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Postglacial vegetation and climate dynamics in the Seymour-Belize Inlet Complex, central coastal British Columbia, Canada: palynological evidence from Tiny Lake

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ABSTRACT: A pollen-based study from Tiny Lake in the Seymour-Belize Inlet Complex of central coastal British Columbia, Canada, permits an evaluation of the dynamic response of coastal temperate rainforests to postglacial climate change. Open *Pinus* parklands grew at the site during the early Lateglacial when the climate was cool and dry, but more humid conditions in the later phases of the Lateglacial permitted mesophytic conifers to colonise the region. Early Holocene conditions were warmer than present and a successional mosaic of *Tsuga heterophylla* and *Alnus* occurred at Tiny Lake. Climate cooling and moistening at 8740 ± 70 ^{14}C a BP initiated the development of closed, late successional *T. heterophylla*–Cupressaceae forests, which achieved modern character after 6860 ± 50 ^{14}C a BP, when a temperate and very wet climate became established. The onset of early Holocene climate cooling and moistening at Tiny Lake may have preceded change at more southern locations, including within the Seymour-Belize Inlet Complex, on a meso- to synoptic scale. This would suggest that an early Holocene intensification of the Aleutian Low pressure system was an important influence on forest dynamics in the Seymour-Belize Inlet Complex and that the study region was located near the southern extent of immediate influence of this semi-permanent air mass.

KEYWORDS: palaeoecology; palaeoclimatology; palynology.

Introduction

Pollen and spores, diatoms, and other palaeoenvironmental proxies preserved in lake sedimentary sequences in Pacific Canada have documented several phases of late Quaternary climate change in this ecologically diverse and unique region (e.g. Heusser, 1956; Mathewes, 1973; Hebda, 1983; Pellatt and Mathewes, 1994, 1997; Nederbragt and Thurow, 2001; Brown and Hebda, 2002, 2003; Chang *et al.*, 2003; Lacourse, 2005; Galloway *et al.*, 2007; Stolze *et al.*, 2007). These include a cold and dry Lateglacial interval, a cool and moist period from ca. 12 000 to 10 000 ^{14}C a BP, and an early Holocene warm and dry phase that was terminated between ca. 7000 and 7500 ^{14}C a BP when climate cooling and/or moistening began (Mathewes, 1973; Pellatt and Mathewes, 1994, 1997; Brown and Hebda, 2002, 2003; Lacourse, 2005). However, recent palaeoclimate research in the Seymour-Belize Inlet Complex (SBIC) of the central mainland coast of British Columbia (BC) documents the transition from an early Holocene xerothermic climate to cooler and moister conditions ca. 1000–1700 a prior to more southern locations, but contemporaneous with sites in the southwestern Yukon, coastal Alaska and parts of northern BC (Cwynar, 1988; Hansen and Engstrom, 1996; Lacourse and Gajewski, 2000; Spooner *et al.*, 1997, 2002; Axford and Kaufman, 2004; Galloway *et al.*, 2007). This pattern of climate asynchrony suggests that early Holocene dynamics in the Aleutian Low (AL) pressure system were an important influence on the climate of this region (Spooner *et al.*, 2003; Galloway *et al.*, 2007).

The SBIC is located adjacent to the oceanic Coastal Transition Domain, which extends from the tip of northern Vancouver Island to Dixon Entrance and is transitional between the downwelling California current system to the south and the upwelling Alaskan current system to the north (Ware and Thomson, 2000). Because the relative position and strength of the AL have been linked to basin wide ocean circulation patterns

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(e.g. the Pacific Decadal Oscillation and the El Niño Southern Oscillation; Trenberth, 1990; Trenberth and Hurrell, 1994), this area is expected to be a sensitive recording area of dynamics in this air pressure system, and thus was targeted for study.

Little is known of the postglacial forest or climate history of the central mainland coast of BC because it is an area that has been poorly studied and represents a spatial gap between sites previously investigated to the north on the Queen Charlotte Islands, the northern mainland of BC, in southern Alaska and the southwestern Yukon, and more intensively studied areas along the coasts of Vancouver Island and the southern mainland of BC, and in northwestern Washington state (Fig. 1). Previous research in the SBIC includes pollen and diatom-based work at Woods Lake (Stolze *et al.*, 2007) and Two Frog Lake (Galloway *et al.*, 2007), and a diatom stratigraphy at Tiny Lake (Doherty, 2005). The three lakes are located along an S–N transect, with approximately 12 km between each site (Fig. 2). All lie between 2 and 4 m above sea level and within the Southern Very Wet Hypermaritime Coastal Western Hemlock variant (CWHvh1) of the Coastal Western Hemlock biogeoclimatic zone (Meidinger and Pojar, 1991; Green and Klinka, 1994; Pojar and Mackinnon, 1994). Tiny Lake, located at the northern extent of the SBIC, was selected for detailed investigation because its northerly position would document postglacial climate dynamics in this poorly studied area. This work will build upon previous research in coastal BC and within the SBIC by exploring the diachroneity of postglacial climate change using pollen analysis, which will facilitate inter-site comparison, and explore the influence of postglacial climate change on regional forest dynamics. Proximity to shoreline and elevation were additional lake selection criteria: accessibility through dense understorey vegetation was a consideration, and lakes with different sill heights were targeted so that a postglacial sea level history could be documented (Doherty, 2005).

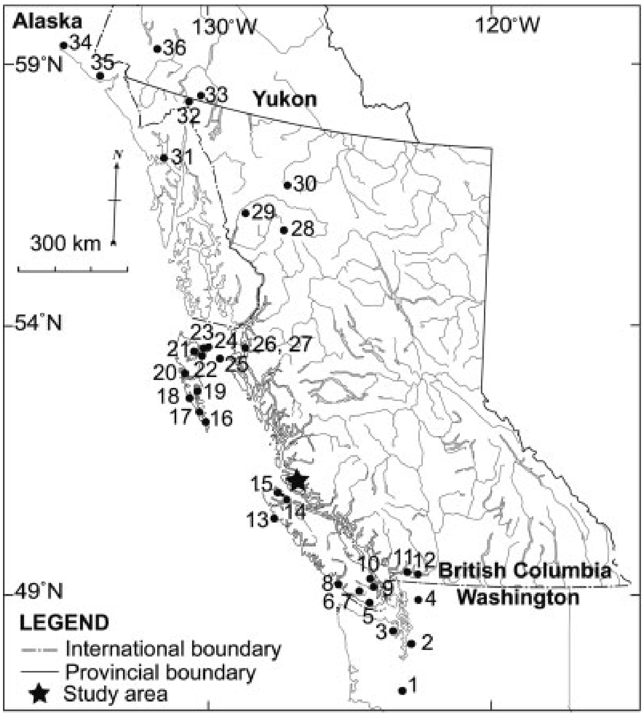

Figure 1 Map of British Columbia, the Yukon, and adjacent US states, showing the location of palaeoclimate investigations mentioned in the text (map reproduced with the permission of Natural Resources Canada, 2008 and courtesy of the Atlas of Canada): (1) Davis Lake (Barnosky, 1981); (2) Lake Washington (Leopold *et al.*, 1982); (3) Crocker Lake and Cedar Swamp (McLachlan and Brubaker, 1995); (4) Kirk Lake (Cwynar, 1987); (5) East Sooke Fen (Brown and Hebda, 2002); (6) Pixie Lake (Brown and Hebda, 2002); (7) Walker Lake (Brown and Hebda, 2003); (8) Whyac Lake (Brown and Hebda, 2002); (9) Saanich Inlet (Pellatt *et al.*, 2001); (10) Porphory Lake (Brown and Hebda, 2003); (11) Marion and Surprise Lakes (Mathewes, 1973; Mathewes and Heusser, 1981); (12) Pinecrest and Squeah Lakes (Mathewes and Rouse, 1975); (13) Brooks Peninsula (Hebda, 1997); (14) Misty Lake (Lacourse, 2005); (15) Bear Cove Bog (Hebda, 1983); (16) (Quickfall, 1987); (17) West Side Pond (Lacourse *et al.*, 2005); (18) SC1 Pond (Pellatt and Mathewes, 1997); (19) Louise Pond (Pellatt and Mathewes, 1994); (20) Shangri-La Bog (Pellatt and Mathewes, 1997); (21, 22) (Warner, 1984); (23, 24) (Quickfall, 1987); (25) Dogfish Bank (Lacourse *et al.*, 2005); (26) (Banner *et al.*, 1983); (27) Diana Lake Bog (Turunen and Turunen, 2003); (28) Skinny Lake (Spooner *et al.*, 2002); (29) Susie Lake (Spooner *et al.*, 1997); (30) Pyramid Lake (Mazzucchi *et al.*, 2003); (31) Pleasant Island (Hansen and Engstrom, 1996); (32) Waterdevil Lake (Spear and Cwynar, 1997); (33) Kettlehole Pond (Cwynar, 1988); (34) Icy Cape (Peteet, 1986); (35) Little Swift Lake (Axford and Kaufman, 2004); (36) Sulphur Lake (Lacourse and Gajewski, 2000)

Study area

Environmental setting

The SBIC is a series of glacially scoured fjords that punctuate the central mainland coast of BC approximately 40 km NE of Port Hardy, Vancouver Island (Fig. 2). The regional bedrock consists of Mesozoic granites and volcanic rocks and, consequently, soils are poorly developed and acidic (Meidinger and Pojar, 1991).

Tiny Lake (51° 11.667′ N, 127° 22.08′ W) is a relatively large (48 ha) and deep (z_{max} 32 m) lake located 250 m south of Mereworth Sound at the northern extent of the SBIC (Fig. 2). The basin is separated from the sea by a 3.28 m sill and has a small stream at the northern margin of the basin (Fig. 3).

Climate

The climate of the CWHvh1 is cool (mean annual temperature 9.1°C) and very wet (mean annual precipitation of 3120 mm; unknown observation period; Green and Klinka, 1994), due to the seasonal influences of the AL and North Pacific High pressure systems (Trenberth and Hurrell, 1994). The AL is a semi-permanent cyclone that intensifies over the Aleutian Islands of Alaska during winter months and delivers warm and moist maritime air from the S/SW to the coast of BC, causing wet and mild winters (Trenberth and Hurrell, 1994; Latif and Barnett, 1996). During the summer months the AL weakens and retreats northwestwards and the North Pacific High pressure system intensifies and moves northward. This anticyclone brings cool and dry continental air from the N/NE into coastal BC and is responsible for the warm and dry summers experienced in this region (Trenberth and Hurrell, 1994).

The relative intensity and position of the AL has changed abruptly with a cyclicity of 50–70 a over at least the last 200 a (the Pacific Decadal Oscillation), and with a longer, undefined period over at least the last 7500 a (Trenberth and Hurrell, 1994; Christoforou and Hameed, 1997; Mantua *et al.*, 1997; Minobe, 1999; Mantua and Hare, 2002; Anderson *et al.*, 2005; MacDonald and Case, 2005). When the AL is on average more eastward and/or stronger than usual, a climate characterised by relatively cool summers and mild winters with high precipitation is experienced in coastal BC. This is in part because

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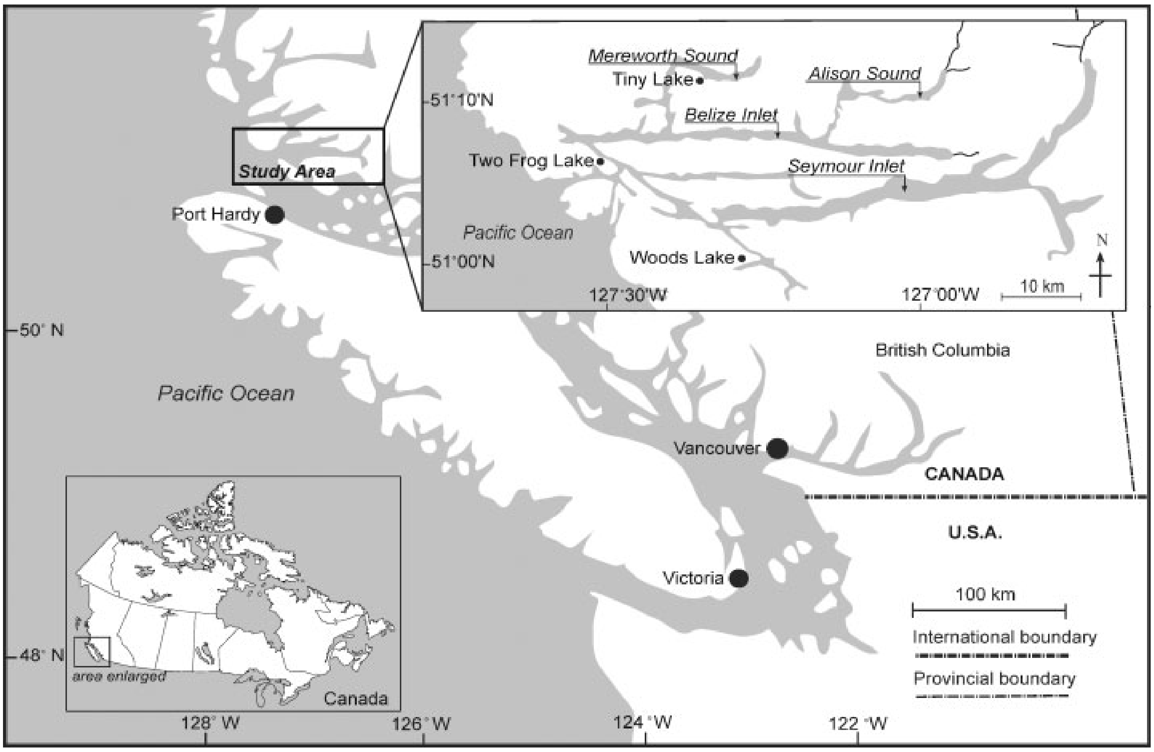

Figure 2 Map of Canada and British Columbia, showing the location of the Seymour-Belize Inlet Complex, Tiny Lake and sites mentioned in text

a more intense and eastward positioned AL affects the direction, frequency and intensity of North Pacific storms by displacing the polar jet stream and westerlies south of their usual position near the Gulf of Alaska, creating a meridional airflow pattern that generates strong mid-latitude (30–40° N) winter cyclones and steers them into the north and central coasts of BC (Klein, 1949; Cayan and Peterson, 1989; Trenberth and Hurrell, 1994).

Vegetation

Tsuga heterophylla and *Thuja plicata* dominate the forests of the CWHvh1 (Table 1; Pojar and Mackinnon, 1994). *Picea sitchensis* and *Abies amabilis* grow in well-drained moist sites. At higher elevations, *Tsuga mertensiana* grows in deep, wet organic soils and *Chamaecyparis nootkatensis* is common in moist to wet, rocky or boggy habitats. *Pinus contorta* grows in low elevation dry or boggy sites and *Pinus monticola* occupies dry to moist open habitats. Both *Alnus rubra* and shrubby *A. viridis* ssp. *sinuata* are common in the CWHvh1, where they occupy open disturbed sites. *Alnus rubra* is more common in riparian habitats and wet areas such as floodplains and swamps, while *A. viridis* ssp. *sinuata* prefers moist and cool upland sites such as north-facing slopes, avalanche tracks and recently deglaciated terrains (Uchytil, 1989a,b; Pojar and MacKinnon, 1994; Fastie, 1995; Hebda, 1997). An understorey of ferns, bryophytes and shrubs form an important aspect of the

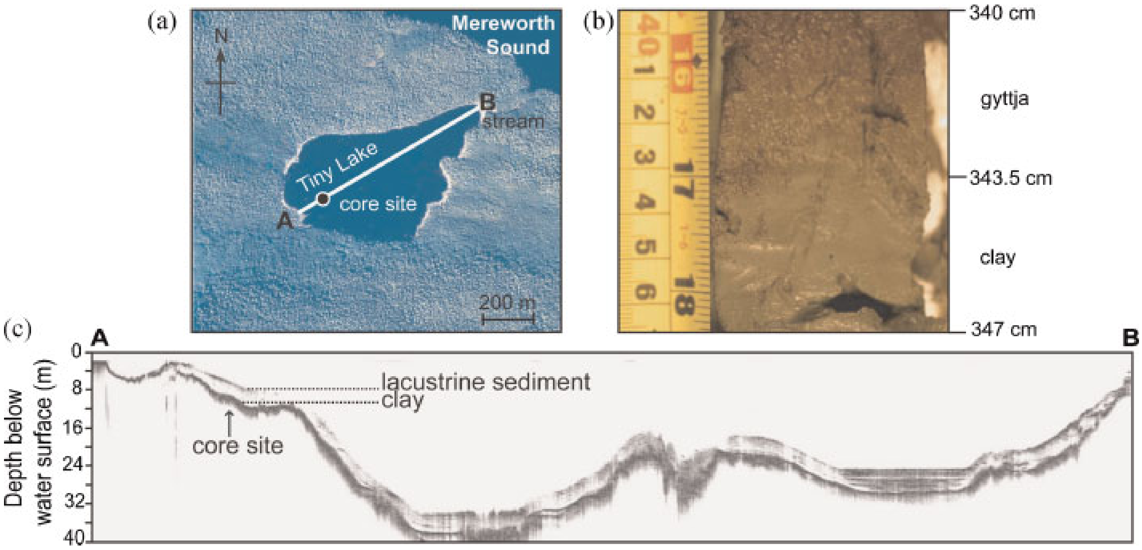

Figure 3 (a) Aerial photograph of Tiny Lake with schematic diagram showing the coring location and transect of the sub-bottom profile. (b) Sub-bottom profile of Tiny Lake. (c) Photograph of the sedimentological contact between basal clay and overlying gyttja in the Tiny Lake sediment core. This figure is available in colour online at www.interscience.wiley.com/journal/jqs

Table 1 Common names of plant taxa mentioned in the text

Latin name	Taxonomic reference[a]	Common name
Abies	Mill.	Fir
Alnus rubra	Bong.	Red alder
Alnus viridis ssp. *crispa*	(Chaix) DC. (Ait.) Turrill	Green alder
Alnus viridis ssp. *sinuata*	(Regel) Love and Loveis	Sitka alder
Artemisia	L.	Sage/woodworm
Betula	L.	Birch
Chamaecyparis nootkatensis	(D. Don) Spach	Yellow cedar
Cupressaceae		Cedar family
Juniperus communis	L.	Common juniper
Lilaceae		Lily family
Lycopodium clavatum	L.	Running clubmoss
Nuphar	Sm.	Pond-lily
Picea sitchensis	(Bong.) Carr.	Sitka spruce
Pinus contorta	Dougl. ex Loud	Lodgepole pine
Pinus monticola	Dougl.	Western white pine
Polypodium vulgare	L.	Common polypody
Polytrichum juniperum	Hedw.	Juniper haircap moss
Polytrichum piliferum	Hedw.	Awned haircap moss
Pseudotsuga menziesii	(Mirb.) Franco	Douglas fir
Pteridium	Gled. ex Scop.	Bracken fern
Pteropsida		Fern subphylum
Rosaceae		Rose family
Sagittaria	L.	Arrowhead
Salix	L.	Willow
Taxus brevifolia	Nutt.	Western yew
Thuja plicata	Donn ex D. Don	Western red cedar
Triglochin	L.	Arrowgrass
Tsuga heterophylla	(Raf.) Sarg.	Western hemlock
Tsuga mertensiana	(Bong.) Carr.	Mountain hemlock
Typha latifolia	L.	Common cattail

[a] Botanical nomenclature after Wherry (1961), Duhamel (1963), Hitchcock and Cronquist (1973), Anderson *et al*. (1990) and Pojar and Mackinnon (1994).

CWHvh1 ecosystem (Meidinger and Pojar, 1991; Klinka *et al.*, 1996).

Methods

Core collection

A 352 cm sediment core was retrieved in October 2002 with a modified Livingstone piston corer (internal barrel diameter 5 cm) from the southern basin of Tiny Lake (Wright *et al.*, 1984), where the occurrence of a conformable sedimentary sequence was inferred from seismic profiling (Fig. 3). The sediment core was wrapped carefully and transported to Carleton University, where it was stored at 4°C until April 2003. The core was subsampled at continuous intervals of 8 or 12 cm for pollen analysis, except between 169–220 cm and 268–304 cm, where sediment was unavailable because it had been used up in other analyses. Additional samples were taken for pollen analysis around the basal transition from clay to organic material. Loss on ignition (LOI) analysis was conducted every 4–20 cm of the core (Dean, 1974).

Radiocarbon dating and modelling

Four bulk sediment samples were submitted for accelerator mass spectrometry (AMS) radiocarbon dating (Table 2). Conventional radiocarbon ages were calibrated to calendar years before present using the INTCAL04 dataset for terrestrial material and the CALIB 5.0.2 computer program (Reimer *et al.*, 2004; Stuiver *et al.*, 2005).

Table 2 Radiocarbon dates and calibrated ages from the Tiny Lake sediment core

Laboratory Code	Depth (cm)	Material	$^{13}C/^{12}C$ ratio ‰	Conventional ^{14}C age (a BP)	Calibrated age (a BP) (95% CI)[b]
BETA-206929	88	Gyttja	−27.8	6860 ± 50	7592–7794 (7693)
TO-12568	136	Gyttja	Not reported[a]	8740 ± 70	9542–9938 (9740)
TO-12569	160	Gyttja	Not reported[a]	8840 ± 60	9698–10169 (9933.5)
SUERC-3090	338–336	Gyttja	−29.0	11 763 ± 87	13 413–13 792 (13 602.5)

[a] Conventional radiocarbon date corrected using a $^{13}C/^{12}C$ ratio (‰) of −25.0.
[b] Calibrated using CALIB REV5.0.2 (Stuiver *et al.*, 2005) with the INTCAL04 dataset (Reimer *et al.*, 2004).
BP denotes before 1950.

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Lateglacial reservoir effects have been observed in limnic sediments from southwestern BC and Washington and Holocene-aged old carbon effects have been observed in Alberta, possibly due to the incorporation of old carbon from carbonate reserves, graphite-containing minerals and/or marine sediments contained in exposed glacial tills (Sutherland, 1980; MacDonald *et al.*, 1991; Hutchinson *et al.*, 2004). No correction was applied to the basal date of 11 763 ± 87 ^{14}C a BP (13 815 cal. a BP) at Tiny Lake, but this age may be as much as ca. 630 a too old (cf. Hutchinson *et al.*, 2004). The other dates obtained from the Tiny Lake core have probably not been affected by the incorporation of old carbon because this effect becomes negligible approximately 1000 a following lake inception as forest and soil development reduce the exposure and weathering rates of tills (Engstrom *et al.*, 2000; Hutchinson *et al.*, 2004).

An age–depth model based on conventional radiocarbon ages and calibrated radiocarbon ages was generated using linear interpolation and model dates were estimated to the nearest 50 a (Fig. 4; Telford *et al.*, 2004). Linear interpolation accounts for potential changes in sedimentation rate better than linear regression, and although this model cannot be correct it is rarely 'unacceptably wrong' (Telford *et al.*, 2004). Age ranges for pollen zones were estimated from the model.

Pollen and spores

Pollen preparation followed methods described by Fægri and Iversen (1989). Forty-five 50 mm^3 aliquots of wet sediment were subjected to hot treatments of 10% hydrochloric acid and 10% potassium hydroxide followed by acetolysis. Sieving and hydrofluoric acid treatments were omitted. Slurries were stained with safranin, dehydrated sequentially with alcohol and stored in silicone oil. One tablet containing a known quantity of *Lycopodium clavatum* spores was added to each sample prior to processing in order to calculate pollen concentrations (batch no. 938 934, $n = 10\,679 \pm 953$ standard error spores/tablet; Benninghoff, 1962; Stockmarr, 1971). Pollen and spores were identified and counted at 400 × magnification with an Olympus BX51 transmitted-light microscope. Total terrestrial pollen and spores counted per slide were consistently above 300 except at one horizon (340 cm), where 182 grains and spores were enumerated.

Pollen keys by McAndrews *et al.* (1973), Fægri and Iversen (1989) and Kapp *et al.* (2000) and a set of reference slides (Aerobiology Institution and Research Pollen Reference Slide Set, Brookline, MA) aided pollen identification. *Pinus* pollen was identified as diploxylon-type, haploxylon-type or was undifferentiated (Fægri and Iversen, 1989). *Juniperus*, *Chamaecyparis nootkatensis*, *Taxus brevifolia* and *Thuja plicata* pollen were grouped together as Cupressaceae since their pollen is difficult to differentiate using light microscopy. *Larix* and *Pseudotsuga menziesii* pollen are morphologically similar, but because *Larix* is uncommon in coastal BC this pollen type is attributed to *P. menziesii*. In cases where uncertainty exists, taxa are suffixed with '-type'. Pteropsida (monolete) spores include all monolete members of the class Pteridophyta, except Polypodiaceae, because the perine is commonly preserved in this family. In this case, spores could be identified as *Polypodium vulgare*-type (Moore *et al.*, 1991). Small (5–8 μm), inaperturate spores with thin exines devoid of sculpturing elements were identified as *Polytrichum*-type spores (Kapp *et al.*, 2000). Fossil *Lycopodium clavatum* is

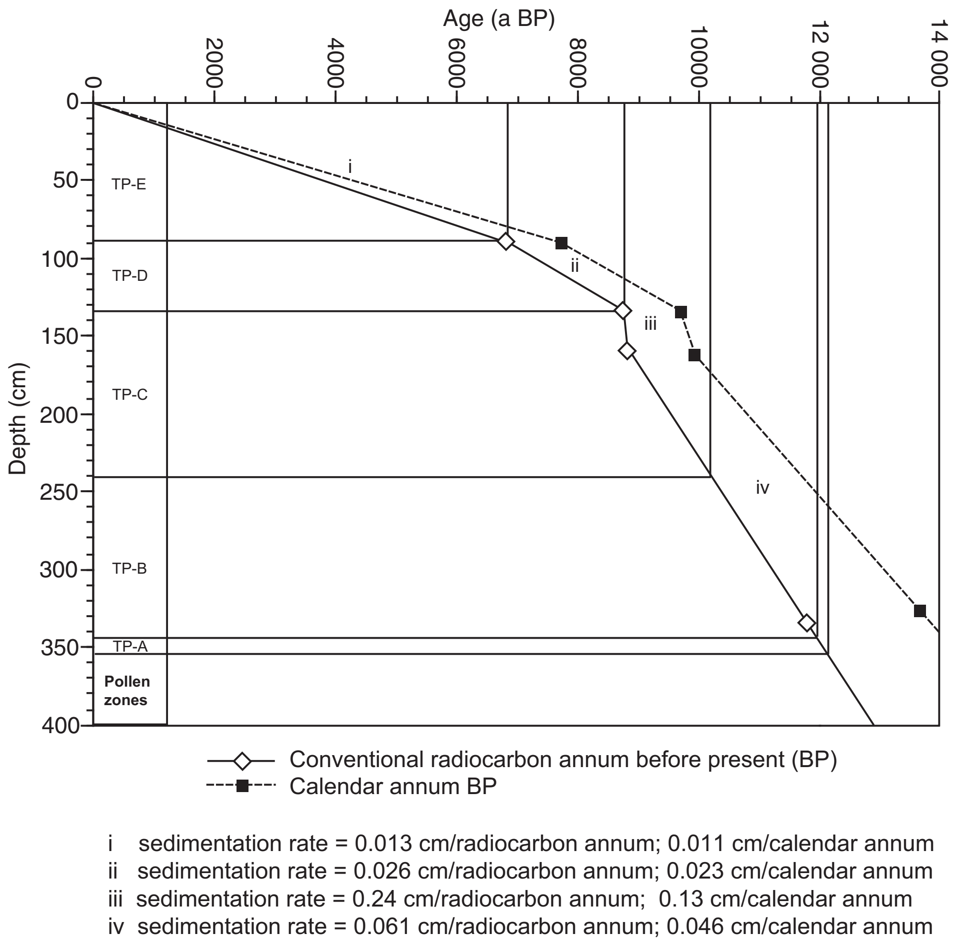

Figure 4 An age–depth model for the Tiny Lake sediment core based on linear interpolation of conventional radiocarbon and calendar ages

distinguished from exotic *L. clavatum* based on differential preservation and stain acceptance following Stanley (1966) and Heusser (1983).

The main pollen sum includes all total terrestrial pollen and spores, including fern and moss spores, since these groups constitute an important component of the vegetation of modern coastal forests in BC (cf. Brown and Hebda, 2002, 2003; Lacourse, 2005). The frequency of aquatic taxa was calculated from the total pollen sum. Calculation of absolute pollen abundance followed Stockmarr (1971). Percentage and concentration pollen data were graphed using Tilia version 2.0 (Grimm, 1993). The CONISS program for stratigraphically constrained cluster analysis using a square root data transformation was applied to aid pollen diagram zonation (Grimm, 1987).

Results

Thirty-eight pollen and spore taxa were identified from 45 horizons in the Tiny Lake sediment core. Five pollen assemblage zones are recognised based on CONISS and visual inspection (Fig. 5).

Zone TP-A (352–345 cm; ca. 12 000–11 900 ^{14}C a BP)

The sediments of this basal pollen zone are 99% inorganic and consist of homogeneous grey (Munsell colour 1/4/10Y) silty clay with sand and gravel, and were deposited under marine conditions (Doherty, 2005).

A high percentage of diploxylon *Pinus* pollen (30%) characterises this pollen zone. Also present, but in low relative abundances, are *Picea* (1–4%), *T. heterophylla* (0–6%), *Alnus* (3–8%), and *Salix* (0–2%) pollen. Cupressaceae pollen reaches 10% in this zone. Non-arboreal pollen types include *Polytrichum*-type spores (~20%) and *Triglochin* pollen (~2%). Total terrestrial pollen concentrations fluctuate between 668 grains mm^{-3} and 3695 grains mm^{-3} and are largely represented by *Pinus* grains (concentration range of 360–1905 grains mm^{-3}).

Zone TP-B (345–240 cm; ca. 11 900–10 150 ^{14}C a BP)

The basal sediments of this zone are homogeneous grey (24/5Bg) clays with silt that were deposited under marine conditions (Doherty, 2005). At 343.5 cm, sediments grade upward over 0.5 cm into grey (1/4/10Y) clay and gyttja with an organic content of ~18%. This material was probably deposited when relative sea level was at the sill level of the basin (Doherty, 2005). A radiocarbon age of 11 763 ± 87 ^{14}C a BP was obtained from 337 cm (Table 2).

At the beginning of this zone *Pinus* pollen decreases from 30% to 10% and increases in the relative abundances of *Picea* pollen (42%), *Abies* pollen (6%) and *Alnus* pollen (13%) occur. *Tsuga heterophylla* pollen peaks to 33% before declining to zero by the end of Zone TP-B at which time *Pinus* pollen increases to reach 30%. *Tsuga mertensiana* pollen is sporadically present near ~1% and Pteropsida (monolete) spores increase throughout the zone to reach 27%. Total terrestrial pollen concentrations are higher in this section than in Zone TP-A (1790–5162 grains mm^{-3}).

Zone TP-C (240–136 cm; ca. 10 150–8740 ± 79 ^{14}C a BP)

The sediments of Zone TP-C are characterised by black (10Yr/2/1) gyttja with minor changes in colour (5Yr/2.5/1 between 222 and 200 cm and 7.4 Yr/2.5/1 between 169 and 143 cm) where a small proportion of fine sand is homogeneously distributed. Organic matter increases to 20–50%, reflecting the transition to lacustrine sedimentation following lake isolation from Mereworth Sound (Doherty, 2005).

Pinus pollen decreases in this zone to less than 10%, while *Alnus* pollen increases to 47%. *Picea* and *Abies* pollen decrease in relative abundances to less than 17% and 6%, respectively. Total terrestrial pollen concentrations fluctuate in this zone between 1316 and 4465 grains mm^{-3}. Zone TP-C ends at 8740 ± 70 ^{14}C a BP (Table 2).

Zone TP-D (136–88 cm; 8740 ± 70 to 6860 ± 50 ^{14}C a BP)

The sediments of this section consist of massive black (7.5Yr/2.5/1) gyttja with an organic content of ~35–60%. *Alnus* pollen decreases to 7%, *Pinus* pollen decreases to 5%, and *T. heterophylla* pollen increases to 49%. Cupressaceae pollen begins to increase and reaches 20% by the end of the zone. Rosaceae and Lilaceae pollen are present at relative abundances of 5% and 1%, respectively. Total terrestrial pollen concentrations range from 1500 to 3688 grains mm^{-3}. A radiocarbon age of 6860 ± 50 ^{14}C a BP was obtained at 88 cm, marking the end of this pollen zone (Table 2).

Zone TP-E (88–0 cm; 6860 ± 50 ^{14}C a BP)

The sediments of Zone TP-E consist of massive black (10Yr/2/1) gyttja that is highly organic (LOI ~40–67%).

This zone is characterised by an increase in Cupressaceae pollen to 73% and a decline in *T. heterophylla* pollen to less than 34%. The relative abundances of *Picea* and *Abies* pollen are low (4%), and Pteropsida (monolete) spores decrease to 2%. Total pollen concentrations fluctuate between 1144 and 2656 grains mm^{-3} and are largely represented by Cupressaceae grains that fluctuate between 655 and 1609 grains mm^{-3}.

Discussion

The Lateglacial (Zones TP-A and TP-B; ca. 12 000–10 150 ^{14}C a BP)

A change from clay-dominated sediments containing marine diatoms to organic lake sediments associated with an assemblage of brackish and freshwater algae at 343.5 cm represents the isolation of Tiny Lake from Mereworth Sound prior to 11 763 ± 87 ^{14}C a BP (Doherty, 2005). Diploxylon *Pinus* pollen is the dominant pollen type in Zone TP-A, but this shade-intolerant tree probably grew as a few scattered

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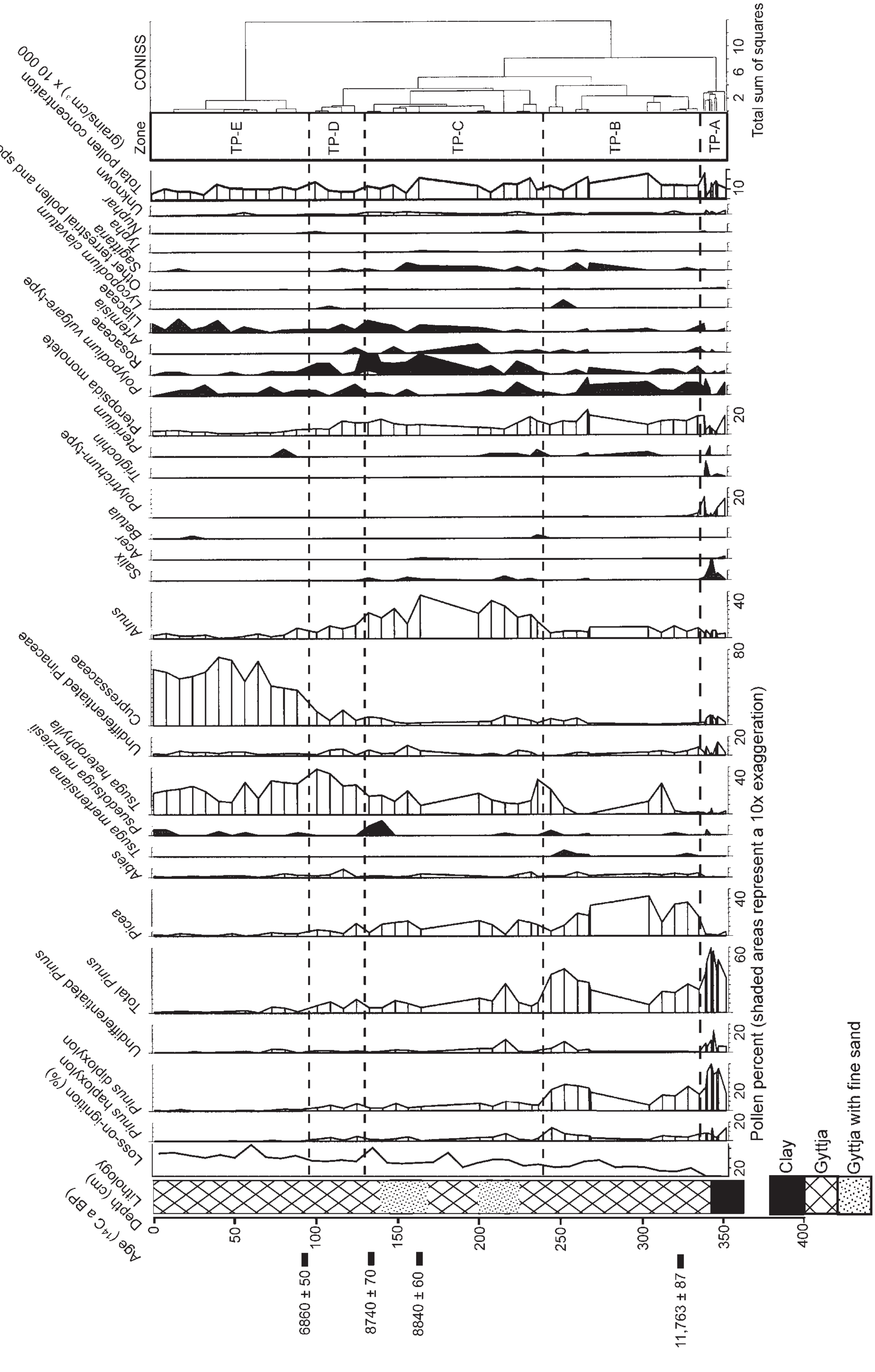

Figure 5 Pollen diagram of the relative abundance of select pollen taxa. Lithology, percent loss-on-ignition and chronology of the Tiny Lake sediment core are included

individuals around the basin at this time (Hebda and Allen, 1993). A possible source of the *Pinus* pollen may be *Pinus contorta*, which is adapted to disturbed habitats and was present on the mainland coast and adjacent islands of BC during the early Lateglacial (Hebda, 1983; Wainman and Mathewes, 1987; Lacourse *et al.*, 2003).

High relative abundances of moss (i.e., *Polytrichum*-type) spores suggest that patches of the landscape at Tiny Lake, probably those newly exposed by the regressing sea, were in the process of primary succession (Crocker and Major, 1955; Meidinger and Pojar, 1991). This unstable environment may have promoted *Pinus*, but the absence of *Picea*, a mesophytic conifer also capable of colonising poorly developed soils (Harris, 1990), suggests that a cool and dry climate excluded other taxa. *Pinus* was geographically widespread in Pacific North America during the early Lateglacial (Mathewes, 1973; McLachlan and Brubaker, 1995; Hansen and Engstrom, 1996; Lacourse, 2005), suggesting that widespread cool and dry conditions prevailed and shaped regional forests. Such conditions may have been caused by the retreating Laurentide Ice Sheet, which is modelled to have affected regional atmospheric dynamics by cooling adjacent air and generating a strong glacial anticyclone that delivered cool and dry easterly winds to the western coast of North America (Whitlock, 1992; Bartlein *et al.*, 1998; COHMAP Members, 1988).

At 11 763 $\pm$ 87 ^{14}C a BP, a rise in *Picea* and *Abies* pollen was accompanied by a marginal decline in *Pinus*. Based on modern pollen rain in coastal BC, these trees likely formed a mixed conifer forest that replaced the open *Pinus* parkland at Tiny Lake (Hebda and Allen, 1993). *Picea* is capable of growth on a wide range of substrates and succeeds *Alnus*, not *P. contorta*, in modern seres (Chapin *et al.*, 1994; Fastie, 1995). Therefore, it is unlikely that soil development or succession was the ultimate cause of its Lateglacial expansion at Tiny Lake. A migration lag is also unlikely because a possible refugium for *Picea* and *Abies* existed on the Queen Charlotte Islands during the Last Glacial Maximum (Warner *et al.*, 1982), suggesting that postglacial recolonisation of the SBIC by these trees would have occurred rapidly had climate conditions been permissive. Soil moisture is restrictive for both taxa in Pacific North America today (Fonda, 1974), so Lateglacial climate amelioration was probably the ultimate cause of Lateglacial vegetation change at Tiny Lake. A similar mixed conifer community existed at Two Frog Lake (Galloway *et al.*, 2007), Woods Lake (Stolze *et al.*, 2007) and throughout Vancouver Island at this time (Hebda, 1983; Brown and Hebda, 2002; Lacourse, 2005), providing further evidence that the formation of this community at Tiny Lake was controlled by regional climate change. Lateglacial climate change in Pacific North America can again be attributed to the waning Laurentide Ice Sheet. As the continental ice sheet and associated glacial anticyclone receded, moist westerly winds were able to penetrate into this region, thus increasing effective moisture (Whitlock, 1992; Whitlock and Bartlein, 1997; Bartlein *et al.*, 1998; COHMAP Members, 1988).

An increase in *Pinus* pollen to 30% and concomitant decline in *Picea* and *Abies* pollen in Zone TP-B suggests that a resurgence of *Pinus* occurred at Tiny Lake between ca. 10 750 and 10 150 ^{14}C a BP at the expense of other conifers. This shift may be due to a reversion to cooler and drier conditions associated with the Younger Dryas Stadial that would have favoured *Pinus* over *Picea* and *Abies*. Younger Dryas cooling has been previously documented in Pacific North America between ca.11 000 and 10 000 ^{14}C a BP (Mathewes, 1993; Mathewes *et al.*, 1993), and may have even been a global event (Peteet, 1995). Vegetation change at this time was accompanied by a $\sim$8% decrease in the organic content of lake sediments, possibly due to increased terrestrial erosion associated with reduced vegetation cover and/or a temperature- driven decline of in-lake productivity that is evidenced by a decrease in total diatoms at this level (Doherty, 2005).

The early Holocene (Zone TP-C; ca. 10 150 to 8740 $\pm$ 70 ^{14}C a BP)

An increase in *Tsuga heterophylla* and *Alnus* pollen at ca. 10 150 ^{14}C a BP suggests that a successional mosaic replaced Lateglacial mixed conifer forests at Tiny Lake.

Alnus pollen was not distinguished to the species level, but is probably attributable to both *A. rubra* and *A. viridis* ssp. *sinuata*; both species are common within open *T. heterophylla* forests in coastal BC today (Uchytil, 1989a,b). Neither taxa can self-regenerate owing to low shade tolerance and, as a result, stands are often even-aged and less than 60–100 a old (Fonda, 1974; Uchytil, 1989a,b). Therefore, the persistence of *Alnus*, irregardless of species, at Tiny Lake throughout most of the early Holocene suggests that an open coniferous canopy was maintained by less than optimal climate conditions and/or disturbance. The presence of pollen from disturbance-adapted plants in Zone TP-C (e.g. *Artemisia*, Rosaceae, *Pteridium*) may be evidence for the latter scenario (Pojar and MacKinnon, 1994).

The rise of *Tsuga heterophylla* following the *Picea* phase is consistent with descriptions of modern successional sequences in western North America where *T. heterophylla* replaces *Picea* over several centuries owing to its superior shade tolerance and longevity (Fastie, 1995). However, the range of *T. heterophylla* in modern coastal populations in BC is limited to regions with mild and humid climate conditions (Gavin *et al.*, 2006), so it is concluded that early Holocene temperatures were higher than the Lateglacial at Tiny Lake and that effective moisture remained high. An increase in *Typha* pollen in this section of the core is additional evidence for higher temperatures (Ritchie *et al.*, 1983; Isarin and Bohncke, 1999).

Portions of this section of the Tiny Lake sediment core were not available for pollen analysis, so an early Holocene absence of *P. menziesii* at Tiny Lake based on pollen percentages of less than 1% can only be speculated (Hebda, 1983). This tree, which requires open, warm and dry conditions for seedling establishment, expanded in range northward during the early Holocene xerothermic climate interval to populate northern Vancouver Island and occur as far north as Two Frog Lake on the central mainland coast (Howes, 1981; Hebda, 1983; Lacourse, 2005; Galloway *et al.*, 2007). A pattern of northward decreasing abundance coupled with the absence of this taxon from early Holocene pollen spectra north of Tiny Lake suggest that the SBIC was located near the northern limit of this species' early Holocene expansion (e.g. Turunen and Turunen, 2003). Owing to a short seed dispersal distance, it is possible that there was insufficient time for populations to expand farther north than the SBIC on the mainland coast of BC during the early Holocene (Tsukada, 1982), or that early Holocene conditions were too cool or moist at more northerly latitudes.

Fine sands are homogeneously distributed within organic sediments between 222–200 cm and 169–143 cm, suggesting prolonged and continuous, rather than catastrophic, deposition during these intervals (Noren *et al.*, 2002; Mazzucchi *et al.*, 2003). The absence of saltwater diatoms in Tiny Lake after 11 763 $\pm$ 87 a BP rule out inorganic sediment input from the transgressing sea (Doherty, 2005). Correlative sand horizons in the Woods Lake sediment core, interpreted to be the result of marine incursions, could indicate a regional mechanism of sand input, such as fires or winds (Stolze *et al.*, 2007). An increase in regional fires may have increased the inorganic sediment load to Tiny Lake by reducing vegetation cover and increasing erosion (Wainman and Mathewes, 1987; Spooner *et al.*, 2003). A detailed postglacial fire history does not exist for this region of coastal BC, but fires were common in southern BC during the early Holocene and an increase in regional fire disturbance could have affected Woods Lake as well, where relatively high levels of the fire indicator *Pteridium* occur (Brown and Hebda, 2002, 2003; Stolze *et al.*, 2007). Increased windiness associated with the warmer than present climate of the early Holocene in central coastal BC is another regional-scale mechanism of sand deposition. Relative sea level was 2–3 m higher during the early Holocene in the SBIC than today, which may have resulted in more open vegetation on the coastal side of Tiny Lake, thus exposing the basin to aeolian inputs (Doherty, 2005). An increase in *Aulocoseira* diatoms in this section of the Tiny Lake core may support this theory because the heavily silicified cells of this planktonic taxon require turbulent water conditions to maintain suspension in the photic zone (Doherty, 2005). An accelerated sedimentation rate is observed in Zone TP-C (Fig. 4) and may be associated with speculated aeolian inputs or erosion during the early Holocene.

Climate models, pollen transfer functions and palynological reconstructions from Pacific North America document a shift to warmer and drier conditions at ca. 10 000 ^{14}C a BP, when an orbitally induced maximum in solar insolation affected temperatures and moisture in the Pacific Northwest (e.g. Mathewes, 1973; Mathewes and Heusser, 1981; COHMAP Members, 1988; Berger and Loutre, 1991; Pellatt and Mathewes, 1994, 1997; Brown and Hebda, 2002; Lacourse, 2005). Regions with a strong maritime influence, such as Tiny Lake, may have been buffered from extreme temperature and drought by cool and moist Pacific air, thus permitting the growth of taxa with low drought tolerance, such as *T. heterophylla* and *Alnus* (Krajina, 1969; Cwynar, 1987; Packee, 1990).

The early Holocene to mid Holocene (Zone TP-D; 8740 ± 70 to 6860 ± 50 ^{14}C a BP)

An increase of *T. heterophylla* and Cupressaceae pollen (to 49% and 17%, respectively) occurred at 8740 ± 70 ^{14}C a BP. Based on known pollen representation and ecology of these taxa, the initial expansion of Cupressaceae is interpreted to mark the initiation of Holocene cooling and moistening and the development of closed, late-successional *T. heterophylla*–Cupressaceae forests at Tiny Lake (Krajina, 1969; Minore, 1990; Packee, 1990; Klinka *et al.*, 1996). It is unlikely that fluctuations in relative sea level influenced early Holocene vegetation at Tiny Lake because detailed diatom research throughout the SBIC has constrained early Holocene sea level movement in this region to less than 2 m, a breadth that is unlikely to have had a substantive effect on water table elevation (Doherty, 2005). In addition, a shift from planktonic (e.g. *Aulacoseira distans, A. lacustris*) to benthic (e.g. *Pinnularia microstauron*, *Frustulia rhomboides, F. rhomboides* var. *saxonica*) diatom communities occurred at ca. 8800 ^{14}C a BP in Tiny Lake, a common ecological response to decreasing air temperatures (Psenner and Schmidt, 1992; Sommaruga-Wögrath *et al.*, 1997; Wolfe, 2002; Rühland *et al.*, 2003; Doherty, 2005).

The timing of vegetation and algal change at Tiny Lake preceded change at Two Frog Lake, marked by an initial increase of Cupressaceae to a sustained relative abundance of >10%, by ca. 740 ^{14}C a, and at Woods Lake by ca. 1140 ^{14}C a, where change was marked by the initial increase of Cupressaceae to a sustained relative abundance of >40% (Galloway *et al.*, 2007; Stolze *et al.*, 2007). An ocean reservoir effect from early Holocene marine incursions into Woods Lake may mean that the inferred age of initial Holocene cooling and moistening at ca. 7600 ^{14}C a BP is a maximum estimate, which could make the diachroneity of this event within the SBIC even greater (Stolze *et al.*, 2007). It is possible that old carbon effects among lakes in the SBIC may account for some of the chronological offset observed within this region and that, in reality, climate and vegetation change was synchronous. However, if the radiocarbon chronologies reported in this paper and from other lakes in the SBIC (Galloway *et al.*, 2007; Stolze *et al.*, 2007) are accepted, an alternative hypothesis is that early Holocene storm tracks and/or precipitation gradients resulted in spatially variable moisture regimes that were a strong influence on postglacial forest dynamics in this region (cf. Brown and Hebda, 2002). In a regional context, the timing of early Holocene climate and vegetation change at Tiny Lake and Two Frog Lake is remarkable. At sites where Cupressaceae was present (e.g. the Fraser Lowlands, Vancouver Island and the low-lying northern mainland coast of BC), initial increases of this pollen type (from 0 to 10%) did not occur until ca. 7500–6600 ^{14}C a BP or later (Mathewes, 1973; Brown and Hebda, 2002, 2003; Turunen and Turunen, 2003; Lacourse, 2005). Climate models, pollen transfer functions and palaeoecological data document a period of maximum temperatures and minimum precipitation in western Washington and south coastal BC centred at ca. 8000 a BP (Mathewes, 1973; Barnosky, 1981; Leopold *et al.*, 1982; Hebda, 1983; Hebda and Mathewes, 1984; Heusser *et al.*, 1985; Kutzbach and Guetter, 1986; McLachlan and Brubaker, 1995; Hebda, 1995; Brown and Hebda, 2002, 2003; Lacourse, 2005). Instead, early Holocene climate change at Tiny Lake and Two Frog Lake is contemporaneous with sites in southwestern Yukon, coastal Alaska and some locations in northern BC (Fig. 6). A possible mechanism for climate heterogeneity on a synoptic scale in coastal BC is a dynamic AL pressure system (Dean and Kemp, 2004). This semi-permanent air mass is modelled to have intensified during the early Holocene in response to an orbitally induced decrease in solar insolation, a pattern that would have generated more intense and numerous mid-latitude cyclones and steered them into northern BC and Alaska (Klein, 1949; Heusser *et al.*, 1985; COHMAP Members, 1988; Cayan and Peterson, 1989; Trenberth and Hurrell, 1994; Mantua and Hare, 2002; Spooner *et al.*, 2003). The meso-scale climate asynchrony possibly observed within the SBIC at this time suggests that this region was at the southern extent of immediate influence of this intensifying air mass. Sites previously studied in the low-lying forests of the Coastal Western Hemlock biogeoclimatic zone on the Queen Charlotte Islands and immediately adjacent mainland may have been buffered from this effect due to their leeward location (Warner, 1984; Fedje, 1993; Turunen and Turunen, 2003; Lacourse and Mathewes, 2005).

The mid to late Holocene (Zone TP-E; 6860 ± 50 ^{14}C a to present)

At 6860 ± 50 ^{14}C a BP Cupressaceae pollen increased markedly to 60–70% of the pollen spectra. It is unlikely that this pollen type is overrepresented because Cupressaceae pollen is delicate and often poorly preserved (Heusser, 1960).

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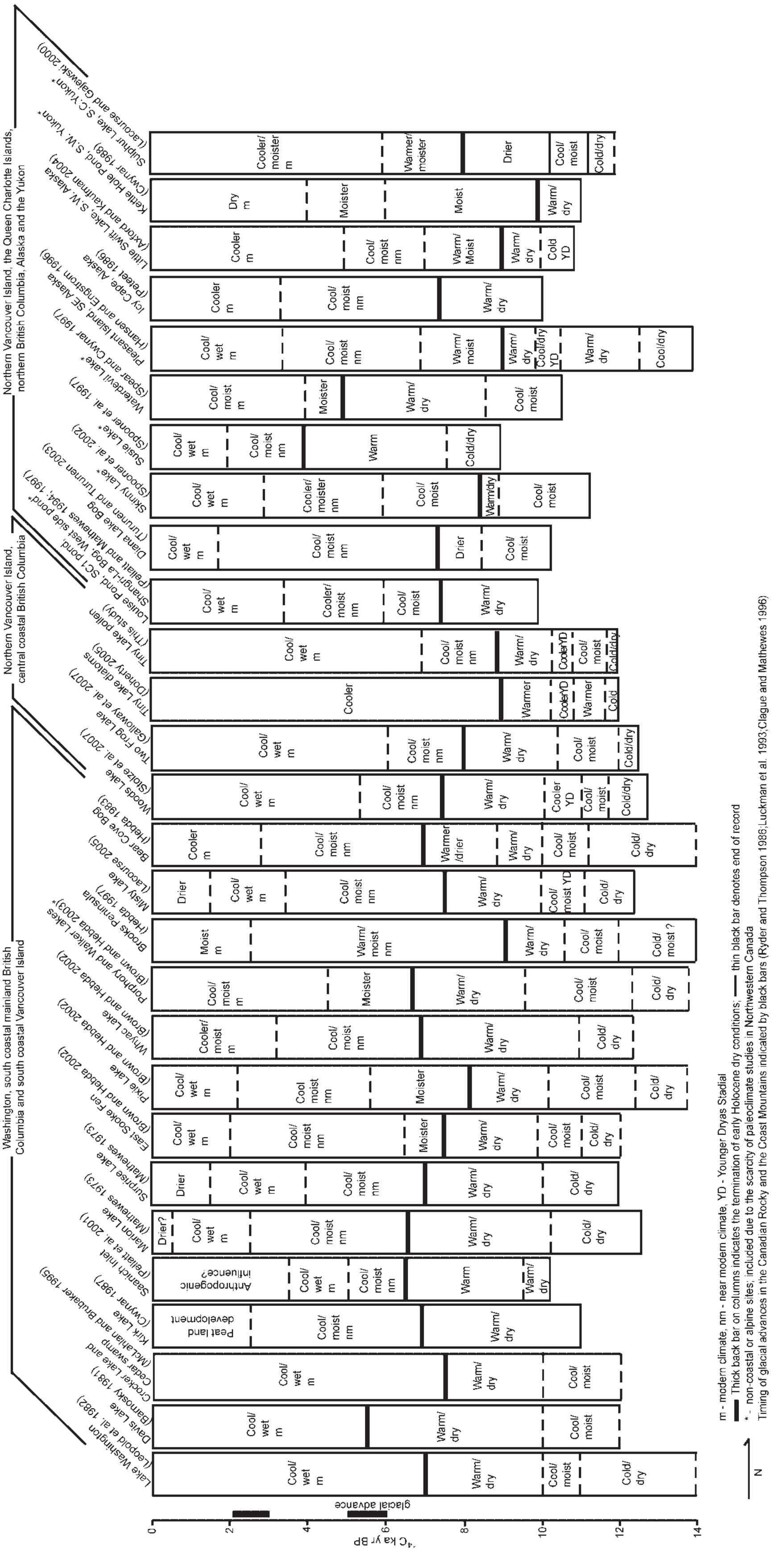

Figure 6 Postglacial climate histories of select sites in Pacific North America

In addition, Cupressaceae pollen was relatively high (~80%) in correlative sections at Two Frog Lake and Woods Lake (Galloway *et al.*, 2007; Stolze *et al.*, 2007). Stomate evidence from Woods Lake indicates that both *T. plicata* and *C. nootkatensis* were present in the SBIC at this time, but that *T. plicata* was predominant (Stolze *et al.*, 2007). Both species require wet and cool conditions, so their occurrence at Tiny Lake at this time is interpreted to mark the establishment of a modern temperate and wet climate (Krajina, 1969). This event is correlative with the onset of cooler and moister conditions

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throughout Pacific North America and Neoglacial glacial activity in the Canadian Rocky Mountains and Coast Mountains of BC (Porter and Denton, 1967; Mathewes, 1973; Ryder and Thompson, 1986; Luckman *et al.*, 1993). Peak expansion of Cupressaceae at Tiny Lake at ca. 3900 ^{14}C a BP corresponds to a period of very cool and wet conditions that were ubiquitous in coastal BC, and linked to a weakening of high-frequency pulses in solar activity at the Gleissberg cycle band, similar to what occurred during the 'Little Ice Age' (Mathewes, 1973; Hebda, 1983; Friss-Christensen and Lassen, 1991; Jirikowic and Damon, 1994; Spear and Cwynar, 1997; Lacourse, 2005). Multi-proxy reconstructions of mid–late Holocene climate indicate that not only were conditions extremely cool and wet, but also that storms were of higher intensity and were more frequent in southern Alaska and northern BC than at any other time during the Holocene (Heusser *et al.*, 1985; Cwynar, 1993; Spooner *et al.*, 1997; Mazzucchi *et al.*, 2003). This period of storminess may be linked to dynamics in the AL, which was more eastward and/or intense at this time than at any time during the past ca. 6600 a (Anderson *et al.*, 2005). The mid–late Holocene extremes in the position and intensity of this air mass may account for the large geographical extent of its influence during the mid–late Holocene compared to the weaker dynamics of the early Holocene that appear to have affected a smaller geographical area (Anderson *et al.*, 2005).

Conclusions

A pollen-based study of postglacial climate and vegetation change at Tiny Lake reveals that the central mainland coast of BC experienced considerable climate variability over the past ca. 12 000 a. Following deglaciation of the SBIC, an open *Pinus* parkland grew locally when the climate was relatively cool and dry. Climate amelioration at ca. 11 900 ^{14}C a BP permitted mesophytic conifers to colonise the site but trends were reversed between ca. 10 750 and 10 150 ^{14}C a BP when cooling possibly associated with the Younger Dryas Stadial punctuated the warming Lateglacial climate. Early Holocene conditions were warmer than present and supported a successional mosaic of *T. heterophylla* and *Alnus* at Tiny Lake. *Tsuga heterophylla* and Cupressaceae increased at 8740 ± 70 ^{14}C a to form late successional, near-modern forests when Holocene cooling and moistening was initiated. A diatom-based climate reconstruction at Tiny Lake confirms this inference. Climate cooling and moistening culminated at ca. 3900 ^{14}C a BP, correlative with changes in solar activity and Holocene extremes in the position and/or strength of the Aleutian Low pressure system.

The onset of early Holocene climate cooling and moistening at Tiny Lake is remarkable in a regional context. The initiation of climate moistening at this site is more contemporaneous with early Holocene climate dynamics at locations in the southwestern Yukon, coastal Alaska, and some sites in northern BC, rather than Vancouver Island, south coastal BC and Washington state. The synoptic-scale pattern of climate heterogeneity observed in this study suggests that an early Holocene intensification and/or eastward movement of the AL was an important control on coastal climates in BC, and the meso-scale climate asynchrony within the SBIC suggests that this area was located at the southern extent of immediate influence of this air mass.

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