Sea and Whitlock, 1995) and the general pattern of vegetation history starts with a landscape dominated by *P. contorta* forests or woodlands from circa 14,000-11,500 ybp, though non-arboreal pollen and spore (NAP) assemblages occurred before that time in unglaciated regions. A shift to a mixed conifer forest containing *Abies*, *Picea*, *T. heterophylla*, and *T. mertensiana* with *P. contorta* occurred at approximately 11,500 ybp and persisted until 10,000 ybp, when *Pseudotsuga* forests coupled with a non-arboreal component became established. An increase in *T. heterophylla* pollen indicates this species expanded at approximately 7,000 ybp. Present-day lowland forests were established when *T. plicata* invaded the landscape approximately 4,000 ybp (Hebda and Mathewes, 1984).

Vegetation History: Northwest United States

Sites located to the south of Fraser glaciation limits are often characterised by stratigraphic sequences that extend back beyond the late Wisconsinan glaciation (ca. 30,000-13,000 ybp) (Heusser, 1977; Sugita and Tsukada, 1982; Barnosky, 1985a,b; Barnosky et al., 1987; Clague, 1991). During the Vashon Stade (ca. 17,000-13,500 ka) areas located to the south of the maximum ice extent were characterised by a NAP assemblage consisting of Poaceae (grass family), Cyperaceae (sedge family), *Artemisia*, and *Asteraceae* combined with *Pinus*. Low levels of *Abies*, *T. mertensiana*, *Alnus*, and *Salix* (willow) and moderate values of *Picea* are recorded at Battle Ground and Mineral lakes, Washington State, during this interval, suggesting open parklands persisted (Sugita and Tsukada, 1982; Barnosky, 1985a). Climate is interpreted as cool and humid. During the late glacial, NAP dominated assemblages were replaced by forests containing *P. contorta*, *Picea*, *Abies*, *T. mertensiana*, *T. heterophylla*, and *Alnus*. Climate warmed relative to the Vashon Stade but remained moist. In the early Holocene, open forests dominated by *Pseudotsuga* and *Alnus* characterised the landscape as climate warmed and dried. Expansion of *Q. garryana* woodlands during the middle Holocene is evident at Battle Ground, Carp, and Mineral lakes. A mid-late Holocene increase in *T. heterophylla* and *T. plicata* at ca. 5,000 ybp suggests that the climate became more humid at this time. A slight increase in *T. mertensiana* at Mineral Lake during the late Holocene implies that climate cooled in this interval (Barnosky, 1985a).

Cwynar (1987) examined both vegetation and fire changes following deglaciation at Kirk Lake in northwestern Washington State. Following deglaciation >12,000 ybp open forests consisting of *P. contorta*, *T. mertensiana*, *Abies*, and *Populus* dominated the landscape. During the late Pleistocene these forests were replaced by mixed conifer forests containing *P. contorta*, *T. mertensiana*, *Picea*, and *Abies* with *Alnus*. At approximately 11,200 ybp, climatic warming caused a shift in vegetation composition and structure and fire disturbance. *Pseudotsuga*, *Alnus*, and *Pteridium aquilinum* (L.) Kuhn (Bracken fern) expanded. Cwynar (1987) interprets this shift to represent an increase in fire frequency and a closed forest consisting of a mosaic of successional stages. The increase in *Alnus* and *Pteridium* coupled with an increase in Poaceae could also be interpreted to represent a more open forest as opposed to a closed canopy. The mid and late Holocene were characterised by expansion of *T. heterophylla* and Cupressaceae (cypress family) respectively and a decline in fire-adapted taxa and charcoal deposition.

Vegetation History: British Columbia

In the Fraser River Valley of southwestern British Columbia, Mathewes (1973; 1985) shows that the post-glacial history started with *P. contorta* woodlands or forest with *Salix* and *Shepherdia canadensis* (L.) Nutt. (Canadian buffalo-berry) before 12,350 ybp. During the late Pleistocene between ca. 12,400-10,500 ybp, forests containing *Abies*, *Picea*, and *T. mertensiana* with *Alnus* and *P. contorta* expanded. The late Pleistocene forests were replaced by *Pseudotsuga* and *Alnus* dominated forests with *Pteridium* and other ferns in the understory which persisted between 10,500-6,600 ybp. Forests co-dominated by Cupressaceae and *T. heterophylla* with *Pseudotsuga*, *Abies*, and *Alnus* characterise the interval between 6,600-present ybp.

Hebda (1983; 1997b) examined the vegetation history of northern Vancouver Island (Figure 1). At Bear Cove Bog, *P. contorta* woodlands formed the pioneering vegetation on the deglaciated landscape from about 14,000-11,500 ybp during a cool dry climatic interval. The *P. contorta* woodlands were replaced during the late Pleistocene by *Picea* and *T. mertensiana* dominated forests from ca. 11,500-10,000 ybp under a cool moist climate. *T. heterophylla* replaced *T. mertensiana* at 10,000 ybp as climate warmed. From ca. 8,800-7,000 *Pseudotsuga* and *Picea* forests with *Pteridium* dominated. Forests dominated by *T. heterophylla* and *Picea* persisted during the warm, moist mid Holocene from about 7,000-3,000 ybp. Extant Cupressaceae and *T. heterophylla* dominated forests have persisted from ca. 3,000-present as climate cooled and moistened.

In general, the Brooks Peninsula was initially characterised by *P. contorta* woodlands between ca. 13,500-12,000 ybp during a cool dry climatic interval (Hebda, 1997b). Mixed conifer forests consisting of *T. mertensiana*, *Abies*, *Picea*, and *T. heterophylla* replaced the *P. contorta* woodlands in the late Pleistocene from 12,000-10,500 ybp during a cool wet climatic interval. *Pseudotsuga* expanded into the region during the early Holocene between ca. 10,500-9,000 ybp as climate warmed and dried. At this time, forests dominated by *Picea* and *Abies* with *Alnus* and *T. heterophylla* prevailed. The warm, moist mid Holocene (ca. 9,000-2,500 ybp) was characterised by *T. heterophylla*, *Abies*, and Cupressaceae forests, whereas the cool, moist late Holocene (ca. 2,500 ybp-present) consisted of *T. heterophylla* and Cupressaceae forests.

According to Allen (1995) and Hebda (1995), the post-glacial history of southeastern Vancouver Island started with open *P. contorta* woodlands during the late glacial between ca. 12,800-11,800 ybp. Climate is interpreted as cool and dry at this time. During the cool moist late Pleistocene (ca. 11,800-10,000 ybp) the *P. contorta* biogeochron was replaced by closed mixed conifer forests consisting of *Picea*, *Abies*, and *T. heterophylla*. Pellatt et al. (in press) used high resolution pollen and spore analyses to examine the Holocene vegetation history on southern Vancouver Island and their results are in good agreement with coarser resolution reconstructions (Heusser, 1985; Allen, 1995). Open *Pseudotsuga* and *Alnus* forests with Poaceae and *Pteridium* expanded during the warm dry early Holocene (ca. 10,000-7,000 ybp). Between 7,000-8,000 ybp *Quercus* and Cupressaceae increased in abundance (Pellatt et al., in press). *Quercus* remained abundant until 3,000-2,000 ybp when *T. heterophylla* and Cupressaceae increased. Extant CDF forests dominated by *Pseudotsuga* and CWH forests consisting of *T. heterophylla* and *T. plicata* were established in the late Holocene (3,000-0 ybp) as climate cooled and moistened.

Heusser (1983) shows that the area around Saanich Inlet was dominated by *P. contorta* woodlands during the late glacial interval from ca. 12,000-11,000 ybp. Between ca. 11,000-7,000 ybp forests containing *Pseudotsuga* and *T. heterophylla* with *Alnus*, *Pinus*, and ferns dominated. During the mid Holocene from about 7,000-2,000 ybp, forests containing *Pseudotsuga*, *T. heterophylla*, and *Quercus* with *Abies*, *P. contorta*, and *Alnus* prevailed. These forests were replaced in the late Holocene (ca. 2,000 ybp-present) by *Pseudotsuga*, *T. heterophylla*, and Cupressaceae dominated forests.

Paleoclimate Reconstructions

Interpretations of climate change are often derived from palynological studies (Barnosky et al., 1987; Hebda, 1995). In the coastal Pacific Northwest region a general pattern of climate change has emerged from palynological and other paleoecological analyses (Heusser, 1960; Mathewes, 1973; 1991; 1993; Hebda and Rouse, 1979; Mathewes and Heusser, 1981; Sugita and Tsukada, 1982; Hebda, 1982; 1983; 1995; Heusser, 1983; Barnosky, 1985a,b; Ritchie, 1987; Wainman and Mathewes, 1987; Barnosky et al., 1987; Anderson, 1988; Mathewes and King, 1989; Allen, 1995; Sea and Whitlock, 1995). The climatic conditions during the late glacial (ca. 14,000-11,500 ybp) are interpreted to have been cool and continental. During the late Pleistocene between ca. 11,500-10,000 ybp climate remained cool but moistened. The early Holocene ushered in warm dry conditions, possibly 1-2 °C warmer than present. Clague and Mathewes (1989) indicate that the treeline between 9,100-8,200 ybp at Castle Peak, British Columbia, was 60-130 m higher, suggesting climate was 0.4-0.8 °C warmer. The mid and late Holocene intervals are characterised by increasing moisture at ca 7,000 ybp and decreasing temperature at ca. 4,000 ybp.

According to Hebda (1983) and Wainman and Mathewes (1986), the general climatic record based on pollen evidence suggests cool continental conditions occurred in southwest British Columbia prior to about 11,500 ybp. Heusser (1960) and Mathewes (1973) interpret cool and moist conditions between ca. 12,400-10,500 ybp, whereas Mathewes (1993) states that maximum cooling, coupled with high humidity on land, occurred between 10,700-10,000 ybp. Hebda (1995) interpreted cool moist conditions prior to 10,000 ybp. Mathewes (1973) suggests conditions became somewhat warmer and perhaps drier around 10,500 ybp but maintains that abundant moisture was still prevalent.

Heusser (1960) interpreted post-glacial warming and drying between 8,500-3,000 ybp. Mathewes (1973) showed increased warming and drying between ca. 10,500-6,600 ybp, whereas Hebda (1983) indicated temperatures were warmer during the early Holocene between 8,800-7,000 ybp. More recently, Hebda (1995) suggests warming and drying commenced between 10,000-9,000 ybp. Allen (1995) and Hebda (1995) suggest that climate moistened at ca. 7,000 ybp and cooled at ca. 4,000 ybp. By about 4,000-3,000 ybp cool wet conditions similar to the present existed (Hebda 1983; 1995; Heusser, 1983; Allen, 1995).

Heusser et al. (1980) and Mathewes and Heusser (1981) used regression equations to show that climate was cold and dry during the full glacial (ca. 16,000-13,000 ybp), whereas during the late glacial and late Pleistocene (ca. 13,000-10,000) climate was generally cool and moist. The early Holocene climate between ca. 10,000-7,000 ybp was warm and dry, whereas the mid-late Holocene climate was cooler and moister than in the early Holocene.

Surface Sample Studies

The surface pollen and spore signal is often used to document the characteristic pollen and spore signature of extant vegetation and to relate the distribution of pollen types to various biogeoclimatic attributes. Several authors have examined the modern pollen and spore spectra in northwestern North America using moss polster, forest litter, and lake surficial sediments (Heusser, 1973; 1977; Mack and Bryant, 1974; Ritchie, 1974; Adam, 1985; Dunwiddie, 1987; Anderson and Davis, 1988; Moore et al., 1991; Hebda and Allen, 1993; Pellatt et al., 1997, Allen et al., 1999; Gavin and Brubaker, 1999). These studies reveal that (1) vegetation types can produce diagnostic pollen and spore signatures that can be used to interpret fossil pollen and spore assemblages; (2) long distance transport of pollen grains can modify the pollen and spore spectra, especially in grasslands and tundra, leading to erroneous vegetation reconstructions; and (3) some trees, such as *Pinus* and *Alnus*, produce copious amounts of pollen and are typically overrepresented, whereas other trees are underrepresented. In general, these studies also indicate that the advantage of using moss polster and forest litter samples is that vegetation cover can be estimated, permitting examination of the over- and underrepresentation of species. In addition, the herbaceous component is typically better represented. The advantage of using analysis of lake surficial sediments is that the pollen and spore spectra are usually derived from larger regions than polster and litter samples and can be directly compared to subsurficial lake sediment samples.

Hebda and Allen (1993) examined the pollen and spore spectra from 64 polster and litter samples collected in 5 separate BEC zones. Their study shows the CWH is characterised by *T. heterophylla*, *Alnus*, and Cupressaceae pollen and that *Pinus* pollen is overrepresented. *T. heterophylla*, *Pseudotsuga*, and Cupressaceae pollen are neither over- nor underrepresented, whereas *Picea* and *Abies* are underrepresented. Dunwiddie (1987) also examined the over- and underrepresentation of species, concluding that *Pinus* and *T. heterophylla* are overrepresented, whereas *Abies* and *T. mertensiana* are underrepresented.

Pellatt et al. (1997) used cluster analysis, detrended correspondence analysis, and canonical correspondence analysis to compare sediment-surface sample data to each other and to environmental variables. According to their results, the CWH, MH, and

Engelmann Spruce – Subalpine Fir (ESSF) zones all produce characteristic pollen and spore signatures. In general, their results showed that the CWH is characterised by relatively high percentages of Cupressaceae, *T. heterophylla*, and *Alnus rubra* type pollen, whereas the MH zone could be identified using *T. mertensiana*, *Abies*, and *Alnus crispa* (Ait.) Pursh (Sitka alder) type pollen. Surprisingly, percentages of *T. heterophylla* pollen did not distinguish the CWH and MH, although *T. mertensiana* pollen and *T. mertensiana/T. heterophylla* pollen ratios proved diagnostic.

Heusser (1977) showed that the characteristic pollen signature from the Pacific slope of Washington changes with elevation. Surface samples collected from lowland forests of *T. heterophylla*, *T. plicata*, and *P. sitchensis* contain pollen from the same species, whereas montane forests consisting of *A. amabilis* and *T. heterophylla* trees were identifiable by peak occurrences of *T. heterophylla* pollen and moderate levels of *Abies* pollen. Subalpine forests dominated by *T. mertensiana*, *Abies lasiocarpa* (Hook.) Nutt. (subalpine fir), *A. amabilis*, and *C. nootkatensis* contain a mixture of *T. heterophylla*, *T. mertensiana*, and *Abies* pollen. High elevation alpine tundra was characterised by *T. heterophylla*, *A. lasiocarpa*, and herbaceous pollen. Gavin and Brubaker (1999) showed that subalpine meadows and alpine parkland in Washington contain abundant *Pinus*, *T. heterophylla*, and *Abies* pollen with lesser yet characteristic amounts of Cupressaceae, Poaceae, Cyperaceae, and Asteraceae (sunflower family). Barnosky's (1981) study from western Washington shows *Picea* pollen occurs at lower elevations and that the percentage of *Artemisia* and Poaceae pollen increases with elevation, attaining highest levels in alpine parkland environments. *Dryas* and *Valeriana sitchensis* Bong. (Sitka valerian) pollen is recorded only in alpine meadows.

Mack and Byrant (1974) used soil surface samples to show *Pinus* pollen is ubiquitous in the steppe communities of the Columbia Basin, largely because of long distance transport. *Artemisia*, Poaceae, Chenopodiaceae (goosefoot family), and Asteraceae pollen characterise arid sites.

Lake Level Investigations

Several authors have examined Quaternary lake-levels and used the recorded fluctuations as proxy indicators of climate change (Harrison, 1993; Harrison and Digerfeldt, 1993; Yu and McAndrews, 1994; Mathewes and King, 1989). According to Harrison (1993) higher past lake levels can be identified using geomorphic features such as wave-cut terraces, beach ridges, and marginal sediment exposures such as well-sorted sands representing beach or nearshore deposits. Lithological and geochemical changes in lake cores provide additional information on high and low lake levels. Paleoecological evidence used to reconstruct paleolake levels includes aquatic pollen assemblages, terrestrial pollen preservation, diatoms, ostracods, chironomids, and molluscs (Digerfeldt, 1986).

Aquatic pollen and macrofossil records are a major source of paleoecological information pertaining to past lake levels. Digerfeldt (1986) and Harrison and Digerfeldt (1993) suggest that the distribution of a certain species in a lake environment is partially determined by depth, resulting in a zonation of emergent, floating-leaved, and submerged species from the littoral zone to the lake centre.

Mathewes and King (1989) used sediment stratigraphy, plant macrofossils, molluscs, and pollen to show that lake levels in the Interior Douglas-fir Biogeoclimatic

Zone have fluctuated during the Holocene. Hebda (1994) showed that lakes, ponds, and wetland systems in southern and central interior British Columbia were severely reduced in size or completely dried up during the early Holocene warm dry interval. For example, Phair Lake formed at about 7,000 ybp when climatic conditions became cooler and wetter. Mathewes and King (1989) were able to identify two major rises in lake levels at 5,650 ybp and 2,000 ybp. Studies of past lake levels on southern Vancouver Island might provide critical and independent data on climate to corroborate climatic interpretations from regional vegetation and charcoal.

Fire Studies

Several techniques exist for reconstructing the past incidence of fire. The typical methods employed include analyses of microscopic and macroscopic charcoal particles in sediment by point count methods in petrographic thin sections and pollen slides (Clark, 1982; 1984), fire-scar data, organic carbon content of sediment samples, geochemistry of sediment samples, sedimentology, and timing of the establishment of even aged forest stands. To date, however, no standardised method for reconstructing paleofire regimes exists (Patterson et al., 1987).

According to MacDonald et al. (1991) charcoal consists of carbon derived from the incomplete combustion of plant tissue. Examination of fossil charcoal deposited in lacustrine basins is frequently used to reconstruct fire histories. Patterson et al. (1987) report factors such as variations in the spatial extent, duration, intensity, fuel type, and meteorological conditions of fires affects charcoal production and deposition.

Clark and Royall (1995) conclude that fire reconstruction is difficult because of the uncertainty associated with characterising and identifying charcoal particles in pollen slides and on thin sections, lack of calibration with other fire indicators, differential transport and deposition, and inconsistency of results between different methods of charcoal preparation and analyses. Sander and Gee (1990) show that fossil charcoal can be identified by characteristics such as silky lustre, high reflectivity, cuboidal shape, brittleness, colour, cleavage along the radial plane, and low density. Swain (1973) used charcoal in lake sediments to identify past fire regimes but was unable to discern between fire frequency and magnitude. Tolonen (1986) suggests under certain conditions fires are climate-controlled and can be used as an index of paleoclimate.

Several authors have examined relationships between charcoal particle size and proximity to the source region for use in paleofire reconstruction (Patterson et al., 1987; MacDonald et al., 1991; Clark and Royall, 1995). Patterson et al. (1987) suggest that microscopic charcoal from small lakes does not represent regional fire activity. MacDonald et al. (1991) indicate that microscopic charcoal corresponds in abundance to regional fire activity, whereas macroscopic charcoal does not correlate with regional fire activity. However, both microscopic and macroscopic charcoal do not consistently record local fire activity. Clark and Royall (1995) show that charcoal particles derived from thin sections represent local fires, whereas charcoal particles present in pollen slides represent regional fires. Whitlock and Millspaugh (1996) conclude that deep lakes with steep watersheds record local fire activity and that charcoal particles between 125-250 μm diameter accurately record local fire events.

In the region, several authors have reconstructed the post-glacial fire history using charcoal analyses (Sugita and Tsukada, 1982; Cwynar, 1987; Dunwiddie, 1987; Patterson et al., 1987; Wainman and Mathewes, 1987; Henderson et al., 1989; MacDonald et al., 1991; Parminter, 1991; Burney et al., 1995; Clark and Royall, 1995; Olney, 1997; Long et al., 1998). In general, these studies show that fire was absent from the late glacial landscape and that fires first occurred in the latest Pleistocene. A marked increase in fire incidence during the early Holocene is likely related to the warm dry conditions at that time. A general decrease in fire incidence is evident throughout the mid and late Holocene until historical times. Campbell and Flannigan (1999) project that fire incidence may increase in the future because climate change will increase tree mortality and thus increase available fuel.

Geographic Information Systems

Although geographic information systems (GIS) have not yet been extensively used to reconstruct paleoclimates and predict future climates, Hughes (1991) proposed that the GIS GeoSphere project has the potential to generate computer pictures of the earth: past, present, and future. GIS technology has been applied in modern landscape management and conservation of biodiversity (Rodcay, 1991; Maclean et al., 1992; Aspinall, 1994; Aspinall and Matthews, 1994; Mackay et al. 1994; Anderson, 1996). The methods employed in previous GIS research can also provide a framework for approaching paleovegetation and paleoclimatic reconstructions.

Rodcay (1991) indicates old-growth forest data can be acquired using Landsat 5 Thematic Mapper images and old-growth forest stands located precisely using Trimble Navigation's Pathfinder Basic GPS. In addition to locating ancient stands, it is also possible to record other physical features such as slope, aspect, and species composition at the site level. This data can then be used to determine the stand's location on a geocoded satellite image, which is then downloaded and combined with other data in Arc/Info® to generate a more comprehensive picture of the ecosystem. Techniques such as this are useful for identifying potential surface sample sites that can be used to calibrate pollen ratios and climate.

Anderson (1996) demostrated the value of GIS to compile, analyse, and summarise snow distribution data collected from various sites around North America. In this case, a GIS was used to integrate diverse and geographically dispersed data sources, incorporate the data into workable models, and produce custom maps and data sets. Spatial interpolation programs, models of snow characteristics between scattered points and transect measurements, were then used to develop raster maps and images of snow accumulation.

Lathrop et al. (1994) used a forest ecosystem model and a grid cell based GIS to estimate the regional impacts of climate change on forest ecosystems in the northeastern Unites States. Aspinall and Matthews (1994) modelled the predicted impacts of climate change on the distribution and abundance of wildlife in Scotland using a GIS. Modern distributions of wildlife were analysed using map data that described variations in climatic factors. Both modern and predicted distributions were then modelled using a GIS by establishing a relationship between species distribution and climate.

Future Conditions

More than 170 years ago, a French scientist named Jean-Baptiste Fourier suggested that the earth's atmosphere functioned like a natural greenhouse, keeping the planet warm (Dotto, 1999). In essence, the presence of atmospheric gases such as water vapor, carbon dioxide, methane, and nitrous oxides keeps the planet warm and capable of sustaining life by permitting passage of incoming short wave solar radiation through the upper and lower atmospheres to the earth's surface and by absorbing re-radiated longer wavelengths. A fascinating aspect of this process is that the "greenhouse gases" other than water vapour account for <1% of the volume of the atmosphere (nitrogen and oxygen account for 78 and 21% respectively). Therefore, a small change in the concentration of these gases in the atmosphere can trigger a profound change in climate.

It is proposed that anthropogenic activity, such as industrial development and consumption of fossil fuels, has altered the concentration of greenhouse gases in the atmosphere. The result is an enhanced greenhouse effect (Dotto, 1999). According to a 1992 International Panel on Climate Change (IPCC) report the global mean surface air temperature has increased between 0.3-0.6 °C during the last 100 years. The report suggests increasing atmospheric concentrations of greenhouse gases such as carbon dioxide, methane, chlorofluorocarbons, and nitrous oxide (as well as natural temperature variation) may be contributing to the observed warming trend. The report acknowledges several uncertainties exist in global warming calculations such as timing, magnitude, and regional patterns of climate change. Kerr (1995) indicates that global warming has commenced and reports that current climatic models predict global warming of 0.08-0.3 °C/decade, values that are consistent with early Holocene temperatures (Heusser et al., 1980; Mathewes and Heusser, 1981; Hebda, 1998).

Franklin et al. (1991), Hebda (1997a), and Thompson et al. (1998) conclude that forests in the Pacific Northwest are vulnerable to changes in climate, particularly changes in effective precipitation, because of the influence local and region climatic gradients have on vegetation distribution and ecosystem functioning (e.g. rates of productivity and nutrient cycling). In addition, altered future disturbance regimes and pest and pathogen outbreaks may accelerate any future changes in forest conditions (Franklin et al., 1991). Projected changes include (1) a decrease in available moisture for plant growth; (2) an increase in evapotranspiration; (3) a shift in species distribution; (4) the upward migration of treelines; (5) expansion of nonforested ecosystems; (6) fewer wetlands; and (7) loss of species (Hebda, 1998). Analyses of the effects of the warm dry interval between 10,000-7,000 ybp have the potential to provide insight into assessing the possible impacts of present-day warming trends on southern Vancouver Island and elsewhere.

Summary

This study seeks to use the aforementioned proven techniques plus some innovations, coupled with the results of previous investigations, to examine post-glacial landscape development on southern Vancouver Island. This work will also yield insight into potential future landscapes resulting from climate change.

CHAPTER 4: METHODS

Coring

A wooden raft provided a working platform for coring Pixie, Porphyry, Walker, Enos, and Boomerang lakes, whereas the Whyac Lake bog and ESF were cored from the wetland surface (Figure 3). A piston peat corer was used to core hard-to-penetrate fibrous material, whereas a Livingston corer was used to recover all other types of limnic sediments. The corers were manually pushed into the sediment in 100 cm intervals. Additional 100 or 150 cm titanium-zircon rod sections were attached for greater subsurface penetration. Recovered sediment was transferred from the corer to a plastic core tube and subsampled at 2 cm, 5 cm, or 10 cm intervals, depending on the degree of sediment homogeneity and depth (Figure 4). Deep core sections were sampled at high resolution in order to better document any vegetation response associated with late Pleistocene climate changes. The outer portions of sediment for each interval were scraped off to avoid any possible contamination by younger material. The samples are stored in labelled plastic bags at the Royal British Columbia Museum, Victoria, Canada.

Pollen Preparation and Analyses

All surface and sediment samples were prepared using standard pollen and spore preparation techniques (Berglund and Ralska-Jasiewiczowa, 1986; Moore et al., 1991). For surface samples, about 30 cm^3 of moss or litter was processed without the addition of an exotic marker. For sediment samples, typically 1-2 cm^3 of sediment was collected

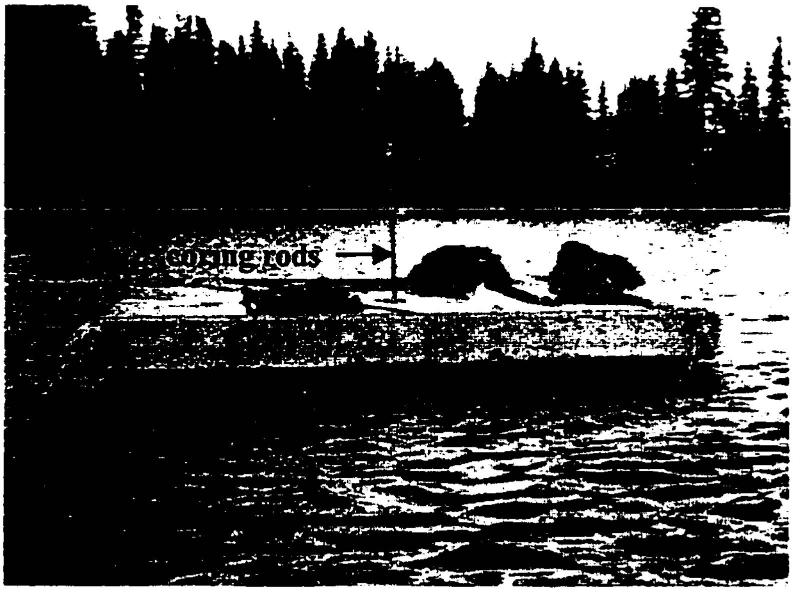


Figure 3. The coring raft anchored in position on a lake. The handle and rods of the Livingston corer are visible (oriented vertically), whereas the core barrel is in the sediments below.

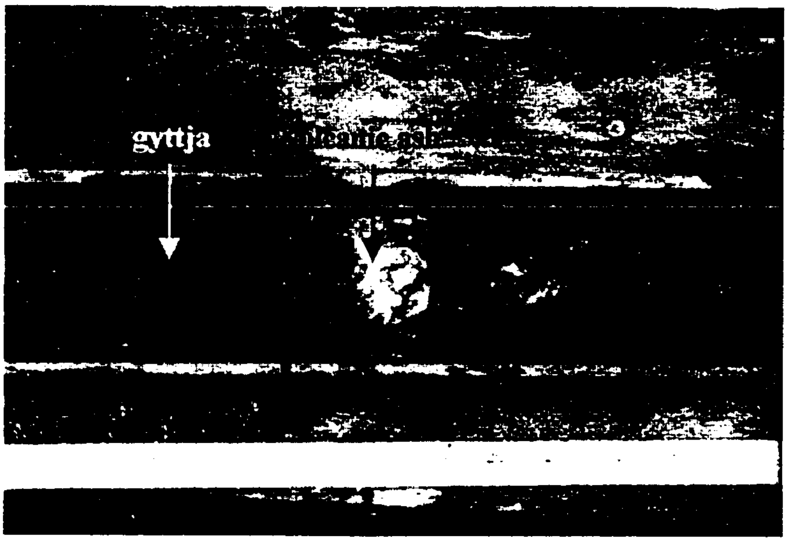


Figure 4. Typical gyttja and volcanic ash sediment recovered during coring. The sediment is temporarily housed in plastic tubing as it is subdivided into samples on site.

from the middle portion of each core sample. Every second sample was spiked with *Lycopodium* tablets containing 12,077 +/- 378 or 11,267 +/- 370 spores to calculate pollen concentrations and influx rates.

All samples were boiled in 100 ml of 5% potassium hydroxide (KOH) for 20 minutes to disaggregate the sediment and remove humic components and then filtered through a 150 μm sieve. The residue passing through the sieve was neutralised with approximately 3-5 ml 5% potassium carbonate (K_2CO_3). If present, carbonates were removed using 10-20 ml of 10% hydrochloric acid (HCl). Silicates were removed with hydrofluoric acid (HF). The remaining residue was boiled in standard acetolysis mixture to remove cellulose and other organics (Moore et al., 1991). The samples were filtered through a 10 μm Nitex screen and the residues were well mixed with one drop of glycerine jelly and mounted on a glass microscope slide.

For clay samples, a volume of approximately 25-50 cm^3 of sediment was stirred and suspended in 100 ml water. The suspensions were decanted to remove the rapidly settling material (mainly sands). This process was repeated until only a small amount of rapidly settling material remained. To concentrate the slowly settling material, the suspension was allowed to stand 12-16 hours and most of the supernatant fluid decanted. The slowly settling material was concentrated into a pellet by centrifugation. The clay pellets were resuspended in 30 ml of 0.1 M sodium pyrophosphate ($Na_2P_4O_7$) to deflocculate the clays (45 minutes at 50°C with stirring every 10 minutes; Moore et al., 1991). To remove the deflocculated clays, samples were centrifuged (5 minutes), the supernatant fluid decanted, and the sample washed 3 times with water. Further preparation of samples follows the procedure described above for pollen preparation from organic sediment beginning with the step to remove carbonates.

Pollen and spores were examined under a Nikon Biophot light microscope (400x and 1000x magnification). Individual pollen and spore grains were identified with the aid of standard keys (Moore et al., 1991) and Royal British Columbia Museum pollen reference slides (Figure 5). At least 300 pollen grains and spores were examined per sample. All raw pollen counts were tabulated in a Microsoft Works™ spreadsheet, converted to percentages and pollen influx rates, and plotted using Tiliagraph 2.0 software (Grimm, 1993). Pollen and spore percentage values were calculated using all palynomorphs excluding *Isoetes* (quillwort). *Isoetes* was plotted separately as a percentage of the total excluding *Isoetes* (i.e. an *Isoetes* value of 100 represents a 1:1 ratio of total pollen and spores to *Isoetes* spores) because it overwhelmed the pollen and spore signal at Porphyry Lake. The NAP curve represents all pollen and spores produced by non-arboreal plants. A stratigraphically constrained cluster analysis assisted in defining the placement of zones boundaries (Grimm, 1987) by identifying clusters of similar vegetation. The pollen zone boundaries where then adjusted slightly by visual inspection. Adjustment of the zone boundaries was deemed necessary because the zones define time dimensional ecosystems that have structural, hydrological, and disturbance characteristics in addition to relatively homogeneous vegetation. Accordingly, the ecological characteristics of the zone vegetation, the zone stratigraphy, and charcoal records were used to adjust the placement of zone boundaries where necessary to better capture these additional biogeochron features.

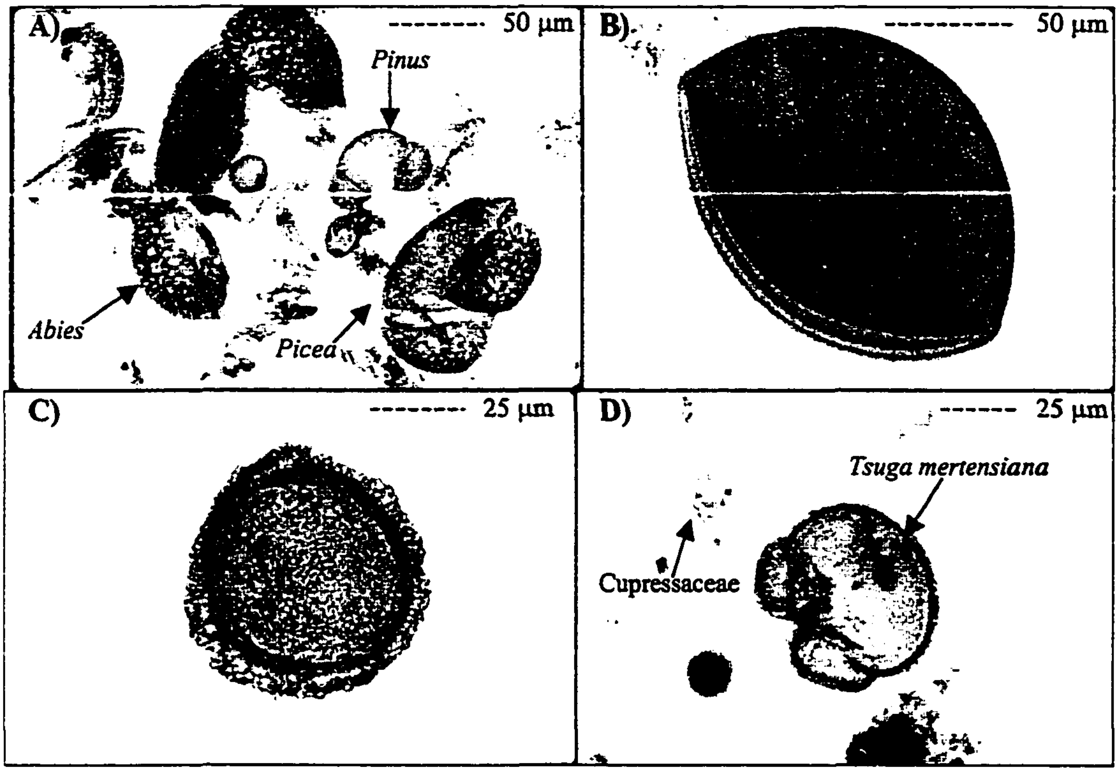


Figure 5a. Pollen grains of *Abies*, *Pinus*, and *Picea*. Figure 5b. *Pseudotsuga* pollen that has been folded. Figure 5c. *Tsuga heterophylla* pollen. Figure 5d. *Tsuga mertensiana* and Cupressaceae pollen grains. Approximate size scales are shown.

The following pollen types were selected as indicators of climate on southern Vancouver Island because *Pseudotsuga* is a low elevation hygrophyte that has deep roots and can tolerate drought conditions, *T. heterophylla* is a low elevation hygrophyte in moist areas, and *T. mertensiana* is a high elevation hygrophyte (Figure 5). Therefore, a ratio consisting of *Pseudotsuga* and *T. heterophylla* can be used as an index of precipitation (Allen, 1995; Hebda, 1998; Allen et al., 1999) and a ratio of *T. heterophylla* and *T. mertensiana* can be used as an index of temperature. These ratios are referred to as DWHI (Douglas-fir-western hemlock index) and THMI (*T. heterophylla-T. mertensiana* index) respectively (Eqn. 1 and 2). DWHI ratios range between 0 and 1.0 with low values representing dry conditions and high values representing wet conditions. THMI ratios have a similar range, with 0 representing warm conditions and 1.0 representing cold conditions. The importance of these two ratios is that they distinguish precipitation trends from temperature trends.

Eqn 1. DWHI = 1-(*Pseudotsuga* / *Pseudotsuga* + *T. heterophylla*)

Eqn 2. THMI = 1-(*T. heterophylla* / *T. heterophylla* + *T. mertensiana*)

Over- and underrepresentation graphs showing the relationship between surface sample percentage pollen and spores and percentage vegetation cover were measured as relative percentages of the total (Hebda and Allen, 1993). For the vegetation cover, the total percentage was derived from the combined percentages of tree, shrub, and herbaceous taxa, all of which were estimated visually at the time the sample was collected. By presenting the pollen and spore and vegetation cover data in relative terms, it is possible to compare directly between samples.

Charcoal Analyses

Charcoal preparation methods were adapted from Whitlock and Millspaugh (1996), whereby exactly 2.5 cm^3 of sediment was removed from each core interval. The charcoal samples were gently rinsed with warm water through 500 µm, 250 µm, and 150 µm sieves which separated the charcoal into >500 µm, 250-500 µm, and 150-250 µm size classes. Material passing through the 150 µm sieve was discarded.

Charcoal particles from each size class were suspended in water in a gridded petri dish. All samples were examined under a dissecting microscope (20 X or 40 X). Burned wood and charcoal from *in situ* charcoal horizons collected from a bog at Millstream, Vancouver Island, provided reference material for verifying charcoal. Charcoal particles were identified as black, opaque, highly reflective particles showing cellular structure (Figures 6a and 6b; Patterson et al. 1987). All charcoal particles of each size class for each core interval were counted.

Carbon-14 Dating

Selected peat, gyttja, and dy samples were sent to Beta Analytic Inc., University Branch, Miami, Florida for standard ^{14}C dating by ß-counting. Samples were treated with acid washes to increase surface area as much as possible and hydrochloric acid was applied repeatedly to the samples to ensure the absence of carbonates. All radiocarbon dates were based on the Libby half life of 5,568 years and referenced to 1950.

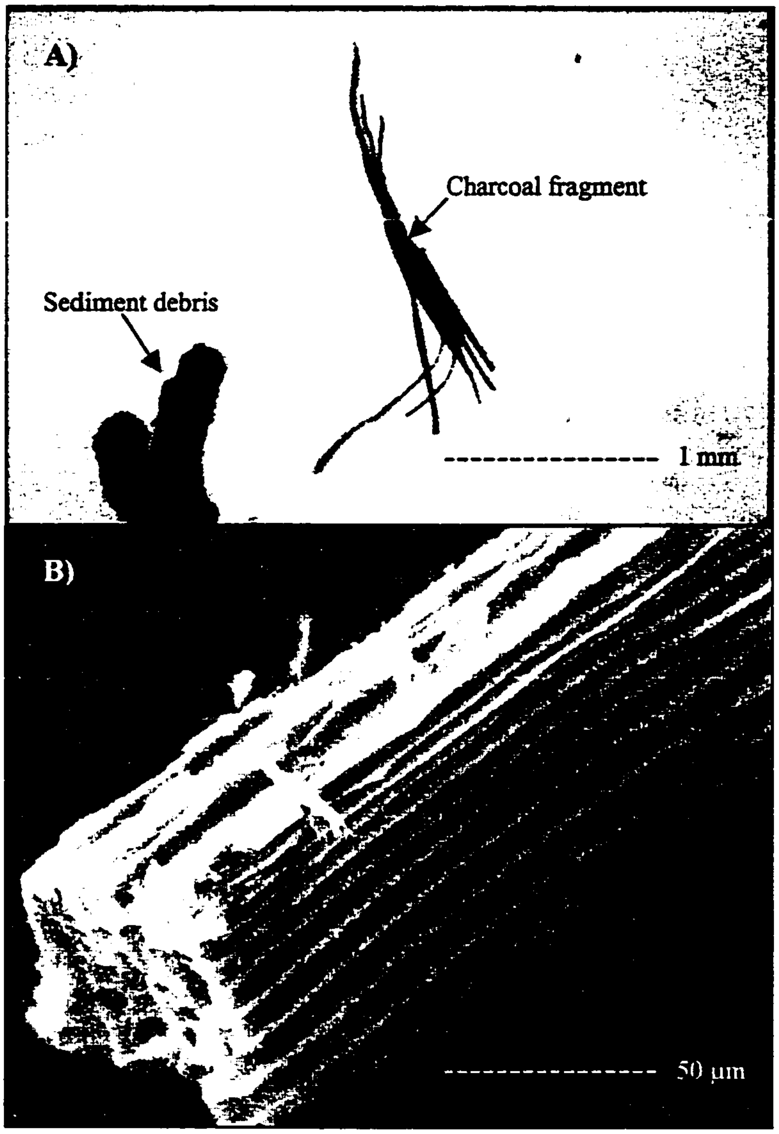


Figure 6a. Photograph of a charcoal fragment taken under a dissecting microscope showing the black color and cuboidal and opaque characteristics of charcoal. Figure 6b. A scanning electron microscope image of charcoal. Note the visible cellular structures.

CHAPTER 5: SURFACE SAMPLE RESULTS

Sample Sites

Analysis of pollen and spore surface samples is frequently used to describe and interpret modern ecosystems and fossil assemblages (Allen et al., 1999). This assumes the modern and fossil pollen and spore spectra are representative of plants whose ecological characteristics have not changed significantly (Hebda and Allen, 1993).

A total of 179 surface samples representing 85 sites were collected from all major BEC zones on southern Vancouver Island south of 49 °N (Table 1; Figure 2). The samples consisted primarily of moss polsters and forest litter, although surface sediment samples from 8 lakes are also included. This description and analysis includes data from Allen (1995) combined with new data collected from 35 sites as part of this study. At several sites, a total of 5 subsamples were collected within a $10m^2$ quadrat to permit analysis of variability of samples. Subsequently, results from these subsamples were combined to form a single sample site.

The percent cover of arboreal and non-arboreal taxa was estimated for each site following the methods of Hebda and Allen (1993). Sites were typically located in parks, community watersheds, or other protected lands that contained a representative "old-growth" component. By targeting these sites, it is hoped that the modern pollen and spore spectra had not been significantly modified by disturbance so that results can be compared with fossil assemblages more accurately. Surface samples are used to identify pollen and spore signatures characteristic of regional vegetation and to examine over- and underrepresentation of different pollen types.

Table 1. Location, topographic, and biogeoclimatic characteristics and pollen ratios of surface samples.

ID	Sample	Latitude (°N)	Longitude (°W)	Elevation (m)	Variant	DWHI	THMI
1	S93-A	48.40	123.30	10	Grassland	0.75	0.09
2	S93-B	48.40	123.30	10	Grassland	0.67	0
3	S93-C	48.40	123.30	10	Grassland	0.7	0.09
4	S93-D	48.40	123.30	10	Grassland	0.78	0.03
5	S93-E	48.40	123.30	10	Grassland	0.84	0.07
6	S93-28	48.42	123.35	20	Garry oak	0.34	0.09
7	S93-29	48.42	123.35	20	Garry oak	0.42	0.13
8	S93-30	48.42	123.35	20	Garry oak	0.38	0.14
9	S93-31	48.42	123.35	20	Garry oak	0.65	0.06
10	S93-32	48.42	123.35	20	Garry oak	0.34	0.06
11	S94-3	48.48	123.44	90	CDFmm1	0.06	0
12	S94-2	48.49	123.45	90	CDFmm1	0.07	0
13	S94-4	48.48	123.45	60	CDFmm1	0.12	0.25
14	S94-1	48.49	123.45	80	CDFmm1	0.09	0
15	DL0-10	48.55	123.47	60	CDFmm1	0.3	0
16	FL0-10	48.52	123.48	60	CDFmm1	0.17	0.07
17	PL0-10	48.55	123.50	60	CDFmm1	0.29	0
18	LL0-20	48.45	123.53	60	CDFmm1	0.26	0.01
19	MB-1	48.45	123.60	420	CWHxm1	0.71	0.03
20	MB-2	48.45	123.60	420	CWHxm1	0.52	0.06
21	MB-3	48.45	123.60	420	CWHxm1	0.15	0.29
22	MB-4	48.45	123.60	420	CWHxm1	0.19	0.13
23	MB-5	48.45	123.60	440	CWHxm1	0.07	0.12
24	MB-6	48.45	123.60	340	CWHxm1	0.96	0
25	S93-40	48.32	123.65	120	CWHxm1	0.68	0.02
26	ESF	48.35	123.68	155	CWHxm2	0.42	0
27	S93-36	48.34	123.68	100	CWHxm2	0.44	0.01
28	S93-1	48.57	123.71	230	CWHxm1	0.3	0.04
29	S93-2	48.57	123.72	330	CWHxm1	0.5	0.03
30	S93-3	48.57	123.72	370	CWHxm1	0.21	0.13
31	S93-4	48.57	123.72	430	CWHxm2	0.16	0.09
32	S93-5	48.57	123.73	540	CWHxm2	0.19	0.05
33	S93-6	48.57	123.73	620	CWHmm2	0.28	0.09
34	S93-7	48.57	123.73	740	CWHmm2	0.3	0.08
35	S93-8	48.59	123.73	380	CWHxm2	0.62	0.02
36	R8	48.65	123.73	280	CWHmm2	0.27	0
37	R7	48.66	123.74	400	CWHmm2	0.18	0
38	S93-14	48.63	123.80	170	CWHxm1	0.21	0.22
39	S93-13	48.91	123.83	1120	MHmm1	0.75	0.61
40	S93-10	48.90	123.84	1060	MHmm1	0.69	0.71
41	PORPHYRY	48.91	123.84	1100	MHmm1	0.95	0.29
42	S93-11	48.90	123.84	1080	MHmm1	0.67	0.69
43	S93-12	48.90	123.87	1200	MHmm1	0.62	0.68

44	S93-9	48.87	123.84	800	CWHxm2	0.69	0.21
45	MILE-21.5AE	48.48	123.84	700	CWHmm2	0.91	0
46	SL-AE	48.59	123.86	460	CWHmm1	0.59	0.02
47	MILE-11AE	48.51	123.89	500	CWHmm1	0.64	0.03
48	S83-16	48.68	123.92	1030	CWHmm2	0.66	0.2
49	S93-25	48.69	123.93	1060	MHmm1	0.87	0.5
50	WALKER	48.53	124.00	950	MHmm1	0.96	0.25
51	S83-58	48.48	124.11	680	CWHvm2	0.97	0.07
52	S83-54	48.48	124.11	700	CWHvm2	0.98	0.01
53	S83-55	48.48	124.11	700	CWHvm2	1	0.09
54	S83-56	48.48	124.11	690	CWHvm2	0.98	0.1
55	S83-57	48.49	124.12	670	CWHvm2	0.96	0.11
56	S95-8A	48.66	124.14	360	CWHmm1	0.59	0.04
57	S95-9A	48.67	124.14	260	CWHxm2	0.9	0
58	S95-7A	48.66	124.14	440	CWHmm1	0.68	0.03
59	S95-6A	48.66	124.14	460	CWHmm1	0.65	0
60	S95-5A	48.64	124.17	220	CWHmm1	0.82	0
61	S95-3AE	48.61	124.19	60	CWHmm1	0.75	0
62	S95-4A	48.61	124.19	420	CWHvm1	0.74	0
63	PIXIE	48.60	124.20	70	CWHvm1	0.92	0
64	S91-6	48.60	124.23	40	CWHvm1	0.99	0
65	S91-2	48.49	124.26	210	CWHvm1	1	0.01
66	S95-1AE	48.58	124.28	10	CWHvm1	0.93	0.03
67	S91-5	48.59	124.29	20	CWHvm1	1	0
68	S95-2A	48.59	124.33	10	CWHvm1	0.97	0
69	S91-3	48.59	124.35	20	CWHvm1	0.98	0.04
70	S91-4	48.59	124.35	20	CWHvm1	1	0.02
71	NL-4	48.78	124.70	20	CWHvm1	0.96	0.01
72	NL-2	48.76	124.73	240	CWHvm1	0.91	0.03
73	NL-3	48.76	124.73	10	CWHvm1	0.95	0
74	NL-1	48.70	124.80	10	CWHvm1	0.99	0
75	WL-1	48.67	124.84	10	CWHvh1	0.95	0.02
76	WL-2	48.67	124.84	10	CWHvh1	1	0.01
77	WL-3	48.67	124.84	10	CWHvh1	0.95	0
78	WL-4	48.67	124.84	10	CWHvh1	0.98	0.02
79	WL-5	48.67	124.84	10	CWHvh1	0.93	0
80	WHYAC	48.67	124.84	15	CWHvh1	0.98	0
81	S91-10	48.81	125.12	50	CWHvh1	1	0
82	S91-9	48.81	125.15	40	CWHvh1	1	0.01
83	S83-50	48.79	125.16	10	CWHvh1	1	0.01
84	S83-52	48.80	125.17	20	CWHvh1	0.99	0.01
85	S83-51	48.80	125.17	20	CWHvh1	1	0.03

Table 1. continued.

Regional Vegetation Pollen and Spore Signatures

Results are described using Coastal Douglas Fir (CDF), Coastal Western Hemlock (CWH), and Mountain Hemlock (MH) biogeoclimatic ecological classification (BEC) zones (Meidinger and Pojar, 1991). The characteristic pollen signatures were further classified using BEC subzones, variants, and associations (Figure 7).

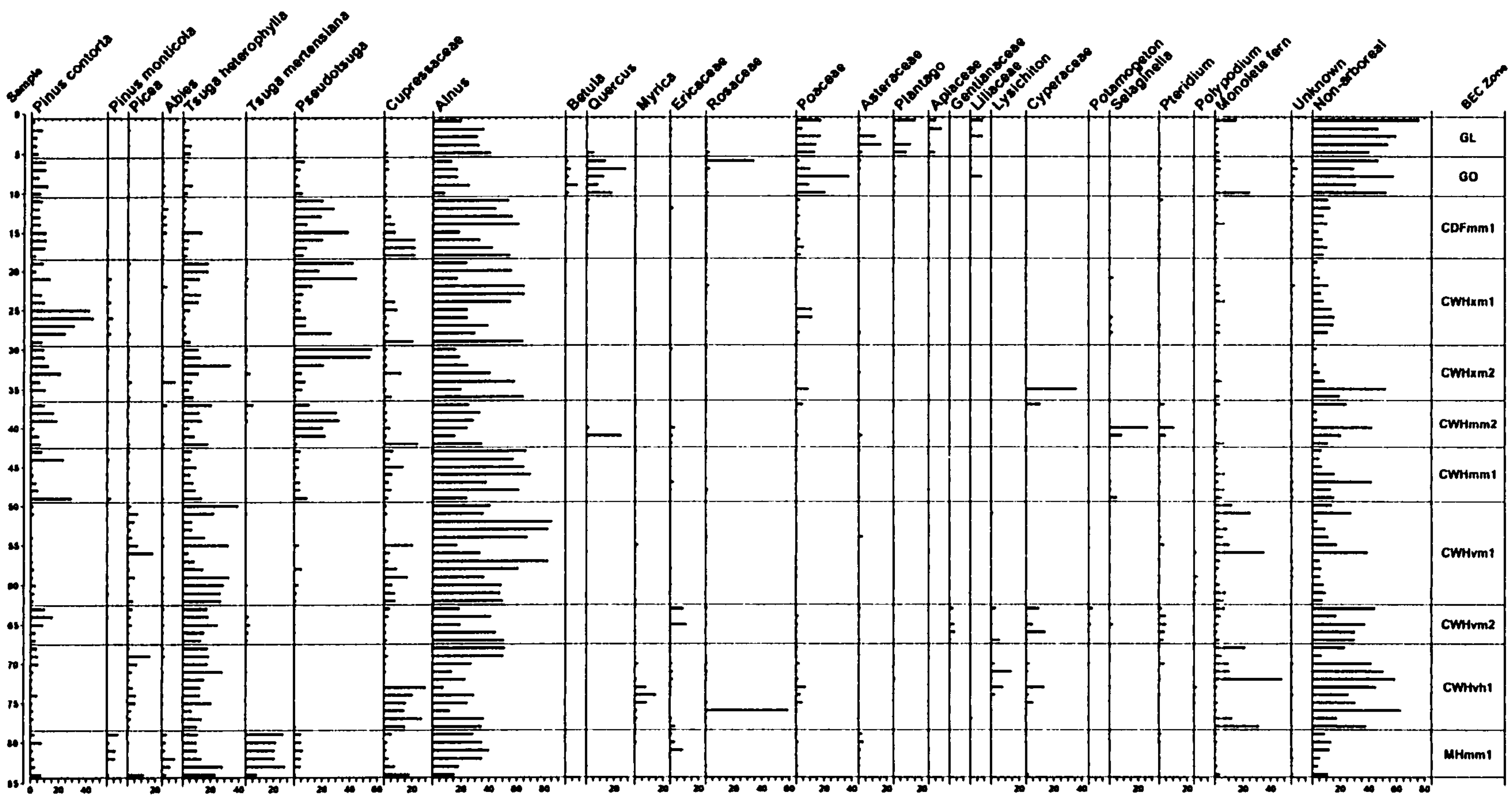
Coastal Douglas Fir (CDF) Biogeoclimatic Zone

The three units (GL, GO, CDFmm) of this zone differ clearly because of differences in dominant species. *Alnus* dominates the arboreal component, although *Pseudotsuga* and *Q. garryana* pollen are diagnostic when these trees dominate the flora. NAP values are high in the grassland (GL) and Garry oak (GO) associations.

Grassland (GL) Association

Grassland spectra are characterised by low arboreal values (30-50%) and a diverse non-arboreal pollen and spore (NAP) assemblage consisting of Poaceae (ca. 5-20%), Asteraceae (ca. 2-15%), *Plantago* (Plantain; ca. 2-15%), Apiaceae (carrot family; ca. 1-10%), and Liliaceae (lily family; ca. 1-10%). The arboreal pollen component is relatively poorly developed with 5% *Q. garryana* and 20-40% *Alnus* pollen characterising the samples. The relatively high *Alnus* pollen percentages likely represent the regional pollen rain because no *Alnus* grows at the sampling sites.

Figure 7. Surface sample percentage pollen and spore diagram.



Garry Oak (GO) Association

The GO association is characterised by high (30-60%) NAP values that consists predominately of Poaceae and monolete spores. *Q. garryana* pollen is well represented and comprises 10-30% of the pollen and spore spectra. Other taxa comprising about 5% of the pollen signature include *T. heterophylla*, *Pseudotsuga*, and *Betula* (birch). No *T. heterophylla* trees occur near the sampling sites, so the *T. heterophylla* must be derived from the regional pollen rain, whereas the *Betula* pollen represents horticultural specimens (Allen et al., 1999). *Alnus* pollen percentages are relatively low, comprising about 7-25% of the pollen spectra.

Coastal Douglas-fir Zone (CDFmm)

The CDFmm is characterised by a well developed arboreal pollen (ca. 80-95%) signal. *Pseudotsuga* (ca. 10-40%) and *Alnus* (ca. 20-60%) pollen dominate this zone. The high *Alnus* values represent the regional pollen rain as well as stands developed as a result of local disturbance. Cupressaceous pollen, likely from *T. plicata*, ranges from ca. 2% in dry sites to ca. 10% in moist sites. *Abies* pollen, likely from *A. grandis*, occurs consistently through the zone at ca. 1-5%. The pollen spectrum is also characterised by *P. contorta* (ca. 5-15%) and *T. heterophylla* (ca. 2-10%). *Q. garryana* (ca. 1-2%) pollen occurs throughout this zone, even though no oak trees were present at the sampling sites. The NAP (ca. 15%) signature consists mainly of Poaceae, *Pteridium*, and monolete fern spores.

Coastal Western Hemlock (CWH) Biogeoclimatic Zone

In general, the CWH is characterised by *T. heterophylla*, *Picea*, and Cupressaceae and *Alnus* pollen. *P. contorta* and *Pseudotsuga* occur in the drier CWH subzones and variants, whereas *Abies* appears more frequently in the wetter subzones and variants. The CWH NAP signal is dominated by monolete spores, although *Myrica gale* (L.) (sweet gale), Ericaceae (heath family), *Lysichiton americanum* Hultén & St. John (Skunk cabbage), and Cyperaceae are locally common in samples from the wetter variants of the zone.

CWHxm1 Variant

This variant is characterised by *T. heterophylla* (ca. 6-20%), *Pseudotsuga* (ca. 10-40%), and *Alnus* (ca. 10-80%) pollen. *P. contorta* pollen occurs in all samples, ranging from ca. 2-45%. Cupressaceous pollen (ca. 2-20%) occurs throughout the variant. *Picea* and *Abies* pollen (both ca. 1%) are uncommon. The NAP averages ca. 10% and consists mainly of monolete fern spores, although Poaceae pollen and *Selaginella wallacei* Hieron. (Wallace's selaginella) spores occur intermittently.

CWHxm2 Variant

The CWHxm2 variant is dominated by *T. heterophylla* (ca. 5-30%), *Alnus* (ca. 15-65%), and *P. contorta* (ca. 2-20%). *Pseudotsuga* pollen is common in the variant, ranging between 2-60%. The incidence of *Picea*, *Abies*, and cupressaceous pollen is comparable to CWHxm1. The NAP signature is poorly developed compared to other units and consists mainly of monolete fern spores.

CWHmm1 Variant

This variant is dominated by *T. heterophylla* (ca. 5-10%) and *Alnus* (ca. 25-70%) pollen. Cupressaceous pollen occurs consistently throughout the unit averaging ca. 7%, whereas *Pseudotsuga* pollen occurs throughout at about 3%. *Picea* pollen is low and occurs intermittently. The amount of *P. contorta* pollen is generally low (ca. 10%). The low NAP consists predominately of monolete fern spores with occasional ericaceous pollen.

CWHmm2 Variant

The CWHmm2 variant is characterised by abundant *T. heterophylla* (ca. 5-20%) and *Pseudotsuga* (ca. 2-35%) pollen in all samples. *Alnus* ranges from ca. 20-40%. *P. contorta* pollen is well represented, ranging from 4-15%. *Picea* and cupressaceous pollen occur throughout the unit, averaging ca. 1 and 3% respectively, whereas *Abies* pollen is uncommon. *Q. garryana* pollen is recorded at 2 sites, both of which have *Q. garryana* trees growing nearby. The NAP ranges from ca. 5-40% and consists mainly of Ericaceae, *Selaginella*, *Pteridium*, and monolete fern spores.

CWHvm1 Variant

The CWHvm1 is dominated by *Alnus* (ca. 20-85%), *T. heterophylla* (ca. 5-40%), and Cupressaceae (ca. 20%) pollen, although the latter is not present in every sample. The percentage of *Picea* (ca. 1-15%) pollen generally increases relative to drier eastern sites, whereas *Pseudotsuga* (ca. 3%) pollen decreases. *P. contorta* and *Abies* pollen are not common in this zone. The NAP (ca. 3-25%) signal is dominated by monolete ferns.

CWHvm2 Variant

Variant CWHvm2 is similar to CWHvm1, containing both *T. heterophylla* (ca. 18%) and *Alnus* (ca. 20-50%) pollen. One noticeable difference, however, is the amount of *Picea* and Cupressaceae pollen has decreased to ca. 0.5-3 and 3% respectively from CWHvm1. *P. contorta* and *T. mertensiana* increase slightly from CWHvm1 to ca. 5-20 and 3% respectively. The NAP signature increases to ca. 15-45% and becomes more diversified, consisting of Ericaceae, Poaceae, Asteraceae, Gentianaceae (gentian family), *Lysichiton*, Cyperaceae, *Potamogeton* (pondweed), *Pteridium*, and monolete fern spores.

CWHvh1 Variant

High percentages of *T. heterophylla* (ca. 15-30%) and *Picea* (ca. 3-15%) pollen and a well-developed NAP (ca. 10-60%) are diagnostic of the CWHvh1 variant. *P. contorta* and *Abies* pollen are rare and *Pseudotsuga* pollen is absent from many samples. Cupressaceous pollen percentages are highly variable in the samples, ranging from ca. 0-30%. The composition of the NAP is similar to CWHvm2, consisting mainly of *Myrica*, Ericaceae, Rosaceae (rose family), Poaceae, *Lysichiton*, Liliaceae, and *Polypodium* and monolete fern spores.

Mountain hemlock (MH) Zone

Several pollen types are diagnostic of the MHmm subzone. *T. mertensiana* and *Abies* pollen are more abundant in this zone compared to all others, ranging between ca. 20-30% and about 5% respectively. *Pinus monticola* pollen (ca. 1-10%) also characterises this zone. *P. contorta*, *Pseudotsuga*, and cupressaceous pollen each comprise about 5% of the total pollen, whereas *Alnus* pollen accounts for ca. 20-40% of the pollen spectrum. The NAP (ca. 5-15%) is moderately developed and consists of Ericaceae (ca. 1-10%), Poaceae (ca. 1%), Asteraceae (ca. 2%), and monolete ferns (ca. 1-5%).

Discussion

The surface pollen and spore spectra from southern Vancouver Island reveal that BEC zones, some subzones, and associations can be distinguished according to their characteristic pollen signature (Figure 7; Allen et al., 1999). The GL association is identifiable based on high NAP values dominated by Poaceae and to a lesser extent Liliaceae. The GO association is distinguishable because of high percentages of *Q. garryana* pollen coupled with a well developed NAP component containing abundant Poaceae. Even though the GO association is dominated by *Q. garryana* trees, the oak pollen values range only between ca. 10-30%. A low percentage of *Q. garryana* pollen in a fossil spectrum likely reflects the growth of the tree near the site. According to Allen et al. (1999), the *Plantago* pollen that characterises the GL association is derived from native, as well as, adventive vegetation and is therefore only of limited use in identifying this association in the fossil record.

A combination of *Pseudotsuga*, *Abies*, and Cupressaceae pollen, coupled with high percentages of *Alnus*, characterise the CDFmm zone. The CWHxm1, CWHxm2, CWHmm1, and CWHmm2 are identifiable based on moderately high levels of *P. contorta*, *T. heterophylla*, *Pseudotsuga*, combined with low Cupressaceae pollen percentages. Wetter variants (CWHvm1 and CWHvm2) are characterised by low percentages of *P. contorta* pollen, moderate levels of *Picea* and cupressaceous pollen, and high levels of *T. heterophylla* pollen. The wettest CWH variant, the CWHvh1, is similar to the CWHvm1 and CWHvm2 variants except that the NAP is well developed and diverse. The MH zone is identifiable using *T. mertensiana*, *Abies*, and *P. monticola* pollen.

Surface sample analysis also suggests that certain pollen and spores may be indicative of the openness of a forest canopy. The low NAP values that characterise the CDFmm, CWHxm1, CWHxm2, CWHmm1, CWHmm2, and CWHvm1 subzones and variants reflect the low light levels in the forest understory (Allen et al., 1999), indicating closed canopies compared to the GO association. The low levels of *P. contorta* pollen in the CWHvm1 variant also suggests the canopy is closed in these forests, likely because disturbance is infrequent. Allen et al. (1999) indicate that *Selaginella* grows in moss-lichen mats on open rocky knolls, suggesting that *Selaginella* spores may be a useful indictor of canopy openness. The dry CWH forests have a characteristic *Selaginella* spore signal that is not present in the wetter CWH forests. The presence of *Selaginella* spores in the early Holocene at Pixie and Whyac lakes and on the Brooks Peninsula (Hebda, 1997) suggests open rocky knolls persisted at this time. In contrast, the occurrence of *Selaginella* spores at East Sooke Fen throughout the Holocene suggests open areas have persisted in this region. The high levels of NAP in the CWHvm2 and CWHvh1 reflects the presence of wetlands in these regions.

Perhaps the most important aspect emerging from the surface sample analysis is the relationship between pollen and spore percentages and the corresponding vegetation cover percentage. Traditionally, several pollen types have been used as "indicator species" to describe and interpret fossil pollen assemblages in terms of paleovegetation and paleoclimate (Moore et al., 1991; Mathewes, 1973; 1985; Hebda, 1983; 1995; Hebda and Brown, 1999; Allen, 1995; Pellatt, 1996). However, could these interpretations be misleading because of differential rates of pollen production? For example, a tree that produces copious amounts of pollen might be well represented in the pollen spectrum even if only a few individuals were present at the site and inversely a tree that is common at a site but that does not produce much pollen might be poorly represented in the pollen spectrum.

Examination of the surface sample data (excluding samples from Allen, 1995), presented in scatter diagrams (Figure 8), reveals over- and underrepresentation trends where overrepresented pollen types cluster close to or along the y-axis (percent pollen) and underrepresented types scatter more closely to the x-axis (percent taxon cover). These data suggest that *Pinus* pollen is typically overrepresented by about 10% in the pollen spectra, an estimate that likely represents the regional pollen rain. However, it is possible that *Pinus* pollen can constitute upwards of about 45% of the total pollen and spores even when the tree is absent (Figure 8). When *Pinus* trees account for ca. 5% or greater of the vegetation cover, *Pinus* pollen will contribute 30-40% of the total pollen. Hebda and Allen (1993) record a similar trend and suggest that *Pinus* pollen percentage

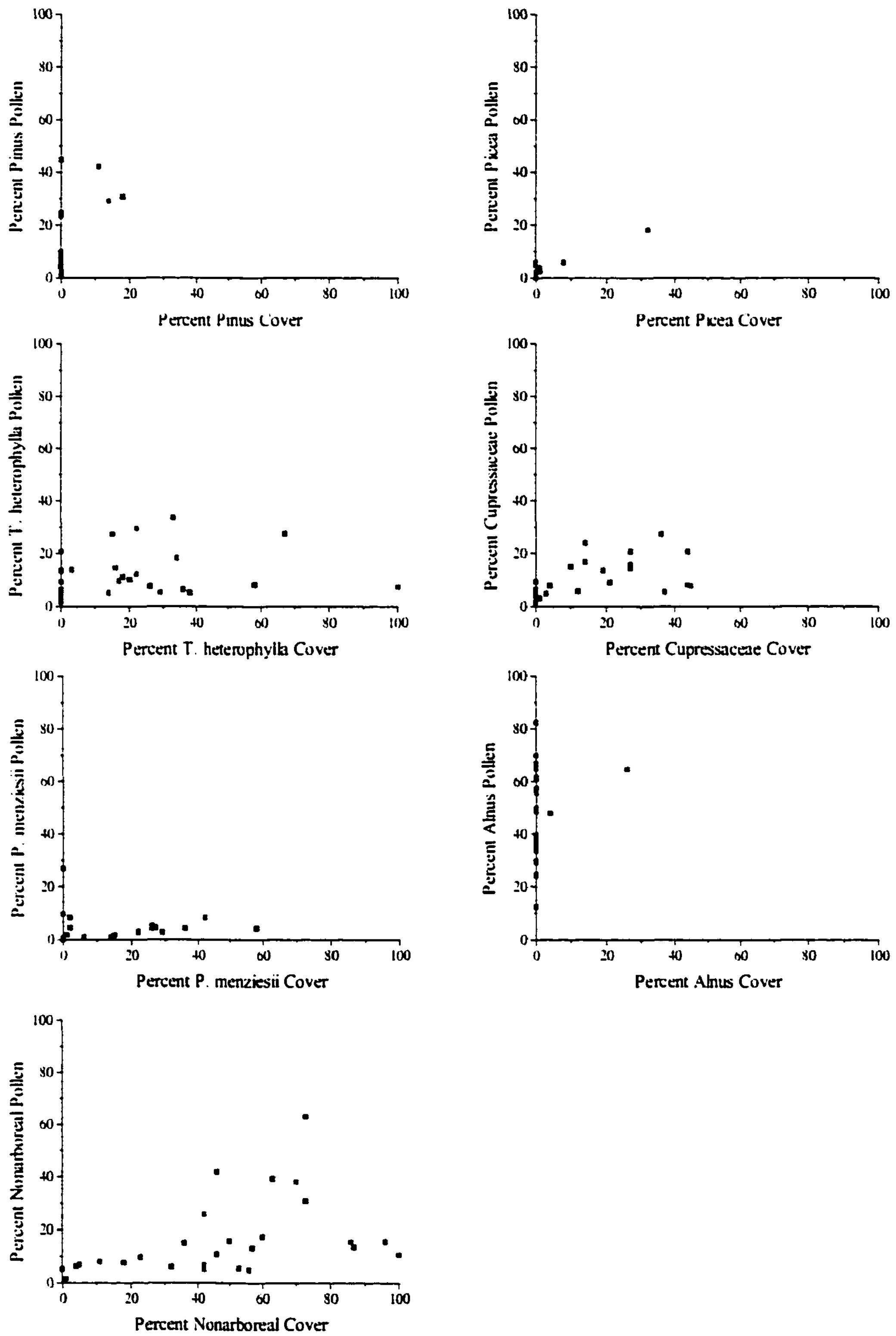


Figure 8. Relationship between percentage cover and percentage pollen and spores for selected taxa.

values depend not only on the productivity of the tree but also on the productivity of other species. Dunwiddie (1987) also demonstrated that *Pinus* pollen is overrepresented. In summarising, *Pinus* pollen percentage values between 0-10% indicate *Pinus* trees are probably not present, ca. 10-30% suggest *Pinus* is growing nearby, and values 30% or greater suggest *Pinus* is growing locally. Hebda and Allen (1993) show that the surface pollen spectra from pine forests contains ca. 80-90% *Pinus* pollen. These data suggest the *P. contorta* pollen zone that is characteristic of many cores in British Columbia (Hebda, 1995) and which often has >60% *Pinus* pollen (Mathewes, 1973; 1985; Hebda, 1983; 1995; Heusser, 1983; Allen, 1995; Pellatt, 1996), may have been an open woodland or a pine forest.

Picea pollen can be ca. 1-8% of the total even when the tree is absent, suggesting a very modest regional pollen rain. In general, the percentage of *Picea* pollen is about one-half the value suggested by the percentage of *Picea* cover, indicating that *Picea* pollen is slightly underrepresented and that low percentages of *Picea* pollen actually indicate the presence of *Picea* trees. More data is required to confirm this interpretation. Hebda and Allen (1993) found a similar trend with a regional base of 1-4% pollen. Dunwiddie (1987) and Hebda and Allen (1993) found *Abies* to be similarly underrepresented. Like *Picea*, *T. heterophylla*, Cupressaceae and *Pseudotsuga* pollen are generally underrepresented. *T. heterophylla* pollen appears to have an extra local or regional pollen signal ranging between ca. 2-22%. Between values of ca. 20-40% cover, *T. heterophylla* pollen percentage and coverage are in good agreement. However, after ca. 40%, *T. heterophylla* pollen is underrepresented. Hebda and Allen (1993) show a similar scatter of *T. heterophylla* percentage points and suggest that more sampling sites are required to define the correlation, whereas Dunwiddie (1987) suggests *T. heterophylla* is overrepresented. These inconsistencies may reflect sampling size and location, but suggest more work is required to better understand the relationship of *T. heterophylla* pollen in the present day pollen rain. The phenomenon of the relationship between *T. heterophylla* cover and percentage pollen may be non-linear.

The extra-local or regional Cupressaceae pollen signal ranges between ca. 0-10% even when the tree is absent. The percentage of Cupressaceae pollen appears to be about one-half the percentage of Cupressaceae cover and although slightly underrepresented, Cupressaceae pollen appears to increase with increased coverage. Dunwiddie (1987) and Hebda and Allen (1993) identified a similar trend.

Underrepresentation is well demonstrated by *Pseudotsuga*. In general, *Pseudotsuga* pollen comprises ca. 0-10% of the total pollen regardless of coverage values. Hebda and Allen (1993) suggest *Pseudotsuga* is neither over- nor underrepresented and results from Dunwiddie (1987) are inconclusive because too few sampling points were used, although the trend appears to suggest underrepresentation. These observations suggest that the early Holocene interval, which frequently contains an abundance of *Pseudotsuga* pollen (Mathewes, 1973; 1985; Hebda, 1983; 1995; Heusser, 1983; Allen, 1995), was likely comprised of extensive *Pseudotsuga* dominated forests.

Alnus pollen is overrepresented in the pollen spectrum and can comprise ca. 12-82% of the pollen even when the tree and is not locally present, suggesting that the regional *Alnus* pollen signal is considerable. As a result, *Alnus* pollen is not diagnostic of any BEC unit. In fact, the high levels of *Alnus* pollen recorded in all surface samples, especially those in open landscapes such as the GL and GO associations, likely represents the regional pollen rain signal as opposed to the presence of the trees themselves (Allen et al., 1999). Heusser (1983; 1985) has suggested that the high levels of *Alnus* pollen in the early Holocene indicate that *Alnus* trees may have been a major forest element. The surface sample analyses, however, suggest *Alnus* trees were likely a minor forest element that produced copious amounts of pollen, relatively reducing the signal from other taxa.

Low percentages of NAP should be expected when nonarboreal species comprise less than ca. 40% of the total species cover. Surface pollen percentages, although still underrepresented, appear to better reflect the vegetation between 40-80% coverage. After 80%, the NAP percentages appear to decline to low levels, suggesting that the nonarboreal component is significantly underrepresented when it covers much of the ground. These data suggest that the early and late Holocene increase in NAP may reflect well developed understories with high trees or perhaps significant openings in the forest canopy such as meadows or wetlands. The difficulty associated with a NAP scatter plot showing over- and underrepresentation is that the NAP includes a mixture of species with different pollen productivity and relative representation.

CHAPTER 6: EAST SOOKE FEN

Study Site

The southeastern-most study site is a small fen (1,250 m^2) located in East Sooke Regional Park at 48°21'07" N and 123°40'54" W at approximately 155 m asl. (Figure 1). Dominant vegetation surrounding ESF consists of *Pseudotsuga*, *T. heterophylla*, *T. plicata*, *P. contorta*, and *A. rubra*. Non-arboreal species include *Gaultheria shallon* Pursh (salal) and *Salix*. Fen vegetation consists of *Spiraea douglasii* Hook. (hardhack), Poaceae, and Cyperaceae. ESF is located in the Nanaimo Lowland and is underlain by basaltic rocks from the early-middle Tertiary (Yorath and Nasmith, 1995).

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

Four ^{14}C dates were obtained for the ESF core and the presence of Mazama ash provided an additional date of approximately 6,800 ^{14}C years before present (ybp) (Figure 9; Table 2; Bacon, 1983). The 855 cm long ESF core begins in fine grey sand between 855-851 cm depth which was deposited before 11,700 ybp. Olive grey gyttja containing abundant sand and pebbles is present between 851-801 cm and was deposited until ca. 11,200 ybp. A medium-coarse grained sand and pebble unit is present at 800 cm. Olive grey gyttja with conifer needles occurs between 800-650 cm depth. Deposition of this unit ended just before 10,300 ybp. Between 794-793 cm tephra like material occurs as a thin and discontinuous layer. Fibrous olive brown limnic peat containing abundant sedge fragments is present between 650-450 cm and was deposited between ca. 10,300-9,000 ybp. Reddish brown fibrous sedge peat occurs between 450-0 cm depth, an interval representing 9,000 ybp-present. At 267-265 cm there is a thin beige

Figure 9. East Sooke Fen percentage pollen and spore diagram (outline x10).

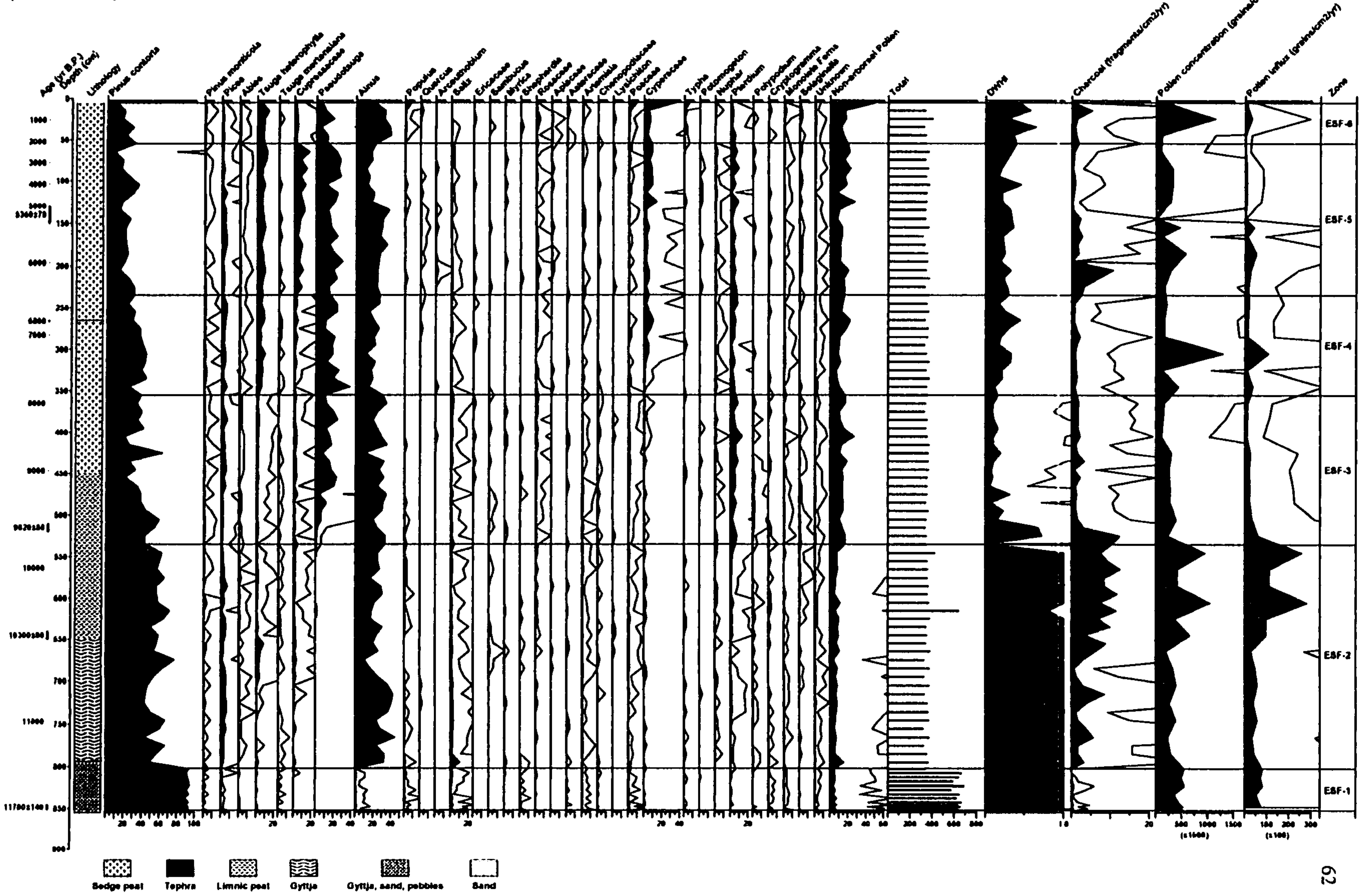


Table 2. Bulk ^{14}C sediment and tephra dates from East Sooke Fen.

Sample Number	**Sediment Type**	**Sample Depth (cm)**	**Conventional ^{14}C Date (ybp)**
Beta-86808	Sedge peat	130-150	5,360±70
	Tephra	265-267	6,800
Beta-85181	Limnic peat	510-520	9,820±80
Beta-85182	Limnic peat	640-650	10,300±80
Beta-86809	Gyttja	845-851	11,700±140

tephra that because of its stratigraphic position relative to a 5,360±70 ^{14}C date at 570-580 cm is likely Mazama ash (Bacon, 1983). Wood fragments occur at 248-245 cm.

According to the radiocarbon chronology, most of the ESF record spans the late glacial and early Holocene. Sedimentation rates at ESF are variable throughout the core (Table 3). The basal portion of the ESF core consists of fine sands that have an unknown sediment accumulation rate because no ^{14}C control exists. Between 11,700-10,300 ybp sedimentation rates are high (0.145 cm/yr) and reflect a relatively unstable, easily erodable late Pleistocene landscape. At 11,200 ybp the change in sediment from gyttja-sand to gyttja reflects a transition to increased forest cover. The sediment change at 10,300 ybp from gyttja to limnic peat coincides with an increase in the sedimentation rate (0.271 cm/yr) and is possibly related to production of more autochthonous material in a warmer climate with increased lake productivity and lower lake levels. The transition from limnic peat to sedge peat at 9,000 ybp signals local fen development associated with hydrosere succession and basin infilling. The sedge peat originally accumulated at rates of 0.082 and 0.088 cm/yr. Within the last 5,360±70 years, however, sediment has accumulated at a slower rate of 0.026 cm/yr and may reflect increased aeration and decomposition associated with fen development and accumulation of organic matter above the water table.

Table 3. Characteristics of the East Sooke Fen sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-140	5,360	0.026	Sedge Peat
140-266	1,440	0.088	Sedge Peat
266-515	3,020	0.082	Sedge Peat
515-645	480	0.271	Sedge Peat/Limnic Peat
645-848	1,400	0.145	Gyttja

Pollen Zones

Six pollen zones were identified in the ESF sediment core (ESF-1 to ESF-6; Figure 9).

ESF-1: Pine Zone
(852-802 cm; >11,700-11,400 ybp)

In Zone ESF-1 *P. contorta* dominates, accounting for ca. 92% of the pollen and spore assemblage. *Alnus* and *Populus* values range from 0-2%. Other conifers such as *Pinus monticola*, *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* are rare (<0.5%). *Salix* (ca. 1-3%) and *Shepherdia* (ca. 0.5-1%) occur throughout the zone. The presence of NAP (ca. 1%) plants such as Poaceae and *Artemisia* suggest some open areas existed. Pollen concentration values for the zone are about ca. 478,000 grains/cm^3, whereas pollen influx values are ca. 60,000 grains/cm^2/yr. Charcoal concentrations range from 0-4 fragments/cm^3, whereas charcoal influx ranges from 0-0.6 fragments/cm^2/yr.

ESF-2: Pine-Spruce-Fir-Hemlock Zone
(802-535 cm; 11,400-9,900 ybp)

P. contorta and *Alnus* dominate this zone averaging ca. 56% and 27% respectively. Other conifers such as *P. monticola*, *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* attain average values of ca. 0.5, 4, 1, 1.5 and 0.5% respectively. Cupressaceae pollen occurs in the upper part of the zone at ca. 1.5%. *Salix* averages ca. 2%, although one sample contained ca. 10% *Salix* pollen. The non-arboreal component averages ca. 8% and consists mainly of Poaceae, *Artemisia*, Rosaceae, *Pteridium*, *Polypodium* (licorice fern), *Cryptogramma crispa* (L.) R. Br. ex Hook. var.

acrostichoides (Parsley fern), and unidentified monolete fern spores. The relative abundance of Poaceae and *Artemisia* increases throughout the zone. *Selaginella*, an indicator of open areas, occurs near the top of the zone.

Pollen concentrations attain maximum values of ca. 1,039,000 grains/cm^3 near the top of the zone but only averages 449,000 grains/cm^3. Pollen influx averages 102,000 grains/cm^2/yr. The lower part of the zone records four charcoal peaks that increase in amplitude from the early to late part of the zone and contain a maximum of 60 charcoal fragments/cm^3 or 8.8 fragments/cm^2/yr. The intervals between the charcoal peaks contain ca. 8 charcoal fragments/cm^3 or 1.2 fragments/cm^2/yr. In contrast, the upper part of the zone is characterised by the continuous deposition of charcoal, averaging 34 charcoal fragments/cm^3 or 8.8 fragments/cm^2/yr.

ESF-3: Douglas-fir-Alder-Bracken Zone
(535-355 cm; 9,900-7,900 ybp)

Pseudotsuga appears for the first time at the bottom of this zone and averages ca. 12%. *P. contorta* pollen values decrease to an average of ca. 38%. *Alnus* values average ca. 27% and are relatively consistent, although a low value of ca. 10% occurs at 425 cm depth. Other notable conifers include *Picea* (ca. 3%), *T. heterophylla* (ca. 1.5%), and Cupressaceae (ca. 2%). *Salix* persists from the preceding zone. The NAP component averages ca. 14% and is mainly characterised by Rosaceae (ca. 1.5%), Poaceae (ca. 1.5%), *Selaginella* (ca. 0.5%) and *Pteridium* (ca. 6%).

Pollen concentration decreases from a high of ca. 386,000 grain/cm^3 near the bottom of the zone to a low of 101,000 grains/cm^3 near the top. The average pollen concentration is 230,000 grains/cm^3. The yearly pollen influx average is 23,000 grains/cm^2/yr. Charcoal concentration throughout the zone is low (ca. 21 charcoal fragments/cm^3) but continuous. Charcoal influx averages 2.2 fragments/cm^2/yr. DWHI values are the lowest in the core, averaging 0.19.

ESF-4: Douglas-fir-Western hemlock Zone
(355-235 cm; 7,900-6,400 ybp)

The most notable feature of this zone is the increase in *T. heterophylla* pollen (average ca. 6%) compared to ESF-3. *Pseudotsuga* ranges from ca. 9-38% and averages ca. 19%. *P. contorta* values generally decline from ESF-3, ranging between 23-44%. The *Alnus* average decreases to ca. 20%. Other notable conifer species present throughout the zone include *Picea* (ca. 3%), *Abies* (ca. 1%), and Cupressaceae (ca. 2%). The NAP percentage increases from the preceding zone to ca. 13% mainly because of an increase in Cyperaceae from ca. <1% at the bottom to ca. 10% near the top. *Nuphar polysepalum* Engelm. (yellow pond-lily) occurs at ca. <1%. *Pteridium* values vary between 1-8%.

Pollen concentration averages 391,000 grains/cm^3 although an anomalous value of 1,288,000 grains/cm^3 occurs at 305 cm depth. Pollen influx increases from the preceding zone to an average of ca. 32,000 grains/cm^2/yr. Charcoal concentration remains low (ca. 14 charcoal fragments/cm^3) and continuous with no singular peaks. Charcoal influx averages 1.2 fragments/cm^2/yr. DWHI increases from a low of 0.11 near the bottom to a high of 0.44 near the top.

ESF-5: Douglas-fir-Western hemlock-Cedar Zone
(235-55 cm; 6,400-2,100 ybp)

Pseudotsuga is abundant throughout the zone averaging ca. 19%. *T. heterophylla* pollen values average ca. 7% with values near the top of the zone slightly greater than those near the bottom. Cupressaceae pollen appears for the first time in significant quantities, attaining an average value of ca. 8% and ranging between 2-14%. *P. contorta* values decrease from the previous zone to an average of 22%. *Alnus* is more abundant in the bottom of the zone (ca. 28%) than at the top (ca. 17%) with an average of 23%. *Picea* and *Abies* are present in all intervals at ca. 3% and 1% respectively. *Q. garryana* occurs in the lower portion of the zone, attaining a maximum of ca. 1%. The NAP value increases to ca. 15% from zone ESF-4. Cyperaceae values range from 3% in the lower part of the zone to 8% in the upper portion. *Nuphar*, *Pteridium*, and monolete fern values remain unchanged from the previous zone.

The total pollen concentration averages ca. 285,000 grains/cm^3, whereas the yearly influx is ca. 18,000 grains/cm^2/yr. Charcoal concentrations increase to an average of 33 fragments/cm^3, whereas charcoal influx increases 2.1 fragments/cm^2/yr. A single charcoal peak containing 121 fragments/cm^3 or 10.7 fragments/cm^2/yr is evident at 201 cm. DWHI averages of 0.27.

ESF-6: Douglas-fir-Western hemlock-Non Arboreal Zone
(55-0 cm; 2,100-0 ybp)

Pseudotsuga percentages vary from a low of ca. 4% to a high of ca. 19% (average ca. 10%). *T. heterophylla* values are relatively constant throughout the zone averaging ca. 8%. Cupressaceae pollen values decrease from the preceding zone to an average of ca. 2%. *P. contorta* values average ca. 20%. *Alnus* shows an increase in abundance compared to ESF-5 to ca. 30%. *Picea*, *Abies*, and *Populus* represent ca. 1, <1, and 2% of the pollen total. The NAP component averages ca. 22% and consists of by Rosaceae (ca. 2%), Apiaceae (<1%), and Poaceae (ca. 2%). Cyperaceae pollen values range from a low of 4% to a high of ca. 36% and averages ca. 11%. *Nuphar* is rare throughout the zone, whereas *Typha* (cattail) is present at all levels, averaging ca. 1%. *Pteridium* (ca. 3%) and monolete ferns (<1%) are recorded at all depths.

Pollen concentration averages ca. 473,000 grains/cm^3 and the yearly influx averages ca. 12,000 grains/cm^2/yr. Charcoal concentrations range between 2-198 fragments/cm^3 and charcoal influx ranges between 0.1-5.2 fragments/cm^2/yr. The average charcoal concentration (64 fragments/cm^3) is greater than in the preceding zone, whereas the average charcoal influx (1.7 fragments/cm^2/yr) is less. DWHI increases to an average of 0.45.

Interpretation

The vegetation changes recorded at ESF paralles that from other sites in southern Vancouver Island (Allen 1995; Hebda, 1995). The overwhelming dominance by *P. contorta* pollen in ESF-1 suggests *P. contorta* woodlands initially characterised the post-glacial landscape. The initial success of *P. contorta* may reflect the infertile nature of post-glacial mineral soils (Lotan and Critchfield, 1990). It seems likely *P. contorta* colonised an unstable landscape poor in organic nitrogen. The occurrence of *Alnus* and *Shepherdia*, both nitrogen fixing plants, supports the interpretation of an initially unstable landscape (Mathewes, 1973) that was poor in organic nitrogen but rich in other nutrients such as calcium, sodium, and potassium. *Populus* and *Alnus* presumably occupied glaciofluvial outwash plains, floodplains, and/or disturbed sites. *Salix* likely grew in moist open sites around the basin. In this way, late-glacial landscape evolution appears to follow a relay-floristics style of development (Barbour et al., 1987), with *P. contorta* attaining an edaphic climax status. The relatively low concentration of NAP possibly reflects mostly closed forests with scattered canopy openings. The dearth of charcoal suggests fire was rare or absent.

Presently, *P. contorta* is an ubiquitous species that occurs in a variety of climatic conditions (Lotan and Critchfield, 1990), mandating care with respect to climatic interpretation of zone ESF-1. However, the presence of some *T. mertensiana* (Figure 9) pollen suggests climate was cool-cold. The scarcity of moisture requiring taxa such as *Picea* may reflect dry conditions (Adam and West, 1983; Hebda, 1983).

Relatively high *P. contorta* pollen percentages in ESF-2 suggest *P. contorta* remained an important component of the forests during this interval. However, Hebda and Allen (1993) and Allen et al. (1999) show *P. contorta* is overrepresented in the pollen spectra which implies *P. contorta* may not have been as dominant as the pollen record suggests. The pollen data shows *P. contorta*, *Picea*, *Abies*, and *T. mertensiana* mixed conifer forests replaced the late glacial *P. contorta* stands. The *Abies* pollen may represent either *A. amabilis* or *A. lasiocarpa*, both species are found on Vancouver Island at the present time. *T. heterophylla* and Cupressaceae, possibly *T. plicata*, *C. nootkatensis*, or *Juniperus* (juniper), increase during the latter part of interval. An increase in shade-intolerant *Alnus* throughout the zone is related to fire disturbance and the ability of *Alnus* to quickly colonise disturbed sites.

Initially, NAP values are relatively low suggesting the forest structure was closed. However, the NAP component increases somewhat throughout the zone suggesting some canopy openings late in the zone. *Salix* likely occupied open moist sites around the basin and along streambanks. By the end of this interval, a mosaic of forests may have existed, ranging from recently disturbed (burnt) areas dominated by *Alnus* and *Pinus* to old growth stands characterised by shade-tolerant *Picea*, *T. heterophylla*, and *T. mertensiana*.

Climate is interpreted as cool and moist. The initial presence of *Picea* suggests climate was moist, whereas *T. mertensiana* and (possibly) *A. lasiocarpa* suggest a cool and moist climate characterised by heavy winter snowfall (Alaback et al., 1994). *T. mertensiana* typically occupies maritime areas characterised by cold winters and short, warm-cool growing seasons and abundant precipitation (Means, 1990). Present-day distribution of *A. lasiocarpa*, relative to other species, partially depends on climatic variables such as cool summers, cold winters, and deep winter snowpacks (Alexander et al., 1990). The appearance of *T. heterophylla* later in zone ESF-2 suggests that the climate possibly warmed but remained moist, whereas a change in sediment from gyttja to peat at about 10,300 ybp implies lowered water levels, possibly because evaporation rates increased at this time associated with increased temperatures.

In ESF-3 forest structure and composition deviate considerably from ESF-2. ESF-3 is characterised by open areas, dominated by early seral shade-intolerant taxa such as *Alnus* and *Pteridium*, and frequently disturbed by low intensity fire. Fire-resistant *Pseudotsuga* appears for the first time and attains a climax status. *P. contorta* and *Alnus* occupy recently burned areas. Other conifers such as *Picea*, *T. heterophylla*, and

Cupressaceae occupied moist sites or formed climax stands in areas not subject to repeated fire. *Polypodium* probably occurred on moist, mossy surfaces on these trees or on rocks. *Salix* occupied moist, open areas. A substantial increase in shade-intolerant NAP types such as Rosaceae, Poaceae, and *Pteridium* indicate gaps in forest canopy were present.

The low but continuous accumulation of charcoal suggests low intensity fires were common. The low charcoal influx may also reflect a more open ecosystem and less available biomass for consumption or differences in charcoal transport mechanisms. This data is supported by the increase in *Pteridium* which may reflect frequent, low intensity burning (Tolhurst, 1990), possibly by First Peoples.

The appearance of *Pseudotsuga* coupled with presence of *T. heterophylla* in ESF-3 enables the examination of paleoprecipitation using DWHI ratios. Average DWHI values for the zone indicate dry conditions (Allen et al., 1999). The increase in *Pseudotsuga* suggests climate was warm and dry. A reduction in *T. mertensiana* suggests warming and possibly drying. A sediment change to sedge peat suggests lowered water levels and hydrosere succession, possibly in response to warming and drying.

The increase in *T. heterophylla* pollen during ESF-4 suggests that this taxon began to grow near the site. Thus the forests consisted of shade-intolerant *Pseudotsuga* and shade-tolerant *T. heterophylla* and *Picea* with minor *Abies* and Cupressaceae. The continuous nature of charcoal deposition implies frequent low intensity fires. However, the decline in early seral species such as *P. contorta* and *Alnus* coupled with a decrease in charcoal influx suggests fires were not as important a disturbance agent as in the previous zone. The occurrence of these palynomorphs is likely derived from the regional pollen signal (Allen et al., 1999). The increase in Cyperaceae is associated with fen development by hydrosere succession. An increase in *Nuphar* suggests a possible rise in water levels.

An increase in *T. heterophylla* suggests ESF-4 is moister than ESF-3. Fen development also suggests that the climate was moist. The occurrence of *Nuphar* throughout ESF-4 suggests relatively high water levels, possibly because of an increase in precipitation and a decrease in temperature.

Modern forests are established in ESF-5. *T. heterophylla* and Cupressaceae with *Pseudotsuga* are major forest elements. Minor forest constituents include *Picea*, *Abies*, *P. contorta*, and *Alnus*. *Q. garryana* appears in zone ESF-5 at ca. 6,400 ybp, attains a maximum abundance at approximately 5,500 ybp, and declines thereafter. The *Q. garryana* maximum corresponded to an increase in *Alnus* and may be related to fire activity. Relatively high Poaceae values suggest openings are common, whereas high percentages of Cyperaceae attest to further fen development, possibly by paludification. Increased charcoal influx suggests a low intensity fire disturbance persisted. A single, possibly stand-destroying, fire event occurred at approximately 6,200 ybp.

An increase in *T. heterophylla* and Cupressaceae coupled with an increase in DWHI suggests climate moistened in ESF-5. Climate is interpreted as moist and possibly cooler relative to the ESF-3 and ESF-4.

CWHxm biogeoclimatic zone forests become established in zone ESF-6. Principal forest components include *T. heterophylla* and *Pseudotsuga* with minor *P. contorta*. *Picea*, and *Abies*. The decrease in Cupressaceae during the last 2,000 years is difficult to explain but may be related to First Peoples application of fire to remove forests and increase availability of fruiting shrubs and herbaceous "edible root" plants (Turner, 1999). The increase in *Alnus* pollen values may also be associated with human landscape modification. Increases in Poaceae, Cyperaceae, and *Typha* indicate continued fen development at the site. The observed increase in charcoal in the topmost sediments likely represents increased burning associated with aboriginal landscape management and/or European settlement.

The relatively high DWHI index in ESF-6 suggests moist conditions prevailed. A decrease in *Pseudotsuga* suggests wetter and possibly cooler conditions. Modern mild and wet climate is established.

CHAPTER 7: PIXIE LAKE

Study Site

Pixie Lake is located in the CWHvm subzone east of Port Renfrew and north of the San Juan River at 48°35'47" N and 124°11'48" W (Figure 1). Pixie Lake is approximately 350 m long and 150 m wide and is approximately 70 m asl. The vegetation surrounding Pixie Lake consists of *T. heterophylla*, *T. plicata*, and *A. amabilis*. *G. shallon* and *Vaccinium* spp. (i.e. blueberries and huckleberries) characterise the shrub stratum. Pixie Lake is located adjacent to the San Juan River floodplain at the western edge of the South Vancouver Island Ranges, which in this area, consists of mountains characterised by early to middle Jurassic granitic and gneissic plutons. These mountains attain maximum elevations of approximately 1,000-1,100 m asl (Yorath and Nasmith, 1995).

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The Pixie Lake core is 885 cm long and ^{14}C dates of bulk sediment agree chronostratigraphically with Mazama ash (Figure 10; Table 4). Grey clay is present from 885-870 cm depth and was deposited until ca. 12,990 ± 110 ybp. Olive brown gyttja comprises most of the remaining core from 870-539 and 538-0 cm. A beige tephra horizon occurs between 538-539 cm and is bracketed by ^{14}C dates of 8,330 ± 100 at 600-610 cm and 5,450 ± 70 at 430-440 cm. The ash is interpreted to be from the eruption of Mt. Mazama at 6,800 ybp (Bacon, 1983).

Sedimentation rates vary throughout the core (Table 5) with the section at the clay/gyttja transition accumulating at 0.012 cm/yr. The rate increases following the

Figure 10. Pixie Lake percentage pollen and spore diagram (outline x10).

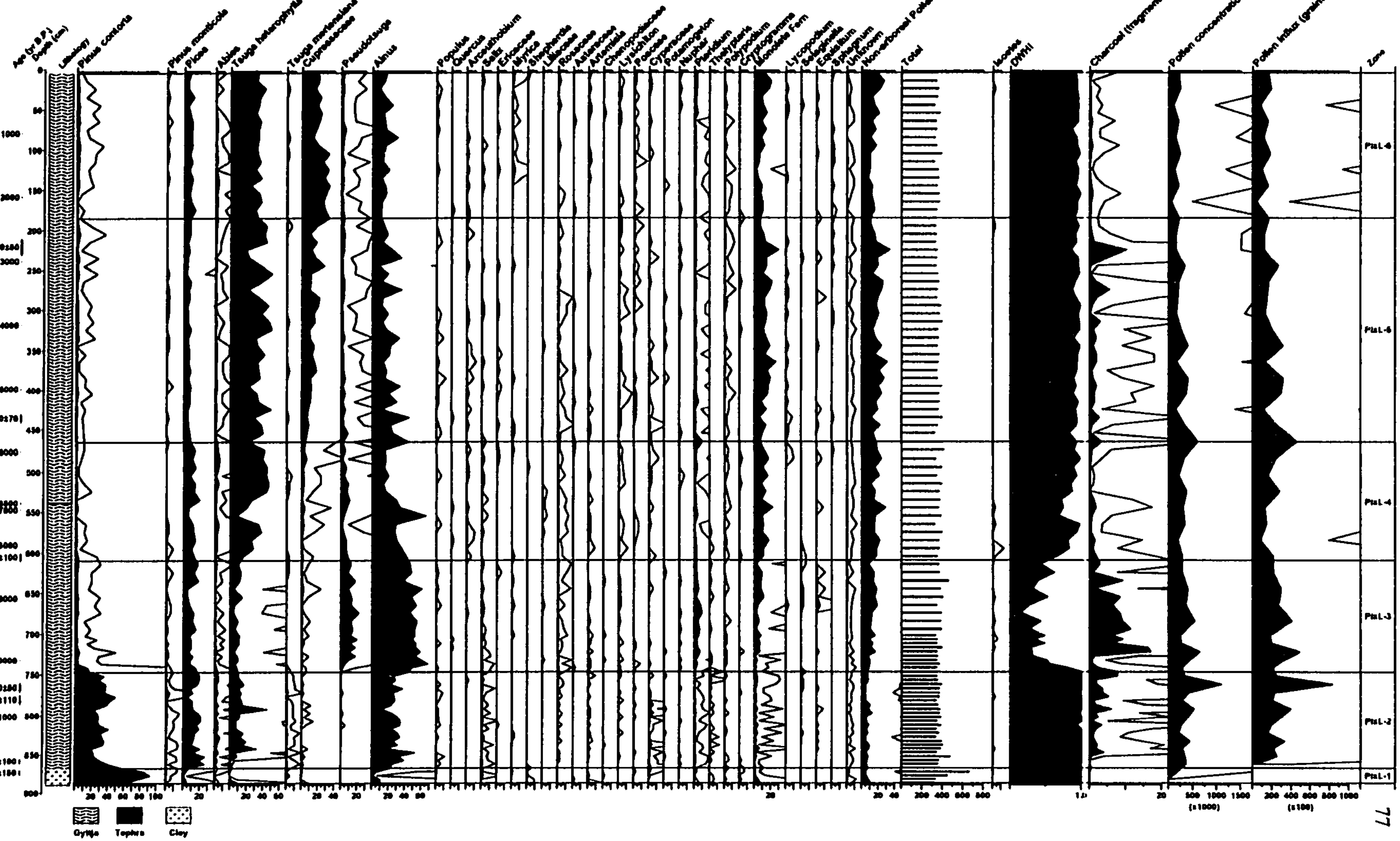


Table 4. Bulk ^{14}C sediment and tephra dates from Pixie Lake.

Sample Number	Sediment Type	Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-86805	Gyttja	210-230	2,770±80
Beta-85176	Gyttja	430-440	5,450±70
	Tephra	538-539	6,800
Beta-85177	Gyttja	600-610	8,330±100
Beta-86806	Gyttja	760-770	10,440±80
Beta-86807	Gyttja	775-785	10,720±110
Beta-81085	Gyttja	855-860	11,750±100
Beta-81084	Organics in clay	870-875	12,990±180

Table 5. Characteristics of the Pixie Lake sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-220	2,770	0.079	Gyttja
220-435	2,680	0.080	Gyttja
435-538.5	1,350	0.076	Gyttja
538.5-605	1,530	0.043	Gyttja
605-765	2,110	0.076	Gyttja
765-780	280	0.054	Gyttja
780-857.5	1,030	0.075	Gyttja
857.5-872.5	1,240	0.012	Gyttja/Clay

change from clay to gyttja at 870 cm, ranging from 0.043 cm/yr to 0.080 cm/yr in the remainder of the core.

Pollen Zones

Six pollen zones are recognised in the Pixie Lake core (PixL-1 to PixL-6; Figure 10).

PixL-1: Pine Zone
(887.5-867.5 cm; >12,990-12,600 ybp)

P. contorta dominates PixL-1 with percentages attaining a maximum of ca. 92% and averaging ca. 75%. *Alnus* values fluctuate between <1% and ca. 22%, averaging ca. 10%. Other notable arboreal pollen types include *Picea* (ca. 3%), *Abies* (ca. 1%), and *T. heterophylla* (ca. 2%). *T. mertensiana* occurs rarely near the top of the zone. *Salix* is present in the upper portion of the zone and averages <1%. The NAP component ranges from a high of ca. 11% in the lower part of the zone to ca. 4% near the top of the zone. *Shepherdia* (ca 1%) and *Artemisia* (ca. 2%) pollen and fern spores (ca. 6%) constitute NAP in the lower part of the zone, whereas Cyperaceae (ca. 2%), *Polypodium* (ca. 0.3%), and *Cryptogramma* (ca. 0.4%) are present in the upper part. Pollen and spore concentration is low, averaging ca. 2000 grains/cm^3. Charcoal occurs only at the PixL-1/PixL-2 zone boundary where 5 fragments/cm^3 were counted.

PixL-2: Pine-Spruce-Fir-Hemlock Zone
(867.5-747.5 cm; 12,600-10,200 ybp)

P. contorta decreases from the preceding zone to an average of ca. 31%. *Picea* increases to an average of ca. 15%, whereas *Abies* increases to ca. 3%. *T. heterophylla* values are variable throughout the zone and range between a low of <1% and a high of ca. 44%, averaging 12%. *T. mertensiana* occurs at an average of ca. 1%. *Alnus* increases to an average of ca. 29% and ranges between ca. 11% and 52%. *Salix* is present throughout the zone at ca. 0.7%. The NAP signature averages ca. 6% and consists mainly of Rosaceae (ca. 0.3%), Cyperaceae (ca. 1%), *Pteridium* (ca. 1%), and monolete ferns (ca. 2%).

Pollen concentration increases to an average of 407,000 grains/cm^3 and pollen influx rises to ca. 28,000 grains/cm^2/yr. Single fire events recorded as distinct charcoal peaks containing ca. 50-100 fragments/cm^3 or 4-7.7 fragments/cm^2/yr are separated by charcoal-poor intervals consisting of ca. 0-30 fragments/cm^3 or 0-2 fragments/cm^2/yr.

PixL-3: Douglas-fir-Alder-Bracken Zone
(747.5-610 cm; 10,200-8,400 ybp)

Pseudotsuga appears consistently for the first time, attaining an average of ca. 12%. *Alnus* and *Pteridium* values increase compared to PixL-2, reaching values of ca. 52% and ca. 4% respectively. *Alnus* values decrease from a high of ca. 68% near the base to a low of ca. 37% near the top of the zone. *Picea*, *Abies*, *T. heterophylla*, and *P. contorta* values decrease to ca. 10%, 0.8%, 8%, and 3% respectively. *Salix* is present at the bottom of the zone (ca. 1%). NAP increases from a low of ca. 7% near the bottom of the zone to a high of ca. 18% near the top with the main constituents being Rosaceae (ca. <1%), *Pteridium* (ca. 2%), and monolete ferns (ca. 5%). Chenopodiaceae (<1%) occur intermittently.

Pollen concentration remains comparable to the preceding zone, averaging ca. 377,000 grains/cm^3 and pollen influx changes little, averaging ca. 29,000 grains/cm^2/yr.

Charcoal concentration attains the highest levels of any zone, averaging ca. 86 fragments/cm^3 and recording a high of 222 fragments/cm^3 near the base. Charcoal influx averages 6.5 fragments/cm^2/yr and records of high of 16.9 fragments/cm^2/yr near the base. DWHI averages 0.42.

PixL-4: Western hemlock-Spruce-Fir Zone
(610-465 cm; 8,400-5,800 ybp)

T. heterophylla increases throughout the zone, averaging ca. 31% and ranging between a low of ca. 7% and a high of ca. 47%. *Picea* values rise slightly to an average of ca. 11%. Relatively high *Abies* values recur throughout the zone, averaging ca. 2%. Cupressaceae pollen percentages increase to ca. 5% near the top. *Pseudotsuga* values decrease to an average of ca. 5%. *Alnus* decreases to ca. 29%, although there is a high value of 66% at 555 cm depth. *P. contorta* decreases to ca. 1%. The NAP signal comprises ca. 18% and consists mainly of *Pteridium* and other fern spores. *Pteridium* values decrease from PixL-3 to ca. 2%, although there is a high of ca. 10% at the PixL-4/PixL-5 boundary. Monolete ferns are present at ca. 12%. Rosaceae pollen is present throughout the zone at ca. 0.6%. *Lysichiton* (ca. 0.4%) and Cyperaceae (ca. 0.3%) occur periodically throughout the zone.

Pollen concentration averages ca. 321,000 grains/cm^3. Pollen influx decreases slightly to an average of ca. 20,000 grains/cm^2/yr, ranging from ca. 8,000 grains/cm^2/yr at bottom of the zone to 46,000 grains/cm^2/yr at the top. Charcoal concentration decreases from zone PixL-3 to an average of 15 fragments/cm^3, whereas influx decreases to an average of 0.8 fragments/cm^2/yr. DWHI increases from a low of 0.66 at the bottom to 0.95 near the top and averages 0.84.

PixL-5: Western hemlock Zone
(465-185 cm; 5,800-2,300 ybp)

Zone PixL-5 is characterised by abundant *T. heterophylla* and increasing Cupressaceae pollen. *T. heterophylla* values average ca. 36% and range between ca. 18% and ca. 50%. Cupressaceae values rise from ca. 6% to ca. 33% at the top. *Picea*, *Abies*, and *Pseudotsuga* decrease to ca. 6%, 1%, and 3% respectively. *Alnus* values fluctuate from a low of 7% to a high of 45% and average ca. 20%. *P. contorta* values are similar to the previous zone. NAP values average ca. 19% and consist mainly of Rosaceae (ca. 0.5%), *Lysichiton* (ca. 0.4%), *Pteridium* (ca. 2%), *Polypodium* (ca. 0.5%), and monolete fern spores (ca. 14%).

Pollen concentration and pollen influx decrease slightly throughout the zone and average 242,000 grains/cm^3 and 19,000 grains/cm^2/yr respectively. Charcoal concentration and influx both increase slightly to an average of 23 fragments/cm^3 and 1.8 fragments/cm^2/yr respectively. Two singular fire events are present at 275 cm and 225 cm depth. DWHI increases to an average of 0.96.

PixL-6: Western hemlock-Cedar Zone
(185-0 cm; 2,300-0 ybp)

T. heterophylla values remain comparable to zone PixL-5, averaging ca. 33%. Cupressaceae attains highest values of any zone, averaging ca. 23%. *Picea* increases marginally to an average of ca. 8%. *Abies* (ca. 1%), *Pseudotsuga* (ca. 2%), and *P. contorta* (ca. 2%) values are similar to the previous zone. Average *Alnus* values decrease to ca. 15%. The NAP component (ca. 14%) and is dominated by *Pteridium* (ca. 2%) and other monolete fern spores (ca. 10%). Poaceae and *Polypodium* are present throughout the zone at ca. 0.4%.

Pollen concentration reaches the lowest value of any zone (ca. 48,000 grains/cm^3) and the average decreases to ca. 165,000 grains/cm^3. Pollen influx reaches a low of ca. 3,800 grains/cm^2/yr and an average of ca. 13,000 grains/cm^2/yr. Charcoal concentration decreases to ca. 5 fragments/cm^3 and exhibits little variation throughout the zone. Charcoal influx similarly declines to an average of 0.4 fragments/cm^2/yr. DWHI remains high, averaging 0.94.

Interpretation

Zone PixL-1 represents the late glacial, a time when the landscape was easily erodable and characterised by mineral soils (Allen, 1995). Although *P. contorta* percentage values are high, the concentration and influx values are low, implying scattered trees separated by open areas (Hebda and Allen, 1993). Allen et al. (1999) show that *P. contorta* is overrepresented in the pollen record which suggests individual *P. contorta* trees were not densely clustered around the site. Rapid sedimentation rates at the top of the zone and/or lake flushing may also explain the low influx values. Scattered *Alnus*, *Shepherdia*, *Artemisia*, and ferns grew in open areas. *Polypodium* and *Cryptogramma* suggest that open rocky sites were common. Cyperaceae likely grew in moist, open areas around the lake basin. Fires were absent from the landscape.

A mixed conifer forest developed during PixL-2 with *Picea* and *T. heterophylla* becoming the major forest elements. *Abies*, possibly *A. lasiocarpa* (Allen, 1995), may have grown in the forest as *Abies* is slightly underrepresented in the pollen spectra (Allen et al., 1999). *T. mertensiana* probably grew with the other species. Charcoal peaks are spaced at approximately 400 year intervals, suggesting fires burned regularly. The observed increase in *Alnus* and *Pteridium* may be the result of stand initiation following fire disturbance (Oliver, 1980; Mathewes, 1985). There was likely a mosaic of forests ranging from recently disturbed early seral stands dominated by *Alnus* to mixed conifer old growth. The presence of shade-intolerant rosaceous taxa indicates the openness of the forest, associated with early succession following fire disturbance. *Salix* was present in moist areas such as along stream banks, whereas Cyperaceae likely grew around the basin. Ferns occupied moist environments.

T. heterophylla and *Picea* suggest moist conditions prevailed. *T. mertensiana* presently occurs in areas with cool summers, mild-cold winters, and abundant precipitation (Means, 1990), suggesting a comparable climate occurred during the late Pleistocene. If *A. lasiocarpa* was present, then cool summers, cold winters, and deep winter snowpacks may have been common (Alexander et al., 1990). Climate is interpreted to have been cool-cold and moist. Growing seasons were likely of short duration because snowpacks persisted for much of the year.

A major shift in forest composition and structure occurred in PixL-3, as indicated by expansion of *Pseudotsuga*, decline of *P. contorta*, and replacement of old-growth forests by fire induced early seral stands. Open forests consisted of *Pseudotsuga* with successional *Alnus* stands and *Picea* and *T. heterophylla* in more moist areas. Rosaceous taxa and *Pteridium* were common in open areas. Ferns may have characterised the understory of moist forest sites. An increased frequency of stand destroying fires is evident by a two-three fold increase in charcoal. *P. contorta*, however, essentially disappears from the forests, a peculiar phenomenon because *P. contorta* should have responded positively to increased fire activity, which suggests competition with other early seral species such as *Alnus* and *Pseudotsuga* caused the observed decline. *P. contorta* probably persisted only on rocky shorelines or in acidic wetlands. Chenopodiaceae may have colonised mud flats that were exposed from low lake levels, suggesting climate was warm and dry (Mathewes, 1985).

The expansion of *Pseudotsuga* and low DWHI ratios suggest climate was warm and dry and climate is interpreted to have been warmer and drier than today. The decrease in *T. mertensiana* and *T. heterophylla* from the preceding zone is consistent with a warmer, drier climate. The increase in fire incidence is directly related to climatic warming and drying.

The combination of *T. heterophylla* and *Picea* with minor *Abies*, Cupressaceae, *Pseudotsuga*, and *Alnus* indicates that the forests in Zone PixL-4 began to resemble modern CWH forests. Fires burned less intensely and frequently. A concurrent shift in forest canopy structure from open to more closed is supported by a decrease in *Alnus* and *Pteridium*. The occurrence of rosaceous taxa suggest shrubs such as *Spiraea* may have grown at the lake margin. Ferns occurred on the moist mossy forest floor. An increase in *Lysichiton* and Cyperaceae suggests wetland development perhaps associated with paludification.

In addition to broad changes, the zone records an example of forest succession following fire as revealed by a charcoal peak prior to 7,000 ybp. Initially, *T. heterophylla*, *Picea*, and *Abies* decline. Perhaps early seral ferns and *Alnus* increased during stand initiation. Moderate values of rosaceous taxa may indicate the openness of the forest generated by fire. Shade-intolerant *Pseudotsuga* eventually overtopped the early seral colonisers and is eventually replaced by shade-tolerant *T. heterophylla*, *Picea*, and *Abies* as climatic climax communities return.

DWHI values appear to increase throughout the zone suggesting a moistening trend and expansion of *T. heterophylla*. Wetland expansion and paludification support an interpretation of increased moisture.

PixL-5 is comparable to the preceding zone except for higher values of Cupressaceae. The major forest constituents were *T. heterophylla*, Cupressaceae, *Picea*, and *Alnus*. *Pseudotsuga* and *Abies* were minor elements. *Pteridium* may have occupied open areas and understories, whereas *Polypodium* and other ferns may have been present on wet mossy surfaces. Wetland development continued as recorded by persistent *Lysichiton* and Cyperaceae. Slight yet distinct increases in *Pseudotsuga* at 215 and 270 cm depth appear to correspond to charcoal peaks, suggesting *Pseudotsuga* survived the fires or occupied the sites during early succession, whereas late seral conifers not adapted to fire decreased. In both cases, forest succession after fire disturbance is apparent following these charcoal peaks. Forests in zone PixL-5 were likely a mixture of shade-intolerant early seral and shade-tolerant mixed conifer climax stands.

Cupressaceae expansion throughout the zone suggests increasing moisture and possibly changes in soil conditions. High levels of *T. heterophylla* suggest climate was moist. Climate was likely moist and possibly cool (Hebda, 1983; 1995).

CWHmm forests dominated by *T. heterophylla* and Cupressaceae with *Picea*, *Abies*, and *Pseudotsuga* are established in PixL-6. The decrease in *Alnus* and Rosaceae corresponds to a reduction in fire disturbance and closure of the forest canopy. Low charcoal influx suggests fires were rare. Poaceae and *Myrica* pollen implies further development of wetlands along the lakeshore. *Pteridium* and *Polypodium* occur on wet mossy ground in the subcanopy.

High DWHI values imply a moist climate. The increase in Cupressaceae suggests climate was likely moist and possibly cool. Climate is interpreted as modern, being moister and cooler than any other Holocene interval. The reduction in fire activity is consistent with a moist climate.

CHAPTER 8: WHYAC LAKE

Study Site

Whyac Lake is situated at 48°40'20" N and 124°50'40" W in the CWHvh subzone adjacent to the mouth of glacially scoured Nitinat Lake (Figure 1). Whyac Lake rests approximately 15 m asl and is approximately 250 m long and 100 m wide. A 50 x 50 m shore bog occupies the northeast shore of the lake. Surrounding forest includes *T. plicata*, *T. heterophylla*, and *P. sitchensis* with *Malus fusca* (Raf.) Schneid. (Pacific crab apple) at the edge of moist openings. The shrub component consists of *G. shallon*, *Rubus spectabilis* Pursh (salmonberry), and *Vaccinium parvifolium* Sm. in Rees (red huckleberry). Thickets of *M. gale* crowd the lakes edge. Aquatic plants present include floating *Nuphar* and emergent *Scirpus* (bulrush). Whyac Lake occurs in the Estevan Lowland with middle Tertiary Carmanah Group conglomerate, sandstone, and shale bedrock (Yorath and Nasmith, 1995).

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The 450 cm long sediment core begins with basal grey clay, silt, and sand at 450-341 cm with rootlets at 380-360 cm depth (Figure 11). A thin band of fine sand occurs between 341-338 cm. Grey silty clay containing plant fragments occurs at 338-320 cm and a silty peat at 320-300 cm depth. Limnic peat occurs between 300-200 cm and was deposited after 10,860 ± 130 ybp (Table 6). Fibrous brown peat from 200-0 cm has been deposited since approximately 7,800 ybp to the present. Woody rootlets are common between 50-100 cm depth whereas, sedge fragments are present from 50-0 cm depth.

Figure 11. Whyac Lake percentage pollen and spore diagram (outline x10).

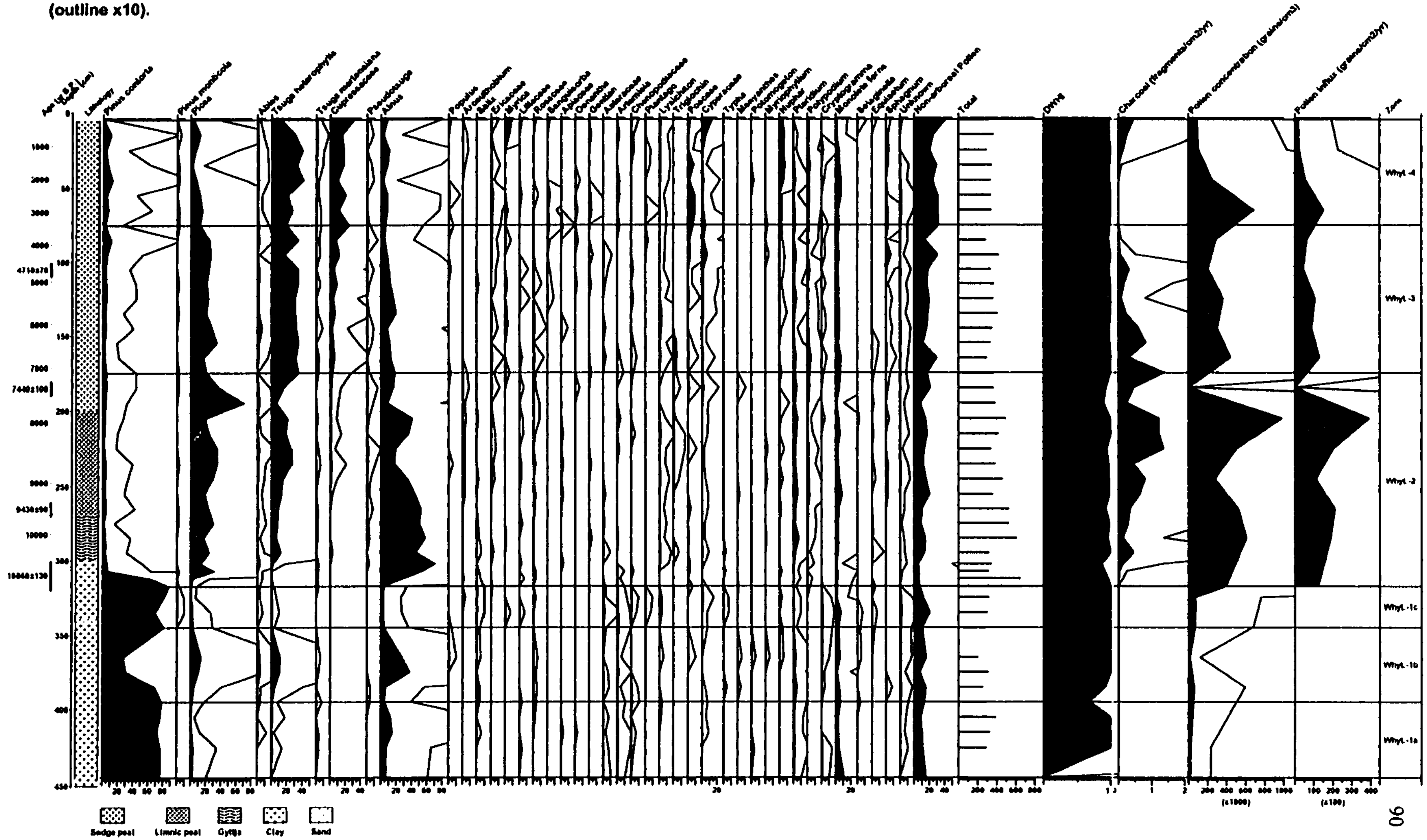


Table 6. Bulk ^{14}C sediment data from Whyac Lake (N/A = not available).

Sample Number	Sediment Type	Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-85184	Peat	100-110	4,710±70
N/A	Peat	180-190	7,440±100
Beta 85185	Gyttja	260-270	9,430±90
N/A	Peat	300-310	10,860±130
N/A	Peat	310-320	10,860±130

Of five radiocarbon dates determined for Whyac Lake, two adjacent samples yielded the same radiocarbon date (Table 6). Mazama ash was not deposited in Whyac Lake. The sedimentation rate in the Whyac Lake bog core declined slightly throughout the Holocene, ranging from a high of 0.040 cm/yr in the early Holocene to a low of 0.022 cm/yr in the late Holocene (Table 7). A reduction in the sedimentation rate occurred at or near the gyttja/peat interface. The decrease in sedimentation corresponds to climatic cooling and suggests a decrease in lake productivity under a cooler climatic regime.

Pollen Zones

Four pollen zones (WhyL-1 to WhyL-4; Figure 11) were identified in Whyac Lake. Zone WhyL-1 is divided into three subzones (WhyL-1a, WhyL-1b, WhyL-1c).

WhyL-1: Pine Zone
(445-317.5 cm; >10,860 ybp)

The WhyL-1 zone occurs within the basal clay unit and represents the interval following deglaciation. In general, this zone is dominated by *P. contorta* and contains no charcoal. Subzones WhyL-1a and WhyL-1c contain abundant *P. contorta* (ca. 76% and 79% respectively), whereas WhyL-1b is characterised by a reduction in *P. contorta* (ca. 52%). The following descriptions focus on taxa other than *P. contorta* that help characterise the subzones of zone WhyL-1.

Table 7. Characteristics of the Whyac Lake sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-105	4,710	0.022	Sedge Peat
105-185	2,730	0.029	Sedge Peat
185-265	1,990	0.040	Limnic Peat
265-310	1,430	0.031	Gyttja/Clay

WhyL-1a: Pine Zone
(445-395 cm; >10,860 ybp)

Alnus is present throughout the subzone, averaging 9% and ranging from a low of ca. 4% to a high of ca. 15%. *Picea* is the only other conifer that appears consistently throughout the subzone, averaging ca. 2%. *T. heterophylla* and *T. mertensiana* are occasionally present. The NAP signal ranges between 9%-15%. *Cryptogramma* (ca. 1%) is present only in the lower portion of the zone. Asteraceae (ca. 0.5%), *Artemisia* (ca. 1%), Chenopodiaceae (ca. 0.4%), *Pteridium* (ca. 1.5 %), and monolete ferns (ca. 6%) occur throughout the subzone. *Salix*, *Lysichiton*, and Cyperaceae are rare and occur only in the upper part of the subzone. Pollen and spore concentrations in subzone WhyL-1a are the lowest of any zone in the core, averaging ca. 23,000 grains/cm^3.

WhyL-1b: Pine-Spruce-Fir-Hemlock
(395-345 cm; >10,860 ybp)

Picea, *Abies*, and *T. heterophylla* increase in abundance to ca. 8%, 2%, and 7% respectively. *Alnus* pollen values are greater than WhyL-1a, averaging ca. 18%. *Populus* (ca. 0.7%) is present in the upper portion of the subzone. The NAP component comprises ca. 12% and consists mainly of *Artemisia* (ca. 1%), *Pteridium* (ca. 2%), *Cryptogramma* (ca. 0.8%), and monolete ferns (ca. 4%). *Salix*, Rosaceae, Asteraceae, *Lysichiton*, *Menyanthes* (buckbean), *Lycopodium* (clubmoss), and *Selaginella* are rare throughout the subzone. Pollen concentrations range between 12,000-67,000 grains/cm^3.

WhyL-1c: Pine Zone
(345-317.5 cm; >10,860 ybp)

Picea (ca. 1%), *Abies* (ca. 0.4%), *T. heterophylla* (ca. 0.6%), and *Alnus* (ca. 3%) are present throughout the subzone but at lower percentages from the preceding subzone. The NAP component increases marginally to an average of ca. 13%. Main NAP taxa include *Salix* (ca. 1%), Asteraceae (ca. 1%), *Artemisia* (ca. 1%), Cyperaceae (ca. 1%), *Typha* (ca. 0.4%), *Pteridium* (ca. 0.8%), *Cryptogramma* (ca. 1%), and monolete ferns (ca. 3%). The pollen concentration increases throughout the subzone from ca. 73,000 grains/cm^3 at the bottom of the subzone to ca. 390,000 grains/cm^3 at the top. Pollen influx was calculated above the ^{14}C date of 10,860 ± 130 and is ca. 12,000 grains/cm^2/yr.

WhyL-2: Spruce-Hemlock-Alder Zone
(317.5-175 cm; >10,860-7,100 ybp)

P. contorta declines sharply from ca. 62% in the bottom sample to an average of ca. 3.5% throughout the zone. *Picea* comprises ca. 2% of the pollen in the bottom sample and then increases to an average of ca. 28% for the rest of the zone. *T. heterophylla* averages ca. 13%, increasing from 0% at the bottom to ca. 35% at the top. *Alnus* attains the highest values (ca. 71%) for the core in the basal portions of the zone and gradually decreases up core to a value of ca. 8%. *Abies* is present throughout the zone at ca. 1%. *Pseudotsuga* occurs throughout most of the zone, reaching a high of 1.8 % near the top. Cupressaceae pollen is present in the upper portion of the zone and averages ca. 1%. The NAP component averages ca. 13% and consists mainly of *Lysichiton* (ca. 0.8%), Cyperaceae (ca. 0.6%), *Pteridium* (ca. 3%), *Polypodium* (ca. 1%), and other ferns (ca. 4%).

Pollen concentrations increase to an average of ca. 578,000 grains/cm^3, ranging between 275,000-976,000 grains/cm^3. Pollen influx exhibits a similar trend, increasing from the preceding zone to an average of ca. 22,000 grains/cm^2/yr and ranging between 11,000-39,000 grains/cm^2/yr. Charcoal concentrations attain the highest values throughout the core, averaging 16 fragments/cm^3 and ranging between 0-48 fragments/cm^3. Charcoal influx averages 0.6 fragments/cm^2/yr. The DWHI index of precipitation averages 0.95.

WhyL-3: Spruce-Hemlock-Cedar Zone
(175-75 cm; 7,100-3,400 cm)

Picea percentages decrease from the preceding zone to an average of ca 23%, whereas *T. heterophylla* increases to ca. 30%. Cupressaceae values rise throughout the zone from a low of ca. 2% near the bottom to a high of ca. 23% near the top. *P. contorta* and *Abies* increase to an average of ca. 4% and 2% respectively. *Pseudotsuga* (ca. 0.5%) occurs only intermittently. *Alnus* averages ca. 10%, generally decreasing throughout the zone from ca. 19% to ca. 4%. The non-arboreal component comprises ca. 21 %, ranging from a low of ca. 11% to a high of ca. 32%. It consists predominately of Ericaceae (ca. 0.7%), *Lysichiton* (ca. 1 %), Poaceae (ca. 2%), *Pteridium* (ca. 2%), *Polypodium* (ca. 2%), monolete ferns (ca. 4%), *Lycopodium* (ca. 1%), and *Sphagnum* (peat moss; ca. 2%). Cyperaceae values increase to a high of ca. 7% near the top.

Pollen concentrations and influx decrease to an average of ca. 319,000 grains/cm^3 and 8,500 grains/cm^2/yr respectively. The concentration of charcoal fragments decreases throughout the zone from 28 fragments/cm^3 at 155 cm to no charcoal at the top. Charcoal influx also decreases to an average of 0.3 fragments/cm^2/yr. DWHI increases slightly to an average of 0.99.

WhyL-4: Hemlock-Cedar Zone
(75-0 cm; 3,400-0 ybp)

T. heterophylla and Cupressaceae pollen dominate this zone, averaging ca. 30% and 17% respectively. *P. contorta* (ca. 6%) and *T. mertensiana* (ca. 0.8%) increase from the preceding zone. *Picea*, *Abies*, and *Alnus* values decrease to ca. 8%, 1%, and 7% respectively. A diverse NAP component comprises ca. 29%, and consists mainly of Poaceae (ca. 5%), Cyperaceae (ca. 4%), *Nuphar* (ca. 4%), and monolete ferns (ca. 4%) but also includes Ericaceae (ca. 0.9%), *Lysichiton* (ca. 1%), *Pteridium* (ca. 1%), *Polypodium* (ca. 2%), and *Sphagnum* (ca. 0.7%). *Sanguisorba* (rose; ca 2%), and *Gentiana* (ca. 2%) occur in the basal part of the zone. High values of *Myrica* (ca. 7%) are restricted to the upper part of the zone.

Pollen concentrations decrease throughout the zone from a high of ca. 686,000 grains/cm3 to a low of ca. 87,000 grains/cm^3. The pollen influx exhibits a similar pattern, ranging from a high of ca. 15,000 grains/cm^2/yr near the bottom of the zone to a low of 1,900 grains/cm^2/yr near the top. Charcoal is absent in the basal part of the zone but increases in the top 30 cm of the core, averaging 13 fragments/cm^3 and ranging between 6-21 fragments/cm^3. Charcoal influx ranges between 0-0.5 fragments/cm^2/yr, averaging 0.3 fragments/cm^2/yr near the top. DWHI remains unchanged from the preceding zone, averaging 0.99.

Interpretation

The record begins with *P. contorta* woodlands during the late-glacial interval in zone WhyL-1 (WhyL-1a and WhyL-1c) with a moister mixed conifer phase (WhyL-1b). Pollen representation studies (Hebda and Allen, 1993) and low pollen concentration values suggest these woodlands were open. *T. heterophylla*, *T. mertensiana*, and *Picea* likely grew in the woodlands, perhaps in moist sites. *Alnus* pollen likely arrived from long distance transport (Allen et al., 1999). Asteraceae, *Artemisia*, *Pteridium*, and fern values imply open areas. Chenopodiaceae pollen suggests landscape disturbance or perhaps the proximity of salt marshes. Areas around moist depressions supported *Salix*, *Lysichiton*, and Cyperaceae. The absence of charcoal indicates that fires were absent. The preponderance of *P. contorta* suggests climate was generally cool and dry (Hebda, 1983).

Zone WhyL-1b is characterised by mixed conifer forests. The presence of shade-tolerant *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* imply a closed canopy and possible moist conditions. However, the continued abundance of *P. contorta* and *Alnus* suggest possible dry or disturbed sites or nutrient poor soils. Small amounts of shade-intolerant Rosaceae, Asteraceae, *Artemisia*, *Pteridium*, *Cryptogramma*, and ferns likely grew in openings. Low pollen concentrations also imply open forests. *Salix* and *Populus* grew along floodplains and around lakes. Local wetland development is evident by the increase in *Lysichiton*, *Menyanthes*, and *Lycopodium*. *Selaginella* grew on rocky outcrops. The lack of charcoal implies fires were absent, suggesting moist conditions. Other disturbances such as windthrow may have also contributed to the high *Alnus* values. Climate is interpreted as cool but moister than WhyL-1a. Wetland expansion also suggests wetter conditions.

P. contorta dominated forests recur in WhyL-1c. *Alnus*, however, does not appear to be as abundant as in WhyL-1a. *T. mertensiana*, *Picea*, and *Abies* were minor forest elements compared to WhyL-1b. The NAP component suggests open areas were nearby. *Salix*, Cyperaceae, and *Typha* grew around or near the basin. Fires continued to be absent. Climate seems to have been cooler and drier than in WhyL-1b.

P. contorta dominated forests were abruptly replaced by *Picea* dominated forests with *T. heterophylla* in WhyL-2. *Alnus* grew abundantly in areas disturbed by fire. *Abies* and fire adapted *Pseudotsuga* were minor forest elements. Forest openings generated by disturbance were quickly colonised by *Pteridium* and possibly other ferns. The first occurrence of charcoal indicates fires were a critical feature on the landscape. The appearance of Cupressaceae pollen late in the zone suggests *T. plicata* and possibly *C. nootkatensis* became part of the forest. Wetlands persisted as evident by *Lysichiton* and Cyperaceae. *Polypodium* was present in moist, mossy understories. The increase in pollen concentration and influx suggests forest closure.

The abrupt decrease in *P. contorta* values at the beginning of the zone suggests a sudden shift in climatic conditions. High DWHI values indicating a relatively wet climate are consistent with relatively high *T. heterophylla*, *Picea*, and Cupressaceae pollen percentage values. However, the presence of *Pseudotsuga* suggests that there were edaphically dry sites and climate is interpreted as relatively warm and moist, especially compared to subzone WhyL-1c.

Forests closed and *T. heterophylla* becomes more abundant in WhyL-3. *Picea* and Cupressaceae, presumably *T. plicata* became major forest elements. A decline in early seral taxa such as *Alnus* and fire adapted *Pseudotsuga* corresponds to a reduction in charcoal and together imply fewer fires. A modern shrub stratum containing ericaceous taxa develops, suggesting moist, acidic, organic soil mats had developed (Hebda, 1983; Alaback et al., 1994). Locally, bogs developed and expanded as indicated by an increase in Poaceae, Cyperaceae, *Lycopodium*, and *Sphagnum*. *Pteridium* likely occupied disturbed or boggy sites, whereas *Lysichiton* grew in swampy areas. The increase in *P. contorta* corresponds to the expansion of bog habitat. *Polypodium* and other ferns grew in the moist understories or as epiphytes on trees.

The increase in *T. heterophylla* and Cupressaceae is consistent with the moistening trend. A reduction in fire is consistent with increased precipitation. The high DWHI values reflect the very wet climate. Climate is interpreted as moist and possibly warm (Hebda, 1995).

Extant forests dominated by *T. heterophylla* and Cupressaceae became established in WhyL-4. *Picea* formed only a minor forest element, likely growing in near-pure stands along the marine shoreline nearby. *P. contorta* continued to persist in bogs. The mixed conifer forests attain old-growth climax status because fire disturbance is rare or absent. The modern forest understory dominated by ericaceous taxa became well established. *Polypodium* and other ferns grew in the forest understory. *Sanguisorba* grew in the shore bog and *Myrica* forms thickets at the lake edge. *Gentiana*, *Lysichiton*, Poaceae, Cyperaceae, *Pteridium*, and *Sphagnum* suggest wetlands continued to expand.

An increase in *Nuphar* suggests a rise in lake levels. A slight increase in charcoal between about 1,000 ybp-present, suggests a slight increase in fires during this interval.

The increase in *T. heterophylla* and Cupressaceae and expansion of wetland communities indicate increasing moisture. Increased *T. mertensiana* implies decreasing temperatures and increasing precipitation and snowfall at higher elevations. High DWHI values continued to reflect a wet climate. Climate is interpreted as wet and cool relative to other intervals in the Holocene (Hebda, 1995).

CHAPTER 9: PORPHYRY LAKE

Study Site

Porphyry Lake is situated west of Chemainus on Mount Brenton at approximately 48°54'20" N and 123°50'00" W in the MH zone (Figure 1). Porphyry Lake is approximately 70 m long and 50 m wide and is located at approximately 1.100 m asl. A shore bog consisting of *Sphagnum*, Cyperaceae, *Eriophorum* (cottongrass), *Blechnum spicant* (L.) Roth (deer fern), *Cornus canadensis* L. (bunchberry), *Lysichiton*, *Salix*, *P. monticola*, *A. amabilis*, and *T. mertensiana* surrounds Porphyry Lake. Nearby forests consist primarily of *T. mertensiana*, *A. amabilis*, and *C. nootkatensis* with *Vaccinium* in the understory. *Pseudotsuga*, *T. heterophylla* and *T. plicata* dominated forests occur at lower elevations about 0.5 km away. Porphyry Lake occurs in the Nanaimo Lakes and Highlands physiographic region and is underlain by Paleozoic porphyritic basalts (Yorath and Nasmith, 1995).

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The Porphyry Lake core is 251 cm long and begins in gray clay from 251-237 cm that was deposited before 12,540±200 ybp (Figure 12; Table 8). Gyttja occurs from 237-0 cm and represents the interval from approximately 12,540±200 ybp to present. Plant fragments are present in the gyttja from 72-0 cm and a sand horizon occurs at 58-59 cm depth. At 73-72 cm a volcanic ash is present, although it is not believed to be from Mt. Mazama because of its stratigraphic position between two ^{14}C dates of 5,950±110 and 4,000±60 (Bacon, 1983). Unintentional resampling or contamination of the sediment

Figure 12. Porphyry Lake pollen and spore percentage diagram (outline x10).

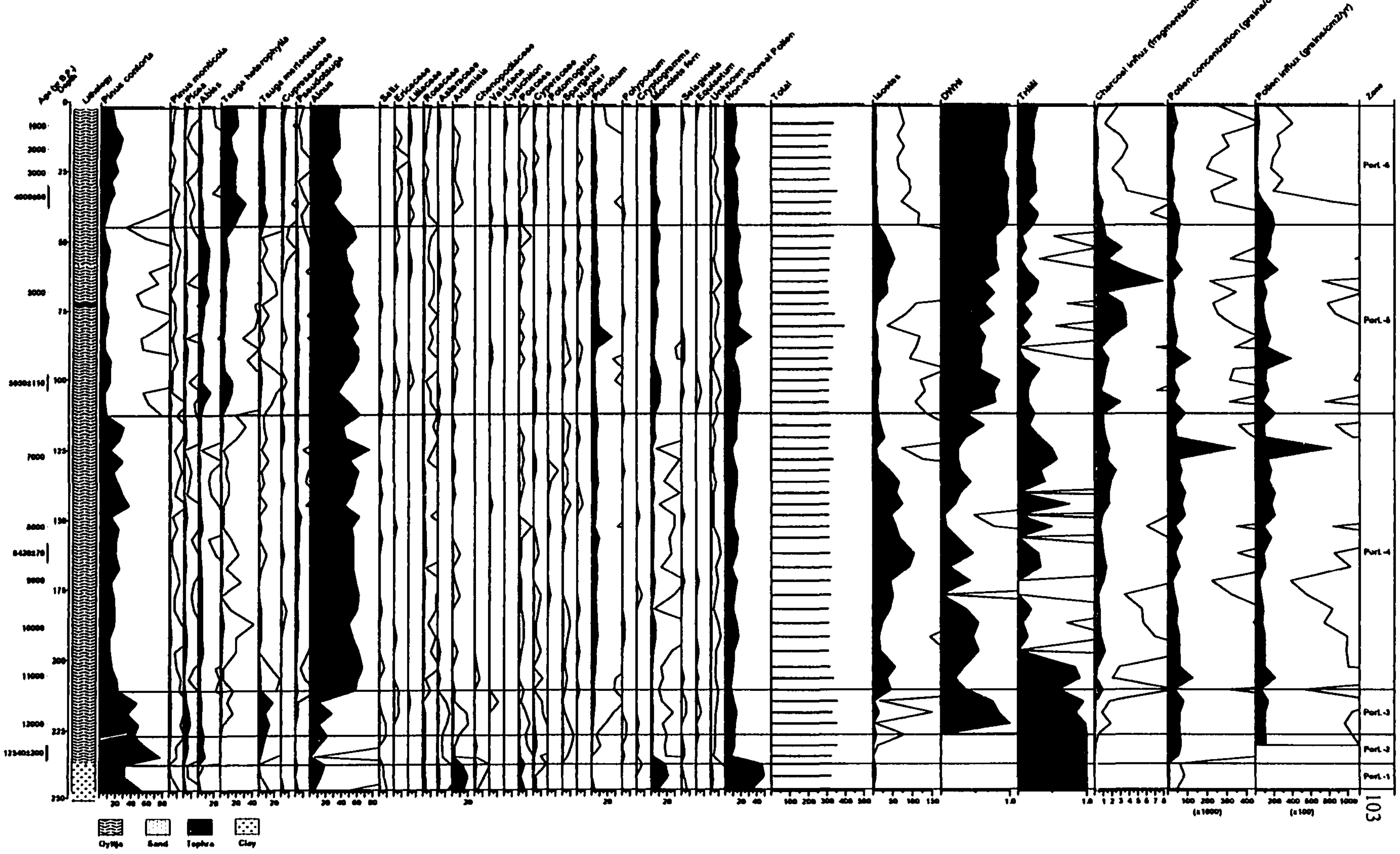


Table 8. Bulk ^{14}C sediment dates from Porphyry Lake.

Sample Number	Sediment Type	Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-118843	Gyttja	30-38	4,000±60
Beta-118844	Gyttja	98-104	5,950±110
Beta-118845	Gyttja	158-165	8,420±70
Beta-111741	Gyttja	230-236	12,540±200

may have resulted in erroneous age determination of the tephra. However, this seems unlikely because the core was collected in 1 m sections and the ash was retrieved in the middle portion of the first meter of sediment extracted. Welch et al. (1985) indicate that because ash layers are more dense than uncompacted lacustrine sediment, it is possible that they can sink into the sediment by 10 cm or greater depth. Therefore, the ash in Porphyry Lake could possibly correlate to the Mount St. Helen's Yn ash and has subsequently been displaced downward several centimeters.

The sedimentation rate in the Porphyry Lake core varied throughout the Holocene, being relatively high throughout the post-glacial until it declined during the late Holocene to 0.0085 cm/yr (Table 9). The highest sedimentation rates occurred during the early (0.024 cm/yr) and mid (0.034 cm/yr) Holocene. Because the ash is of unknown origin, it was not used to compute sedimentation rates.

Pollen Zones

Six pollen zones (PorL-1 to PorL-6) are designated in Porphyry Lake (Figure 12).

PorL-1: NAP Zone
(251-238 cm; >12,540 ybp)

NAP accounts for ca. 43% of the pollen and spores and consists mainly of Asteraceae (ca. 2%), *Artemisia* (ca. 15%), Chenopodiaceae (ca. 1%), Poaceae (ca. 6%), and ferns (ca. 16%). Low amounts (<1%) of *Salix*, Cyperaceae, and *Cryptogramma* also occur. The main arboreal constituents include *P. contorta* (ca. 39%) and *Alnus* (ca. 13%) with *Picea* (ca. 1%). Pollen concentration is the lowest throughout the core, averaging 63,000 grains/cm^3 and charcoal is absent.

Table 9. Characteristics of the Porphyry Lake sediment core.

Depth Interval (cm)	**Duration (yrs)**	**Sedimentation Rate (cm/yr)**	**Sediment Type**
0-34	4,000	0.0085	Gyttja
34-101	1,950	0.034	Gyttja
101-161.5	2,470	0.024	Gyttja
161.5-233	4,120	0.017	Gyttja

PorL-2: Pine Zone
(238-227 cm; >12,540-12,300 ybp)

Arboreal taxa dominate as the NAP component is reduced to ca. 10%. *P. contorta* averages ca. 60%, but ranges from a high of ca. 77% near the bottom to ca. 44% near the top. Significant quantities of *Picea* (ca. 4%), *Abies* (ca. 7%), and *T. mertensiana* (ca. 5%) are present, suggesting these taxa grew near the lake. *Alnus* values are similar to zone PorL-1, averaging ca. 11%. Poaceae and ferns decrease from the preceding zone to an average of ca. 1% and 2% respectively, whereas Cyperaceae and *Sparganium* (bur-reed) increase to ca. 3% and 1% respectively. Pollen concentration increases significantly to ca. 589,000 grains/cm^3. Pollen influx averages 11,000 grains/cm^2/yr. Charcoal is rare, averaging 1 fragment/cm^3 and 0.2 fragments/cm^2/yr.

PorL-3: Pine-Spruce-Fir-Mountain Hemlock Zone
(227-211 cm; 12,300-11,300 ybp)

P. contorta, *Alnus*, and *T. mertensiana* dominate this zone, averaging ca. 38%, 27%, and 10% respectively. *P. contorta* decreases throughout the zone from ca. 49% to 22%, whereas *Alnus* increases from ca. 11% to 58%. Other notable conifers include *Picea* (ca. 5%), *Abies* (ca. 4%), and *T. heterophylla* (ca. 1%). *Pseudotsuga* (ca. 3%) occurs near the top of the zone. The NAP averages ca. 11% and consists mainly of Asteraceae (ca. 1%), *Artemisia* (ca. 1%), Poaceae (ca. 1%), Cyperaceae (ca. 1%), *Pteridium* (ca. 3%), and ferns (ca. 2%).

Pollen concentration averages ca. 569,000 grains/cm^3, whereas pollen influx averages ca. 10,000 grains/cm^2/yr. The average charcoal concentration is 20 grains/cm^3, however, charcoal abundance increases throughout the zone from 5 fragments/cm^3 near the bottom to 55 fragments/cm^3 near the top. Charcoal influx averages 0.3 fragments/cm^2/yr. DWHI ranges from 1.00 near the bottom to 0.36 at the top, whereas THMI ranges from 1.00 at the bottom to 0.58 at the top.

PorL-4: Fir-Douglas-fir-Alder Zone
(211-113 cm; 11,300-6,500 ybp)

Alnus pollen values increase from the preceding zone to an average of ca. 57% whereas *P. contorta* decreases to ca. 20%. Other notable conifers include *Picea* (ca. 2%), *Abies* (ca. 3%), *T. heterophylla* (ca. 1%) and *Pseudotsuga* (ca. 3%). The NAP averages 12% and consists mainly of Rosaceae (ca. 2%), *Pteridium* (ca. 6%), and ferns (ca. 3%).

Pollen concentration is the highest throughout the core, averaging 719,000 grains/cm^3. An unusually high value of 3,425,000 grains/cm^3 occurs at 125 cm depth. However, if the 125 cm sample is excluded then the pollen concentration is reduced to an average of ca. 590,000 grains/cm^3. Pollen influx averages 16,000 grains/cm2/yr. Charcoal concentration averages 50 fragments/cm3, ranging from 12 fragments/cm^3 near the bottom to 103 fragments/cm^3 near the top. Charcoal influx increases from the preceding zone to an average of 1.1 fragments/cm^2/yr. DWHI averages 0.33, whereas THMI ranges from an average of 0.86 near the bottom to 0.13 at mid zone levels to 0.35 near the top. However, the THMI fluctuations near the top of the zone may be an artefact of the ratio because *T. heterophylla* and *T. mertensiana* pollen occur in low numbers and a small change in their relative percentage values manifests into a large change in THMI.

PorL-5: Fir-Western hemlock-Douglas-fir-Alder Zone
(113-45 cm; 6,500-4,300 ybp)

Alnus and *P. contorta* decrease from PorL-4 to ca. 53% and ca. 8% respectively, whereas *Abies* (ca. 8%) and *T. heterophylla* (ca. 7%) increase from the preceding zone. Other conifers present include *Picea* (ca. 2%), *T. mertensiana* (ca. 1%), and *Pseudotsuga* (ca. 2%). NAP increases to ca. 17% and is mainly characterised by Rosaceae (ca. 1%), *Pteridium* (ca. 7%), and ferns (ca. 7%).

Pollen concentration averages 434,000 grains/cm^3 and pollen influx averages 14,000 grains/cm^2/yr. Charcoal concentration is the highest in the core, averaging 74 fragments/cm^3 and ranging between 21-231 fragments/cm^3. Charcoal influx averages 2.4 fragments/cm^2/yr and ranges between 0.7-7.8 fragments/cm^2/yr. DWHI increases to 0.72, whereas THMI remains relatively low, averaging 0.15.

PorL-6: Western hemlock-Mountain Hemlock-Cedar Zone
(45-0 cm; 4,300-0 ybp)

Alnus (ca. 35%) and *T. heterophylla* (ca. 19%) dominate this zone. *P. contorta, T. mertensiana*, and Cupressaceae pollen values increase to an average of ca. 17%, 6%, and 3% respectively. Other notable conifers include *Picea* (ca. 1%), *Abies* (ca. 3%), and *Pseudotsuga* (ca. 1%). NAP averages ca. 14% and mainly contains Ericaceae (<1%), *Pteridium* (ca. 4%), and ferns (ca. 7%).

Pollen concentration averages 306,000 grains/cm^3 and pollen influx averages 4,500 grains/cm^2/yr. Charcoal concentrations decrease to 32 fragments/cm^3 and charcoal influx similarly decreases to 0.4 fragments/cm^2/yr. Both DWHI and THMI increase from the preceding zone and average 0.95 and 0.24 respectively.

Interpretation

High values of Poaceae and *Artemisia* suggest an open, tundra-like ecosystem prevailed in zone PorL-1, possibly during the full or late glacial. The presence of Asteraceae pollen further supports the concept of an open landscape and *Cryptogramma* spores suggest that there were open rocky areas. *Chenopodiaceae* likely grew on the disturbed mineral soils, whereas *Salix* and Cyperaceae likely grew in moist areas around the basin. Some of the *Salix* pollen may be derived from a dwarfed species such as *Salix artica* Pallas (arctic willow), which likely grew in both moist and dry sites.

Although percentages of *P. contorta* and *Alnus* are relatively high, Dunwiddie (1987), Hebda and Allen (1993), and Allen et al. (1999) show these taxa are overrepresented in the pollen record, indicating they likely were not common at the site or they have been blown in from elsewhere. It is also possible that the *Alnus* pollen represents scattered *A. crispa* shrubs that persisted at Porphyry Lake. The low pollen concentrations suggest an open landscape with few trees. The low pollen concentration might also represent rapid mineralogical sedimentation. Unlike *Pinus*, the low values of *Picea* suggest this tree may have grown near the site.

Perhaps, tundra expanses representing glacial refugia separated alpine and valley glaciers during the last glaciation. The mineral sediment that characterises this zone implies erodable soils, possibly derived from periglacial activity and solifluction, were widespread. Overall, the assemblage was probably an open steppe to tundra-like assemblage like those interpreted for the full to late glacial intervals by Heusser (1977), Cwynar and Ritchie (1980), Colinvaux (1981), Smith and Anderson (1992), and Mathewes (1989). The lack of charcoal implies fires were absent. The presence of a tundra-like pollen assemblage suggests climate was cold and the limited occurrence of moisture requiring taxa suggests climate was dry.

P. contorta woodlands containing some *Picea*, *Abies*, and *T. mertensiana* possibly with *Alnus* replaced the NAP biogeochron in the late glacial (PorL-2). A corresponding change from mineral to organic sediment is evident as soils became more stabilised (Figure 12). *Picea*, *Abies*, and *T. mertensiana* taxa may have been relatively important woodland elements even though their pollen percentage values are relatively low. The increase in pollen concentration and the reduction in Poaceae and ferns is consistent with a more treed landscape. Cyperaceae grew around the basin and *Sparganium* grew submerged or floating in shallow water (Alaback et al., 1994).

The lack of charcoal indicates that fires were not yet a landscape disturbance feature. The dominance of *P. contorta* suggests climate may have been cool and dry (Hebda, 1995) but the occurrence of *Picea*, *T. mertensiana*, and *Abies* suggests moist conditions may have occurred in high elevations at this time.

At ca. 12,300 ybp (PorL-3), mixed conifer forests characterised by *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* with *P. contorta* replaced the *P. contorta* woodlands. Moderately high *P. contorta* pollen percentages are recorded but because *P. contorta* pollen is overrepresented (Allen et al., 1999) it likely formed a minor forest element. The presence of underrepresented *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* suggests these taxa were widespread and the forest canopy closed. An increase in shade-intolerant *Alnus* suggests forest openings did persist, possibly because of occasional fires. The presence of Asteraceae, *Artemisia*, Poaceae, and *Pteridium* is consistent with occasional canopy openings too. Ferns may have occupied open areas or moist mossy understories. Cyperaceae continued to grow around the basin.

The occurrence of charcoal likely represents the first incidence of high elevation fires on southern Vancouver Island. The presence of *T. mertensiana* suggests climate was cool and relatively moist. The occurrence of abundant *Picea* with *T. heterophylla* suggests climate was moist and warmer than the preceding zone.

A change in forest composition and structure is evident in PorL-4. Shade-intolerant and early seral *Alnus* and *Pseudotsuga* became more abundant as forests became more open and were disturbed by fire. *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* persisted as minor forest elements in moist areas that burned less frequently. A decrease in *P. contorta* pollen values suggests *P. contorta* was restricted to nutrient-poor and possibly dry areas where it could outcompete other tree taxa. Relatively high Rosaceae and *Pteridium* values are consistent with a more open canopy. Ferns likely occupied moist, partially open forest understories.

Charcoal concentration and influx generally increases throughout the zone, possibly reflecting an increase in fire frequency and intensity. The presence of *Pseudotsuga* suggests climate was warmer and drier compared to any other zone.

Shade-tolerant *T. heterophylla*, *T. mertensiana*, and *Abies*, possibly *A. amabilis*, increase in PorL-5 at 6,500 ybp, whereas *Pseudotsuga* and *Alnus* remain comparable to the preceding zone. Therefore, the forests at this time consisted of both shade-tolerant and intolerant components, suggesting structure ranged from open to closed or perhaps *Pseudotsuga* persisted amongst rocky outcrops. *Picea* remained a minor forest element, whereas a further decrease in *P. contorta* values suggests *P. contorta* pollen was likely derived from the regional pollen rain (Allen et al, 1999). The occurrence of Rosaceae and *Pteridium* imply open areas were relatively common.

A 2-3 fold increase in charcoal from the previous zone reveals an increase in the incidence of fire. A sand unit that correlates to a peak in charcoal at ca. 4,700 ybp may represent an erosion event associated with the removal of vegetation following an intense fire. The increase in *Abies* and *T. heterophylla* suggests climate was becoming moist and the persistence of *Pseudotsuga* from the preceding zone suggests climate remained warm.

Several changes in forest composition, structure, and disturbance are evident in PorL-6 as extant sub-alpine *T. mertensiana* dominated forests became established about 4,300 ybp. Elevated *T. heterophylla*, *T. mertensiana*, and Cupressaceae pollen, both *C. nootkatensis* and *T. plicata*, suggest a mixed closed canopy forest. The increase in *P. contorta* is likely related to local bog development and the opportunity for *Pinus* expansion. The decline in *Pseudotsuga* and *Alnus* suggests that these taxa were no longer major forest elements on the summit of Mt. Brenton. The modern ericaceous understory was established as evident by an increase in Ericaceae pollen and comparison to surface samples (Allen et al., 1999).

The continuous accumulation of charcoal suggests that fires continued to burn. However, both the concentration and influx of charcoal is less than in PorL-5, suggesting fires were less intense or spatially limited, possibly because of the moister climate. The increase in *T. heterophylla*, *T. mertensiana*, and Cupressaceae coupled with the decline in *Pseudotsuga* suggests climate moistened and cooled during this interval.

CHAPTER 10: WALKER LAKE

Study Site

Walker Lake is located on the San Juan Ridge at 48°32'05" N and 123°58'45" W in the MH zone (Figure 1). Walker Lake is approximately 75 m long and 50 m wide and is approximately 990 m asl. Cyperaceae occurs around Walker Lake and forests consisting of *T. mertensiana*, *A. amabilis* and *C. nootkatensis* with ferns in the understory grow almost to the lake edge. *T. heterophylla* and *T. plicata* dominated forests with *Alnus* occur at low elevations. Walker Lake is located on an east-west oriented ridge in the South Vancouver Island Ranges physiographic region and is underlain by Tertiary basalts (Yorath and Nasmith, 1995).

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The Walker Lake core is 520 cm long and contains gray clay at the base from 520-500 cm, representing an interval before 12,240±120 ybp (Figure 13; Table 10). Gyttja is present from 500-0 cm and represents the interval from 12,240±120 ybp to present. A volcanic tephra at 299-300 cm is likely from Mt. Mazama because of its stratigraphic position relative to a ^{14}C date of 6,190±70 ybp at 295 cm depth (Bacon, 1983). A sand lense that was deposited ca. 5,200 ybp occurs at 230-225 cm depth. Plant macrofragments are present in the gyttja from 225-0 cm.

Sedimentation rates at Walker Lake vary throughout the late Pleistocene and the Holocene (Table 11). The most rapid sedimentation rates (0.050-0.074 cm/yr) occurred in the early and mid Holocene and likely represent increased lake productivity. Lower

Figure 13. Walker Lake pollen and spore percentage diagram (outline x10).

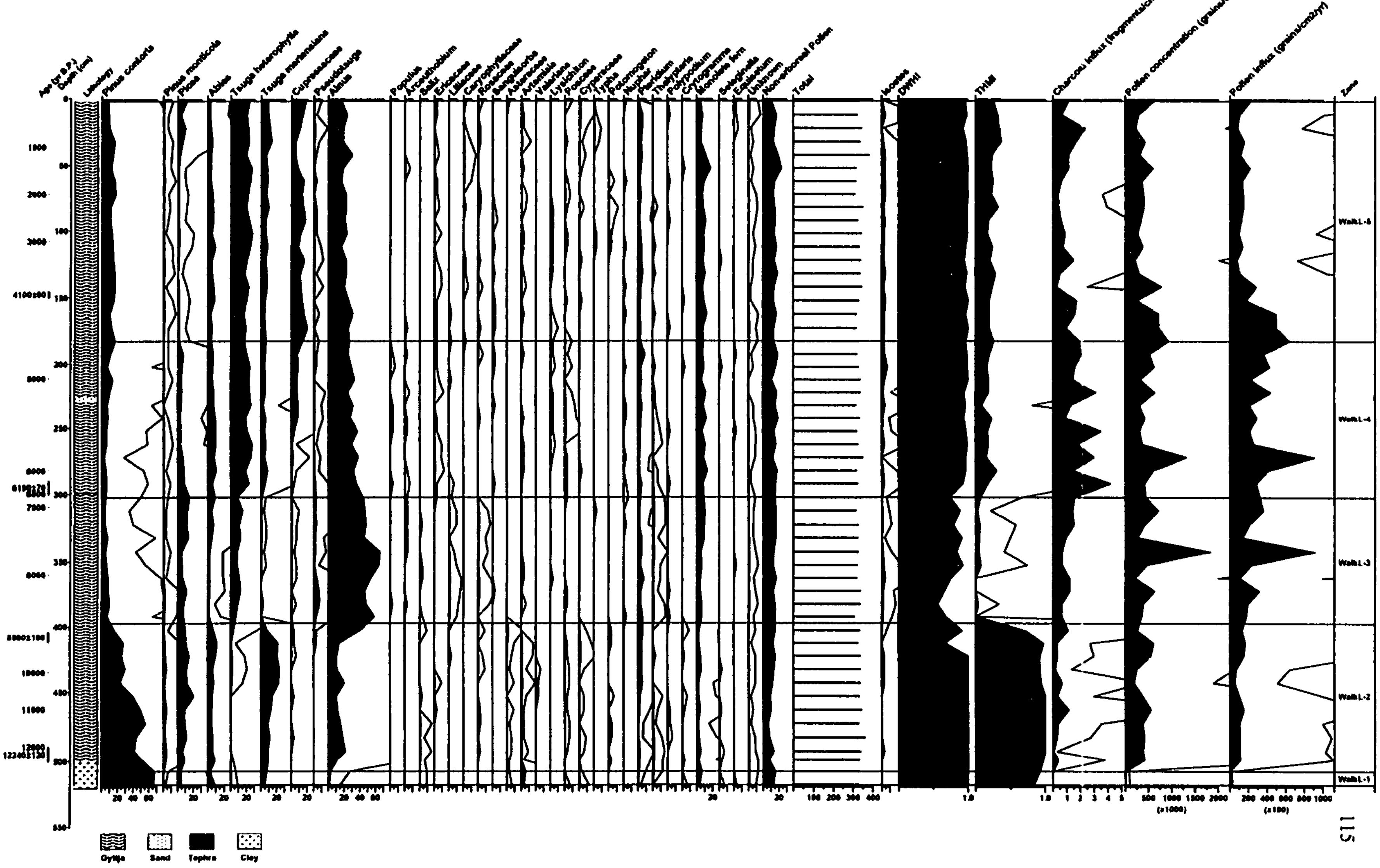


Table 10. Bulk ^{14}C sediment and tephra dates from Walker Lake.

Sample Number	Sediment Type	Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-111738	Gyttja	145-150	4,100±60
Beta-94802	Gyttja	290-300	6,190±70
	Tephra	299-300	6,800
Beta-111739	Gyttja	404-412	8,980±160
Beta-111740	Gyttja	490-500	12,240±120

Table 11. Characteristics of the Walker Lake sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-147.5	4,100	0.036	Gyttja
147.5-295	2,090	0.071	Gyttja
295-299.5	45	0.074	Gyttja
299.5-408	2,180	0.050	Gyttja
408-495	3,260	0.027	Gyttja

sedimentation rates occurred during the late Pleistocene (ca. 0.27 cm/yr) and late Holocene (0.036 cm/yr) when climate was cool and lake productivity was reduced.

Pollen Zones

Five pollen zones (WalkL-1 to WalkL-5) were identified in Walker Lake (Figure 13).

WalkL-1: Pine Zone
(520-507.5 cm; >12,240 ybp)

This zone is dominated by *P. contorta* (ca. 66%), although significant quantities of *Picea* (ca. 4%), *Abies* (ca. 5%), *T. heterophylla* (ca. 1%), and *T. mertensiana* (ca. 6%) are recorded. *Alnus* values are the lowest in the core, averaging only ca. 2%. The NAP averages ca. 14% and consists mainly of *Salix* (ca. 1%), *Artemisia* (ca. 4%), Cyperaceae (ca. 1%), and ferns (ca. 5%). Pollen concentration is low relative to the rest of the core, averaging 8,300 grains/cm^3. Charcoal is absent and THMI averages 0.88.

WalkL-2: Pine-Spruce-Fir-Mountain hemlock Zone
(507.5-397.5 cm; >12,240-8,800 ybp)

This zone is dominated by arboreal pollen but *P. contorta* is less abundant, decreasing to ca. 36%, whereas *Picea*, *Abies*, and *T. mertensiana* increase to ca. 11%, 7%, and 14% respectively. *Alnus* increases from the preceding zone to ca. 16%. *T. heterophylla* is present only in the upper part of the zone, averaging ca. 2%. The NAP is comparable to WalkL-1, averaging ca. 11% and consisting of Asteraceae (<1%), *Artemisia* (ca. 1%), Cyperaceae (ca. 1%), *Pteridium* (ca. 3%), and other ferns (ca. 3%).

Salix (ca. 1%) occurs only at the bottom of the zone, and Poaceae pollen is rare but occurs throughout the zone.

A very large increase in pollen concentration from the preceding zone is recorded, reading average values of 393,000 grains/cm^3. Pollen influx averages 11,000 grains/cm^2/yr. Charcoal is present throughout the zone, averaging 15 fragments/cm^3 and 0.4 fragments/cm^2/yr. THMI declines from 1.0 near the bottom to 0.71 at the top.

WalkL-3: Spruce-Western hemlock-Douglas-fir-Alder Zone
(397.5-302.5 cm; 8,800-6,900 ybp)

Alnus and *Pseudotsuga* attain highest values of any zone, averaging ca. 51% and 3% respectively, whereas *P. contorta* (ca. 6%) and *T. mertensiana* (<1%) decrease to the lowest levels in the core. *Picea* and *Abies* are present at ca. 9% and 3% respectively. *T. heterophylla* rises from a low of ca. 6% near the bottom to ca. 15% near the top. Cupressaceae pollen is rare (<1%) but occurs throughout the zone. The NAP increases slightly from WalkL-2 to ca. 15%, consisting of Liliaceae (ca. 1%), Rosaceae (ca. 1%), *Pteridium* (ca. 3%), *Thelypteris*-type (beech fern; ca. 1%), and other ferns (ca. 7%).

Pollen concentration averages 565,000 grains/cm^3 with an unusually high value of 1,831,000 grains/cm^3 occurring at 342.5 cm depth. Pollen influx averages 29,000 grains/cm^2/yr. The concentration of charcoal increases from the preceding zone to an average of 21 fragments/cm^3. Charcoal influx also shows an increase to 1.0 fragments/cm^2/yr. Average DWHI (0.77) and THMI (0.03) reach the lowest of any zone. DWHI is lower in the bottom portion (0.66) of the zone relative to the top portion (0.85). THMI exhibits a similar trend increasing from an average of <0.01 near the bottom to 0.05 in the upper part.

WalkL-4: Spruce-Fir-Western hemlock-Alder Zone
(302.5-182.5 cm; 6,900-4,600 ybp)

T. heterophylla and *T. mertensiana* increase markedly from the preceding zone, averaging ca. 22% and ca 5% respectively. Other notable conifers include *Picea* (ca. 5%) and *Abies* (ca. 7%). *P. contorta* and Cupressaceae both increase throughout the zone from a low of ca. 3% and <1% near the bottom to a high of ca. 17% and 14% near the top respectively. Both *Pseudotsuga* (ca. 1%) and *Alnus* (ca. 30%) decrease from WalkL-3. The NAP percentage remains unchanged from WalkL-3, averaging ca. 15%. Ericaceae (<1%), Poaceae (ca. 1%), *Pteridium* (ca. 3%), and ferns (ca. 9%) comprise the majority of the NAP palynomorphs.

Pollen concentration (559,000 grains/cm^3) is comparable to WalkL-3, whereas pollen influx (39,000 grains/cm^2/yr) increases from the previous zone. Charcoal concentration increases from 21 to 31 fragments/cm^3 and several charcoal peaks are visible near the bottom of the zone. Charcoal influx increases to an average of 2.2 fragments/cm^2/yr. Both DWHI and THMI increase from WalkL-3, averaging 0.97 and 0.19 respectively.

WalkL-5: Western hemlock-Mountain hemlock-Cedar Zone
(182.5-0 cm; 4,600-0 ybp)

This zone is dominated by *T. heterophylla* (ca. 21%), *T. mertensiana* (ca. 7%), and Cupressaceae (ca. 13%). *P. contorta* increases from the previous zone to an average of ca. 13%, whereas *Picea* and *Abies* decrease slightly to ca. 3% and 5% respectively. *Pseudotsuga* and *Alnus* continue to decrease from the preceding zone to <1% and ca.

21% respectively. NAP remains unchanged, averaging ca. 15%. The NAP mainly consists of *Pteridium* (ca. 3%) and ferns (ca. 9%). Ericaceae, Caryophyllaceae (Pink Family), Rosaceae, *Artemisia*, and Poaceae are rare (<1%) and occur intermittently throughout the zone.

Pollen concentration averages 415,000 grains/cm^3, whereas pollen influx averages 18,000 grains/cm^2/yr. The average charcoal concentration decreases to 24 fragments/cm^3, with a peak of 65 fragments/cm^3 occurring at 22.5 cm depth. The average influx of charcoal decreases to 1.0 fragments/cm^2/yr. DWHI is similar to WalkL-4, averaging 0.98, whereas THMI increases to an average of 0.24.

Interpretation

P. contorta pollen percentages are high in WalkL-1 suggesting *P. contorta* stands occurred during this interval. However, because *P. contorta* pollen is overrepresented (Hebda and Allen, 1993; Allen et al., 1999) and pollen concentration values are low in this zone, it is likely that the stands were open. The percentages of *Picea*, *Abies*, *T. heterophylla* and *T. mertensiana* pollen suggest these trees grew nearby, possibly as scattered individuals or in isolated clusters (Allen et al., 1999). The *Abies* pollen may represent *A. lasiocarpa* (Allen, 1995) or *A. amabilis*. The low pollen concentration is consistent with open woodlands.

The lack of charcoal indicates fires were absent. The presence of *P. contorta* stands suggests climate was cold (Hebda, 1995). The mixed character of the forest including *Picea* and *Abies* suggest climate was also moist and cool-cold. The local lack of *T. heterophylla* (THMI 0.88) further suggests climate was cool. Abundant winter snow may have characterised the site, as evident by the autecological characteristics of *T. mertensiana* and *A. lasiocarpa* (Alexander et. al, 1990; Means, 1990).

In Walk-2, closed mixed conifer forests containing *Picea*, *Abies*, and *T. mertensiana* possibly with *P. contorta* replaced the late glacial *P. contorta* woodlands. Closed mixed conifer forests may have developed later in the interval because *T. mertensiana* is a shade-tolerant, minor climax species (Means, 1990) and *Picea* is a shade-tolerant late seral species (Harris, 1990). Patches of *Alnus* probably grew in open or disturbed areas. The increase in *T. heterophylla* pollen values likely reveal that *T. heterophylla* trees spread to grow near the basin, likely in response to warming. *Salix* thickets and Cyperaceae fens occupied the wet zone next to the lake. Scattered but consistent occurrence of *Artemisia* and other Asteraceae may reflect open subalpine meadows near the basin. At this time, *Pteridium* must have been relatively abundant in the openings. The increase in pollen concentration is consistent with the expansion of conifers and the development of closed forests. A change at this time from clay to gyttja implies soil stabilisation, an increase in forest cover, and the development of humus cover and organic litter on the soil surface.

The increase in charcoal concentration and influx, coupled with the continuous deposition of charcoal, suggests fires were frequent. The occurrence of *T. mertensiana* suggests climate was cool and moist and *Picea* and *Abies* reinforce the interpretation of a moist climate. Expansion of *T. heterophylla* late in the zone suggests climate warmed but remained moist.

A pronounced change in forest structure and composition is evident in Walk-3. Relatively high *Pseudotsuga* and *Alnus* pollen values suggest that forests were open.

Picea trees remain an important component of the forest. Shade-tolerant *T. heterophylla* trees expand around the site at this time. *C. nootkatensis* or *T. plicata* trees occur consistently for the first time, but were a minor forest element. The abundance of *T. mertensiana* and *Abies* trees decline at this time. The mixture of shade-tolerant and intolerant taxa suggests open and closed forests coexisted with *Pseudotsuga* dominated forests occupying dry sites and *Picea-T. heterophylla* forests occupying moist areas. Soil moisture likely varied from xeric on dry outcrops in the open communities to mesic in the closed. Liliaceae and Rosaceae grew in open areas, perhaps around the lake margin, whereas *Thelypteris*-type and other ferns persisted in moist understories. *Pteridium* continued to occupy open dry sites.

The continuous charcoal records suggest fires burned frequently but the lack of any charcoal peaks suggests fire intensity did not vary significantly. Expansion of *Pseudotsuga* suggests climate was warm and dry. *Picea* and *T. heterophylla* trees suggest climate was warm but that moist areas existed. The decline in *T. mertensiana* provides additional evidence for a warm, dry climate at this time.

Distinct changes in forest composition occurred at the beginning of WalkL-4. Increased *T. heterophylla*, *T. mertensiana*, and *Abies* values and lower *Pseudotsuga* and *Alnus* values, reflect more moist and possibly more closed forests. Increased Cupressaceae, likely both *T. plicata* and *C. nootkatensis*, values also suggest a moister condition. The increase in *P. contorta* is related to wetland expansion and colonisation of bog surfaces. Modern-day vegetation understory began to develop as evident by an increase in ericaceous pollen.

Charcoal deposition continued reflecting frequent fires. Several charcoal peaks near the bottom of the zone likely represent intense fire events. A distinct sand horizon near a charcoal peak at ca. 225 cm depth may represent landscape erosion following an intense fire that removed vegetation cover. The increase in *T. heterophylla* and *T. mertensiana* suggests climate cooled and moistened relative to the preceding zone. The increase in cupressaceous pollen indicates conditions became progressively more moist and possibly cooler. The decline in *Pseudotsuga* pollen likely reflects cooler, moister conditions and possibly the development of more hydric soils.

Extant forests dominated by *T. mertensiana*, *T. heterophylla*, and Cupressaceae were established in WalkL-5 at 4,600 ybp, reflecting cool, moist conditions. An increase in *P. contorta* suggests wetlands continued to expand, likely by paludification. *Picea* and *Abies* became minor forest elements. *Alnus* likely grew in open sites around the basin. *Pseudotsuga* no longer grew near the basin but likely occupied areas at lower elevation. Ericaceous and rosaceous plants likely formed an extensive shrub community around the basin. Slower sedimentation rates at this time may reflect decreased productivity associated with a cool climate. Pollen concentration decreases from the preceding zone, suggesting that the forests remained relatively closed but open areas (wetlands) were more common or that the trees produced less pollen.

Although charcoal was deposited continuously throughout the zone, a reduction in charcoal concentration and influx suggests fires burned less intensely or were spatially more limited. The reduction in charcoal may also represent wetland expansion around the basin and the interception of charcoal washing into the basin. Continued high levels of *T. mertensiana* and *T. heterophylla* coupled with an increase in Cupressaceae suggest climate was cool and moist. An increase in Cyperaceae late in the zone likely reflects wetland expansion at the lake margins and a cool, wet climate.

CHAPTER 11: ENOS AND BOOMERANG LAKES

Study sites

Enos Lake is located at 49°16'40" N and 124°09'15" W in the CDF zone (Figure 1). Enos Lake is about 1,400 m long and 200 m wide and is approximately 50 m asl. Forests dominated by *Pseudotsuga* and *A. grandis* coupled with an understory dominated by *G. shallon* grow to the lake edge. Boomerang Lake occurs at 49°10'30"N and 124°09'W in the CWHxm zone (Figure 1). Boomerang Lake is about 750 m long and 100 m wide and is approximately 360 m asl. Scattered *Pseudotsuga* trees with fire scars and *Alnus* grow around Boomerang Lake. The understory at the lake margins is dominated by *G. shallon* and *Ledum groenlandicum* Oeder (Labrador tea).

Enos Lake

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The 1,000 cm core from Enos Lake begins in fine grey sand that was deposited before ca. 12,840 ybp from 1,000-995 cm depth (Figure 14; Table 12). Grey clay containing shell fragments was deposited from before 12,840 ybp to ca. 11,620 ybp and occurs between 995-820 cm. A gradational boundary is evident at 820-810 cm as the clay is replaced by gyttja, which is present from 810-0 cm depth representing the interval from ca. 11,620 ybp-present.

A total of 9 bulk sediment ^{14}C dates were obtained from Beta Analytic, Florida (Table 12). These dates agree chronostratigraphically with each other and were used to determine sedimentation rates (Table 13). The sedimentation was rapid at Enos Lake during the late glacial and late Pleistocene (0.100 cm/yr). During the early Holocene,

Figure 14. Enos Lake charcoal diagram (outline x10).

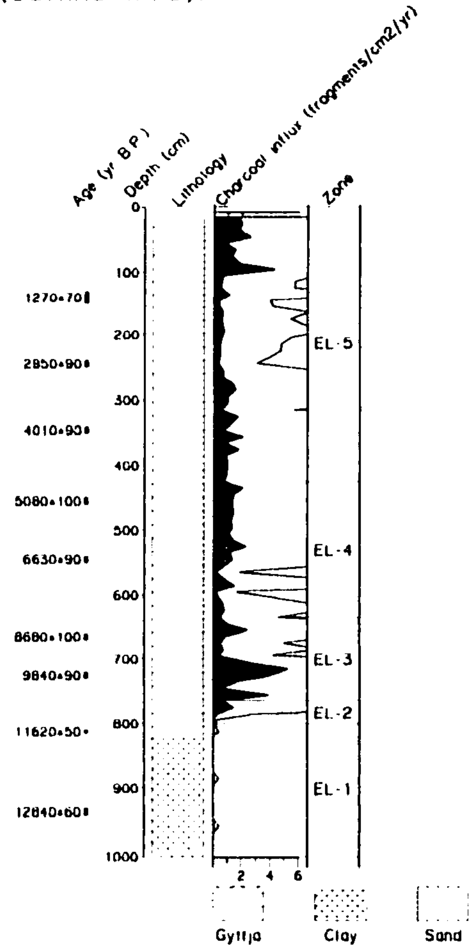


Table 12. Bulk ^{14}C sediment dates from Enos Lake.

Sample Number	Sediment Type	Sample Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-91202	Gyttja	130-150	1,270±70
Beta-91203	Gyttja	240-250	2,950±90
Beta-91204	Gyttja	340-350	4,010±90
Beta-91205	Gyttja	450-460	5,080±100
Beta-91206	Gyttja	540-550	6,630±90
Beta-91207	Gyttja	660-670	8,680±100
Beta-91208	Gyttja	720-730	9,840±90
Beta-91209	Gyttja	810-815	11,620±50
Beta-91210	Gyttja	930-940	12,840±60

Table 13. Characteristics of the Enos Lake sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-140	1,270	0.110	Gyttja
140-245	1,680	0.062	Gyttja
245-345	1,060	0.094	Gyttja
345-455	1,070	0.103	Gyttja
455-545	1,550	0.058	Gyttja
545-665	2,050	0.058	Gyttja
665-725	1,160	0.052	Gyttja
725-812.5	1,780	0.049	Gyttja
812.5-935	1,220	0.100	Clay

sedimentation decreased to the lowest rate throughout the core (0.049 cm/yr) and then increased throughout the mid and late Holocene (0.052-0.103 cm/yr). The most rapid sedimentation rates occur with the upper 150 cm.

Charcoal Zones

Charcoal accumulation was determined for Enos Lake according to methods outlined in Chapter 3. Five charcoal zones (EL-1 to EL-5) were recognised for the sequence (Figure 14).

Charcoal Zone EL-1
(1,000-800 cm; >12,840-11,200 ybp)

Charcoal was absent from this zone, although black mineral and rock fragments were visible within the clay.

Charcoal Zone EL-2
(800-765 cm; 11,200-10,650 ybp)

Charcoal concentration increases in this zone from a low of 5 fragments/cm^3 near the bottom to a high of 30 fragments/cm^3 near the top. Charcoal influx averages 0.6 fragments/cm^2/yr.

Charcoal Zone EL-3
(765-635 cm; 10,650-8,200 ybp)

The concentration of charcoal fragments increases considerably from the preceding zone, attaining a maximum value of 100 fragments/cm^3 and averaging 36 fragments/cm^3. Charcoal influx also increases to an average of 1.9 fragments/cm^2/yr.

The lower part of the zone is characterised by more charcoal (averaging 60 fragments/cm^3 and 3.0 fragments/cm^2/yr) than the upper part (averaging 17 fragments/cm^3 and 0.9 fragments/cm^2/yr).

Charcoal Zone EL-4
(635-425 cm; 8,200-4,800 ybp)

Charcoal concentration decreases from the preceding zone to an average of 18 fragments/cm^3 and ranges between 3-40 fragments/cm^3. Charcoal influx averages 1.2 fragments/cm^2/yr. The lower part of the zone shows relatively more variation in charcoal concentration compared to the upper part of the zone, which is characterised by a relatively stable level of ca. 20 fragments/cm^3 and 1.3 fragments/cm^2/yr.

Charcoal Zone EL-5
(425-0 cm; 4,800 ybp-present)

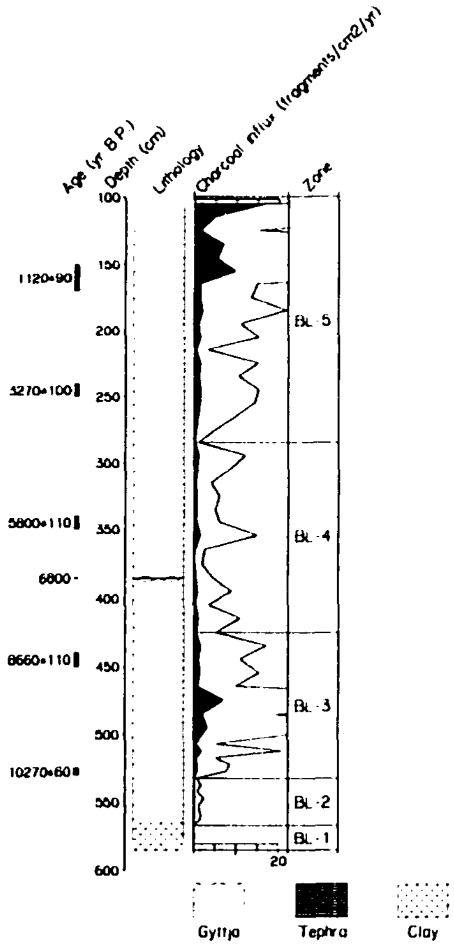
Zone EL-5 is characterised by a general decrease in charcoal relative to the zone EL-4. Charcoal concentration in zone EL-5 averages 12 fragments/cm^3, whereas charcoal influx averages 1.1 fragments/cm^2/yr. A noticeable increase in charcoal occurs in the top 100 cm as concentrations attain values as high as 39 fragments/cm^3 and influx reaches 4.3 fragments/cm^2/yr.

Boomerang Lake

Stratigraphy, Radiocarbon Dates, and Sedimentation Rates

The sediment core collected from Boomerang Lake is 585 cm long (Figure 15). Grey clay and pebbles that were deposited before 10,270 ybp characterise the core from

Figure 15. Boomerang Lake charcoal diagram (outline x10).



585-564 cm (Table 14). Gyttja was deposited before 10,270 ybp-present and occurs between 564-100 cm. A tephra layer at 386-385 cm is believed to be Mazama Ash (Bacon, 1983) because of its stratigraphic position between ^{14}C dates of 5,800±110 and 8,660±110 ybp. The upper 100 cm of the core was poorly consolidated and not retrieved, although traces of sediment in the corer confirm that gyttja was present between 100-0 cm depth.

A total of 5 ^{14}C dates were obtained for Boomerang Lake from Beta Analytic, Florida (Table 14). The presence of Mazama Ash provides another stratigraphic marker of 6,800 ybp (Bacon, 1983). In general, the sedimentation rate at Boomerang Lake (Table 15) was relatively low (0.031-0.051 cm/yr) throughout the early and mid Holocene and increased during the late Holocene (0.142 cm/yr). Late glacial sedimentation rates are unknown because no ^{14}C dates were obtained from the deepest core section.

Charcoal Zones

The influx of charcoal fragments was analysed for the entire post-glacial sequence, excluding the top 100 cm. Core zoneation recognised 5 zones (BL-1 to BL-5) in Boomerang Lake (Figure 15).

Charcoal Zone BL-1
(585-567.5 cm; >10,270 ybp)

Charcoal is essentially absent from this zone and only 1 charcoal fragment was identified at 575-570 cm depth.

Table 14. Bulk ^{14}C sediment and tephra dates from Boomerang Lake.

Sample Number	Sediment Type	Depth (cm)	Conventional ^{14}C Date (ybp)
Beta-91211	Gyttja	150-170	1,120±90
Beta-91212	Gyttja	240-250	3,270±110
Beta-91213	Gyttja	340-350	5,800±110
	Tephra	385-386	6,800
Beta-91214	Gyttja	440-460	8,660±110
Beta-91215	Gyttja	525-530	10,270±60

Table 15. Characteristics of the Boomerang Lake sediment core.

Depth Interval (cm)	Duration (yrs)	Sedimentation Rate (cm/yr)	Sediment Type
0-160	1,120	0.142	Gyttja
160-245	2,150	0.040	Gyttja
245-345	2,530	0.040	Gyttja
345-385.5	880	0.046	Gyttja
385.5-445	1,940	0.031	Gyttja
445-527.5	1,610	0.051	Gyttja

Charcoal Zone BL-2
(567.5-532.5 cm; >10,270 ybp)

The concentration of charcoal increases slightly at the beginning of this zone, averaging 3 fragments/cm^3. Charcoal influx also increases slightly to an average of 0.1 fragments/cm^2/yr. Charcoal concentration and influx show little variability throughout the zone.

Charcoal Zone BL-3
(532.5-425 cm; >10,270-8,100 ybp)

A conspicuous increase in charcoal occurs in Zone BL-3 in which the average concentration rises to 37 fragments/cm^3 and the average influx increases to 1.8 fragments/cm^2/yr. The concentration of charcoal ranges between 10-139 fragments/cm^3 with a notable peak at 475 cm depth. The influx also ranges considerably from 0.5-7.1 fragments/cm^2/yr.

Charcoal Zone BL-4
(425-285 cm; 8,100-4,300 ybp)

Average charcoal concentration and influx decreases in zone BL-4 compared to BL-3. Concentration values show little variability relative to the preceding zone and average 17 fragments/cm^3, whereas influx averages 0.6 fragments/cm^2/yr. Notably, there are no conspicuous peaks.

Charcoal Zone BL-5
(285-0 cm; 4,300 ybp - present)

Charcoal concentrations increase throughout zone BL-5 from 13 fragments/cm^3 at the bottom of the zone to a high of 118 fragments/cm^3 at the top. The charcoal concentration averages 38 fragments/cm^3. Influx increases similarly from 0.5 fragments/cm^2/yr at the bottom to 16.8 fragments/cm^2/yr at the top and averages 3.3 fragments/cm^2/yr.

Interpretation

The charcoal records from Enos and Boomerang lakes indicate that fires were absent or infrequent and weak on the late glacial landscape. Sedimentation rates were high at this time, likely because unconsolidated glacial sediments were widespread and forest cover was incomplete. The first fires appear to have occurred during the late Pleistocene at about 11,500 ybp. The low-moderate yet continuous concentration and influx of charcoal suggests fires burned frequently and were either of low intensity or spatially restricted, possibly because natural fire breaks such as exposed outcrop were common or snow patches persisted later into the growing season.

During the early Holocene, the marked increase in charcoal suggests an increase in the incidence of fire. Perhaps frequent, high intensity fires occurred at this time. The increase in charcoal also suggests that the fires may have been more widespread because climate was warmer and drier (Allen, 1995; Hebda, 1995; Heinrichs et al., 1999). At the same time, the relatively low sedimentation rates may reflect the development of continuous vegetation cover around the lakes.

A decrease in charcoal concentration and influx during the mid Holocene at both sites suggests fewer fires and a reduction in fire intensity, likely because climate moistened (Hebda, 1995). Sedimentation rates that are similar to the early Holocene provide additional evidence for an actual decrease in fires because less charcoal must have entered the basin in a comparable amount of time.

The late Holocene fire history differs slightly at Enos and Boomerang lakes. At Enos Lake, a further decrease in charcoal from ca. 4,800-1,200 ybp suggests fewer fires, likely because climate was cooler and moister relative to earlier Holocene intervals (Allen, 1995; Hebda, 1995). The increase in charcoal at ca. 1,200 at Enos Lake is interesting because it implies an increase in fires even though climate was cooling and moistening, suggesting non-climatic factors such as human landscape modification may be responsible. A similar pattern of increasing charcoal is evident at Boomerang Lake from 4,300 ybp-present. The continuous deposition of charcoal at both sites during the mid and late Holocene suggests fires burned relatively frequently during these intervals compared to sites on the wet western side of Vancouver Island (Brown and Hebda, 1998a,b).

CHAPTER 12: REGIONAL SYNTHESIS

Introduction

The records retrieved during this study provide insight into the landscape history of southern Vancouver Island. In this section, the lowland records will be compared along a precipitation gradient and to other sites. High elevation sites will be similarly compared and contrasted to lowland sites along a temperature gradient. The comparison of sites is divided into three general areas of investigation including vegetation history, climate history, and fire history. Each subject will be explored starting with the oldest deposits and proceeding to the most recent, thus progressing from the last glaciation to present-day in each case.

The records from East Sooke Fen (ESF), Pixie Lake, and Whyac Lake provide critical insight into the vegetation and climate history along a precipitation gradient in the coastal rainforests of southwestern Vancouver Island and agree well with other late- and post-glacial vegetation reconstructions (Figure 16; Mathewes, 1973; Heusser, 1983; Hebda, 1983, 1995, 1997b; Allen, 1995). Of special interest, these records will also assist in defining the maximum Holocene extent of *Q. garryana* meadows and DWHI ratios will provide insight into the development of longitudinal precipitation gradients.

The pollen and spore records from Porphyry and Walker lakes provide the first record of the vegetation, fire disturbance, and climate history of high elevation forests on southern Vancouver Island. The reconstructed vegetation and climate sequences agree generally with other sites in coastal British Columbia (Mathewes, 1973; 1989; Hebda, 1983; 1995; 1997; Allen, 1995; Figures 12 and 16). The high elevation records provide additional information unavailable from lowland sites, including a well developed *T.*

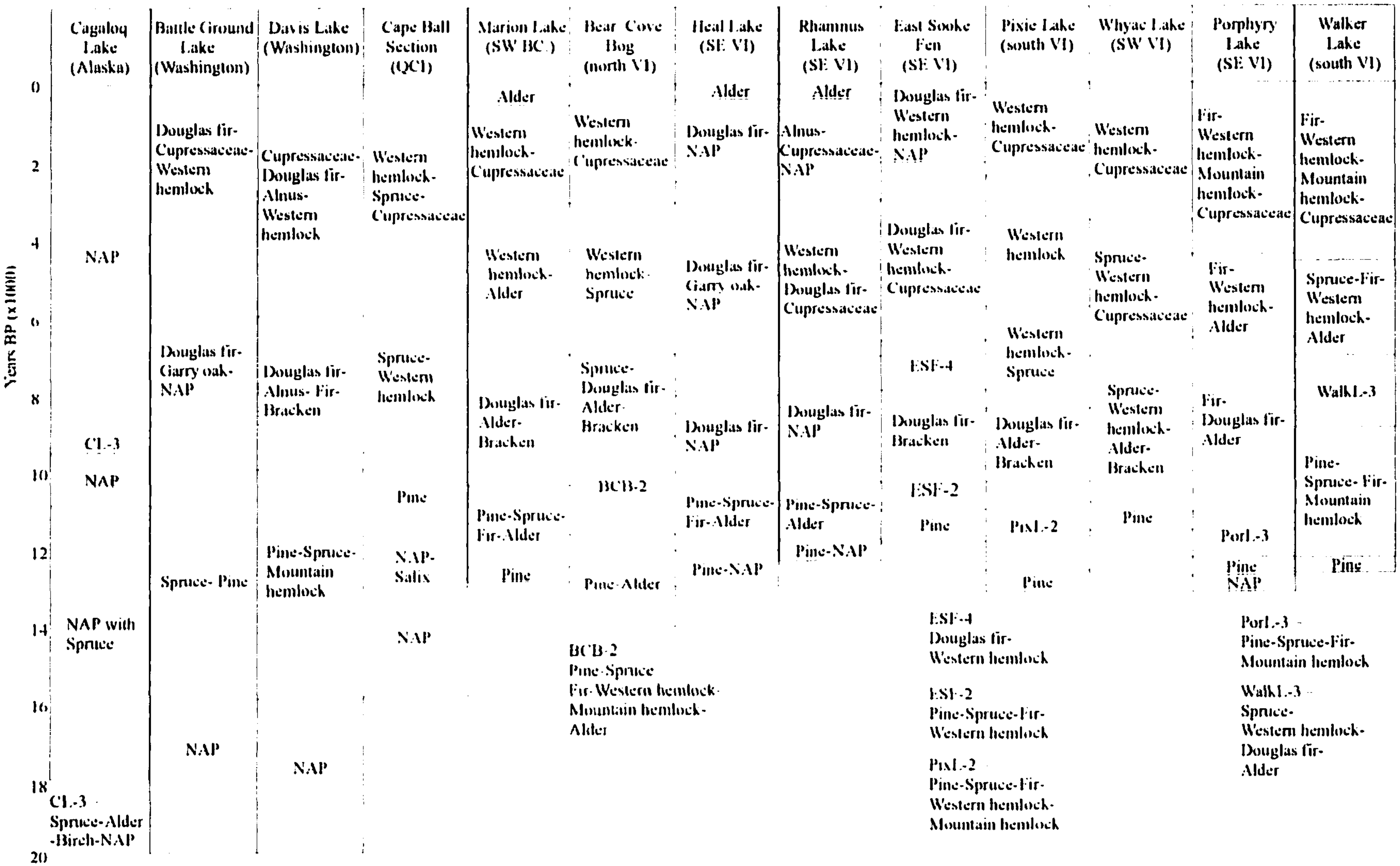


Figure 16. Summary of selected pollen sequences from the Pacific Northwest. The pollen zones are designated according to the major taxa present (QCI=Queen Charlotte Islands; BC=British Columbia; VI=Vancouver Island; SE=southeast; SW=southwest).

mertensiana record and a THMI-derived post-glacial temperature profile. The high elevation DWHI ratios provide additional precipitation records that complement those from lower elevation sites (Allen, 1995).

Charcoal records from aforementioned sites, coupled with those from Enos and Boomerang lakes provide insight into the post-glacial fire history of southern Vancouver Island. Comparison of the charcoal and pollen records at each site will be used to examine vegetation response to fire disturbance.

Regional Vegetation History

This section explores the vegetation history on southern Vancouver Island. In general, the vegetation that characterises each time interval will be described and then compared to other sites. The vegetation unit will then be interpreted as it applies to the development of the landscape.

Full-Early Late Glacial

The record begins with a NAP-dominated assemblage containing Asteraceae, *Artemisia*, Chenopodiaceae, Poaceae, and ferns with *P. contorta* and possibly *Alnus* at Porphyry Lake prior to 12,540 ybp. This assemblage must predate the *P. contorta* biogeochron that is recognised to have occupied deglaciated sites in coastal British Columbia (Hebda, 1995) and this is new to the region and atypical.

The composition of the NAP assemblage is comparable to modern alpine tundra in the Olympic Mountains (Heusser, 1977), modern herb tundra from islands located in the Bering Sea (Colinvaux, 1981), and to modern tundra from the Mackenzie Delta region in the Northwest Territories (Ritchie, 1974), suggesting a tundra or steppe-tundra ecosystem persisted at high elevations on southern Vancouver Island at the time. The pollen assemblage also resembles full-early late glacial assemblages from unglaciated regions south of the Cordilleran ice sheet (Heusser, 1977; Sugita and Tsukada, 1982; Barnosky, 1981, 1985a,b; Barnosky et al., 1987), northern refugia and Beringia (Cwynar and Ritchie, 1980; Colinvaux, 1981; Barnosky et al., 1987; Hu et al., 1995), a glacial refugium from Cape Ball on the Queen Charlotte Islands (Mathewes, 1989), and a site located within a segment of the "ice-free corridor" in southern Alberta (Mott and Jackson, 1982). The similarities between assemblages from unglaciated sites and Porphyry Lake suggest that the Porphyry Lake area may have been ice-free during the Vashon glacial maximum.

The concept of a glacial refugium on Vancouver Island is not new. Hebda (1997b) suggested that the Brooks Peninsula on northwestern Vancouver Island was likely unglaciated, citing a late glacial NAP enriched assemblage at Cassiope Pond, the presence of endemic taxa such as *Ligusticum calderi* Mathias & Const. (Calder's lovage; a restricted ocean species), and the occurrence of *T. mertensiana* trees in late glacial *P. contorta* dominated vegetation as evidence. In describing the composition of the flora of modern nunataks in the Juneau Ice Field, Heusser (1989) noted lichens, bryophytes, ferns, *P. sitchensis*, heath mats, and sedge-grass turf with *T. mertensiana* at lower elevations, an observation generally consistent with inferred vegetation based on the pollen and spore records from Porphyry Lake and Brooks Peninsula.

The area around Porphyry Lake may have escaped glaciation because it is situated on a small plateau that is partially surrounded by small valleys that likely channelled glaciers downslope and away from high elevations. A comparable NAP-dominated assemblage did not occur at Walker Lake possibly because this site is located closer to the Pacific Ocean and likely received more snow which may have persisted in a nivation hollow almost year round.

The timing of the tundra-like assemblage at Porphyry Lake cannot be absolutely placed at full-late early glacial time because no ^{14}C data for the assemblage is available. All that is certain is that the assemblage occurred before 12,540 ybp and before the regional *P. contorta* zone. The *P. contorta* biogeochron was established at ca. 14,000 ybp at Bear Cove Bog (Hebda, 1983), ca. 13,000 ybp at Pyrola Lake (Hebda, 1997b), >12,990 ybp at Pixie Lake, and >12,350 ybp at Marion Lake (Mathewes, 1973). The observation that *P. contorta* pollen is regionally overrepresented provides additional support that the NAP zone at Porphyry Lake cannot be contemporaneous with other *P. contorta* zones because the NAP signal is pronounced, as opposed to being masked by the regional *Pinus* signal.

An alternate explanation is that the NAP assemblage represents a tundra ecosystem that quickly colonised exposed mineral soils following the downwasting of high elevation ice during deglaciation (Clague, 1991). Certainly the lack of >13,000 ybp ^{14}C dates in the region and widespread distribution of diamictons and glaciofluvial deposits (Halstead, 1968; Clague, 1976; Alley and Chatwin, 1979; Howes, 1981; Herzer and Bornhold, 1982; Huntley et al., in press) suggest southern Vancouver Island was extensively glaciated sometime in the past. Indeed, diamictons and tills occur around Porphyry Lake. However, examination of porphyritic clasts in these deposits reveals that extensive weathering of plagioclase phenocrysts (up to a depth of 2cm and creating a vesicular appearance) has occurred (Figure 17). The degree of weathering is exceptional and indeed unlike anything observed in the region previously, thus suggesting a long period of weathering and supporting the concept of ice-free conditions. Southern Vancouver Island is near the southern limits of Vashon glaciation and it is conceivable that unglaciated areas persisted during the Vashon glaciation. The interpretation of the site does not dispute the fact that southern Vancouver Island has been glaciated in the past, but rather questions when that glaciation occurred and how extensive the Vashon glaciation was.

A stratigraphic section near Langford Lake (Figure 1), Vancouver Island may contain the necessary evidence to help resolve the issue of glaciated versus non-glaciated landscapes on southern Vancouver Island (Hebda et al., 1999a). Gray clay of uncertain origin characterises the base of this section. An eolian sand deposit that is dated at about 12,400 ybp and containing *Dryas* leaves and a pollen assemblage consisting mainly of *Alnus*, *Salix*, Caryophyllaceae, and Rosaceae occurs above the clay. The sand unit is followed by fluvial silts and sands showing occasional convoluted structures. An ancient forest floor with *in situ P. sitchensis* stumps dated at 12,400 ybp appears near the top of the section. Do the *Dryas* leaves represent tundra environments during the full-early late glacial or is this deposit much younger as suggested by the ^{14}C dates and convoluted silts and sands? Perhaps they represent pioneering *Dryas* shrubs on river bars in a rapidly aggrading fluvial system. Terasmae and Fyles (1959) identified *P. contorta* pollen and *Dryas drummondii* Richards. in Hook. (yellow mountain-avens) leaves occurring together within a stratigraphic unit from the Englishman River section on Vancouver Island that was dated at 12,000 ybp, suggesting the plants coexisted at this time, possibly

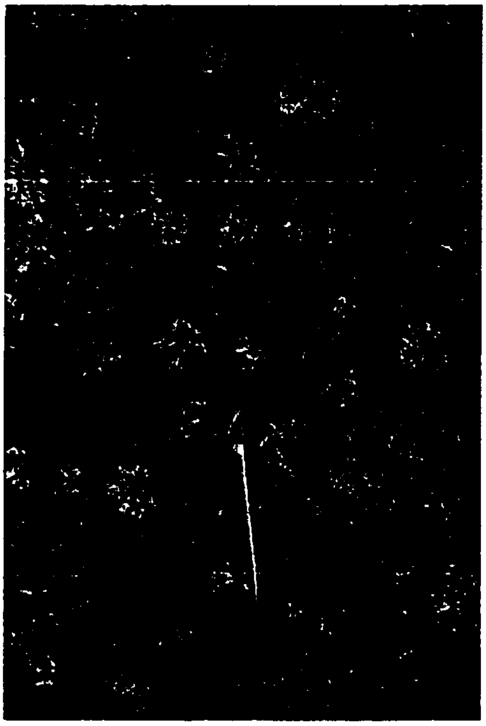


Figure 17. Porphyry clast collected from diamicton near Porphyry Lake. The plagioclase phenocrysts are weathered relative to the basaltic matrix. The toothpick is about 5cm long.

as primary colonisers following deglaciation. Further work is still required to answer these questions and possibly resolve the timing and extent of Vashon glaciation on southern Vancouver Island.

Late Glacial

Following regional deglaciation, the regional landscape on southern Vancouver Island was relatively unstable because of sea-level fluctuations (Clague, 1989; Anundsen et al., 1994) and fluvial sediment transport (Clague, 1991). Other notable landscape features at this time include soil maturation and recolonisation by displaced flora and fauna (Hebda, 1995). Pollen records from ESF and Pixie and Whyac lakes suggest that *P. contorta* woodlands colonised southern Vancouver Island following deglaciation. Hebda and Allen (1993) showed that *Pinus* is typically overrepresented by 15-80% and surface samples from southern Vancouver Island suggest *Pinus* is overrepresented by up to 45%, suggesting the early stages of the *P. contorta* biogeochron may have been open.

Shepherdia, *Artemisia*, Poaceae, ferns, and *Cryptogramma* occupied the openings at ESF and Pixie and Whyac lakes. The small amount of underrepresented *Picea*, *T. mertensiana*, and Cupressaceae, possibly *Juniperus*, pollen (Hebda and Allen, 1993; Allen et al., 1999) suggests these taxa were growing near the sites too. *Alnus* occurs at all three sites, however, according to Hebda and Allen (1993), Allen et al. (1999), and this study *Alnus* is overrepresented in the pollen spectra, suggesting that *Alnus* may have constituted a minor component of the *P. contorta* woodlands. The composition of the *P. contorta* biogeochron at ESF and Pixie and Whyac lakes is comparable to many other sites on Vancouver Island such as Heal, Rhamnus, and Pyrola lakes and on the adjacent mainland such as Marion Lake (Figure 1). The *P. contorta* biogeochron at Kalmia Lake (Hebda, 1997b), however, does not contain a well developed NAP component.

At the high elevations of Porphyry and Walker lakes *P. contorta* woodlands developed quickly on the late glacial landscape. Marked percentages of *Picea*, *Abies*, and *T. mertensiana* pollen occur at this time. Hicock et al. (1982) reported that *Picea engelmannii* Parry ex Engelm. (Engelmann spruce) and *A. lasiocarpa* were present in the Fraser Lowland at 18,000 ybp and Whitlock (1992) found that these species were present in the Puget Trough and the southern Fraser Lowland during the late glacial. The proximity of these areas to southern Vancouver Island, coupled with the discovery of an *A. lasiocarpa* needle in late glacial sediments from Rhamnus Lake (Allen, 1995), suggests that these two species grew with *P. contorta*. At this time, *Artemisia* and Poaceae persisted in open areas, whereas Cyperaceae and *Sparganium* (bur-reed) occupied moist areas around and in the lake basins respectively. Although *Artemisia* pollen may originate from several different sources (Barnosky, 1985a; Whitlock, 1993), the association of *Artemisia* pollen with pollen from cold adapted trees suggests *A. norvegica* (Alaback et al., 1994) may have been present.

An interesting aspect of the *P. contorta* woodlands is that after regional deglaciation they formed a regional biogeochron (Hebda and Whitlock, 1997) along the coast from Alaska to Oregon. But where did these woodlands come from and how did they cover such a large area in a relatively short time interval? Hebda (1983) showed that *P. contorta* was first present on northern Vancouver Island from at least 14,000-11,500 ybp and proposed *P. contorta* originated from a coastal mountain refugium or a now-submerged coastal plain. At Pixie Lake, the *P. contorta* biogeochron lasted more than

400 years and ended at approximately 12,600 ybp. The *P. contorta* biogeochron at ESF persisted for at least 300 years and ended much later at approximately 11,400 ybp, whereas at Whyac Lake, the *P. contorta* biogeochron spanned an unknown time period and ended prior to a basal ^{14}C date of 10,860 ybp. The *P. contorta* biogeochron persisted at Porphyry Lake for only about 200 years from ca. 12,500-12,300 ybp, whereas at Walker Lake *P. contorta* woodlands existed for an unknown length of time ending at ca. 12,200 ybp. The apparent earlier occupation of the Pixie Lake site by *P. contorta* may reflect the migration of taxa occupying continental shelf refugia during low sea levels (Hebda, 1983). In comparison, nearby lowland sites on southeastern Vancouver Island such as Heal and Rhamnus lakes exhibited *P. contorta* woodlands from at least ca. 12,840-11,900 and 12,100-11,800 ybp respectively.

These general differences in spatial and temporal distribution of the *P. contorta* woodlands may serve as a new technique for determining the deglacial history of coastal regions in the Pacific Northwest. Perhaps *P. contorta* occupied northern and western coastal areas prior to other sites on Vancouver Island because it persisted on a continental shelf refugium during full-early late glacial conditions (Hebda, 1983) and then quickly colonised newly-exposed sites as climate warmed, glaciers retreated, and sea levels rose. High elevation sites were colonised early because glacial downwasting exposed upland areas (Clague, 1991). Low-lying inland areas were colonised by *P. contorta* after coastal and upland sites because they were last to be deglaciated, located further from coastal refugia, and perhaps needed to undergo an interval of soil development.

Comparison of records from southern Vancouver Island reveals that lowland sites appear to have supported more *P. contorta* and less *Picea*, *Abies*, and *T. mertensiana* than high elevation sites (Allen, 1995). The difference in conifer abundance may be related to the earlier exposure of high elevations than low elevations (Clague, 1991) which resulted in earlier soil development at high elevations. This process enabled cold-adapted conifers to colonise high elevations even though valley glaciers may have still persisted. If, indeed, colonisation of high elevation sites by mixed conifers occurred when valley glaciers were still at low elevations, then it suggests that regional climate and the development of soils was a more important factor governing vegetation distribution than the propinquity of glaciers. This observation is consistent with Whitlock's (1992) conclusion that large scale changes in atmospheric circulation were more critical in determining the distribution of taxa than the proximity of local glaciers. The differences between high and low sites may alternatively be the result of high elevations receiving more precipitation than low elevations or that lower summer temperatures at high elevations resulted in less drying. Such relatively moister climates might favour conifers such as *Abies* and *Picea* over *P. contorta*.

Further comparison of sites reveals that the abundance of *Salix* and *Shepherdia*, both good indicators of soil instability possibly associated with primary succession, is greater at Marion Lake (Figure 1; Mathewes, 1973) than at any site on southern Vancouver Island during the *P. contorta* biogeochron. This difference may be related to differences in glacial history. Perhaps some sites on Vancouver Island record less *Salix* and *Shepherdia* because they were not glaciated but were instead subject only to periglacial conditions followed by secondary succession on more stable soils.

The presence of *Shepherdia*, a nitrogen fixer, at ESF and Pixie Lake and the presence of mineral dominated sediment in the basal portions of all cores suggests unstable soils and widespread exposed mineral surfaces. These soils likely were easily erodable, washed into depositional basins, and the residual soils coarser-grained which likely favored early seral xeric taxa. It is therefore possible that the *P. contorta* woodlands represent edaphic climax associated with post-glacial primary succession.

At Whyac Lake, an unusual mixed conifer zone with *Picea* and *T. heterophylla* accompanied by relatively high *Alnus* occurs within the *P. contorta* biogeochron and persists for an undetermined interval. The origins and reasons for the occurrence of this unit are unclear and possibly associated with the Younger Dryas cooling event. In eastern Canada, Mayle et al. (1993) suggest an *Alnus* signal was produced during Younger Dryas cooling. The high *Alnus* values in the mixed conifer unit at Whyac Lake may have resulted from solifluction disturbance during a Younger Dryas-like cooling. Lithological evidence supporting this interpretation is the presence of a coarse grained sand unit, possibly representing a colluvial deposit. Mathewes (1993) used the presence of a *T. mertensiana* peak at several sites in the Pacific Northwest as an indication of Younger Dryas. *T. mertensiana* is present throughout the Whyac Lake zone, suggesting possible Younger Dryas origins. However, chronostratigraphic data shows the unit occurred before a ^{14}C date of 10,860 ± 130 ybp and is therefore likely older than Younger Dryas. Alternatively, subzones WhyL-1a and WhyL-1b may represent an error in field sampling and recording of depths of sediment, with the similar assemblages of WhyL-1a and WhyL-1c separated by a section of WhyL-2 type material (Figure 11). However, the lack of charcoal in WhyL-1b compared to WhyL-2 coupled with the differences in sediment type and *P. contorta* percentages suggest different intervals of time. Perhaps the WhyL-1b zone represents late Pleistocene mixed conifer forests, whereas zone

WhyL-2 represents early Holocene vegetation. If, however, the pollen zones are considered as being in correct stratigraphic sequence then Whyac Lake underwent late glacial vegetation change unlike any other coastal region in British Columbia (Hebda, 1995).

Late Pleistocene

The end of the Pleistocene on southern Vancouver Island is characterised by mixed conifer forests containing mainly *Picea*, *Abies*, *T. heterophylla*, and *T. mertensiana* with *Alnus* in the lowlands and *Picea*, *Abies*, and *T. mertensiana* with *Alnus* at high elevations. *P. contorta* apparently remained an important component of these forests, though some of the *Pinus* pollen may have come from stands on dry sites. Allen (1995) demonstrated that *A. lasiocarpa* occurred at Rhamnus Lake (Figure 1), suggesting the *Abies* pollen came from this species and not *A. amabilis* or *A. grandis*.

The reduction in *P. contorta*, coupled with the increase in shade-tolerant taxa such as *Abies*, *Picea*, *T. heterophylla*, and *T. mertensiana*, suggests closure of the forest canopy. An increase in pollen concentration also suggests these forests were more closed and productive than the preceding *P. contorta* woodlands. ESF and Pixie, Porphyry, and Walker lakes show Rosaceae and *Pteridium* were present periodically throughout the late Pleistocene, perhaps representing the development of canopy gaps by disturbances such as fire, which appears for the first time in this zone.

The change in forest dominants from *P. contorta* to a mixture of conifers may reflect a migration lag by slower species colonising a landscape that now contained no local ice masses (Hicock et al., 1982) and was experiencing a changing climate and soil maturation (Hebda, 1995). Disappearance of *P. contorta* woodlands first occurred at Pixie Lake then at Porphyry and Walker lakes, and finally at ESF and Whyac Lake (Figure 16). This pattern may reflect the migration of conifers such as *Picea*, *Abies*, and *T. heterophylla* along an exposed coastal plain under maritime influence, possibly crossing from the Olympic Peninsula to southwestern Vancouver Island (i.e. Pixie Lake) and then expanding both eastward and northward. *T. mertensiana* may have similarly migrated north along the western side of the Coast Mountains. This interpretation is consistent with the later arrival of mixed conifer taxa at Rhamnus and Heal lakes (Allen, 1995) to the east and Pyrola and Kalmia lakes (Hebda, 1997b) and Bear Cove Bog (Hebda, 1983) to the north (Figure 16). Perhaps these forests arrived earlier at Porphyry Lake compared to other eastern sites because this area already had well developed soils.

The mixed conifer assemblage at Pixie Lake was present for 2,400 years and ended at approximately 10,200 ybp, whereas at Walker Lake it lasted for > 3,400 years from >12,240-8,800 ybp. The WhyL-1b assemblage (Figure 11) may represent the mixed conifers at Whyac Lake, which persisted for an unknown interval. The mixed conifer forests at ESF persisted for approximately 1,500 years and disappeared at 9,900 ybp. These forests persisted at Porphyry Lake for 1,000 years from 12,300-11,300 ybp. Examination of other low elevation records from Vancouver Island (Hebda, 1983, 1997b; Allen, 1995) show that the mixed conifer forests were widespread during the late Pleistocene, although the mixed conifer forests at Heal and Rhamnus lakes contain less *Picea*, *Abies*, and *T. heterophylla*. At Bear Cove Bog in the north, these mixed conifer forests lasted for 2,700 years from 11,500-8,800 ybp, whereas in the northwest they persisted for ca. 1,500 years at Kalmia Lake from 12,000-10,500 ybp. On southeastern

Vancouver Island, mixed conifers occurred at Rhamnus and Heal lakes for ca. 1,200-1,900 years between ca. 11,900-10,000 ybp.

The difference in longevity of the mixed conifer forest biogeochron may be related to the diminished influence of dry easterly winds originating from an anticyclonal high pressure cell situated over the Laurentide icesheet (Andersen et al., 1988), intensification of moist westerly winds, and local rainshadow effects, although errors in ^{14}C dating cannot be ruled out. As the Laurentide ice-sheet melted, the influence of cold dry easterly winds on southern Vancouver Island decreased, whereas the influence of moist westerly surface winds increased. Pixie and Walker lakes are located further west than ESF and Porphyry Lake in an area that intercepts westerly weather systems and receives abundant precipitation. The lowland sites and Porphyry Lake likely dried and experienced increased summer warmth during the early Holocene solar maximum prior to Walker Lake because they are either located further from the Pacific Ocean or at lower elevations (Anderson, 1988; Koerner and Fisher, 1990). The interception of precipitation at Walker Lake enabled moisture requiring mixed conifer forests to persist into the Holocene, whereas early Holocene warming and drying led to the decline of the mixed conifer forests elsewhere on southern Vancouver Island. These data suggest that the weather systems and east-west precipitation gradient that presently characterise southern Vancouver Island originated during the early Holocene.

The longevity of the mixed conifer forests suggest that *T. mertensiana* is not a good indicator of the Younger Dryas as suggested by Mathewes (1993). Rather, *Alnus* peaks recorded in sites such as Whyac, Pyrola, and Kalmia lakes (Figure 1; Hebda, 1997b) may more accurately record Younger Dryas cooling and solifluction disturbance.

Mathewes et al. (1993) showed that foraminiferal assemblages collected from the continental shelf north of Vancouver Island record a cooling event between about 11,000-10,200 ybp. Grigg and Whitlock (1998) suggested that an increase in *Pinus*, specifically *P. monticola*, may represent a vegetation response to greater seasonality or short-term cooling during the Younger Dryas. Sites on Vancouver Island that record small peaks in *P. monticola* between ca. 10,500-10,000 ybp include ESF and Pixie and Porphyry lakes. Allen (1995) did not differentiate between *P. contorta* and *P. monticola*.

Early Holocene

Before characterising the early Holocene forests on southern Vancouver Island, it is desirable to examine when in fact the forests were established because some apparent inconsistencies exist. In general, the mixed conifer forests of the late Pleistocene all appear to end close to the Pleistocene/Holocene transition as warmth requiring species such as *Pseudotsuga* expanded into the region, except at some high elevation (Walker Lake) and wet northern (Bear Cove Bog; Hebda, 1983) sites. This observation confirms the occurrence of a near-synchronous change in forest composition over most of Vancouver Island at this time (Hebda, 1983; Allen, 1995).

The transition from late Pleistocene mixed conifer forests to early Holocene lowland-like forests at Porphyry and Walker lakes is diachronous compared to changes at low elevation sites. At Porphyry Lake the transition appears to have occurred at ca. 1,000 years before low elevation sites on Vancouver Island (Figure 16). According to the available ^{14}C chronology, temperate forests persisted at Porphyry Lake for ca. 4,800 years from ca. 11,300-6,500 ybp, although they were more likely present from about

10,000-6,500 ybp based on interpretations from other sites (Allen, 1995). It is unclear why the transition occurred earlier at Porphyry Lake and it seems unlikely that *Pseudotsuga* would have appeared in subalpine sites on southeastern Vancouver Island before lowland sites (Allen, 1995) given that it is a warm climate species (Hermann and Lavender, 1990). It seems more likely that the apparent earlier arrival of *Pseudotsuga* at Porphyry Lake is an artefact of the linear interpolation of time using ^{14}C dates as control points. An additional ^{14}C date from a sample located between the lower 12,540±200 and the upper 8,420±110 ybp dates is required to resolve this apparent inconsistency.

The transition at Walker Lake appears to have lagged behind low elevation sites by almost 1,200 years, with temperate forests persisting for 1,900 years from 8,800-6,900 ybp. Walker Lake lagged behind other sites on Vancouver Island because it is a high elevation site that likely remained cool and moist (due to interception of westerly flowing air masses) well into the early Holocene.

During the early Holocene, southern Vancouver Island became differentiated with respect to forest composition and structure (Figure 16), climate, and fire activity. A *Pseudotsuga* dominated biogeochron was present in a climatically dry region that extended westward beyond Pixie Lake (Figures 1 and 10). The forests around ESF were dominated by *Pseudotsuga* with *Alnus* in open and disturbed sites and *Pteridium* and Poaceae in openings. Forests around Pixie Lake were similar to those at ESF and dominated by *Pseudotsuga* with *Alnus* and *Pteridium* in open and/or disturbed areas. Comparable pollen influx values from ESF and Pixie Lake suggest forests at both locations were open, possibly because of fire disturbance (Figures 9 and 10). Whyac Lake was located in a moister region of southern Vancouver Island and dominated by *T.*

heterophylla and *Picea* with minor *Abies* and later Cupressaceae, likely *T. plicata*. *Alnus* likely grew at the edge of the lake or in disturbed areas. Higher pollen influx values at Whyac Lake further suggest the forests were more closed (Figure 11). These pollen data suggest *Pseudotsuga* dominated forests with *Alnus* and *Pteridium* extended approximately 80-100 km further northwest during the early Holocene xerothermic interval compared to the modern CDF-CWH ecotone (Figure 18). Other sites on southern Vancouver Island (Hebda, 1983; Allen, 1995) and the mainland (Mathewes, 1973) record vegetation assemblages similar to ESF and Pixie lakes, whereas Hebda (1983; 1997b) shows that early Holocene records from sites on the wetter northwest side of Vancouver Island more closely resemble the Whyac Lake record.

In the early Holocene, forests around Porphyry Lake were a mixture of *Picea*, *Abies*, possibly *A. grandis*, *T. heterophylla*, and *Pseudotsuga*. In contrast, the forests around Walker Lake were dominated by *Picea* and *T. heterophylla*, likely because this site was moister, but also contained *Abies* and *Pseudotsuga*. Perhaps some of the *Picea* pollen at Walker Lake reflects nearby lowland coastal *Picea* forests, but based on surface sample data *Picea* is not strongly represented outside its site of occurrence. *T. mertensiana* became less abundant at this time and likely persisted in areas with northern aspects or at higher elevations on north and south Vancouver Island mountain ranges. A significant increase in shade-intolerant, early seral and open habitat taxa such as *Alnus*, Rosaceae, and *Pteridium* suggests the forests were more open at high elevations than in the preceding zone. An increase in Liliaceae at Walker Lake is also consistent with increased openness.

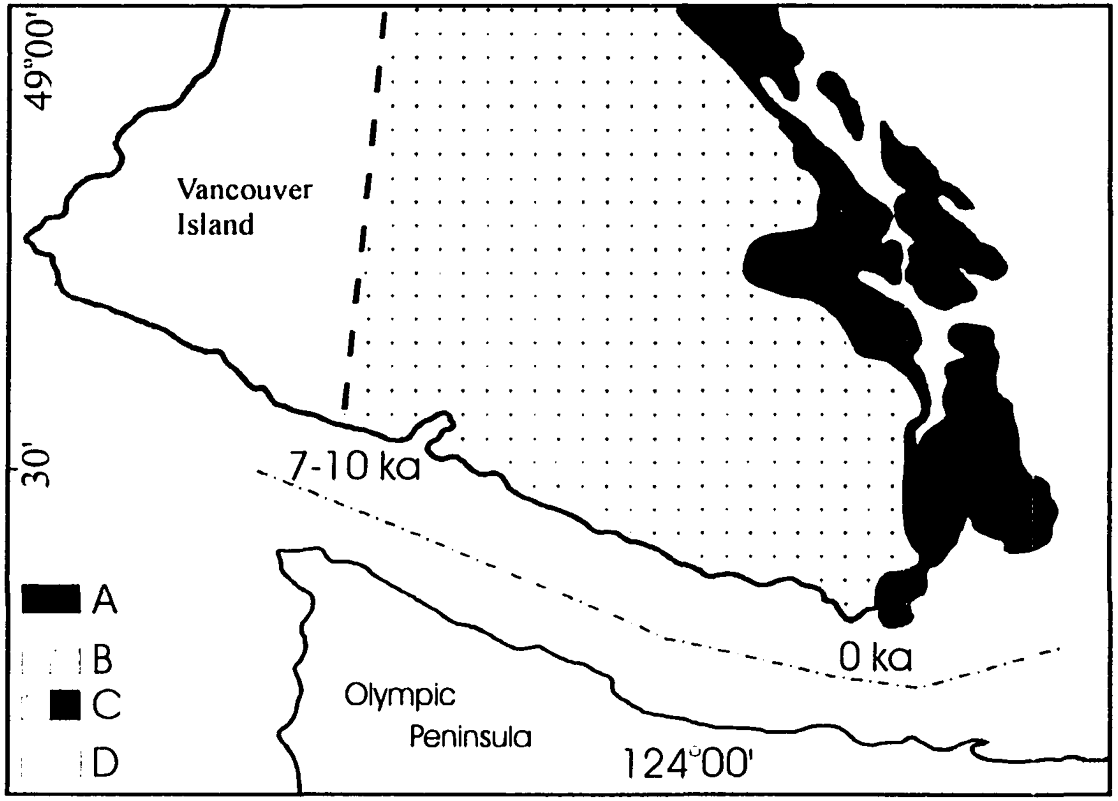


Figure 18. Early and late Holocene ecotones on southern Vancouver Island, where A represents present-day CDF forests, B shows present-day CWH forests; C shows early Holocene CDF-like forests; and D shows early Holocene *Picea-Tsuga heterophylla* forests. The stippled area represents the region that is particularly sensitive to warming and the dashed line represents the position of the early Holocene ecotone.

The expansion of lowland forests at Porphyry and Walker lakes in the early Holocene is generally consistent with records from other sites on southern Vancouver Island (Heusser, 1983; Allen, 1995) and on the mainland (Mathewes, 1973), all showing more abundant *Pseudotsuga* and *Alnus* than during the late Pleistocene. The main difference between high and low elevation forests during the early Holocene is that high elevation forests contain both *T. heterophylla* and *Pseudotsuga*, whereas low elevation forests are dominated by either *Pseudotsuga* in dry areas or by *T. heterophylla* in moist sites.

The high values of *Alnus* and *Pteridium* at all sites likely reflects fire disturbance followed by succession (Page, 1976; Mathewes, 1985). Post-disturbance vegetation was open and dominated by *Alnus*, rosaceous taxa, and *Pteridium*. Relatively open *Pseudotsuga* dominated forests likely became established during understory reinitiation and old-growth phases of succession (Oliver, 1980), perhaps several decades after the fire (Huff, 1995). Fire sensitive taxa such as *Picea*, *Abies*, and *T. heterophylla* with minor Cupressaceae were relegated to minor forest components or persisted only in moist areas not subject to fires. *Picea* may have also persisted in stands along the marine shoreline.

Perhaps the most dramatic change in forest composition during the early Holocene xerothermic interval on southern Vancouver Island is not *Pseudotsuga* expansion or the arrival of Cupressaceae but rather the abrupt disappearance or decline of *P. contorta* at Pixie, Whyac, Porphyry, and Walker lakes. The displacement of *P. contorta* by other trees is an important ecological phenomenon because it is often linked to primary successional processes involving colonisation and soil development. Presumably, once primary succession ended, other species could colonise the landscape, however, this does not appear to be a satisfactory explanation for the disappearance of *Pinus* because the pollen records from southern Vancouver Island show non-primary (successional) species were present within the *P. contorta* biogeochron, especially at high elevations. It is also unlikely that the decline in *P. contorta* can be attributed to changes in disturbance regimes because *P. contorta* should have responded favorably to the increase in fire (Lotan and Critchfield, 1990) during the early Holocene but did not. The reasons for this profound change may include increased competition in response to changing edaphic and climatic conditions, unsuitable climatic conditions, or pest and disease outbreaks possibly linked to a changing climate.

The early Holocene is characterised by a climate that abruptly changed from moist to dry and cool to very warm (Mathewes and Heusser, 1981; Anderson et al., 1988; Koerner and Fisher, 1990; Hebda, 1995). There are several possibilities that relate the decline of *P. contorta* to regional climate change during this interval. Perhaps *P. contorta* persisted in the cool late Pleistocene in areas disturbed by freeze-thaw activity. Warming and drying in the early Holocene likely reduced freeze-thaw activity, which decreased the number of disturbed sites containing *P. contorta*. Also, the early Holocene climate was too dry at many sites for any trees to exist, as evidenced by high NAP values on southeastern Vancouver Island (Allen, 1995; Pellatt et al., in press). For example, early Holocene sites characterised by continental climates such as in the Columbia Basin, Washington (Barnosky, 1985) were dominated by non-arboreal vegetation, whereas moister maritime sites (Mathewes, 1973; Allen, 1995; Hebda; 1995; Sea and Whitlock, 1995) were dominated by arboreal vegetation. However, arboreal vegetation persisted on the central and west side of southern Vancouver Island during the early Holocene suggesting that climate was not too warm and dry for *P. contorta*, except for perhaps in the southeastern-most regions.

Alternatively, *Pseudotsuga* may have been a superior shade-intolerant tree in the warm dry climate of the early Holocene and was able to outcompete *P. contorta* for potentially limiting resources such as water and nutrients in dry sites. *Pseudotsuga* appears to be characterised by a deeper root system than *P. contorta* (Hermann and Lavender, 1990; Lotan and Critchfield, 1990), potentially yielding the competitive advantage to *Pseudotsuga* in warm, dry environments. In addition, *P. contorta* has greater water requirements than does *Pseudotsuga* (Lotan and Critchfield, 1990), favoring *Pseudotsuga* under warm, dry climatic conditions. *Pseudotsuga* is also characterised by thick (fire) insulating bark, whereas *P. contorta* has thin bark suggesting *Pseudotsuga* was better adapted to survive the apparent high frequency of fire during the early Holocene. In those moist sites not subject to frequent fires, shade-tolerant *Picea* and *T. heterophylla* were likely able to outcompete *P. contorta*.

The *P. contorta* decline may be a regional pollen signal phenomenon as other conifers arrived and displaced or eliminated pre-existing *P. contorta* populations. Perhaps a combination of changing climate and fire incidence (Brown and Hebda, 1998a,b) coupled with migration of *Pseudotsuga* onto Vancouver Island during the early Holocene was sufficient to displace *P. contorta* from specific remaining sites. Although a decline in *P. contorta* is evident at ESF in the early Holocene, the preponderance of *P. contorta* pollen at ESF throughout the Holocene is related to an island within the fen containing *P. contorta*. Perhaps the *P. contorta* on this island, which have persisted until present-day, are remnants of the post-glacial *P. contorta* biogeochron.

Mid Holocene

On eastern and southern Vancouver Island two episodes of vegetation change are evident during the mid Holocene. *T. heterophylla* expanded and co-dominated with *Picea* and *Pseudotsuga* at ESF from ca. 7,900-6,400 (Figure 16), whereas from about 6,400-2.000 ybp *T. plicata* expansion around ESF resulted in the establishment of forests containing *T. heterophylla*, *T. plicata*, *Pseudotsuga*, and *Picea*. At Pixie Lake, a similar increase in *T. heterophylla* pollen occurred at 8,400-5,800 ybp as *T. heterophylla* and *Picea* forests with *Abies* and *Pseudotsuga* dominated. Between 5,800-2,500 ybp *T. plicata* expanded around Pixie Lake, establishing *T. heterophylla*, *T. plicata*, and *Picea* forests. Changes in forest composition at Whyac Lake started at ca. 7,100 ybp as *T. heterophylla* and *T. plicata* expanded to co-dominate with *Picea* until 3,400 ybp. During these intervals, the percentages of *Pseudotsuga* pollen decreased at Pixie and Whyac lakes but remained relatively unchanged at ESF.

In addition to changing composition, forest structure also appears to change at some sites. At Pixie and Whyac lakes, the expansion of shade-tolerant taxa coupled with the decline of shade-intolerant taxa such as *Alnus* suggests that the forest canopy closed, although occasional openings possibly related to periodic fires persisted. In comparison, forests around ESF remained more open, as evidenced by *Pseudotsuga* and *Alnus* pollen percentage values that did not change profoundly from the preceding zone.

A near-synchronous change in forest composition occurred at Porphyry and Walker lakes between 6,900-6,500 ybp. Mixed conifer forests of *T. heterophylla*, *T. mertensiana*, *Abies*, likely *A. amabilis*, and *Picea* replaced the *Picea*, *Abies*, *T.*

heterophylla, and *Pseudotsuga* stands of the preceding zone (Figure 16). These forests persisted throughout the mid Holocene until approximately 4,500-4,200 ybp when another near-synchronous change occurred. The increase in shade-tolerant taxa during this interval suggests that the forest canopy became generally closed, although some openings likely existed.

Rhamnus Lake (Figure 1; Allen, 1995) and Saanich Inlet (Heusser, 1983) are similar to ESF and Pixie Lake in that they record an increase in both *T. heterophylla* and Cupressaceae at about 6,900-3,300 ybp and 7,500-3,500 ybp respectively. More recently, Pellatt et al. (in press) showed that *T. heterophylla* and Cupressaceae increased in Saanich Inlet starting at about 8,000 ybp. At Heal Lake (Allen, 1995), *T. heterophylla* increased at ca. 8,000 ybp. Mid Holocene (ca. 7,000-3,000 ybp) *T. heterophylla-Picea* forests at Bear Cove Bog (Figure 1) are comparable to those at Whyac Lake. The forests at Walker Lake are comparable to those found around Pyrola Lake on the Brooks Peninsula (Hebda, 1997b) between 9,500-2,500 ybp.

In general, forest composition at Porphyry and Walker lakes was similar to that at Pixie and Whyac lakes, Kalmia Lake and Cassiope Pond (Hebda, 1997b), and Bear Cove Bog (Hebda, 1983) on west Vancouver Island except that they contain more *T. mertensiana*. They differed markedly from the more open *Pseudotsuga* forests on eastern Vancouver Island of the same age (Heusser, 1983; Allen, 1995) and the mainland (Mathewes, 1973; Mathewes and Rouse, 1974), suggesting that a major climatic change affected plant communities at all elevations and across a wide geographic range at this time (Hebda, 1995).

The change in forest composition may have occurred at ESF and Pixie Lake before Whyac, Porphyry, and Walker lakes because drier more eastern lowland sites likely experienced a relatively greater increase in precipitation compared to wetter western sites and high elevation sites. *T. plicata* first appears at Whyac Lake because this area was moister than around Pixie Lake and ESF. An interesting aspect of the mid Holocene vegetation dynamics is that *T. plicata* expanded at ca. 6,500 ybp at ESF and at ca. 6,000 at Pixie Lake, which is surprising because ESF was drier than Pixie Lake at this time. The apparent earlier expansion of *T. plicata* at ESF relative to Pixie Lake may be related to inadequate ^{14}C dates for chronological control. Limited expansion of Cupressaceae is also detected at Porphyry and Walker lakes starting at about 5,500-5,000 ybp. Wainman and Mathewes (1987) shows that *T. plicata* expanded at Marion Lake at ca. 5,800 ybp, suggesting the *T. plicata* expansion was a regional phenomenon.

During the mid-Holocene from about 6,500-3,000 ybp, *Q. garryana* expanded over the lowlands of southeast Vancouver Island (Heusser, 1983; Allen, 1995; Hebda et al., 1999b, Pellatt et al., in press). Maximum percentages of *Q. garryana* pollen are recorded at ESF in the mid-Holocene, suggesting *Q. garryana* woodlands occurred at their maximum westward extent at this time. The presence of a few *Q. garryana* pollen grains at Pixie Lake suggest that *Q. garryana* may have grown near the lake, a range far beyond the present-day distribution of the tree (Allen et al., 1999).

Late Holocene

At ESF, extant forests co-dominated by *T. heterophylla* and *Pseudotsuga* were established at ca. 2,000 ybp, whereas extant forests dominated by *T. heterophylla* and *T.*

plicata and containing some *Picea* were established at Pixie and Whyac lakes at ca. 2,500 ybp and ca. 3,400 ybp respectively. Relatively abundant *Pseudotsuga* and *Alnus* pollen at ESF suggests the forest structure remained open, whereas expansion of *T. heterophylla* and Cupressaceae coupled with a decline in *Alnus* suggests forest structure remained closed at Pixie and Whyac lakes. Wetlands expanded around lowland sites during the late Holocene and some *P. contorta* grew on or adjacent to the wetlands.

Extant *T. mertensiana*, *T. heterophylla*, and Cupressaceae, likely *C. nootkatensis*, dominated forests with understories containing ericaceous taxa developed at about the same time at Porphyry and Walker lakes (ca. 4,500-4,200 ybp). Other changes such as the establishment of *P. contorta* in acidic wetlands and a decline in shade-intolerant *Alnus*, reflecting a closed canopy and possibly less fire disturbance, suggests that the changes occurred widely across the landscape. These changes are concurrent with changes in lowland sites where *T. heterophylla*, *T. plicata*, and to a less extent *T. mertensiana* also expanded (Mathewes, 1973; Hebda, 1983, 1997b; Heusser, 1983; Allen, 1995).

The amount of *T. plicata* and *Pseudotsuga* at ESF during the late Holocene is less than during the preceding zone, whereas *Alnus* and charcoal concentrations increased suggesting more frequent fire disturbance in the latest Holocene. *T. plicata* expansion appears limited at other nearby lowland sites such as Heal and Rhamnus lakes (Allen, 1995) during the late Holocene, but not at other sites such as Saanich Inlet (Heusser, 1983; Pellatt et al., in press). The Saanich Inlet site, however, is a large depositional basin that contains a regional pollen signal that may partly account for the high percentages of *T. plicata* pollen at this time. Cupressaceae pollen is also recorded for the first time at Bear Cove Bog on northern Vancouver Island (Hebda, 1983). The later arrival of Cupressaceae in the north may represent a migration lag, although Cupressaceae pollen was detected on Brooks Peninsula during the mid Holocene (Hebda, 1997b).

The establishment of extant forests with less *T. plicata* at ESF and Heal and Rhamnus lakes compared to Pixie and Whyac lakes in the west, Marion Lake on the mainland, and Bear Cove Bog in the north is likely because drier conditions prevailed on southeastern Vancouver Island, whereas the moister conditions at the other sites enabled *T. plicata* expansion throughout the late Holocene. The relatively high percentages of *Alnus* pollen at southeastern sites (Heusser, 1983; Allen, 1995; Pellatt et al., in press) suggests disturbance, likely by fire, was more common compared to moister western and northern sites (Hebda, 1983; 1997b) that record less *Alnus* at this time.

Climate Interpretations

This section examines the climate history of southern Vancouver Island starting with the full-early late glacial and proceeding to the present day. A general climate interpretation will be given for each interval, though examples from the study sites are used to illustrate specific points where needed. DWHI and THMI pollen ratios are used to qualitatively interpret past climates in this section. The quantitative application of DWHI and THMI ratios to reconstruct paleoclimates is addressed in the following Chapter 13.

For clarity, it is important to distinguish between continental and maritime climates because mean annual measurements of precipitation and temperature can be similar for both types of climates even though they are profoundly different. Maritime climates are mild year-round because of the modifying effects of nearby bodies of water. In British Columbia, maritime climates along the coast are usually wet in the winter because moist air carried by prevailing westerly winds drops large amounts of precipitation on the windward side of the Coast Mountains as the air is forced up the mountain slopes (Meidinger and Pojar, 1991). The establishment of the north Pacific high during the summer reduces the frequency and intensity of storms, leading to drier conditions. In comparison, continental climates are climates of extremes located away from large bodies of water. In continental climates, cold arctic air predominates in the winter, whereas increased insolation in the summer leads to warm temperatures. Even with the temperature extremes in continental climates, the mean annual temperature is comparable to maritime averages. Interior continental climates in British Columbia are typically drier on an annual basis than coastal regions because of rainshadows, although moist interior regions are found on the windward sides of interior mountain systems.

Full-Early Late Glacial

The occurrence of a NAP dominated assemblage that resembles modern tundra at Porphyry Lake suggests that high elevations on southern Vancouver Island were characterised by a cold climate before 12,540 ybp, during the early late-glacial and possibly full glacial interval. The presence of *P. contorta* and the lack of other moisture requiring conifers suggests climate was dry (Hebda, 1983; 1995). Low pollen concentrations at Porphyry Lake are consistent with tundra vegetation, sparse cover, and cool-cold climates (Barnosky, 1981).

Heusser (1977) and Heusser et al. (1980; 1985) reconstructed paleoclimates using regression equations which suggest the full-early late glacial climate (ca. 20,000-14,000 ybp) of nearby coastal Washington State was characterised by about 10.5 °C mean July temperatures and 1,400 mm mean annual precipitation (MAP). Other full-early late glacial climatic reconstructions for regions south of the Cordilleran glacial limits (Barnosky, 1981; Sea and Whitlock, 1995) are similar to the PorL-1 zone, suggesting that the full glacial climate in the southern part of the Pacific Northwest, including Vancouver Island, was likely shaped by cold continental air derived from "subcontinental katabatic" circulation around the Laurentide ice sheet.

According to Whitlock (1992) full glacial mean annual temperature was about 5-7 °C cooler than present and MAP was 1000 mm less than present in the Pacific Northwest during the full glacial interval because the Laurentide ice (1) caused general cooling in mid-latitudes; (2) split the jet stream which shifted winter storms south and effectively reduced available winter moisture; and (3) intensified cold dry easterly winds influencing the Pacific Northwest.

Even areas presently characterised by maritime climates were probably subject to continental-type conditions at full-early late glacial time with cold winter and relatively warm summer temperatures. Regions with maritime climates were likely limited to areas immediately adjacent to the ocean on the now submerged coastal zone and these "maritime" strips may have been only a few kilometres wide.

Late Glacial

The climate of the subsequent *P. contorta* biogeochron (ca. >13,000-11,500 ybp) late-glacial interval is difficult to interpret because *P. contorta* has a wide ecological and climatic amplitude (Lotan and Critchfield, 1990). However, the dominance by *P. contorta* coupled with the lack of other moisture requiring taxa suggests climate was dry and possibly cool (Hebda, 1983; 1995).

During the *P. contorta* biogeochron, the regional lowland climate was likely cool and dry (Whitlock, 1992; Allen, 1995; Hebda, 1995). Higher elevations, however, were apparently cooler and moister compared to lower elevations, as indicated by more *T. mertensiana*. The climatic difference between high and low elevations suggests that precipitation increased with elevation. The presence of *A. lasiocarpa* and possibly *P. engelmannii* on southern Vancouver during the late glacial suggests that climate was continental with long cold winters and short cool summers.

As argued earlier, it is likely that the *P. contorta* woodlands initially developed on the landscape following regional deglacial. Well developed soils, capable of supporting other tree taxa, likely formed within several decades or centuries and yet the *P. contorta* woodlands appear to have persisted for a millenium or more (Heusser, 1960; Hebda, 1983, 1997b; Barnosky, 1981; Mathewes, 1985; Cwynar, 1987; Allen, 1995). The long tenure of these woodlands has to be related to climatic factors and not only soil development. In addition to the influence of the Laurentide ice sheet on climate, a regressing sea level because glacio-isostatic rebound exceeded eustatic sea-level rise after 13,000 ybp (Hicock et al., 1982; Clague et al., 1997; Peterson et al., 1997) possibly reduced the modifying effect of the Pacific Ocean in western British Columbia at that time and created a more continental-type climate.

Other lowland sites on southeastern Vancouver Island suggest that climate was cool and dry between 13,000-11,800 ybp (Allen, 1995). The presence of *Shepherdia* and possibly *Artemisia* at Marion Lake also support the concept of a cooler, more continental climate from >12,350 ybp (Mathewes, 1973; Clague et al., 1997). Hebda, (1983) indicates that a cool, dry climate characterised north Vancouver Island between 14,000-11,500 ybp. Paleoecological evidence from other sufficiently old sites, transfer function analysis, and global climate models suggest that the late glacial climate was cool and dry (Heusser et al., 1980; 1985; Mathewes and Heusser, 1981; Hicock et al., 1982; Adam and West, 1983; Anderson et. al., 1988). According to Heusser et al. (1980) cool, dry conditions prevailed during this interval. Mathewes and Heusser (1981) derived a mean July temperature of about 14 °C and MAP of 1,900 mm in southwestern British Columbia using transfer functions and these climatic conditions are relatively cooler and slightly drier than other post-glacial intervals, excluding the dry early Holocene.

Late Pleistocene

During the late Pleistocene, expansion of moisture-dependent mixed conifers at all sites implies climate was cool and relatively moist compared to the *P. contorta* biogeochron. The combination of species is characteristic of the Alaskan panhandle region where climates are cool and moist (Alaback and Pojar, 1997). The presence of *T. mertensiana* in these assemblages emphasizes the cool nature of the climate. Non-arboreal indicators such as monolete fern spores also suggest a moist climate. An increase in Cyperaceae and aquatic taxa such as *Potamogeton* and *Sparganium* suggest an increase in lake levels consistent with a moister climate, although this idea requires further verification.

At ESF, the occurrence of late seral conifers suggest a closed forest canopy early in the mixed conifer zone, whereas the presence of Poaceae, *Artemisia*, and *Selaginella* near the top of the zone (Figure 9) suggest openings late in the zone, possibly associated with warming and drying. Changes in DWHI ratios at Porphyry Lake suggest this interval began moist and became drier, but it should be cautioned that these changes likely only reflect the northern migration of *Pseudotsuga* trees at this time. Similarly, Porphyry Lake THMI ratios suggest this interval began cool but became warmer, presumably because of an increase in summer insolation at high latitudes in the northern hemisphere (Broecker and Denton, 1990; Koerner and Fisher, 1990). DWHI and THMI from Walker Lake suggest climate remained cool and moist at this site.

Similar changes in climate are recorded at other nearby sites, suggesting a regional cool moist climate. Heal and Rhamnus lakes (Figure 1; Allen, 1995) record a cool moist climate between 11,800-10,000 ybp. Mathewes (1973) concluded that cool and moist conditions characterised the Marion Lake region from about 12,350-10,400 ybp, whereas Hebda (1983) showed that climate on north Vancouver Island was cool and moist between 11,500-8,800. Increasing moisture in the late glacial (Heusser et al. 1980; 1985; Mathewes and Heusser, 1981) suggests the influence of cold continental air declined because the Laurentide ice sheet had diminished in extent, the jet stream was no longer split, and moist westerly winds exerted a greater climatic control on southern Vancouver Island (Anderson et al., 1988). If the pollen data from several sites do indeed represent the Younger Dryas climatic event, then it is likely that climate around south coastal British Columbia cooled for several centuries during the latest Pleistocene (Mathewes, 1993; Mathewes et al., 1993; Grigg and Whitlock, 1998; Heine, 1998).

Early Holocene

The early Holocene interval is characterised by maximum insolation and a reduction in global volcanic activity, coupled with the reduced size and hence influence on prevailing weather of the Laurentide ice sheet (Anderson et al., 1988; Nesje and Johannessen, 1992; Karlén and Kuylenstierna, 1996). In general, the early Holocene on southern Vancouver Island was warmer and drier than any other post-glacial interval.

Warming and drying in the early Holocene is evident at ESF and Pixie and Whyac lakes by an increase in *Pseudotsuga* and the lowest post-glacial DWHI values. The sediment type at ESF and Whyac Lake changes during the xerothermic interval at ca. 9,000 ybp and 8,000 ybp respectively from gyttja to peat which likely reflects lower water levels consistent with a warm dry climate and hydrosere succession. Lowland DWHI values indicate that precipitation increased from east to west across southern Vancouver Island, suggesting development of modern climatic gradients.

A shift towards more lowland and xeric species at Porphyry and Walker lakes during the early Holocene indicates temperatures warmed and precipitation decreased. The DWHI and THMI ratios from Porphyry and Walker lakes reveal a warmer and drier climate at high elevations than during any other period in the post-glacial interval. The DWHI and THMI data from Walker Lake suggest the early Holocene xerothermic interval (Mathewes and Heusser, 1981) can be subdivided into an initial very warm and extremely dry phase and a later warm, dry phase. DWHI ratios from nearby lowland sites (Allen, 1995) are consistent with those from Porphyry and Walker lakes and suggest that west Vancouver Island was much moister than east Vancouver Island at this time compared to the preceding interval. The earlier shift towards warm and dry conditions at Porphyry Lake compared to Walker Lake is consistent with other low elevation sites (Allen, 1995) that record a rapid warming and drying trend at about 10,000 ybp (Hebda, 1995). Climatic amelioration occurred later at Walker Lake than Porphyry Lake because it is located on the western side of southern Vancouver Island and continued to receive abundant precipitation during the earliest Holocene.

During the early Holocene, the pollen and spore records from south Vancouver Island are generally comparable to mainland records that show an increase in *Pseudotsuga* at this time (Mathewes, 1973). Early Holocene warming and drying is even evident on north Vancouver Island between 8,800-7,000 ybp, as recorded by an increase *Pseudotsuga* pollen and a decrease in aquatic species. On the Queen Charlotte Islands (Figure 1) pollen and macrofossils show that *T. heterophylla* expansion correlates with the early Holocene thermal maximum (Pellatt and Mathewes; 1994). These observations are consistent with other paleoclimatic reconstructions that reveal the early Holocene was about 1-4 °C warmer and drier (Heusser, 1977; Mathewes and Heusser, 1981; Anderson et al., 1988; Clague and Mathewes, 1989; Allen, 1995; Hebda, 1995; Whitlock and Bartlein, 1997). Though these data suggest the change in climate at the beginning of the Holocene was regional, the southern Vancouver Island sites also indicate that the longitudinal precipitation gradients were established at this time.

Mid and Late Holocene

Two general climatic trends characterise the mid and late Holocene: (1) an increase in precipitation during the mid Holocene and (2) decreasing temperatures and further increasing precipitation during the late Holocene. At ESF, an increase in *T. heterophylla* at ca. 7,900 ybp suggests local conditions became moister at this time. *T. heterophylla* values continued to increase throughout the mid-late Holocene at ESF, suggesting that climate continued to become progressively moister. An increase in Cupressaceae pollen, likely *T. plicata*, at ca. 6,500 ybp also suggests relatively moist conditions prevailed in the mid Holocene. A mid and late Holocene increase in Cyperaceae is consistent with local fen development and expansion during moist conditions. Increased *Typha* pollen at 2,000 ybp suggests an increase in the amount of standing water, suggesting a cooler, moister climate. DWHI values at ESF gradually increase throughout the mid-late Holocene (Figure 9), implying progressively more moist conditions.

Pixie Lake records an increase in both *T. heterophylla* and Cupressaceae at approximately 8,400 ybp and 5,800 ybp respectively and a decrease in *Pseudotsuga* at 5,800 ybp, suggesting climate became moister and possibly cooler during the mid and late Holocene respectively. Fires also decreased during the mid-late Holocene, contributing to the *Pseudotsuga* decline because non-fire adapted and shade-tolerant taxa such as *T. heterophylla*, Cupressaceae, *Picea*, and *Abies* were able to respond positively to release (advance regeneration; Barbour et al., 1987) after thinning of the *Pseudotsuga* dominated overstory. An increase in *Lysichiton* starting at 8,400 ybp suggests conditions became moister too as low areas developed into swamps. DWHI show that Pixie Lake became wetter throughout the mid-late Holocene (Figure 10).

Whyac Lake records an increase *T. heterophylla* and Cupressaceae at approximately 7,100 ybp and 3,400 ybp respectively, suggesting climate moistened first then cooled and continued to moisten. An increase in Cyperaceae, and *Sphagnum* at ca. 4,000 ybp indicates bog development under a moist climate. High DWHI values at Whyac Lake suggest that moist conditions characterised southwestern Vancouver Island throughout the Holocene (Figure 11). Increasing *T. mertensiana* pollen values at Whyac Lake after ca. 7,100 ybp suggest climate cooled throughout the mid-late Holocene.

Climatic trends similar to those at lowland sites are evident at high elevations. An increase in moisture-favouring species such as *T. heterophylla*, *Abies*, likely *A. amabilis*, and *T. mertensiana*, as well as, an increase in DWHI and THMI at Porphyry and Walker lakes (Figures 12 and 13) at ca. 6,500 and 6,900 ybp respectively suggests climate moistened and cooled in the mid Holocene. An increase Cupressaceae at ca. 5,500 ybp at Walker Lake is consistent with continued climatic moistening. The cooling trend recorded by an increase in THMI at Porphyry and Walker lakes is more pronounced than the cooling at Whyac Lake, suggesting more cooling at higher elevations compared to lowland sites or that the vegetation response to cooling was greater at higher elevations.

T. heterophylla, *T. mertensiana*, and Cupressaceae values increase further at ca. 4,200 ybp at Porphyry Lake suggesting that precipitation and temperature continued to increase and decrease respectively during the late Holocene. A corresponding increase in DWHI and THMI values reveals the change in climate towards moister, cooler conditions during this interval.

At Walker Lake the percentage of *T. mertensiana* and Cupressaceae pollen increased at ca. 4,500 ybp, suggesting that climate cooled and moistened at this time. The amount of *T. heterophylla* pollen did not increase during the late Holocene at Walker Lake and as a result, the DWHI values at Walker Lake do not change from the preceding interval. These features suggest that near-modern precipitation levels were established as early as ca. 6,900 ybp, an observation consistent with southeastern lowland sites (Allen, 1995). An increase in wetland taxa such as Cyperaceae and *Potamogeton* at Walker Lake during the late Holocene further reflects increasing moisture. THMI values at Walker Lake increase during the late Holocene from 4,500 ybp-present, implying climate cooled during this interval.

The southwestern portion of Vancouver Island likely experienced moister conditions before the southeastern portion because local rainshadows reduced the amount of precipitation over southeastern regions. Other authors (Mathewes, 1973; Hebda, 1983; 1995; Heusser, 1983; Allen, 1995) use the expansion of *T. heterophylla* and *T. mertensiana* to signify a trend of increasing precipitation and decreasing temperatures during the mid-late Holocene. Nearby sites on south and north Vancouver Island (Hebda, 1983; 1995; Heusser, 1983; Allen, 1995), as well as the mainland (Mathewes, 1973) show a near-synchronous trend of increasing moisture starting at ca. 7,000 ybp. Glacial advances and a lowering of the tree line provide additional evidence that climate cooled during the late Holocene (Pellatt and Mathewes, 1994; Luckman, 1994).

DWHI/THMI Evaluation

Examination of the DWHI and THMI trends throughout the Holocene suggests that these pollen ratios are generally good indicators of precipitation and temperature respectively. DWHI ratios appear useful at both low and high elevations, whereas changes in THMI ratios are more pronounced at high elevations compared to low elevations, suggesting that high elevation sites are more useful for reconstructing post-glacial temperatures. Reconstructing climate in non-forested regions using DWHI and THMI is questionable because the ratios can be skewed by the regional pollen rain (Allen et al., 1999) which suggests that other pollen ratios may have to be developed for these areas. DWHI and THMI ratios can also be skewed by other factors such as disturbance and possibly soils. DWHI ratios may also provide a proxy indicator of fire intensity, although this hypothesis requires further verification.

Fire History

This section will examine the fire history of southern Vancouver Island from the full-early late glacial interval to the present-day. The general fire pattern will be discussed as it relates to climate and vegetation. This section will end with a discussion on the use of fire by humans and examine how people may have modified post-glacial fire records. For clarification, it should be noted that fires were qualitatively evaluated using overall fossil charcoal values and charcoal peaks as an estimate of intensity. The continuity of charcoal values between samples was used as an estimate of frequency. Relating fire frequency and intensity to the charcoal record, however, has its limitations because of lack of calibration of charcoal rain with fire frequency and intensities. The relatively coarse sampling resolution in this study permitted reconstruction of the long-term fire history of the region but does not allow detailed documentation of fire frequency and intensity.

The general fire history on southern Vancouver Island consists of a late glacial interval characterised by no fires (Brown and Hebda, 1998a,b). The first regional occurrence of fires occurs in the late Pleistocene at ca. 11,500-10,000 ybp. During the early Holocene warm, dry interval ca. 10,000-7,000 ybp, the establishment of an east-west precipitation gradient on southern Vancouver Island exerted control on both vegetation distribution and fire disturbance. During the early Holocene, fire activity on dry southeastern Vancouver Island was restricted to frequent low intensity fire events, whereas eastern and southern Vancouver Island experienced frequent, high intensity fires. The wet regions located further to the west recorded only a slight increase in fires, possibly because the fires were spatially limited. Increasing moisture in the mid Holocene is reflected by frequent low intensity fires coupled with occasional high intensity stand destroying fires. In the cool, wet late Holocene, eastern and southeastern Vancouver Island experienced frequent, low intensity fires, whereas wetter southwestern regions were characterised by infrequent fires or fire-free intervals.

The general fire history on southern Vancouver Island is consistent with other reconstructions of post-glacial fire in the Pacific Northwest (Sugita and Tsukada, 1982; Cwynar, 1987; Grigg and Whitlock, 1998; Long et al., 1998) that show fires were absent from the landscape during the late glacial, became more frequent just before the Holocene, were common during the early Holocene, and decreased during the mid and late Holocene relative to the early Holocene. Some sites southern Vancouver Island record an ioncrease in charcoal during the latest Holocene.

Full-Late Glacial

The paucity of microscopic charcoal fragments at Porphyry Lake during the full-early late glacial NAP zone and at all sites during the late-glacial *P. contorta* biogeochron suggests little or no fire activity. The lack of fire must be associated with the lack of ignition sources rather than the lack of available fuel since several centuries of biomass accumulation had occurred in *P. contorta* stands and these are well-known to be susceptible to fire (Lotan and Critchfield, 1990). Terasmae and Fyles (1959), however, concluded that during the *P. contorta* zone on Vancouver Island charcoal was abundant and that fires were common because climate was likely dry. Considering that their record came from deltaic sediments the charcoal may have been reworked from older material or opaque minerals may have been misidentified as charcoal. Sugita and Tsukada (1982) record relatively low charcoal influx values at Mineral Lake, Washington between 19,000-12,000 ybp, whereas charcoal is absent at Kirk Lake, Washington before 11,500 ybp (Cwynar, 1987).

Late Pleistocene

The increase in conifer diversity and closure of forest canopies during the late Pleistocene implies a potential increase in fuel load. The charcoal influx increased at ESF and Pixie, Enos, Boomerang, Porphyry and Walker lakes but not at Whyac Lake with the increase in available biomass even though the climate appears to have become moister than in the preceding *P. contorta* biogeochron. These data suggest that the incidence of fire generally increased throughout the late Pleistocene. A similar increase in charcoal influx is evident in Washington State at this time (Sugita and Tsukada, 1982; Cwynar, 1987).

At ESF, distinct charcoal peaks occur between ca. 11,400-10,500 ybp, suggesting a fire return time of about 225 years. The influx of relatively constant amounts of charcoal between ca. 10,500-9,900 at ESF suggests a change to more frequent fires of similar intensity. Pixie Lake charcoal peaks are spaced at intervals of approximately 450 years between ca. 12,500-10,200 ybp. A minor increase in charcoal is evident at Whyac Lake at the end of the late Pleistocene, suggesting a slight increase in fire activity. The first fires at high elevations occurred in the late Pleistocene during the moist climatic interval starting at ca. 12,250 ybp as mixed conifers replaced *P. contorta* dominated woodlands. It is unclear why fires increased at this time of apparently increasing moisture on southern Vancouver Island. There are several possible explanations including (1) more available fuel for combustion; (2) an increase in the frequency of lightning strikes; or (3) arrival of humans who used fire.

The idea of more frequent lightning strikes during the late Pleistocene is intriguing because present-day lightning-ignited fires are more common south and east of the Olympic Peninsula than on Vancouver Island (Pyne, 1982). Perhaps during the late Pleistocene, severe weather events such as thunderstorms occurred further to the north and west. The increase in summer insolation during the late Pleistocene (Anderson et al., 1988) coupled with a transgressed ocean (Clague et al., 1997) may have been sufficient to have promoted the development of cumulonimbus clouds by heating humid air masses near the earth's surface (Skinner et al., 1999). These parcels of air may have risen relatively quickly in response to cold frontal systems or orographic uplift, releasing latent heat and creating cumulonimbus thunder and lightning storms.

Early Holocene

In the early Holocene, little charcoal accumulated in dry eastern sites such as ESF that were characterised by open *Pseudotsuga* forests, suggesting fire activity may have been limited to frequent low intensity burns (Figure 9). A pronounced increase in charcoal at Pixie, Enos and Boomerang lakes suggests an increase in fire activity possibly related to frequent high intensity stand destroying fires (Figures 10, 14, and 15; Brown and Hebda, 1998a,b). Whyac Lake records a slight increase in fire activity compared to the latest Pleistocene, an observation consistent with a warmer and drier early Holocene climate. The charcoal signal at Whyac Lake (Figure 11), however, is much weaker than at Pixie Lake, suggesting fires at Whyac Lake were spatially limited or not as frequent as fires in the drier forests to the south and east. Low amounts of charcoal accumulated continuously at both Porphyry and Walker lakes, suggesting low intensity fires burned frequently at this time. The low influx of charcoal at these sites possibly reflects moist conditions during the early Holocene compared to eastern and southern lowland sites. The continuous accumulation of charcoal at all sites, coupled with the abundance of shade-intolerant indicators of disturbance such as *Alnus* and *Pteridium*, further reflects the likely important role of fires during the early Holocene.

A comparison of the early Holocene ESF and Pixie Lake fire records and reconstructed climate reveals a fire paradox. Even though the climate at ESF was dry, charcoal accumulation is low relative to more moist sites such as Pixie Lake. The explanation of this paradox likely lies in the more open vegetation with less biomass at ESF, which could be expected to produce less charcoal during a burn. Furthermore, the relatively open landscape at ESF may have limited the spread of intense fire and resulted in the production of less charcoal. The absence of a strong increase in charcoal at ESF may also be related to the reduced role of slope wash in bringing charcoal into the basin following a fire under the warm dry climate.

Cwynar (1987) used the seral status of paleovegetation to demonstrate that an increase in charcoal influx during the early Holocene (ca. 10,500-8,000 ybp) at Kirk Lake coincided with an increase in fire frequency. In the study, Cwynar acknowledges that the primary mechanism responsible for post-glacial vegetation change was climate change, but argues that early Holocene warming and drying cannot account for all of the vegetation changes that occurred between the late Pleistocene and early Holocene. The shift from fire avoiding taxa such as *T. heterophylla* and *T. mertensiana* to post-disturbance successional communities of *Pseudotsuga*, *Alnus*, and *Pteridium* likely implies more frequent fires. More convincing is the early Holocene increase in *Alnus*, which grows in both moist and disturbed sites. If the vegetation change in the early Holocene was solely a response to warming and drying, then a shift towards less *Alnus* should have ensued. If, however, early Holocene warming and drying triggered a larger change in the disturbance regime by increasing fire frequency, then *Alnus* should have increased. Examination of the pollen profiles at Kirk Lake and Vancouver Island reveals a marked increase in *Alnus* at this time, suggesting more fires. Sugita and Tsukada (1982) also record an increase in charcoal influx and high *Pseudotsuga*, *Alnus*, and

Pteridium values at both Mineral and Hall lakes in Washington State during the early Holocene between 10,000-7,000 ybp.

Mid Holocene

ESF exhibits a continuous yet limited influx of charcoal deposition during the mid Holocene suggesting low intensity ground fires continued to burn relatively regularly even though climate became wetter at this time. An isolated charcoal peak at ca. 6,000 ybp likely represents a single high intensity fire. An overall decrease in charcoal at Pixie, Whyac, Enos, and Boomerang lakes suggests that fire incidence declined in response to increased moisture. The occurrence of distinct charcoal peaks separated by intervals of low charcoal influx at Pixie Lake suggests a fire regime of frequent ground fires and infrequent high intensity crown or stand destroying fires (Brown and Hebda, 1998b) with ca. 400 year return times. At ESF, the percentages of *Alnus* and *Pteridium* remain comparable to early Holocene values supporting the interpretation of relatively constant fire incidence, whereas the percentages of these taxa at Pixie and Whyac lakes decrease, perhaps reflecting less frequent fires.

In comparison, the influx of charcoal increases at Porphyry and Walker lakes during the mid Holocene, possibly representing an increase in fires or an increase in the amount of charcoal washing into the basins, an observation that is consistent with a moister climate. This observation is not consistent with other fire records from the Pacific Northwest (Sugita and Tsukada, 1982; Cwynar, 1987; Brown and Hebda, 1998b) where fire activity seems to decrease at this time in response to increased moisture. The high elevation charcoal pattern seems to be an unresolved paradox that perhaps reflects a non-climatic influence on the landscape. These data suggest that the mid Holocene fire history from high elevation forests is different than low elevation forests and that fire incidence at high elevations may be less sensitive to climatic conditions. One similarity between the fire records from Porphyry and Walker lakes and other low elevation sites in dry regions (Cwynar, 1987; Brown and Hebda, 1998b) is that charcoal accumulated continuously throughout the mid Holocene, suggesting fires burned relatively frequently.

Late Holocene

A regime of frequent, low intensity fires persisted at ESF and Enos and Boomerang lakes during the late Holocene. Fires at Pixie and Whyac lakes, however, occurred infrequently and a fire-free interval at Whyac Lake spanning ca. 1,700 years is recorded. This change in pattern is probably associated with the development of a moist cool climate, suggesting fire was no longer a common disturbance event. In the late Holocene, fires continued to burn frequently at Porphyry and Walker lakes, although the fire intensity appears to have decreased as indicated by a decrease in charcoal influx. A decrease in *Alnus* and *Pteridium* at Pixie and Whyac lakes and a decrease in *Alnus* at Porphyry and Walker lakes is consistent with reduced fire incidence and a fire behavior pattern consistent with Coastal Western Hemlock (CWH) and Mountain Hemlock (MH) forests respectively. A similar decrease in charcoal influx, coupled with a decline in early seral and fire-adapted taxa is evident in nearby Washington during the late Holocene (Sugita and Tsukada, 1982)

In review, several important observations emerge from the ESF and Pixie, Whyac, Enos, Boomerang, Porphyry, and Walker lakes fire records: (1) fires were much more common in coastal regions in the recent past; (2) the charcoal records reveal that the regional lowland post-glacial fire history is generally related to climate, suggesting climate and specifically the establishment of a Holocene precipitation gradient on southern Vancouver Island controlled fire behavior; (3) high elevation forests generally have a Holocene fire history that differs from low elevations, suggesting that charcoal accumulation at high elevations does not necessarily reflect climatic conditions; and (4) temporal comparisons show that fire in the *P. contorta* zone is anomalous.

Anthropogenic Fires

In general, the near-synchronous response of charcoal patterns to past climatic states and trends from widespread coastal regions in the Pacific northwest (Terasmae and Weeks, 1979; Sugita and Tsukada, 1982; Cwynar, 1987; Hebda, 1995; Brown and Hebda, 1998b; Heinrichs et al., 1999) suggests that fires are largely climatically controlled. However, many of the fire records are inconsistent with climate reconstructions. For example, fires increased during the late Pleistocene even though climate was cool and moistening at the time. Mid Holocene high elevation fire records show an increase in charcoal even though climate was moistening. Many of the charcoal records (i.e. ESF and Whyac, Enos, Boomerang, and Walker lakes) also suggest an increase in fires during the latest Holocene even though climate was cooler and moister relative to all other Holocene intervals. The reasons for these inconsistencies are unclear and perhaps these fires reflect anthropogenic activity.

People likely migrated into the Pacific Northwest region during the last glaciation when a land bridge joined Siberia and North America (Allen, 1977). Beringia remained ice-free during the late Wisconsinan glaciation and was characterized by a cold, dry climate. The Beringian landscape supported a widespread tundra-steppe ecosystem that enabled the migration and survival of floral and faunal species, including people (Giterman et al., 1982; Cwynar, 1988). The people migrating south likely traveled along several routes, including the coast because sea levels were significantly lower which exposed large areas of continental shelf (Hebda, 1983; Clague, 1989) and the ocean modified the coastal climate, making conditions for travel more hospitable (Elias et al., 1992). As these people moved southward (Cavalli-Sforza, 1994), they eventually encountered lands at the southern margins of glacial ice.

Through time, these people developed unique cultures and methods of survival (Hebda and Mathewes, 1984; Hebda and Frederick, 1990), first as fishers or hunters and gatherers and later as structured organizations occupying summer, winter, and permanent settlements. Hebda and Mathewes (1984) demonstrated a positive correlation between expansion of *T. plicata* in coastal forests and the development of woodworking technology between 5,000-2,500 ybp, clearly illustrating people were present in coastal British Columbia by at least the mid Holocene. Turner (1999) and MacCleery (1994) showed that First Peoples widely used fire as a landscape management tool. Consequently, people may have modified the post-glacial charcoal records. In fact, the persistence of frequent low intensity fires on eastern Vancouver Island throughout the Holocene could indeed be attributed to aboriginal landscape management practices (Brown and Hebda, 1998b), suggesting that part of the charcoal record may have an anthropogenic basis. In attempting to determine whether people modified the fire records on southern Vancouver Island, it is necessary to examine the pre-European populations of

First Peoples and some of their use of fire. If it can be shown that a sufficiently large population with a working knowledge of fire existed on southern Vancouver Island, then it is reasonable to infer that the fire patterns were likely modified by people.

Southern Vancouver Island is occupied by two First Nations, the Straits Salish and Nuu-chah-nulth (Suttles, 1990; University of British Columbia, 1994). These groups occupied separate regions of the island, with the Straits Salish habitating the southeastern regions and the Nuu-chah-nulth residing in southwestern areas. Three techniques were used to estimate pre-European Straits Salish and Nuu-chah-nulth populations, including European population estimates and census data (Inglis and Haggarty, 1986; Boyd, 1990; Harris, 1994), First Nations mortality rates (Boyd, 1990; Harris, 1994), and archeological data (Barnett, 1955; Maud, 1978; Haggarty and Inglis, 1984; Inglis and Haggarty, 1986). Estimates of pre-contact populations suggest the Straits Salish population ranged between ca. 600-4,800 people, whereas the Nuu-chah-nulth population ranged between ca. 1,000-6,400 people. The range of pre-contact population estimates likely results from misinterpreted aboriginal migration patterns, unknown birth and mortality rates, inaccurate First Nations population census', and incomplete archeological evidence.

First Peoples used fire for a variety of purposes such as improving game forage by increasing browse, ease of travel, reduction of insect pests, communication, strengthening of defensive positions, increasing berry productivity, and driving game (Barnett, 1955; Pyne, 1982; Boyd, 1986; Turner, 1999; MacCleery, 1994). On southern Vancouver Island, the Straits Salish people purposely burned areas to increase the sustenance yield of a region. For example, economically important plants such as blackberries were abundant 2-3 years following a fire (Suttles, 1966; 1987). In addition, the Straits Salish used fire to indirectly increase the availability of other staples such as deer by increasing the abundance of fodder. Turner (1999) indicates the Straits Salish on southern Vancouver Island possessed an awareness of fire and used fire on a landscape management basis to "burn the country in order to" facilitate "the roots which they eat." Grasslands were frequently burned and the fires moved "along at a great pace." The ability of people "to gallop right through it (i.e. the fire)" suggests the fires were of low intensity. Fire was also used to enhance the yield of *Camassia quamash* (edible blue camas; Suttles, 1987; Turner, 1999).

On the west side of Vancouver Island, the Nuu-chah-nulth also used fire for a variety of purposes (Drucker, 1951; Sprout, 1987). Turner (1999) shows fire was used to increase berry productivity. For example, an area in Clayoquot Sound was burned to facilitate growth and production of fruiting plants such as Alaska blueberries (*V. alaskaense* Howell), red huckleberries (*V. parvifolium* Smith), and salal berries. Sapir (circa 1910-1914) indicates "indians would sometimes set fire to places where dangerous beings were supposed to lurk" suggesting fires were ignited, possibly frequently, for purposes other than sustenance.

It remains difficult to determine if late Pleistocene and early Holocene fire patterns were modified by people because archeological data for these time intervals is scarce (Hebda and Frederick, 1990). Norton (1979) concluded that *Pteridium* was used by aboriginal cultures of the Pacific Northwest coast for sustenance, suggesting high percentages of *Pterdium* spores in the early Holocene interval may reflect aboriginal landscape management. However, *Pteridium* spores were also abundant in Sangamonian sediments (Whitlock and Bartlein, 1997), suggesting that early Holocene disturbance was not caused by humans but rather by natural mechanisms such as lightning or windthrow.

The increase in charcoal influx during the latest Holocene at ESF and Whyac, Enos, Boomerang, and Walker lakes coupled with the fact that thousands of people occupied the region, suggests that the late Holocene fire record could indeed have been, in part, the result of human activity. Late Holocene European settlement throughout North America, and specifically on southern Vancouver Island, further altered late Holocene vegetation and fire records (Pyne, 1982; Heusser, 1983; Brown and Hebda, 1998b). Pyne (1982) recounted that fires burned the suburbs of Victoria in 1864 and again around Victoria and throughout the entire Pacific Northwest in 1868. Heusser (1983) showed that the occurrence of charcoal in Saanich Inlet (Figure 1) doubled at the time of European settlement as logging, farming, and settlement expanded. In this context, it might be possible to use Holocene fire records to determine the spatial and temporal distribution of First Peoples and Europeans along the west coast of North America. The charcoal record may also provide paleoecological researchers with additional "event-markers" that can be used to determine the relative age of sedimentary sequences if these events were well dated and could be identified in the charcoal record.

CHAPTER 13: GIS PALEOCLIMATE RECONSTRUCTION USING POLLEN RATIOS

Introduction

This study has used pollen and spore and charcoal analysis to reconstruct the post-glacial vegetation and fire history on southern Vancouver Island. These reconstructions were then used to make inferences about paleoclimates. Allen (1995), Allen et al. (1999), and this study have proposed that Douglas-fir-western hemlock (DWHI) and *T. heterophylla-T. mertensiana* (THMI) pollen ratios may provide a means of quantifying paleoclimates. This section will review some of the techniques paleoclimate investigators use to reconstruct past climates and then use DWHI and THMI pollen ratios, climate data, and a geographic information system (GIS) to reconstruct Holocene climates on southern Vancouver Island.

Background

Pollen and spore analysis has frequently been used to reconstruct past climates (Moore et al., 1991). Traditionally, these reconstructions used an "indicator species" in a fossil assemblage to estimate past climates based on modern autecological characteristics (Moore et al., 1991; Hebda and Brown, 1999). This technique assumes that the past and present physiological requirements of the indicator species have not changed significantly. The indicator species approach is still a widely used method of reconstructing paleoclimates (Mathewes, 1973; 1985; Heusser, 1983; Hebda, 1983; 1995; Allen, 1995; Pellatt, 1996; Pellatt et al., in press).

An expansion of the indicator species technique was the "assemblage approach" where the entire fossil pollen and spore assemblage was used to reconstruct past climates.

Using this technique, a paleovegetation assemblage is compared to similar modern vegetation (synecology) and the climatic characteristics of the modern ecosystem are assigned to the paleovegetation (Heusser, 1977; Moore et al., 1991; Allen et al., 1999). For example, Davis (1999) compared a fossil pollen assemblage to a modern analogue and averaged the precipitation and temperature values characteristic of the modern ecosystem to reconstruct past climate. This technique, however, is limited because it is only useful when modern analogues exist. Numerous other proxy indicators such as plant macrofossils (Pellatt, 1996), charcoal (Brown and Hebda, 1998a,b; Heinrichs et al., 1999), chronomids (Walker et al., 1999), planktonic foraminifera (Haflidason et al, 1995); treeline fluctuations (Pellatt and Mathewes, 1994; Pellatt et al., 2000), dendrochronology (Zhang, 1996), glacier mass balance (Luckman, 1993; Lewis and Smith, 1999), and dust fluxes and melt layers in ice cores (Broecker and Henderson, 1998; Bourgeois, 1999) have also been used to reconstruct paleoclimates.

Other quantitative estimates of past climates have relied on $\delta^{16/18}O$ isotopic ratios (Broecker and Henderson, 1998; Bourgeois, 1999) and computer generated climate models (Anderson et al., 1988; Weaver et al., 1998). Another frequently used quantitative technique relies on transfer functions to establish a link between fossil (pollen) assemblages and climate (Adam and West, 1983; Bartlein and Webb, 1985) using linear (Heusser et al., 1980; Mathewes and Heusser, 1981; Moore et al., 1991) and nonlinear (Campbell et al., 1998) regressions.

In this study one purpose is to reconstruct the changes in Holocene climates (temperature and precipitation) on southern Vancouver Island at 1,000 year intervals using GIS analyses. The goals are to (1) calibrate present day pollen ratios of indicator taxa obtained from surface samples with contemporary climate (temperature and precipitation); (2) use the above empirically derived relationship to convert fossil pollen ratios into paleoprecipitation and paleotemperatures; (3) generate Holocene isohyet and isotherm maps to show the temporal and spatial variability of climate; and (4) compare the reconstructed climates found from these analyses to other paleoclimate reconstructions.

Climate Data

Contemporary climate data (Environment Canada, 1994) were obtained for southern and central Vancouver Island, Canada (Figure 1). Surface samples and sediment cores from the portion of southern Vancouver Island south of 49°N were used, thereby restricting the region selected for Holocene paleoclimate reconstruction. This portion of southern Vancouver Island is characterised by a precipitation gradient that increases east to west and by elevational temperature gradients.

Methods

Reconstructing Holocene climates on southern Vancouver Island required the implementation of 5 dependent steps and several datasets, namely contemporary climate data, surface sample (moss polsters and lake sediments) data (Table 1; Figures 2 and 7), and fossil pollen data obtained from sediment cores (Figure 1). During step 1, data was collected and input into a GIS, in this case ESRI's GIS product Arc/Info®. Mean annual precipitation (MAP) and mean annual temperature (MAT) were obtained from 31 and 18 weather stations respectively (Table 16). The climate data represents mean annual values derived from 30 year normals for the interval 1961-1990.

A total of 179 surface samples representing 85 sites (Table 1 and Figure 7; Allen, 1995; Allen et al., 1999) were collected from all major biogeoclimatic zones (Chapter 5; Meidinger and Pojar, 1991). DWHI and THMI pollen ratios were calculated as described in Chapter 4 (Table 1).

Eight paleoecological sites, consisting of 5 new cores from this study and 3 pre-existing (Heusser, 1983; Allen, 1995) cores were used in the paleoclimate analyses. Preparation and analyses of the sediment cores used methods described in Chapter 3. The fossil pollen DWHI and THMI ratios for each 1,000 year interval during the Holocene were tabulated (Tables 17 and 18). Chronological control was established using ^{14}C dates and volcanic tephras (Bacon, 1983).

In step 2, contemporary MAP, MAT, DWHI, and THMI point coverages were generated in Arc/Info. First, site location information was imported into Arc/Info and point coverages showing the spatial distribution of the sample sites were generated. Next, the attribute data (the values obtained from each site) were assigned to the corresponding point coverage. The point coverages were then converted into raster-based grids specifying that the cells which did not correspond to a sample location were assigned a no data value (ESRI, 1991). The resultant interpolation grids consisted of a cartesian matrix of 130 rows and 74 columns with each cell representing a spatial resolution of 1 km^2 (Figure 19).

Step 3 involved raster encoding or populating the no data grid cells with an interpolated value that was derived from known values using as inverse distance

Table 16. Location, topographic, and climatic characteristics of weather stations (MAP = mean annual precipitation and MAT = mean annual temperature).

ID	Latitude (°N)	Longitude (°W)	Elevation (m)	MAP (mm)	MAT (°C)
1	48.58	123.42	53	853	
2	48.57	123.37	38	835	
3	48.72	123.55	1	1002	9.5
4	48.83	124.13	177	2147	9.4
5	48.83	124.07	171	2048	9.3
6	48.77	123.68	6	1051	9.4
7	48.43	123.43	12	839	
8	48.38	123.57	122	996	
9	48.62	123.42	61	890	9.8
10	48.65	123.62	137	1226	9.4
11	48.37	123.73	27	1266	
12	48.57	123.65	231	1465	
13	48.42	123.32	70	619	10.1
14	48.47	123.3	43	708	
15	48.5	123.5	152	1138	
16	48.65	123.43	20	858	9.5
17	48.37	123.75	32	1227	9.1
18	48.35	123.53	12	884	9.7
19	49.35	124.17	15	749	
20	49.28	124.58	193	1635	
21	49.15	123.73	46	903	
22	49.05	123.87	30	1144	9.5
23	49.22	123.95	8	956	10.1
24	49.33	124.98	75	2117	9
25	48.83	125.12	4	2876	9.1
26	48.62	124.75	38	2971	
27	49.38	126.55	7	3181	9.2
28	48.72	125.1	37	3102	9
29	49.25	124.83	2	1886	9.3
30	49.08	125.77	24	3296	9
31	48.95	125.52	12	3356	

Table 17. Location and Holocene DWHI pollen ratios from sediment cores (ybp = years before present).

Site ID	Latitude (°N)	Longitude (°W)	Time (ybp) 0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000
ESF	48.35	123.68	0.42	0.5	0.4	0.27	0.28	0.27	0.25	0.24	0.11	0.09
Pixie	48.6	124.2	0.92	0.91	0.95	0.92	0.96	0.89	0.93	0.71	0.82	0.37
Whyac	48.67	124.84	0.98	1	0.98	1	0.96	0.99	0.97	1	0.96	0.97
Porphyry	48.91	123.83	0.95	0.99	0.95	0.9	0.95	0.74	0.73	0.25	0.12	0.18
Walker	48.53	124	0.96	0.97	1	0.98	0.95	0.98	0.97	0.81	0.84	0.8
Saanich	48.33	123.3	0.56	0.67	0.59	0.48	0.49	0.67	0.52	0.53	0.49	0.41
Heal	48.53	123.47	0.23	0.10	0.10	0.28	0.27	0.22	0.13	0.17	0.09	0.17
Rhamnus	48.63	123.72	0.74	0.54	0.59	0.52	0.52	0.51	0.59	0.28	0.10	0.07

Table 18. Holocene THMI pollen ratios from sediment cores (ybp = years before present).

Site ID	Time (ybp)										
	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000
ESF	0	0.02	0	0	0	0	0.01	0.06	0	0.15	0.19
Pixie	0	0	0	0	0	0	0	0	0	0	0
Whyac	0.05	0.03	0.01	0.02	0.01	0.02	0.03	0.01	0	0.01	0.02
Porphyry	0.29	0.23	0.23	0.26	0.27	0.23	0.22	0.54	0.17	0.17	0.2
Walker	0.25	0.36	0.22	0.2	0.24	0.17	0.3	0.04	0.04	0.84	0.92
Saanich	0	0	0	0	0	0	0	0	0	0	0
Heal	0.09	0.00	0.10	0.03	0.07	0.08	0.00	0.12	0.00	0.00	0.00
Rhamnus	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.12	0.17	0.23

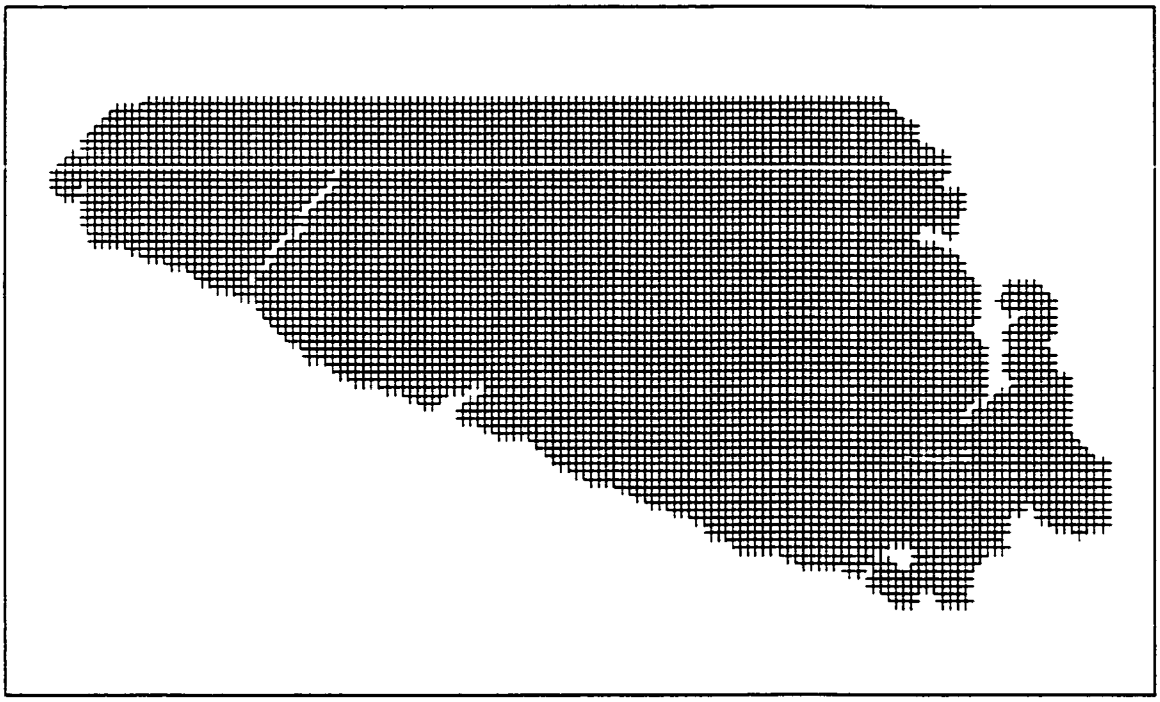


Figure 19. The grid of southern Vancouver Island used during IDW interpolation. The grid cell resolution is 1 km^2.

weighted (IDW) interpolation algorithm (ESRI, 1991). The IDW interpolation determines cell values using a linearly weighted combination of sample points. In this case, the landscape was triangulated using 3 input data points (Figure 20) and the values in the cells within each triangle interpolated. It should be noted, however, that because IDW is a weighted distance average, the interpolated output values cannot exceed the maximum and minimum input values. Application of a trend surface interpolation algorithm would bypass this problem (ESRI, 1991). However, trend surface interpolations use a polynomial regression to fit a least-squares surface to the input points which means the interpolated surface is typically smooth but seldom passes through the original data points. IDW ensures that the interpolated surface is spatially fixed at each input data point and that the interpolated surface passes through these points. During IDW interpolation, MATs were corrected for elevation using a coastal lapse rate of 0.5 ^{o}C/100 m (Heusser, 1989). Following interpolation, the grids were latticeclipped (ESRI, 1991) using an outline of southern Vancouver Island so that only values within the southern Vancouver Island polygon were retained. At the end of step 3, a total of 25 grids, each with a unique theme or set of attributes existed and each grid cell contained either an observed or interpolated value (Table 19).

In step 4, the surface sample and contemporary climate grids were queried using a DOCELL loop (ESRI, 1991) to calibrate MAP and DWHI and MAT and THMI. In essence, the query was accomplished by stacking the selected grids on top of each other and examining the stacked grids on a cell by cell basis. The first query consisted of MAP values and surface sample DWHI ratios, whereas the second query consisted of MAT values and surface sample THMI ratios. In each query, the output consisted of values

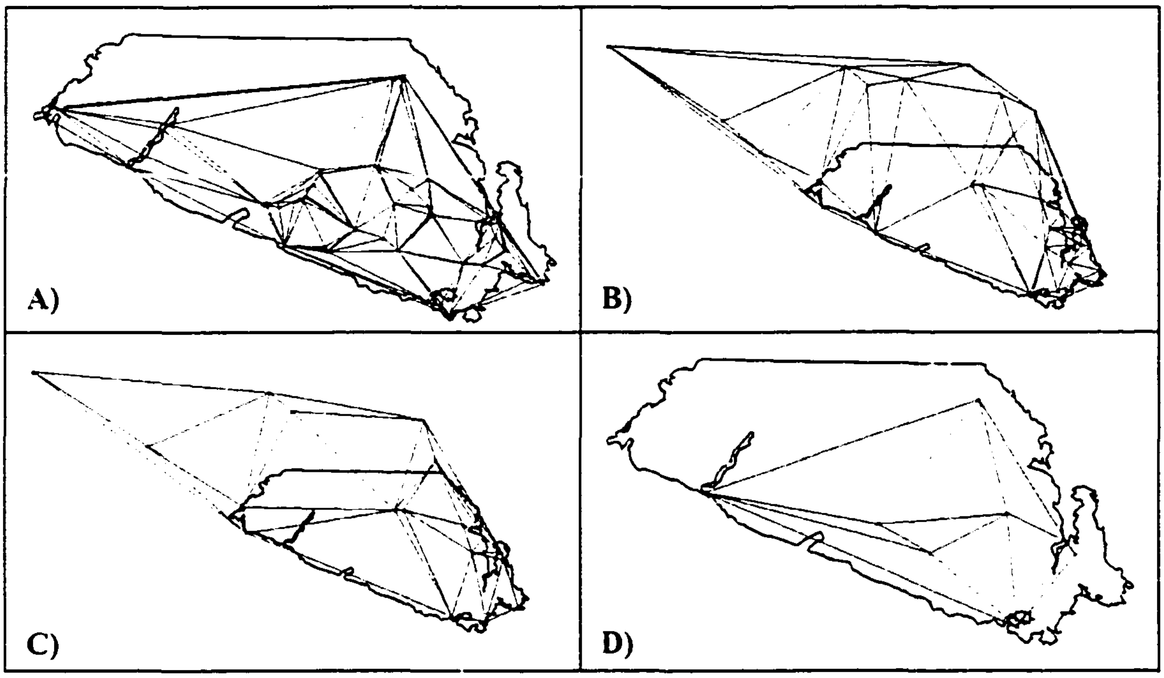


Figure 20. Triangulated irregular networks for A. surface sample; B. MAP; C. MAT; and D. paleosite datasets showing the areas (triangles) influenced by particular data points (nodes) during IDW interpolation.

Table. 19 Grids created in Arc/Info using IDW interpolation (ybp = years before present).

Number of grids created	Grid Attributes
1	Contemporary temperature
1	Contemporary precipitation
1	Surface sample derived DWHI
1	Surface sample derived THMI
10	Fossil pollen-derived DWHI from present day-9,000 ybp
11	Fossil pollen-derived THMI from present day-10,000 ybp

from cells that corresponded in location to each surface sample site, thereby ensuring that the DWHI and THMI ratios were actual observed values and the MAP and MATs were interpolated values. The output data was imported into Microsoft Excel™, plotted, and a regression relationship was established (Figures 21 and 22).

The regression describing the MAP-DWHI relationship (Figure 21) has a R^2 value of 0.51 and a standard error of 191 mm. This equation is applicable to all DWHI ratios between 0-1.0 and calculates MAP values between 460-2770 mm, consistent with contemporary MAP values on southern Vancouver Island which range from ca. 500-3500 mm.

Allen et al. (1999) show that the regional *T. heterophylla* pollen signal skews DWHI ratios towards high values (i.e. wet conditions) in the grassland and Garry oak variants (Table 1) even though these regions are relatively dry (Environment Canada, 1994). These variants did not significantly modify the regression because they are spatially limited and most grassland-derived DWHI values (which were collected from a small island located about 200 m off the southern tip of Vancouver Island) were removed during latticeclipping.

The MAT-THMI regression equation (Figure 22) is not adequate to reconstruct past temperatures because the equation is only useful for predicting MATs between 5-10 °C when THMI values are ≤ 0.2. This equation suggests that sites with a THMI value of 1.0 are characterised by a MAT of ca. 0.2 °C, an observation not consistent with contemporary climate data. The low R^2 (ca. 0.27) value indicates a poor correlation that accounts for only 27% of the THMI variability, indicating the regression has a poor accuracy of prediction.

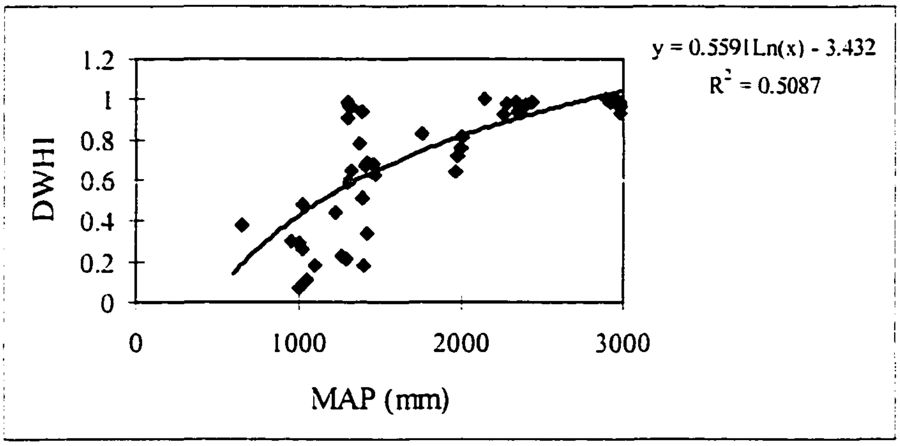


Figure 21. Calibration curve for surface sample DWHI pollen ratios and interpolated mean annual precipitation.

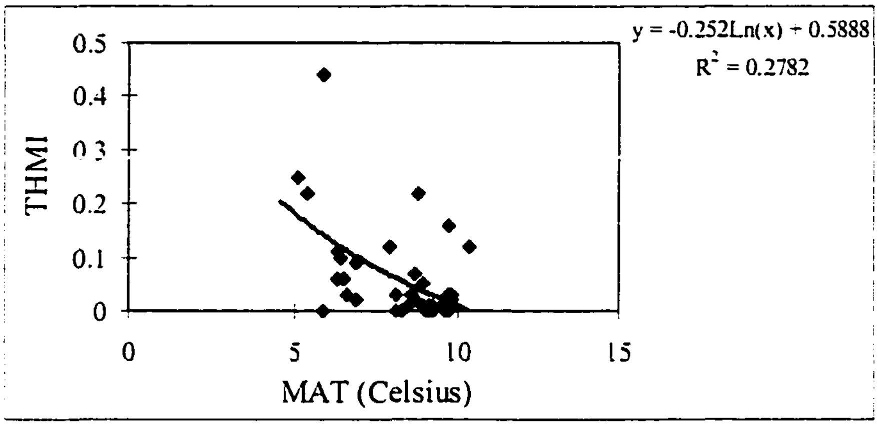


Figure 22. Calibration curve for surface sample THMI pollen ratios and interpolated mean annual temperature.

The established MAT-THMI regression is not useful for reconstructing MATs derived from moderate-high THMI ratios (i.e. high elevation, cool-cold sites) because most of the surface samples were collected from low elevations or montane sites and an insufficient number of high elevation sampling points exist. Pellatt et al. (1997) and Allen et al. (1999) show a pronounced increase in *T. mertensiana* pollen occurs in surface samples collected from the Mountain Hemlock zone (Meidinger and Pojar, 1991), illustrating the need for adequate sampling along elevational transects and specifically at high elevations. These studies also indicate that the THMI-temperature relationship is logarithmic, with high elevation samples being dominated by *T. mertensiana* and low elevation samples by *T. heterophylla*.

By resampling a specified section of the grid, in particular, an area on southern Vancouver Island that has nearby high and low elevation surface sample sites and weather stations, it is possible to generate interpolated output values along an elevational gradient (Figure 23). By forcing the grid to sample cells along an elevational gradient, a more useful MAT-THMI regression may emerge (Figure 24). The nearness of *T. mertensiana*, *T. heterophylla*, and *Pseudotsuga* dominated forests also assisted in defining the area to be resampled (Meidinger and Pojar, 1991). One disadvantage of selecting along this elevational gradient is that the output values are all interpolated values.

The output plot (Figure 24a) reveals that the empirically derived regression can be used for all THMI values (0-1.0) and that a temperature range of ca. 1.6-9.8 °C is established, an observation relatively consistent with interpolated contemporary climate data (ca. 4-10 °C). The plot also reveals a number of points (circled in Figure 24a)

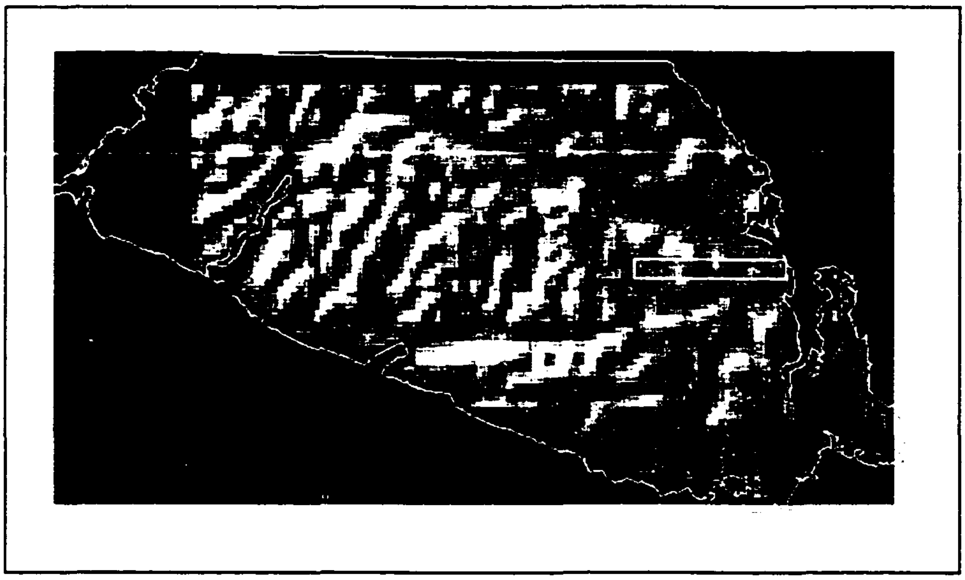


Figure 23. Digital elevation model of southern Vancouver Island showing resampled section of grid (outlined with rectangle).

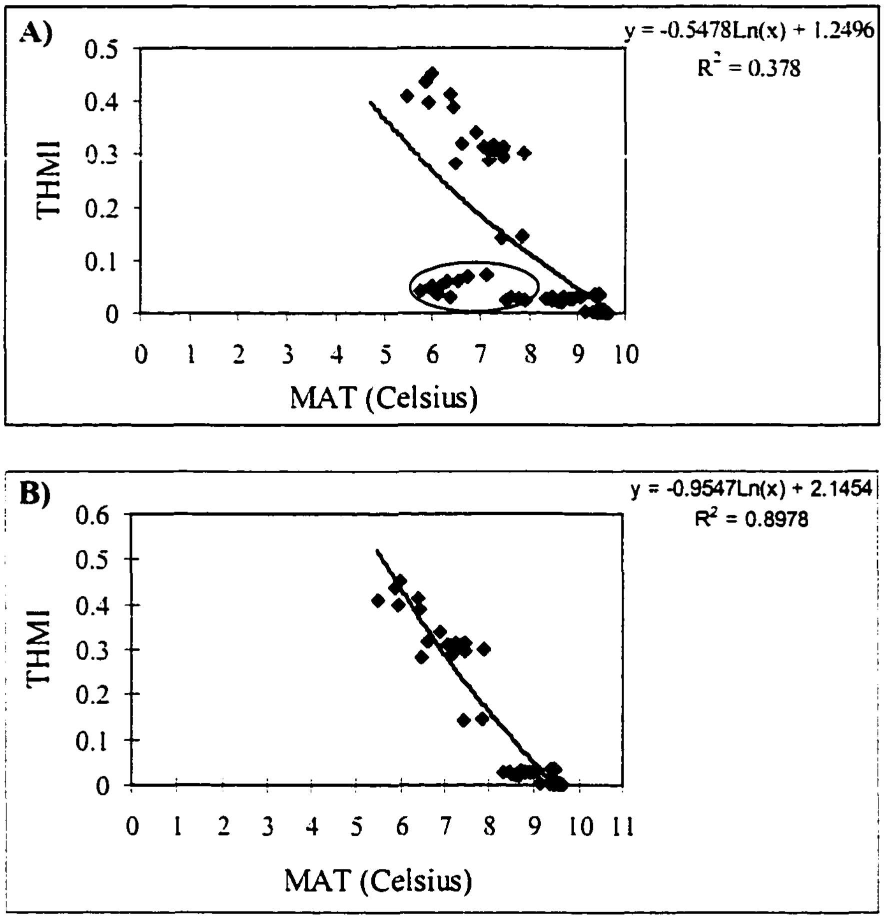


Figure 24a. The effect of an elevational gradient on the MAT-THMI relationship with anomalous points circled. Figure 24b. The MAT-THMI calibration curve along an elevational gradient after removal of anomalous data points.

representing cold temperatures (i.e. high elevations) that are characterised mainly by *T. heterophylla* pollen and low THMI ratios, an observation not consistent with the autecological characteristics and distribution of *T. mertensiana* and *T. heterophylla* trees (Meidinger and Pojar, 1991). Allen (1995) and Allen et al. (1999) clearly show that the regional *T. heterophylla* pollen signal can alter pollen ratios in favor of *T. heterophylla* even when the tree is not present. Perhaps these points come from an area within the resampled section of the grid that has recently been disturbed by logging, enabling the regional *T. heterophylla* pollen signal to overwhelm the underrepresented *T. mertensiana* pollen signal.

Removal of these data points reveals a more constrained MAT-THMI relationship (Figure 24b) that is characterised by a high R^2 value and a standard error of 0.3 °C. This curve can be applied to all THMI values and used to reconstruct MATs between ca. 3.3-9.5 °C, an observation that is more consistent with the interpolated MATs for southern Vancouver Island.

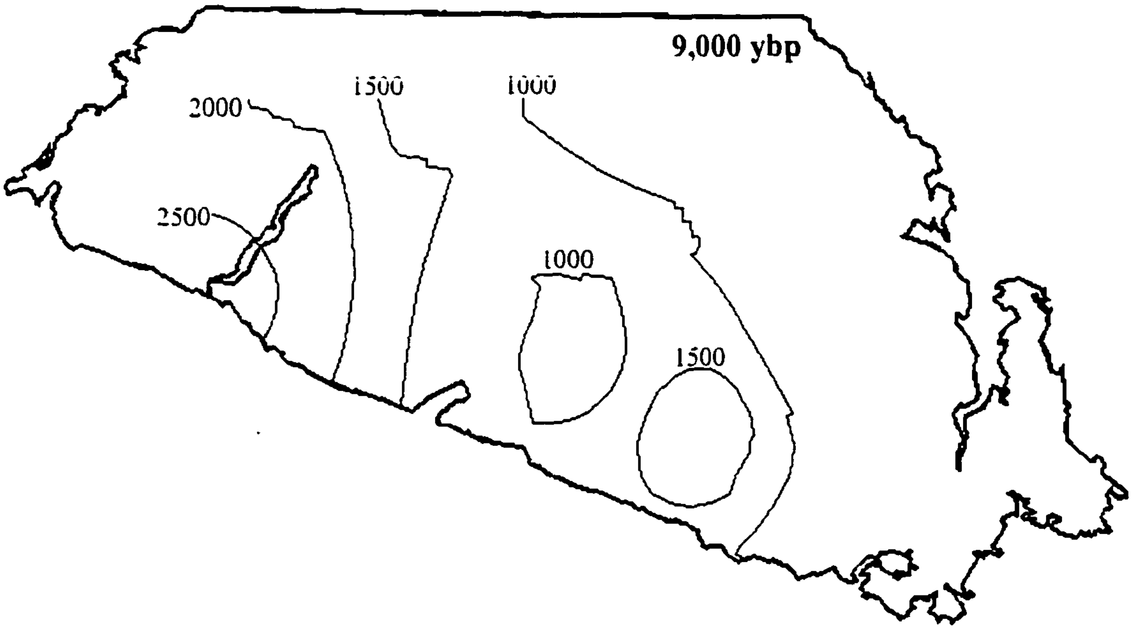
In step 5, the fossil pollen DWHI and THMI grids were converted into past precipitation and temperatures using a DOCELL loop (ESRI, 1991) that integrated the empirical regressions. Isohyets and isotherms were then generated for each 1,000 year interval. For each grid cell, the DWHI values were converted into MAP using the equation $pp = e^{((DWHI+3.432)/0.5591)}$ where pp is past precipitation, e is exponent of the natural log of 1, and DWHI is the fossil pollen ratio. Past MATs were similarly derived using $pt = e^{((THMI-2.1454)/-0.9547)}$ where pt represents past temperature and THMI represents the fossil pollen ratio.

Results

Holocene precipitation was reconstructed from the 9,000 ybp horizon to the present, whereas temperature was reconstructed from 10,000 ybp horizon to the present. Paleoprecipitation was not reconstructed for 10,000 ybp because *Pseudotsuga* trees had just arrived on southern Vancouver Island at this time and many of the core sites record little or no *Pseudotsuga* pollen (Heusser, 1983; Allen, 1995). The late Pleistocene climate on southern Vancouver Island from ca. 11,500-10,000 ybp is interpreted as cool and moist on the basis of other more qualitative techniques (Allen, 1995; Hebda, 1995).

Precipitation

At 9,000 ybp southern Vancouver Island was relatively dry, with the 1,000 mm isohyet located near River Jordan (Figure 25; reference locations are shown in Figure 1b) and another 1,000 mm closed zone occurring near Port Renfrew in the San Juan River valley. Southeastern Vancouver Island, including the area around Victoria, received <1,000 mm at this time. In contrast, the region near Whyac Lake appears to have been moist, with MAP ranging between a low of 2,000 mm to a high of >2,500 mm. The San Juan Ridge was characterised by 1,500 mm MAP. At 8,000 ybp climate remained relatively dry, although a slight increase in MAP is evident. The 1,000 mm isohyet remained near River Jordan, whereas the 1,500, 2,000, and 2,500 mm isohyets migrated eastward approximately 20-40, 25, and 15 km respectively. At this time, the 1,500 mm isohyet was positioned slightly west of River Jordan, whereas the 2,000 and 2,500 mm isohyets were located east of Port Renfrew and Whyac Lake respectively. A 500-1,000 mm increase in MAP occurred in the region around Pixie Lake, whereas MAP on the San



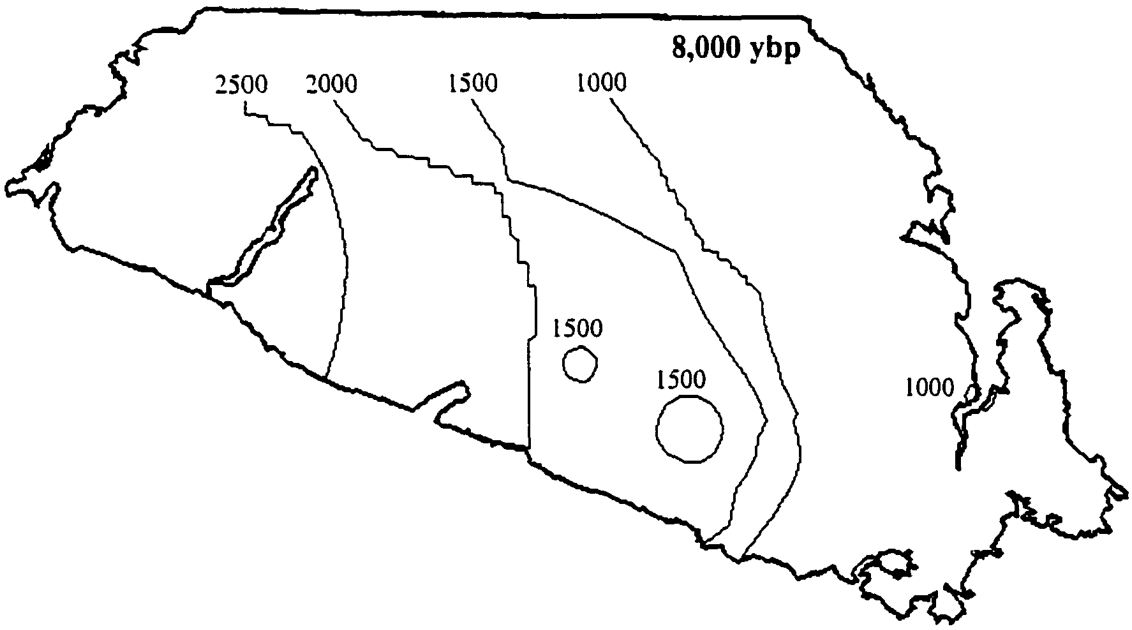
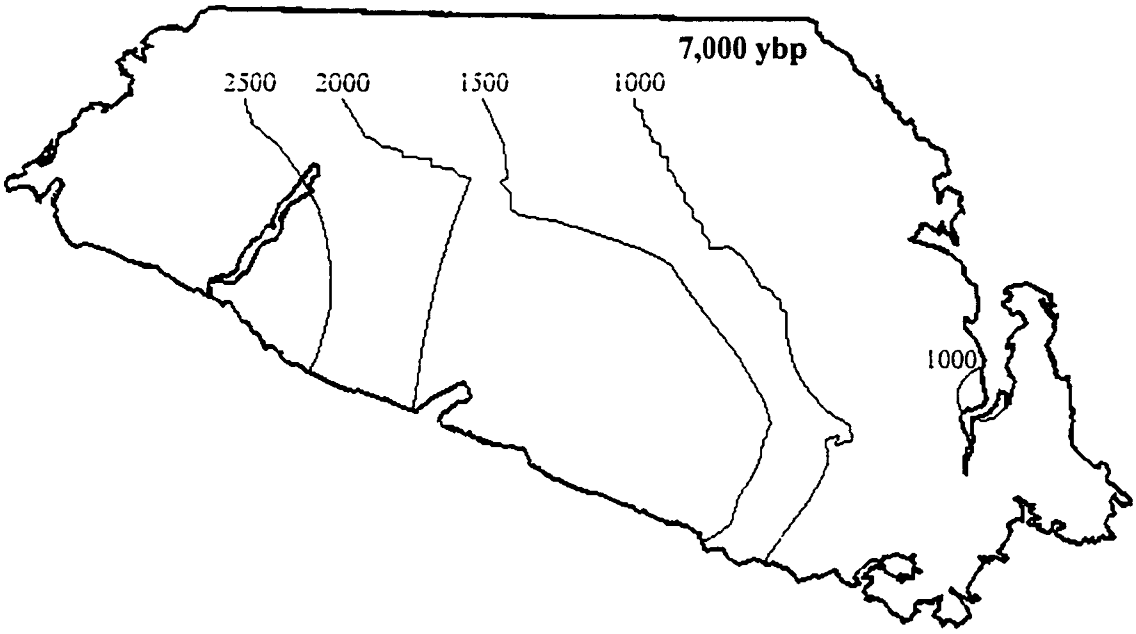


Figure 25. DWHI-derived Holocene isohyets of southern Vancouver Island. The time interval represented is shown in the top right corner and the contour interval is 500 mm. A 30 norm isohyet generated from weather station data is presented last for comparison.



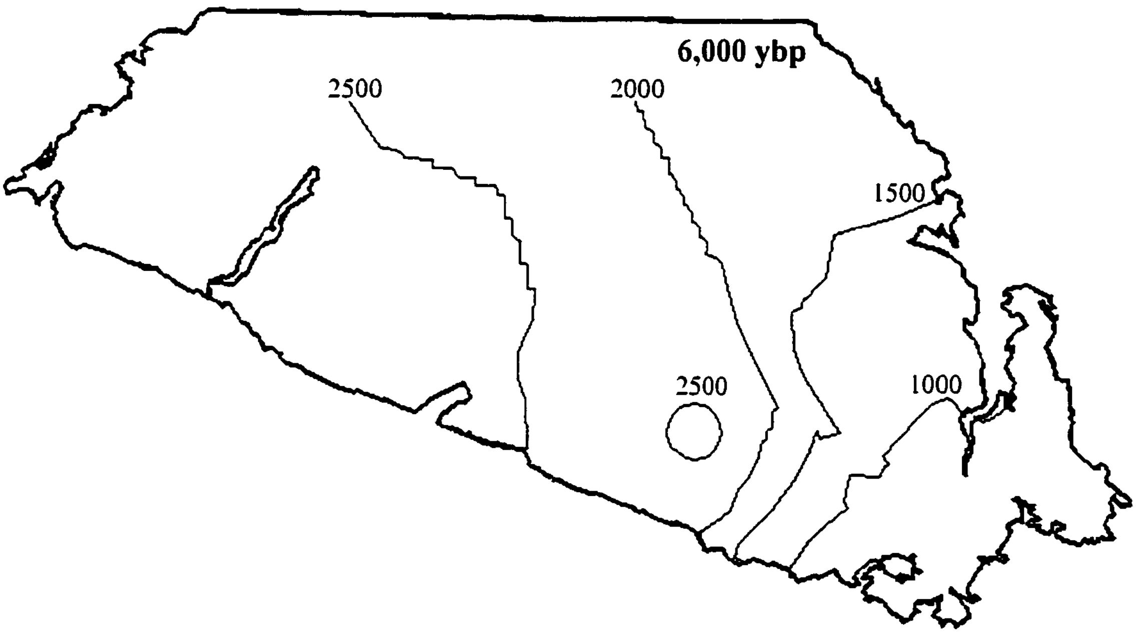
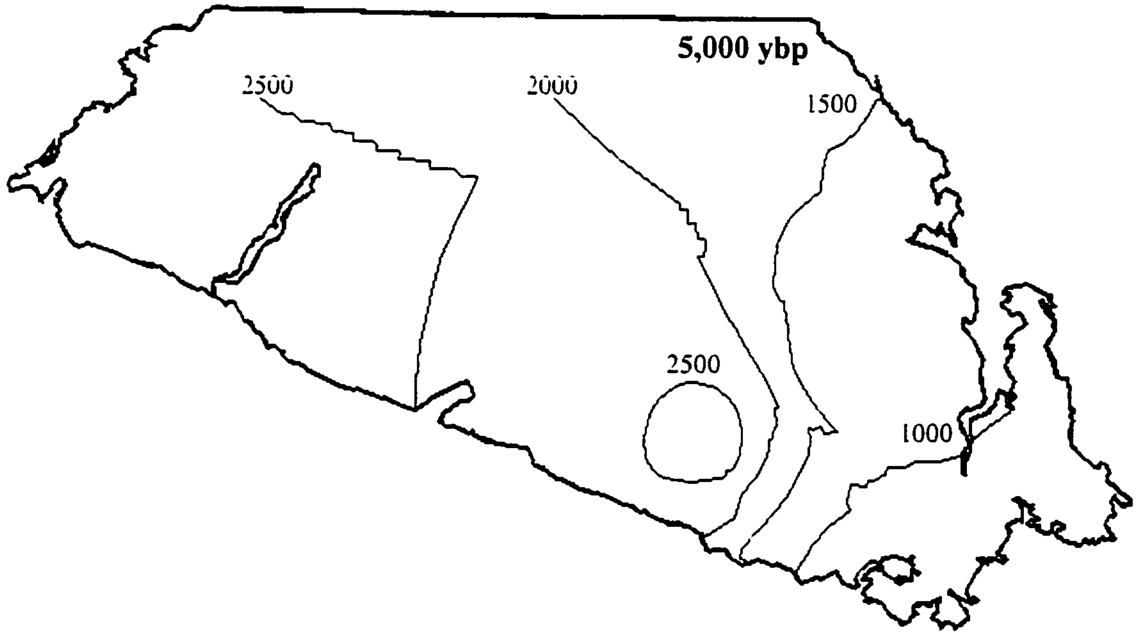
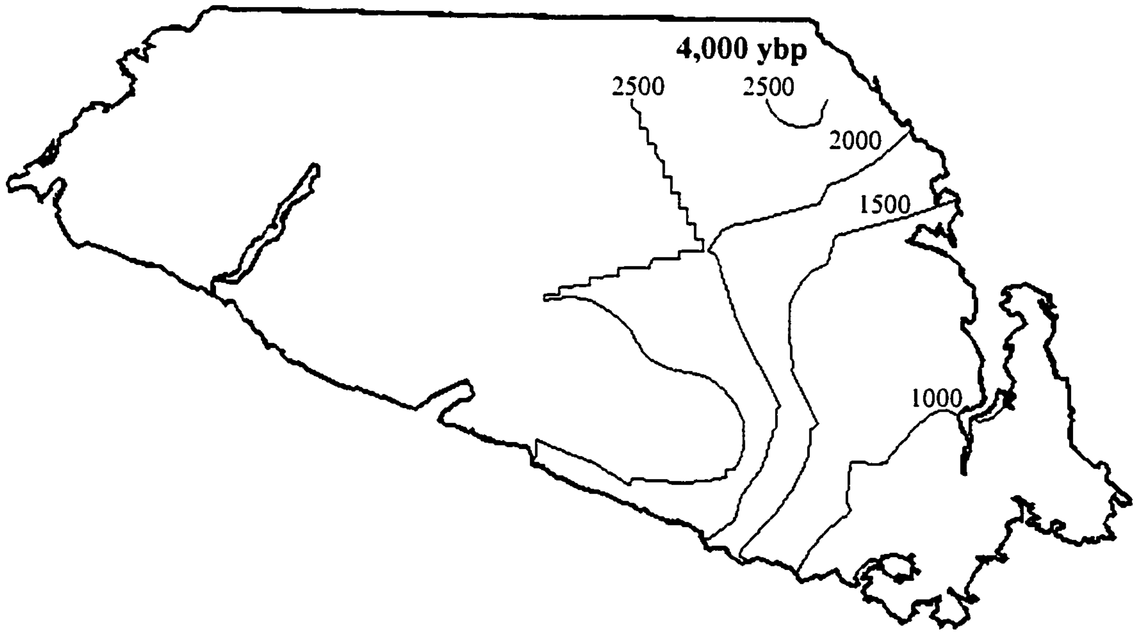


Figure 25 continued.





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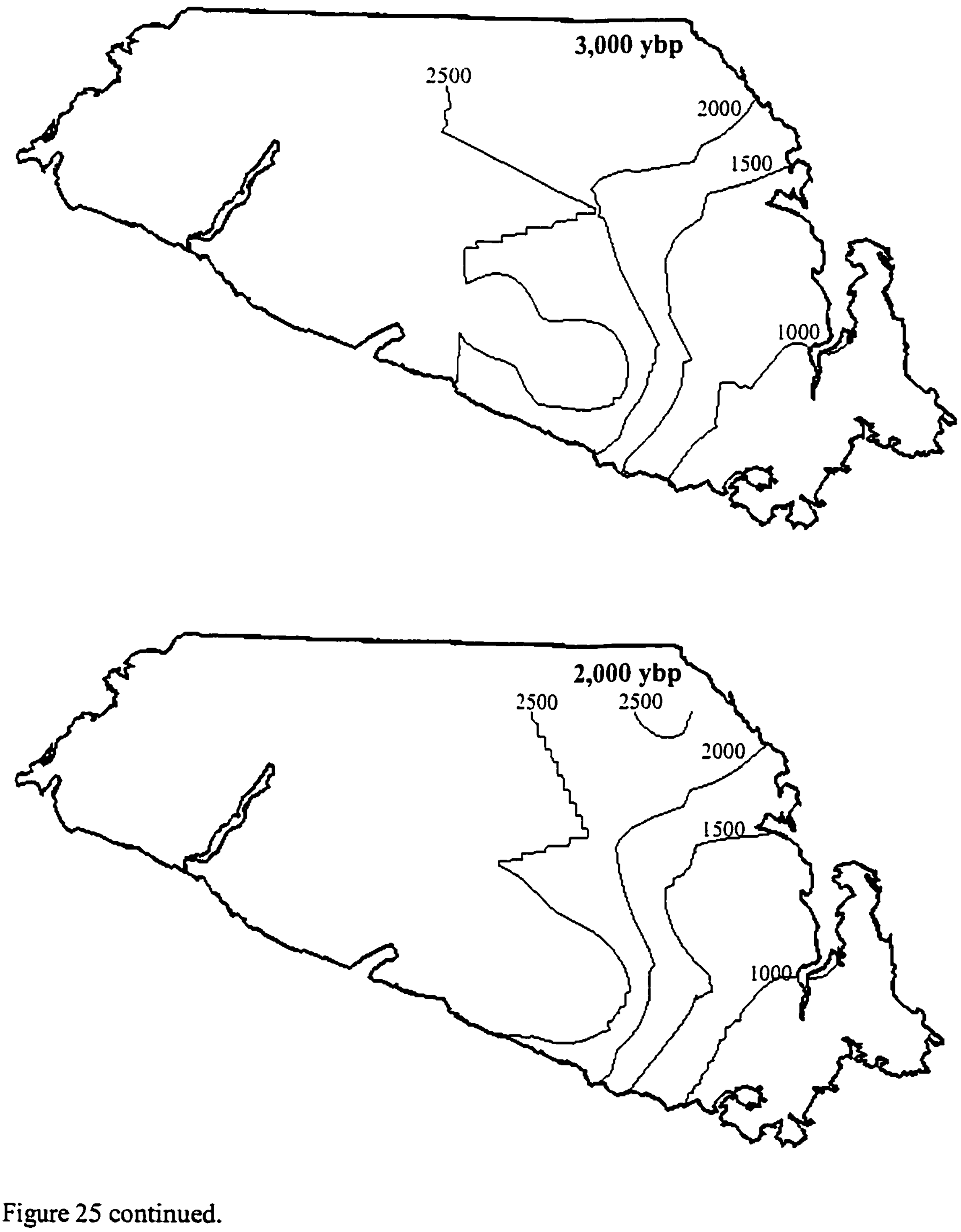
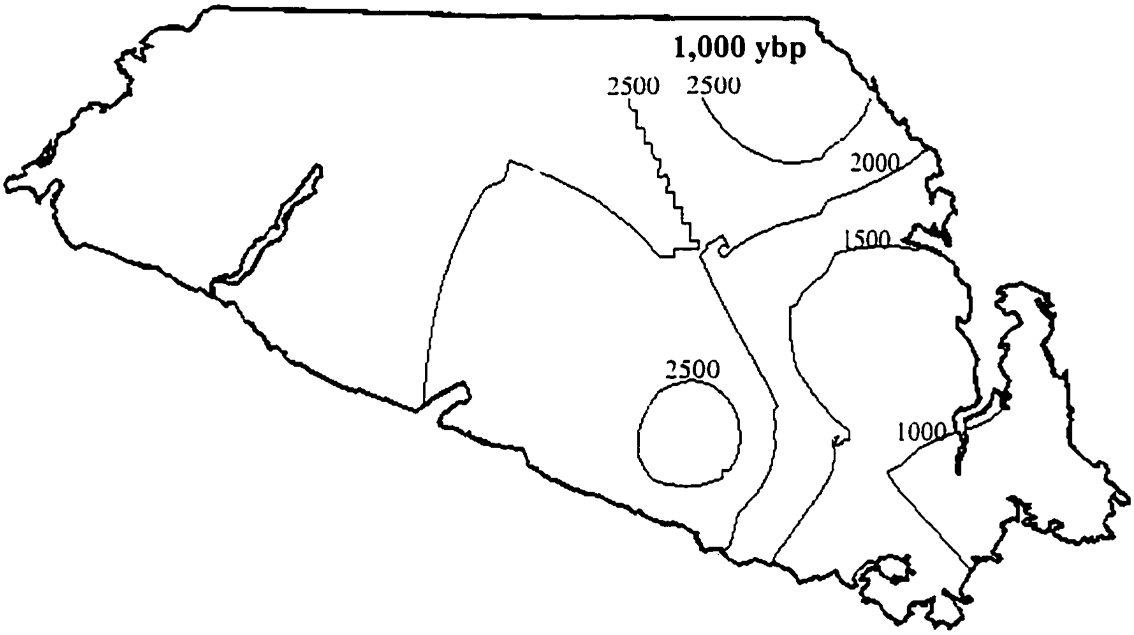
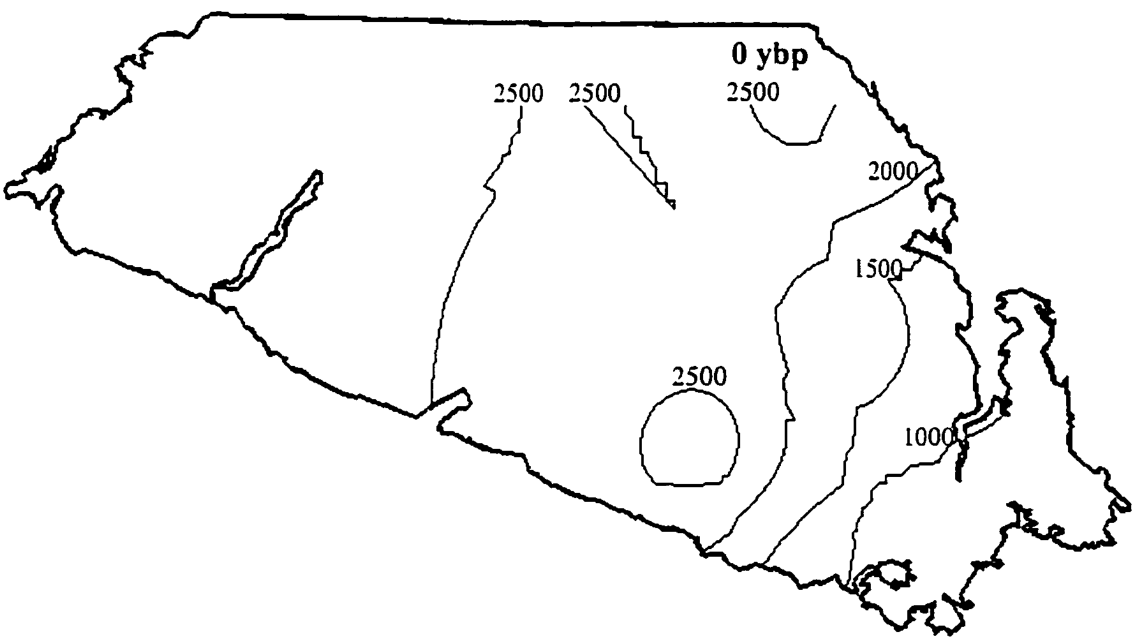


Figure 25 continued.





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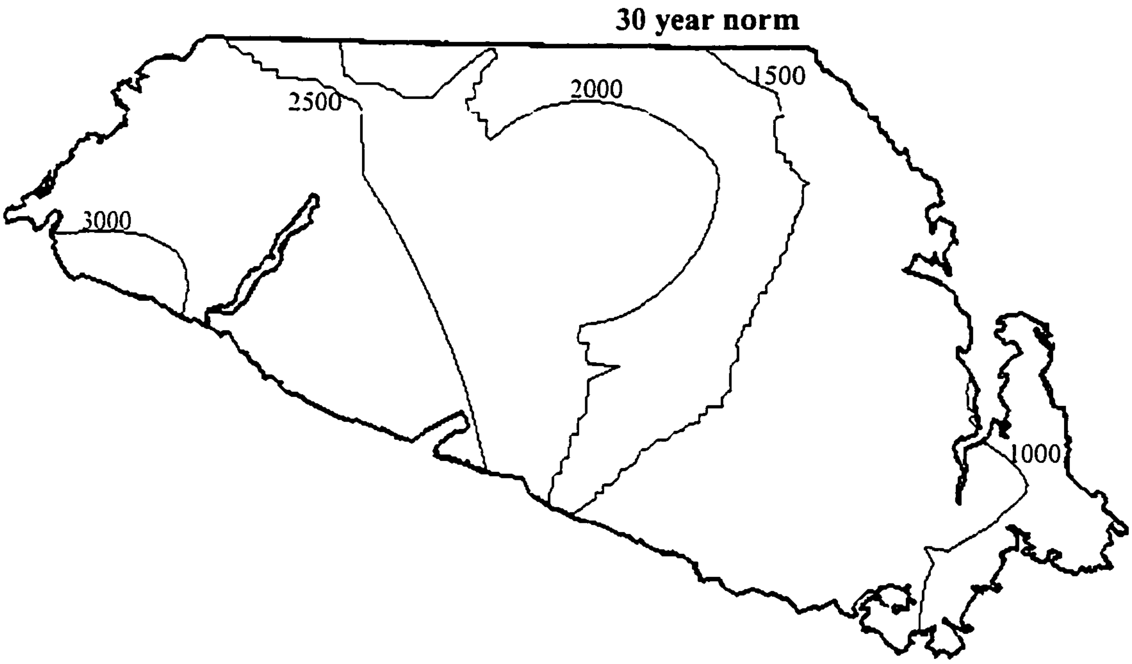


Figure 25 continued.

Juan Ridge did not change significantly. The MAP at 7,000 ybp is similar to the 8,000 ybp interval, suggesting a relatively stable precipitation state persisted between 8,000-7,000 ybp.

Between 7,000-6,000 ybp, however, a noticeable change in isohyet position occurred as southern Vancouver experienced a marked increase in MAP. Along the south coast of Vancouver Island, the 1,000 mm isohyet shifted about 5 km eastward towards Sooke, whereas further inland it migrated approximately 20 km to Saanich Inlet. The 1,500 mm isohyet shifted eastward by about 10 km along the coast and 60 km further inland. The 2,000 mm isohyet migrated approximately 40 km eastward to a position near River Jordan, whereas the 2,500 mm isohyet moved approximately 30 km eastward to a position east of Port Renfrew. A closed 2,500 mm contour developed north of River Jordan suggests high elevations along the San Juan Ridge experienced an increase in MAP of ca. 1,000 mm at this time. The 5,000 ybp interval is comparable to 6,000 ybp, suggesting the amount and distribution of precipitation did not change significantly during this interval.

A change in MAP occurs between 5000-4000 ybp, especially at high elevations. The 2,500 mm isohyet moved eastward ca. 20-30 km to River Jordan and the entire San Juan Ridge received at least 2,500 mm MAP. Also evident at this time is a 500-1,000 mm increase in MAP on Mount Brenton. The 1,500 and 1,000 mm isohyets, however, remained relatively stationary. The 3,000 and 2,000 ybp horizons are comparable to 4,000 ybp, suggesting that another relatively stable precipitation state ensued.

At 1,000 ybp, climatic conditions on southern Vancouver Island moistened. This time, however, the 1,000 mm contour migrated eastward ca. 20 km towards Victoria.

The area west of River Jordan and along the San Juan Ridge remained moist. At 0 ybp, the reconstructed MAP is similar to the 1,000 ybp interval, except that the 1,000 mm isohyet moves ca. 15 km westward towards Sooke. In general, the areas near and west of River Jordan are moist and the areas east of Sooke are relatively dry. High elevation sites such at the San Juan Ridge and Mount Brenton continued to be characterised by moist conditions.

The reconstructed 0 ybp MAP derived from DWHI ratios is similar to the MAP of southern Vancouver Island derived from weather stations except that the isohyets on the weather station map trend northwest, whereas the 0 ybp isohyets trend in a more northern direction. This inconsistency is likely caused by the absence of surface samples from the central region of southern Vancouver Island. Another obvious difference is that the DWHI-derived MAP reconstruction shows that high elevations are characterised by abundant MAP, whereas these regions are not visible on the climate station derived reconstruction, possibly because the weather stations are all located at low elevations.

Temperature

At 10,000 and 9,000 ybp, the San Juan Ridge was characterised by a cold MAT (ca. 4 °C), whereas low elevations near Whyac Lake, the San Juan River valley, and around Sooke and Victoria were characterised by MATs between ca. 8 and >9 °C (Figure 26). These data suggest that steep temperature gradients characterised southern Vancouver Island at this time. By 8,000 ybp, a profound change in MAT had occurred as most of southern Vancouver Island, including the San Juan Ridge, warmed to >9 °C. The coolest site at this time was at Mount Brenton, which was characterised by a 8 °C MAT.

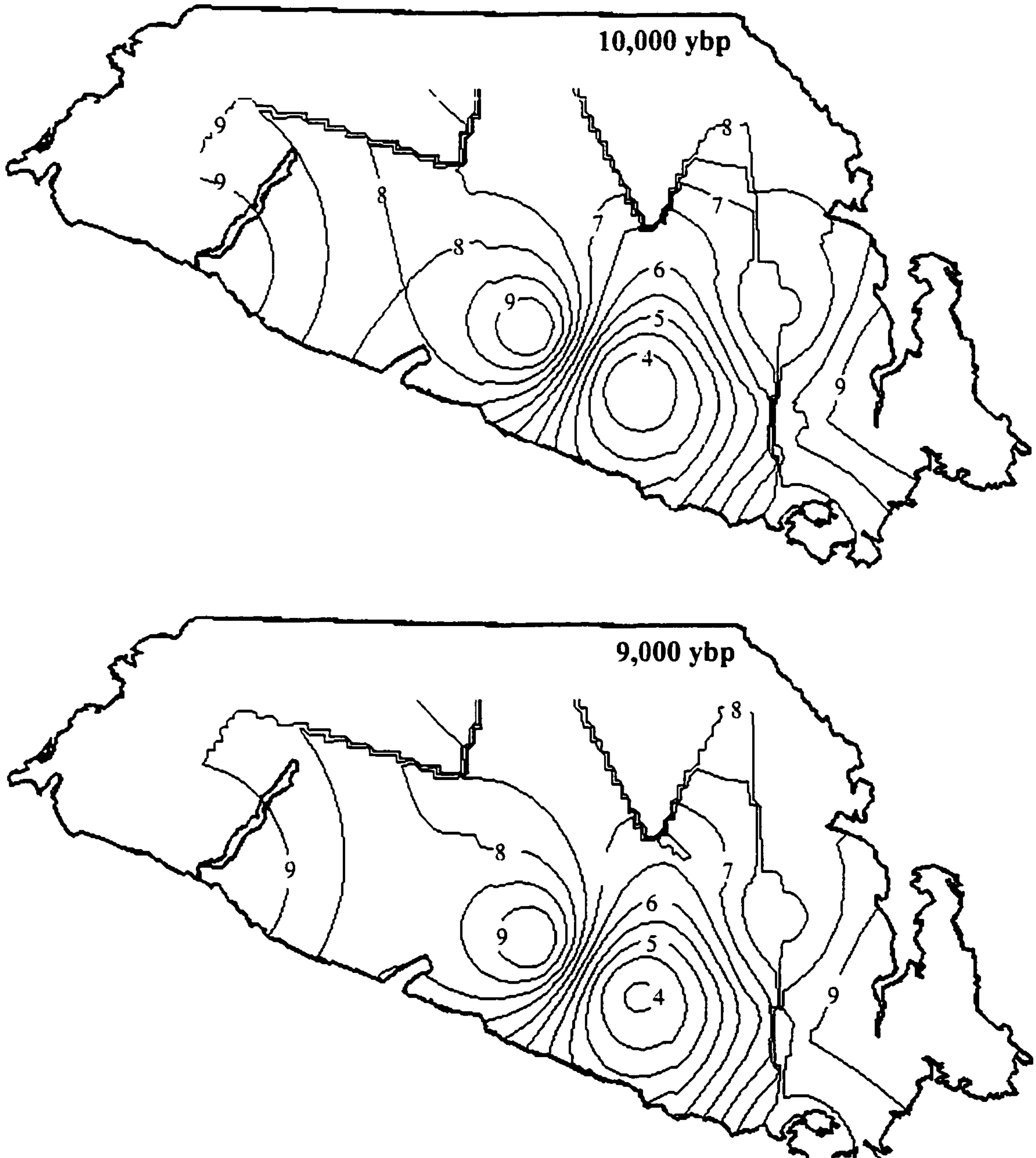
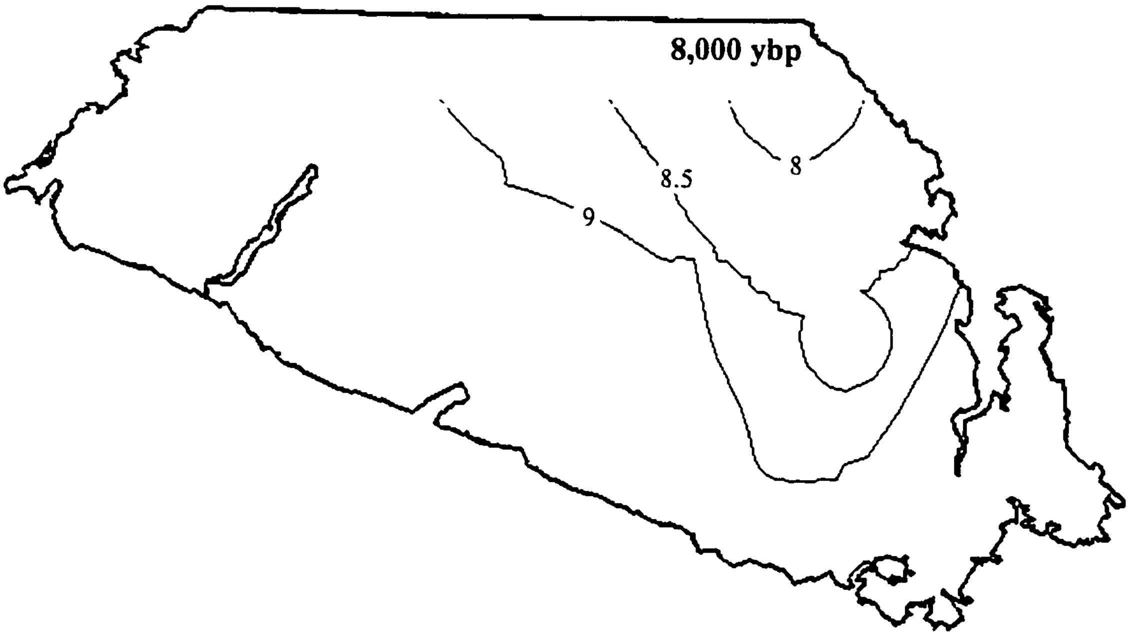
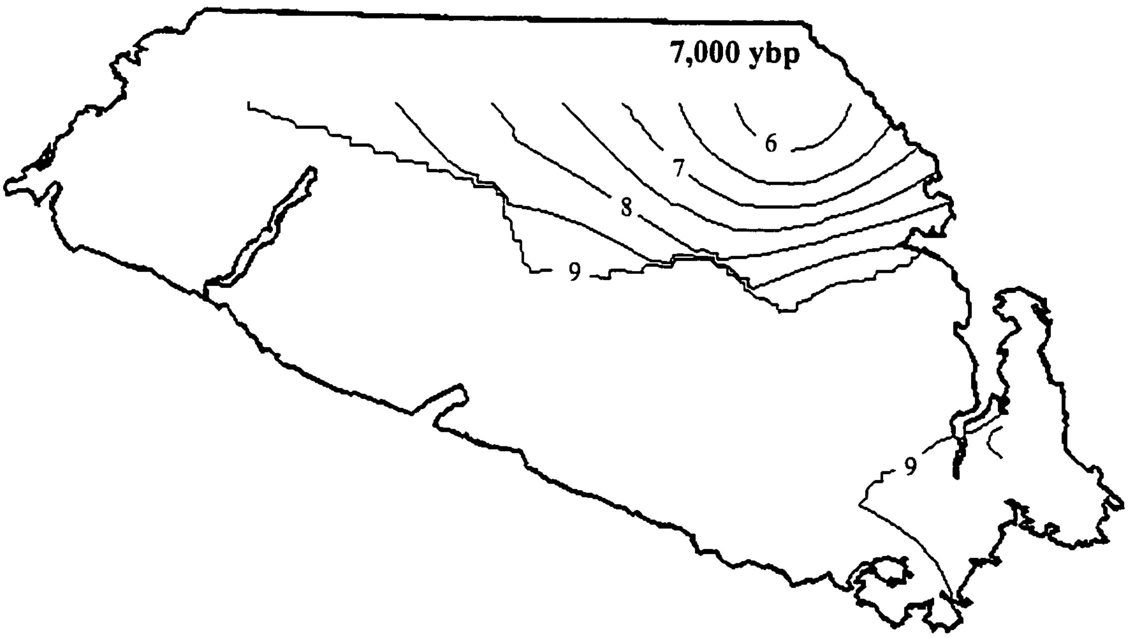


Figure 26. THMI-derived Holocene isotherms of southern Vancouver Island. The time interval represented is shown in the top right corner and the contour interval is 0.5 °C. A 30 norm isotherm generated from weather station data is presented last for comparison.





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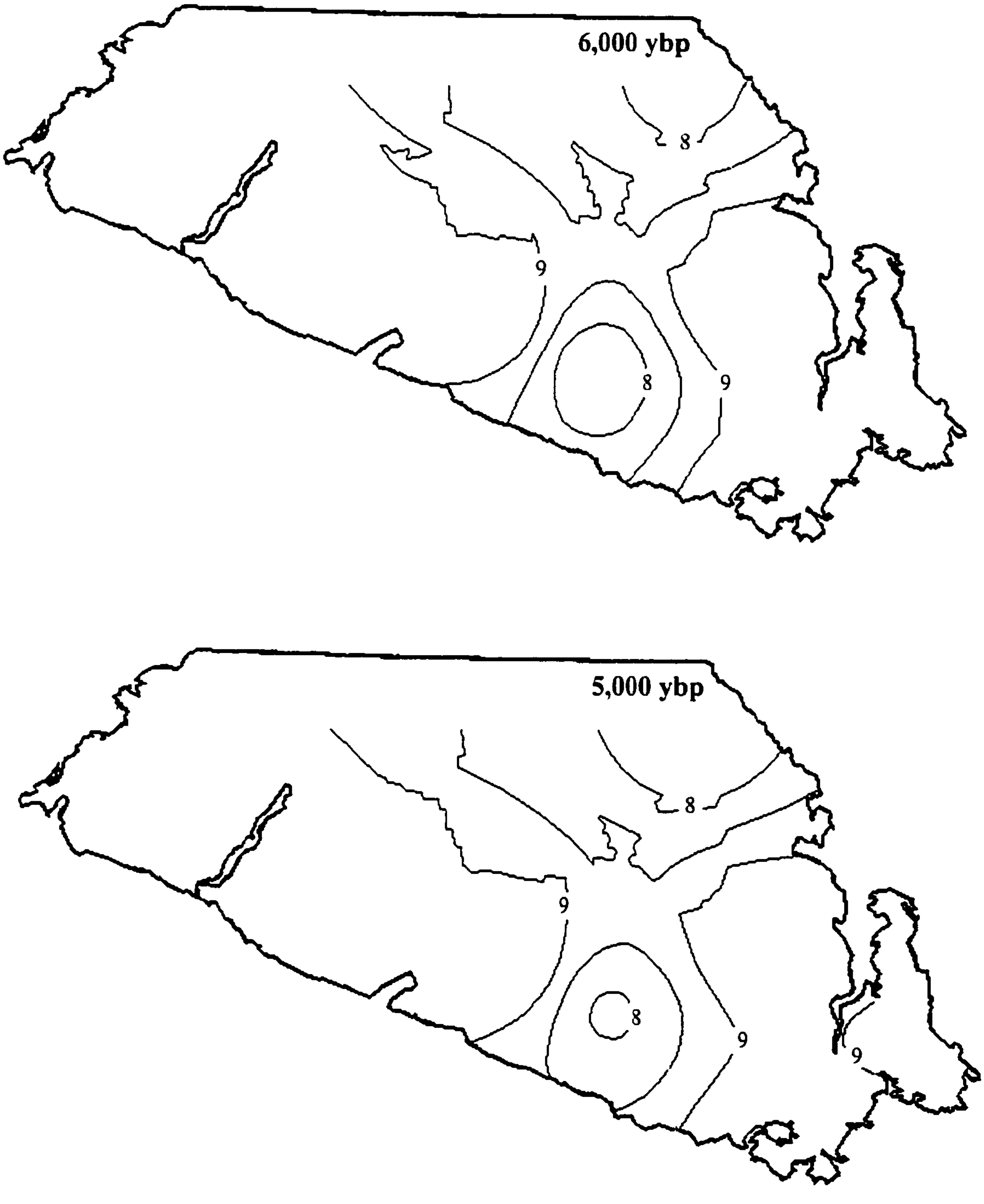

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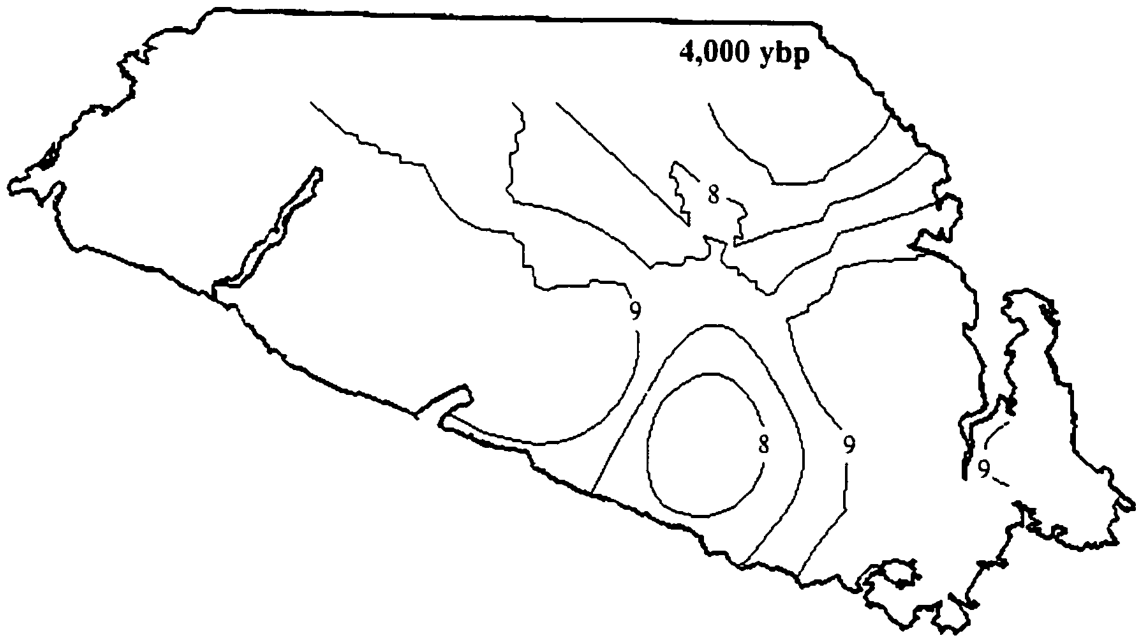

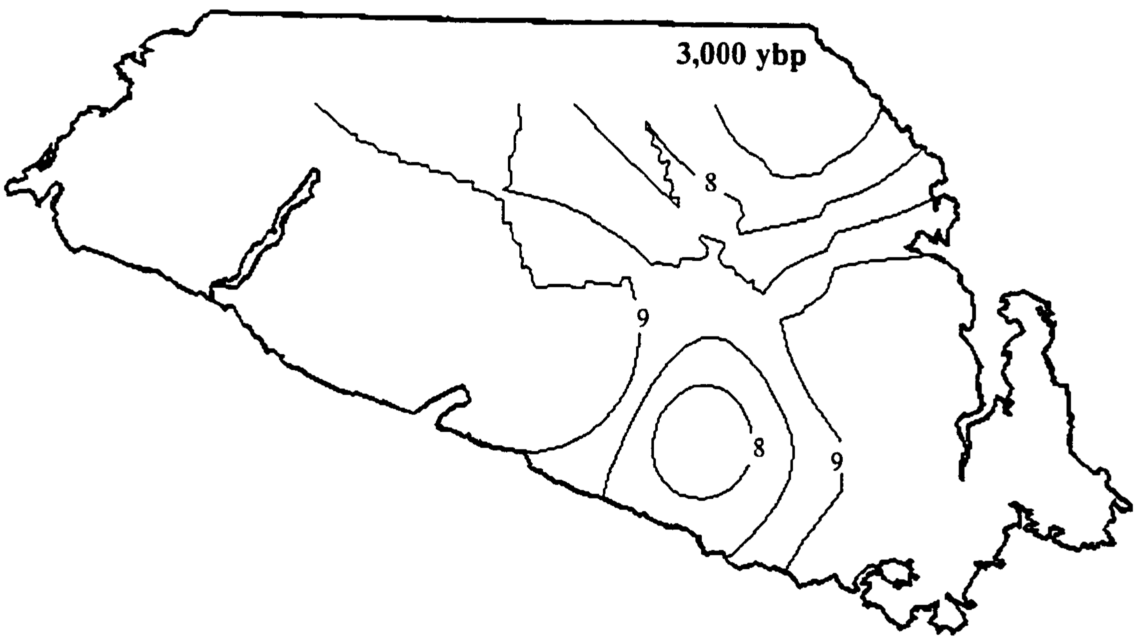

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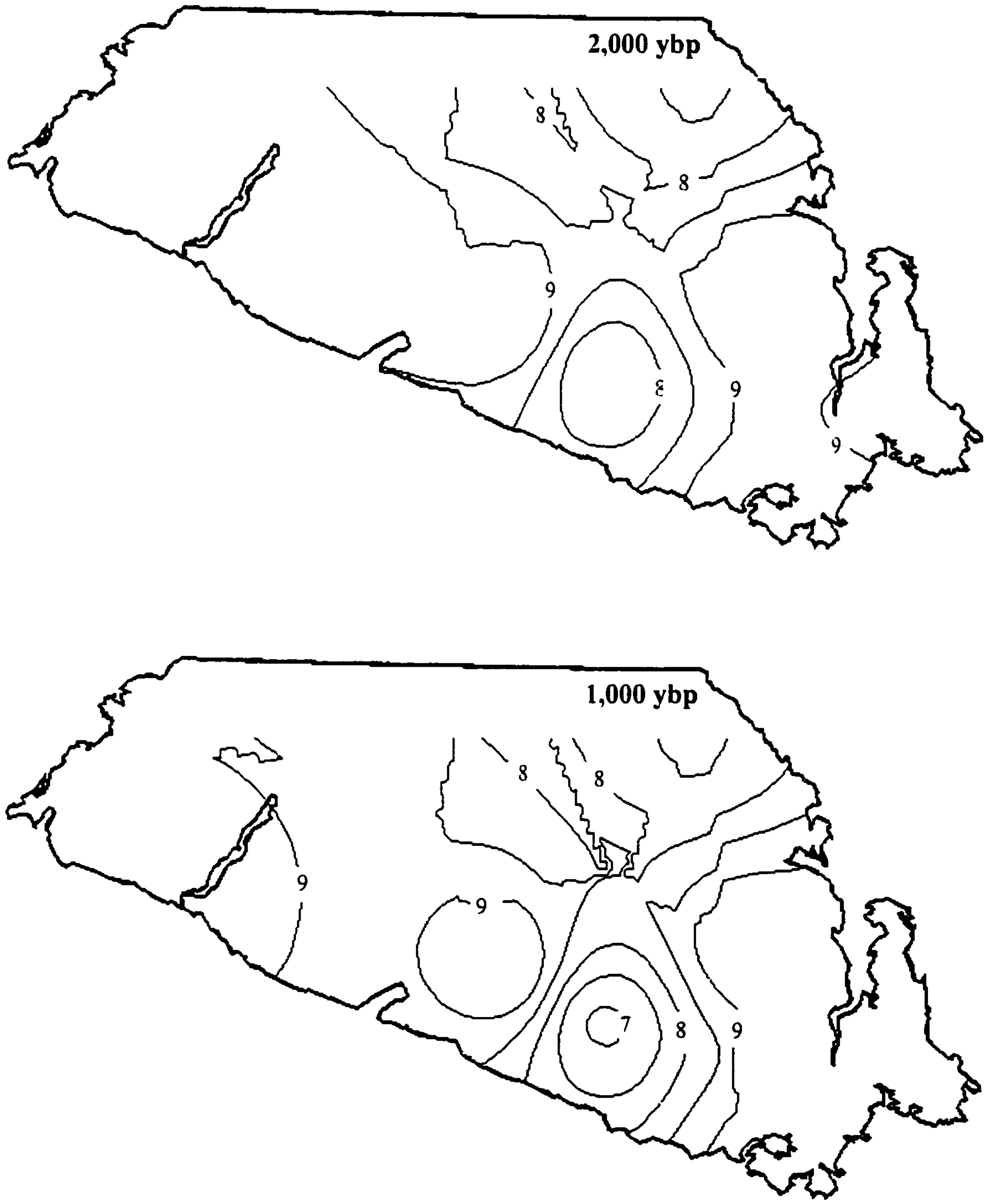
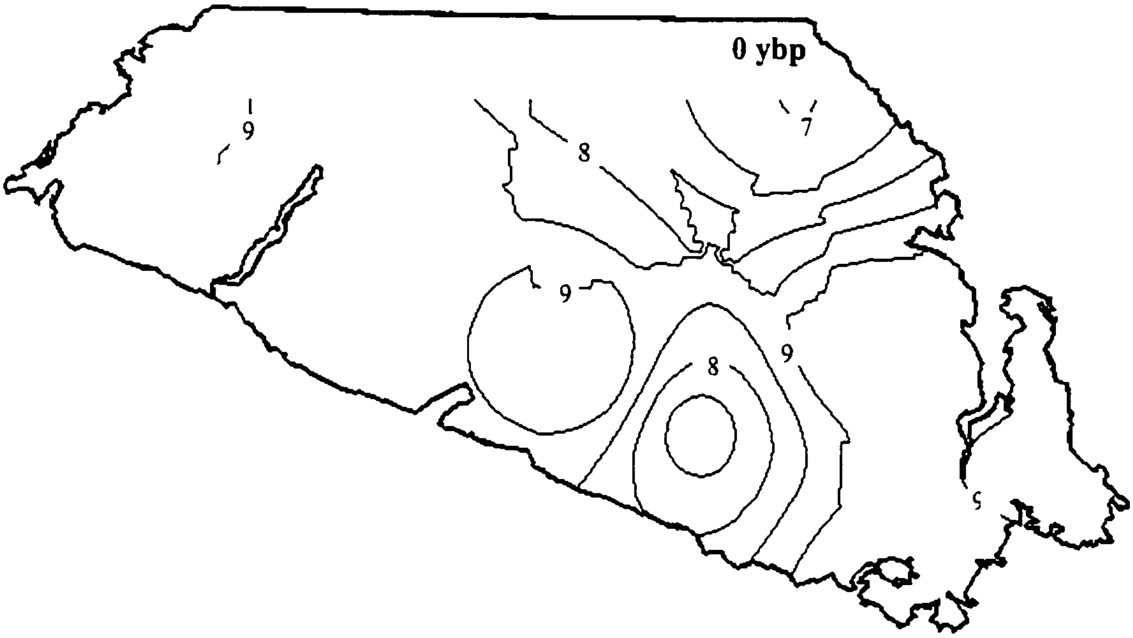


Figure 26 continued.



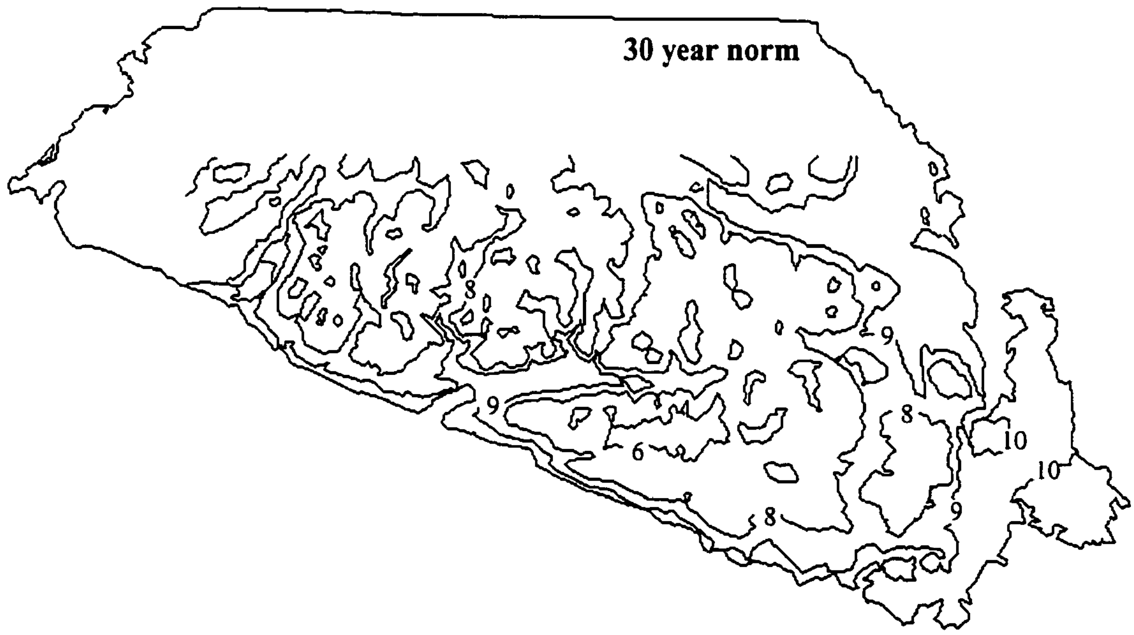


Figure 26 continued.

At 7,000 ybp, warm MATs (>9 °C) still persisted on southern Vancouver Island, although cooling of ca. 2 °C appears to have occurred around Mount Brenton. Cooling of about 0.5 °C appears to have occurred near Victoria at this time as well.

Between 7,000-6,000 ybp, MAT had generally cooled on southern Vancouver Island by about 1 °C. At this time, high elevations such as the San Juan Ridge and Mount Brenton record 8 °C MAT values, whereas low elevations near Whyac Lake, Port Renfrew, Sooke, and Victoria were characterised by MATs between 8.5 and >9 °C. The MATs at all elevations at 5,000, 4,000, 3,000, and 2,000 ybp are comparable to those at 6,000 ybp, suggesting a period of relatively stable temperatures. One noticeable change during the interval from 6,000-2,000 ybp is the ca. 20 km westward migration of the 8 °C isotherm from Mount Brenton.

Cooling on southern Vancouver Island is evident between 2,000-1,000 ybp. During this interval, high elevation sites cooled by about 1 °C with MATs of ca. 7 and 7.5 °C occurring on the San Juan Ridge and Mount Brenton respectively. At low elevations, the regions north of Port Renfrew and Sooke cooled by ca. 0.5 °C. In general, low elevation MATs ranged between 8.5 and >9 °C. The MAT at 0 ybp is generally comparable to 1,000 ybp.

The THMI derived MATs at 0 ybp compare well with the weather station derived MATs for southern Vancouver Island and appear to capture general trends. For example, according to the climate data, the area around Sooke and Victoria is characterised by MATs between ca. 8-10 °C, whereas the THMI data suggests these areas experience MATs between 8.5 and >9 °C. Another consistency occurs at higher elevations where weather data indicates MATs range between ca. 6-8 °C and THMI data suggests MATs are between ca. 7-7.5 °C. Both the climate and THMI data also reveal that the San Juan River valley near Pixie Lake is characterised by a MAT >9 °C. Both sets of data also show that portions of the southern Vancouver Island Ranges have MATs of ca. 8 °C, although the climate data also reveal some areas with MATs < 6 °C. The THMI-derived MAT estimates do not record these colder areas, likely because of insufficient high elevation surface sample points from this part of the island.

Discussion

The GIS based reconstruction of Holocene climates indicates cool conditions persisted at high elevations at 10,000 and 9,000 ybp and that low elevations were relatively warm at this time. In general, warm conditions characterised most of southern Vancouver Island at 8,000 and 7,000 ybp. In terms of precipitation, southern Vancouver Island was generally dry from 9,000-7,000 ybp. In the mid Holocene, slight cooling and a large increase in precipitation occurred between 7,000-6,000 ybp and persisted until ca. 2,000-1,000 ybp. During the last millennium (1,000 ybp-present) temperatures cooled slightly and minor changes in precipitation, especially on southeastern Vancouver Island occurred. The GIS reconstruction also shows that DWHI and THMI ratios are limited in their range of prediction and that other ratios capable of detecting further extremes of climate need to be developed.

The GIS paleoclimate reconstruction is consistent with other qualitative regional climate reconstructions using paleoecological interpretations (Mathewes, 1973; 1985; Heusser, 1983; Hebda, 1983; 1995; Allen, 1995). Generally, these paleoclimatic reconstructions indicate that the early Holocene was warmer and drier than present and that cool, wet conditions developed during the mid and late Holocene. Allen (1995) and Hebda (1983; 1995) further suggest that the mid Holocene may have been warm and moist with cooler and moister conditions developing during the late Holocene.

The GIS based paleoclimatic reconstruction and those derived from other transfer functions generally are in good agreement and reveal comparable trends. Direct temperature comparisons between the GIS based reconstructions and those of Heusser et al. (1980), Mathewes and Heusser (1981), and Adam and West (1983) must be considered with caution because the GIS technique reconstructs MATs, whereas the earlier reconstructions examined mean July temperatures. Other transfer function studies show that warming and drying occurred at about 10,000 ybp (Heusser et al., 1980; Mathewes and Heusser, 1981; Adam and West, 1983; Allen, 1995, Hebda, 1995). These studies all indicate that between ca. 10,000-7,000 ybp, climate was warmer and drier than during any other period in the Holocene. According to Adam and West (1983) climate moistened and cooled throughout mid and late Holocene, an observation consistent with the GIS based paleoclimate reconstruction. Heusser et al. (1980) and Mathewes and Heusser (1981) suggest that the mid Holocene was generally characterised by decreasing temperatures and increasing precipitation. These authors further state that the late Holocene was characterised by a slight warming trend with no pronounced change in precipitation.

Hebda (1995) identified 3 Holocene climate phases, including a warm dry "xerothermic" interval from ca. 9,500-7,000 ybp, a warm moist "mesothermic" interval between ca. 7,000-4,500 ybp, and a moderate and moist interval from 4,500-0 ybp. The GIS-based paleoclimate reconstruction clearly identifies the early Holocene warm dry interval, but does not clearly identify the 4,500 ybp change in climate. Instead, the GIS results suggest that climate remained relatively stable between 7,000-2,000 and then changed slightly at 2000-1000 ybp. Porphyry Lake is the only site in this study that shows a profound change in DWHI and THMI at about 4,500 ybp (Figure 12). In general, the other sites suggest a change in climate at ca. 4,500 ybp through increases in wetland taxa such as *Poaceae*, *Cyperaceae*, and *Sphagnum* but not with DWHI and THMI. The 4,500 ybp change is likely not recorded at many sites because they were already moist and/or cool by this time (i.e. high DWHI and THMI ratios already prevailed), illustrating the need for other, possible more sensitive pollen ratios, that can detect subtle changes in temperature and precipitation trends.

The Pacific Northwest region of North America is characterised by relatively similar paleoclimatic reconstructions using both qualitative and quantitative methods, suggesting that changes in regional climate are primarily responsible for the observed climatic trends and states (Hebda, 1995). Nesje and Johannessen (1992) and Karlén and Kuylenstierna (1996) suggest that changes in Holocene climate are related to changes in solar insolation and global volcanic activity. These studies reveal that the early Holocene warm period resulted from an increase in solar insolation and that mid and late Holocene cooling and moistening resulted from a decrease in solar insolation and increased global volcanic activity (Kelly and Sear, 1984). Campbell et al. (1998), however, propose an alternate explanation and suggest that the Holocene climates in western Canada and, indeed, in other parts of the world were partially modified by a 1,500 year climate cycle that is possibly related to fluctuations in solar output and that paleoclimatic anomalies such as the Younger Dryas, Medieval Warm Period, and Little Ice Age do not require noncyclic explanations. According to the GIS reconstruction, changes in Holocene paleoclimate appear in better agreement with changes in insolation and global volcanic activity.

Conclusion

The major advantage of the GIS based technique is that it enables both temporal and spatial reconstructions of past climates as opposed to other types of reconstructions that generally examine temporal variability at a single site only. The GIS determined paleoclimate reconstruction of southern Vancouver Island revealed climatic states and trends that are consistent with other qualitative and quantitative analyses in the Pacific Northwest region. In general, the paleoclimatic reconstruction showed that the early Holocene on southern Vancouver Island was characterised by warm, dry conditions and that climate moistened and cooled throughout the mid and late Holocene. This technique can be applied to any region that has candidate proxy climate indicators.

CHAPTER 14: APPLICATIONS AND CONCLUSIONS

Introduction

The paleoecological analysis carried out in this study demonstrates the dynamic nature of southern Vancouver Island's ecosystems during the late Pleistocene and Holocene. The research results provide answers to the original questions this study sought to answer.

(1) Have the forests on southern Vancouver Island been unchanging and therefore of a relatively ancient age or do these forests have a relatively recent origin? Paleoecological results show that several different biogeochrons characterised the southern Vancouver Island landscape during the post-glacial and that extant forests developed in the mid and late Holocene.

(2) What major disturbances have affected the forests and what is the relationship between these disturbances, climate change, and forest composition? In general, fire appears to have been a significant disturbance during the late Pleistocene and early Holocene. Fire remained a common disturbance on dry landscapes throughout the Holocene but became less important in wet regions. Other disturbances such as windthrow, disease, and volcanic eruptions very likely operated in the past as well. Fire disturbance appears to be largely controlled by climate, especially at lower elevations, although fuel supplies and people were also important factors. Regions characterised by fire appear to have supported more early seral and fire-adapted vegetation compared to areas that experienced little fire which supported late seral fire-sensitive vegetation.

(3) If forest composition and structure have changed, were the changes sudden or gradual? Rapid changes are evident from the late-glacial and the end of the early

Holocene (ca. >13,000-7,000 ybp), as the landscape switched abruptly from one biogeochron to another. More gradual changes occurred from the mid Holocene to the present (ca. 7,000-0 ybp), as biogeochrons transformed more slowly.

(4) How have individual species responded to climate change and other disturbances? Individual species have certainly responded to both climate change and disturbances. In general, the response has involved changing of distribution. With fire disturbance, fire-sensitive taxa occupied regions with little fire, whereas fire-adapted species persisted in the disturbed regions.

(5) What impact, if any, did First Peoples and European settlers have on local ecosystems? It appears that people used fire to clear and manage the landscape, especially during the late Holocene, thus maintaining open areas with early seral vegetation.

(6) Having established the (past) dynamics of forests, to what extent and in what way might forests on southern Vancouver Island change in response to future climatic conditions? Some of the possible future changes on southern Vancouver Island may include (1) an expansion of *Pseudotsuga*-dominated forests into the CWH zone; (2) expansion of *Pseudotsuga-T. heterophylla* forests into the MH zone; (3) expansion of *Q. garryana* and its associated meadows; (4) drying out of wetlands and lakes, especially those that have undergone hydrosere succession; (5) an increase in disturbance by fire; and (6) changes toward more open forest structure.

Applications

This research provides insight into past vegetation dynamics. In particular, the paleoecological records reveal how vegetation responded to changes in past climates and fire disturbance. This data also reveals the possible impact that people had on the landscape. These results may assist neoecologists examining contemporary ecological issues by providing a long-term ecosystem perspective and could also be used to ground truth climate models.

The results of this research are also applicable to the study of climate dynamics because past changes in precipitation (Douglas-fir-western hemlock index (DWHI)) were separated from temperature changes (*T. heterophylla-T. mertensiana* index (THMI)). Further research in this area will require the calibration of new pollen ratios that can detect climate changes in non-forested regions. This research provides additional insight into climate dynamics because long-term climatic trends, including the temporal and spatial distribution of climate gradients, were identified. The usefulness of a GIS in paleoclimatic research was also established, by showing that the technology can be used to reveal site to site climate changes through time. Future efforts combining GIS technology with paleoecological and climate data should concentrate on mapping past and future vegetation.

In terms of glacial history, this research reveals the importance of basal sediments. The results from Porphyry Lake show that it is important to retrieve as much basal sediment as possible because these sediments may contain records of early late and possibly even full glacial intervals. Also, this research shows that the *P. contorta* biogeochron should be constrained temporally where possible, because it may provide insight into the deglacial history of a region.

The charcoal records may also have an archeological basis, an observation that can be used to assist in understanding when people arrived in a particular area and whether they used fire as a ecosystem management tool.

Using the paleoecological record on southern Vancouver Island as a guide, it is reasonable to infer that any future climate change will result in major changes to the landscape (Franklin et al., 1991; Wotton and Flannigan, 1993; Price and Rind, 1994; Hebda, 1998; Overpeck, 1998; Thompson et al., 1998). Paleoecological investigations provide an insightful and inexpensive method of estimating what future landscapes may be like and the rate at which landscape changes may occur. The forest structure and composition, species distribution, and disturbance characteristics of the early Holocene biogeochrons may be indicative of future ecosystems resulting from global warming.

The application of the paleoecological data gathered during this investigation extends beyond simply understanding past and future forest dynamics. In terms of forest management, this investigation reveals which areas on southern Vancouver Island are particularly sensitive to climate change and which areas appear less sensitive. Forest managers need to consider landscape sensitivity to climate change when discussing present-day and future landuse, especially replanting and stand management strategies. In terms of conservation, perhaps it is more appropriate for policy makers and decision groups to target the less sensitive areas for conservation, since areas that have shown marked changes in the past are likely to change again in the near future these are less desirable areas for protection (Hebda, 1998). The charcoal records reveal that a warmer, drier future climate will likely lead to increased fire activity, suggesting a need to review forest fire strategy.

Conclusions

The surface sample studies reinforce observations that many ecosystems can be distinguished (Heusser, 1977; Pellatt et al., 1997; Allen et al., 1999). In particular, the grassland and *Q. garryana* associations of the CDF can be easily distinguished from arboreal units. The CDF zone and dry CWH subzones can be separated from wetter CWH subzones and the MH zone can be differentiated from lowland zones using *T. mertensiana* pollen. Further development of the surface sample pollen and spore ecosystem signature has the potential to permit greater insight into the paleoecological and paleoclimatic history of the Pacific Northwest region.

The pollen and spore and charcoal records from ESF and Pixie, Whyac, Enos, and Boomerang lakes reveal the history of lowland regions on southern Vancouver Island and show that they have been highly dynamic. In particular, they show that (1) lowland areas were characterised by *P. contorta* woodlands during the cool, dry early late glacial interval; (2) mixed conifer forests replaced the *P. contorta* woodlands in the late Pleistocene during a cool, moist climatic interval; (3) fires first occurred during the late Pleistocene; (4) *Pseudotsuga* forests occurred on eastern and southern Vancouver Island during the warm and dry early Holocene, whereas *T. heterophylla-Picea* forests persisted in western regions, suggesting precipitation gradients were established at this time; (5) fires generally increased during the early Holocene; (6) *T. heterophylla* expanded during the mid Holocene as climate moistened; (7) fires decreased during the mid Holocene; (8)

Cupressaceae expanded in the late Holocene; (9) fires were rare or absent from southern and southwestern Vancouver Island during the late Holocene, whereas fires persisted in eastern and southeastern regions, possibly because of human activity.

The pollen and spore and charcoal records from Porphyry and Walker lakes reveal the history of high elevation forests, climate, and fire on southern Vancouver Island and show that (1) high elevation forests experienced changes at similar times as low elevation forests; (2) the Porphyry Lake area may have been a glacial refugium that was characterised by a tundra-like ecosystem during the last glaciation; (3) the *P. contorta* biogeochron at high elevations included a greater mixed conifer component than at low elevations, suggesting orographic precipitation gradients were established in the late glacial or that cooler temperatures at high elevations resulted in less drying; (4) the late Pleistocene mixed conifer forests at high elevations were generally similar to low elevation forests except that *T. mertensiana* was more abundant; (5) expansion of *Pseudotsuga* and *T. heterophylla* trees into high elevation regions provides evidence that the early Holocene was clearly warmer and drier than the present; (6) mid and late Holocene moistening and cooling is recorded at high elevations by an increase in *T. heterophylla*, *T. mertensiana*, and Cupressaceae pollen; (7) pre-Holocene fire records are similar to those of low elevation sites and show that fire was absent during the late glacial and increased during the late Pleistocene. During this interval, the fire record appears to correlate with climate; and (8) during the Holocene, high elevation fire records differ from low elevation sites and appear less sensitive to changes in climate.

DWHI and THMI pollen ratios can be used as quantitative indicators of precipitation and temperature changes respectively. Modern DWHI ratios when calibrated with mean annual precipitation in a GIS and modern THMI ratios when calibrated with mean annual temperature through regression equations can be used to construct maps of paleoprecipitation and paleotemperatures.

This study illustrates that paleoecological research can provide detailed insight into a regions history and establish a link between vegetation, climate, and disturbance. This paleoecological information can provide critical insight into the impacts of climate change on future landscapes on a site by site basis, suggesting that "the past is indeed a key to the future".

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