Late Holocene vegetation and climate change at Moraine Bog, Tiedemann Glacier, southern Coast Mountains, British Columbia

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Abstract: Moraine Bog lies just outside the outermost lateral moraine of Tiedemann Glacier in the southern Coast Mountains of British Columbia. A sediment core taken from the wetland was analyzed for pollen, magnetic susceptibility, and loss on ignition to reconstruct changes in vegetation and climate during the late Holocene. Vegetation changed little between about 3500 and 2400 ^{14}C years BP. A period of local disturbance marked by deposition of a silty clay bed and increases in *Alnus* pollen, likely reflecting cooler moister conditions, coincides with an extensive Holocene advance of Tiedemann Glacier about 2400 ^{14}C years BP. Warm dry conditions between about 1900 and 1500 ^{14}C years BP are suggested by peak values of *Pseudotsuga* pollen and increasing *Nuphar* screleids; the latter suggests lowered water levels. This period coincides with a time of drought and increased fire frequency in the southernmost Coast Mountains. About 1300 ^{14}C years BP, the forest became more coastal in composition with abundant *Tsuga heterophylla* and *Abies*. An increase in *Tsuga mertensiana* pollen suggests the onset of cool and wet conditions by ca. 500 ^{14}C years BP, coincident with the Little Ice Age. The record of inferred climate change at Moraine Bog is broadly synchronous with other paleoclimate records from the Coast Mountains and, at the centennial scale, with records elsewhere in the world.

Résumé : La tourbière Moraine se trouve tout juste à l'extérieur de la moraine latérale la plus externe du glacier Tiedemann dans le sud de la chaîne Côtière de la Colombie-Britannique. Une carotte de sédiments prélevée du sol marécageux a été analysée pour le pollen, la susceptibilité magnétique et la perte par calcination afin de reconstituer les changements à la végétation et au climat durant l'Holocène tardif. La végétation a peu changé entre les années 3500 et 2400 ^{14}C avant le présent (BP). Une période de perturbation locale marquée par la déposition d'un lit d'argile silteuse et des augmentations de pollen d'Alnus, probablement le reflet de conditions plus fraîches et plus humides, coïncide avec une grande avancée du glacier Tiedemann à l'Holocène, il y a environ 2400 années 14C BP. Des conditions sèches et chaudes entre environ 1900 et 1500 années 14C BP sont déduites de valeurs de crête de pollen Pseudotsuga et une augmentation de sclérites Nuphar; cette dernière augmentation suggérant des niveaux d'eau abaissés. Cette période coïncide avec un temps de sécheresse et d'augmentation du nombre de feux dans la partie à l'extrême sud de la chaîne Côtière. Vers 1300 années ^{14}C BP, la composition de la forêt est devenue plus côtière avec une abondance de Tsuga heterophylla et Abies. Une augmentation du pollen Tsuga mertensiana suggère le début de conditions fraîches et humides vers 500 années ^{14}C BP, ce qui coïncide avec le Petit Âge Glaciaire. Les données de changement climatique inféré à la tourbière Moraine sont généralement synchrones avec les autres données paléoclimatiques de la chaîne Côtière et, à une échelle centenaire, avec des données provenant d'ailleurs au monde.

[Traduit par la Rédaction]

Introduction

Ryder and Thomson (1986) identified a period of glacier expansion in the southern Coast Mountains of British Columbia from about 3300 to 1900 ^{14}C years BP, which they termed the Tiedemann Advance. This period of cool moist

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climate is now recognized throughout western North America. Records of increased sedimentation (Leonard 1986; Souch 1994; Clague and Mathewes 1996), decreased fire frequency (Hallett et al. 2003*a*), a shift to cold stenothermic chironomid assemblages in lakes (Pellatt et al. 1998; Smith et al. 1998; Heinrichs et al. 2002), and glacier advance (Crandell and Miller 1974; Osborn and Luckman 1988; Desloges and Ryder 1990; Luckman et al. 1993; Cashman et al. 2002; Larocque and Smith 2003) have shown that the Tiedemann Advance is a significant regional event. Few of these studies, however, reveal how vegetation changed during this period.

This study was undertaken to (1) provide a reconstruction of environments during and following the Tiedemann Advance (the last 3500 years) through analysis of pollen and sediment records at the site where the advance was originally defined; (2) examine the extent, timing, and nature of the Tiedemann Advance; and (3) compare the record at Tiedemann Glacier with other Holocene paleoecological records from the Cana-

dian Cordillera. Previous studies at Tiedemann Glacier (Fulton 1971; Ryder and Thomson 1986; Larocque and Smith 2003) provide a framework for our study.

Setting

The Coast Mountains extend northwest from southernmost British Columbia to Alaska and coincide with a belt of Mesozoic plutonic and metamorphic rocks (Tipper et al. 1981). Tiedemann Glacier is located in the highest part of the Coast Mountains approximately 250 km northwest of Vancouver (Fig. 1). It flows 24 km from an ice field on the east side of the Waddington Range and terminates in an extensive zone of debris-covered stagnant ice at the head of Tiedemann Creek. Clear geomorphic evidence of former glacier advances is provided by a suite of lateral moraines flanking the lower part of the glacier.

Moraine Bog (51°19.8′N, 124°55.7′W) is a small (<1 ha) wetland, located north of Tiedemann Glacier at an elevation of 891 m (Figs. 2, 3, 4). It is bordered on the southwest by the outermost lateral moraine of Tiedemann Glacier (Fig. 2). The wetland occupies a closed depression, with no outlet channels. Pollen accumulating at the site is derived primarily from local vegetation in the wetland and surrounding forest. The wetland's open canopy, however, also allows for deposition of extra-local and, to a lesser degree, regional pollen (Jacobsen and Bradshaw 1981).

The Coast Mountains are a significant barrier to the easterly movement of moist Pacific air masses, creating a strong west–east environmental gradient across the range. The Aleutian Low and the Pacific High, two semi-permanent pressure systems centred over the Pacific Ocean (Burroughs 1999), are the primary, large-scale controls on climate in the study area.

Biogeoclimatic zones in British Columbia are defined by regional climate, topography, and vegetation (Pojar et al. 1991*b*). The rugged topography surrounding Moraine Bog and the proximity of the site to the Pacific Ocean result in long cool winters with high precipitation, a deep snow pack, and cool wet summers (Pojar et al. 1991*a*; Klinka and Chourmouzis 2002; Environment Canada 2003). Plants growing around the wetland indicate that the site is within the recently defined submaritime Lady fern site association (Klinka and Chourmouzis 2002), an ecotone between the Mountain Hemlock zone and interior Engelmann Spruce – Subalpine Fir subalpine zones. Species dependent on unfrozen ground, namely *Tsuga mertensiana* and *Abies amabilis*, dominate the surrounding forest. *Abies lasiocarpa*, *Picea engelmannii*, *Tsuga heterophylla*, and *Pinus monticola* are also locally present. The understorey consists mainly of *Alnus viridis* shrubs and a variety of ferns. *Sphagnum* is present on the wetland surface. Cyperaceae and *Menyanthes trifoliata* colonize small wet patches in the wetland, and open shallow water supports *Nuphar lutea*.

Pre-Little Ice Age moraines south and southwest of Moraine Bog have been grouped into outer, middle, and inner moraine sets (Fig. 4) (Ryder and Thomson 1986). The outer moraine is a sharp-crested blocky ridge that delimits the maximum extent of Tiedemann Glacier after the decay of the Cordilleran Ice Sheet. It comprises angular to subrounded blocks that, on average, are greater than 1 m across. This moraine is continuous along the length of the glacier from

Fig. 1. Map of southern British Columbia showing the location of Moraine Bog and Tiedemann Glacier.
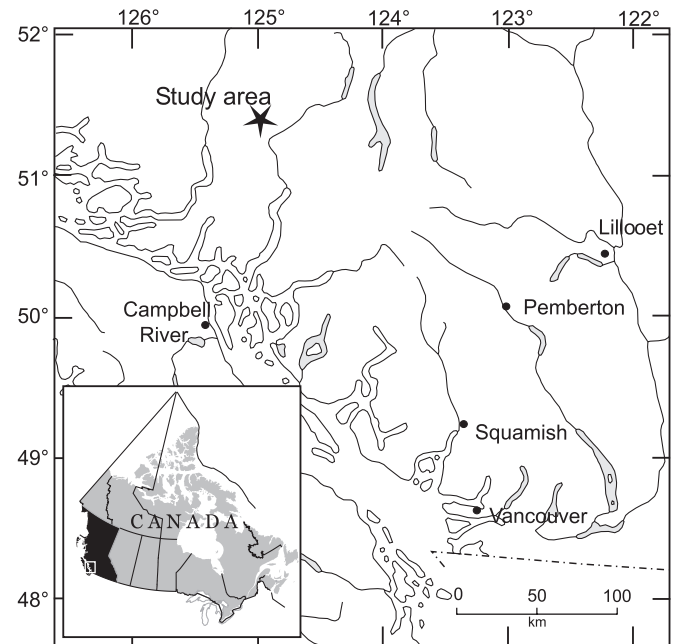
its snout to the point where the inner and outer moraines coalesce, about 7 km upvalley. At least three smaller discontinuous blocky ridges, termed middle moraines, lie between the inner and outer moraines (Fig. 4). Inner Moraine Bog is within the middle moraine set (Figs. 3, 4). The inner sharp-crested moraine impounds both North and South Moraine lakes (termed North Tiedemann and South Tiedemann lakes by Larocque and Smith (2003)) and is parallel to the outer moraine.

Previous work

In 1967, R.J. Fulton collected two cores from Moraine Bog and one core from Inner Moraine Bog. He found a silty clay layer at a depth of 217–227 cm in the 280 cm long Moraine Bog core and bracketed it with radiocarbon ages of 2250 ± 130 ^{14}C years BP (GSC-948) and 2940 ± 130 ^{14}C years BP (GSC-938) (Fulton 1971). Fulton interpreted the silty clay layer as having been deposited when Tiedemann Glacier constructed the outer moraine. He obtained an age of 9510 ± 160 ^{14}C years BP on basal peat in the core, which he interpreted as a minimum age for late Pleistocene deglaciation (Fulton 1971). He also reported an age of 1270 ± 140 ^{14}C years BP on basal peat from his Inner Moraine Bog core.

Ryder and Thomson (1986) mapped the surficial geology of the study area and established a chronology for Neoglacial advances of Tiedemann Glacier, based in part on radiocarbon ages from the innermost composite lateral moraine of the glacier. They recognized two pre-Little Ice Age depositional events, one that began before ca. 3345 ^{14}C years BP and culminated after ca. 2300 ^{14}C years BP, and another that constructed the middle moraines shortly before 1270 ^{14}C years BP. They were unable to determine the amount of glacier recession prior to the first advance of the Little Ice Age and the date of initiation of the most recent Little Ice Age advance.

Larocque and Smith (2003) dated the middle moraine

Fig. 2. (A) Tiedemann Glacier, view west. Arrow indicates location of Moraine Bog. (B) Moraine Bog. (C) Silty clay layer at 158–171 cm in the Moraine Bog core.
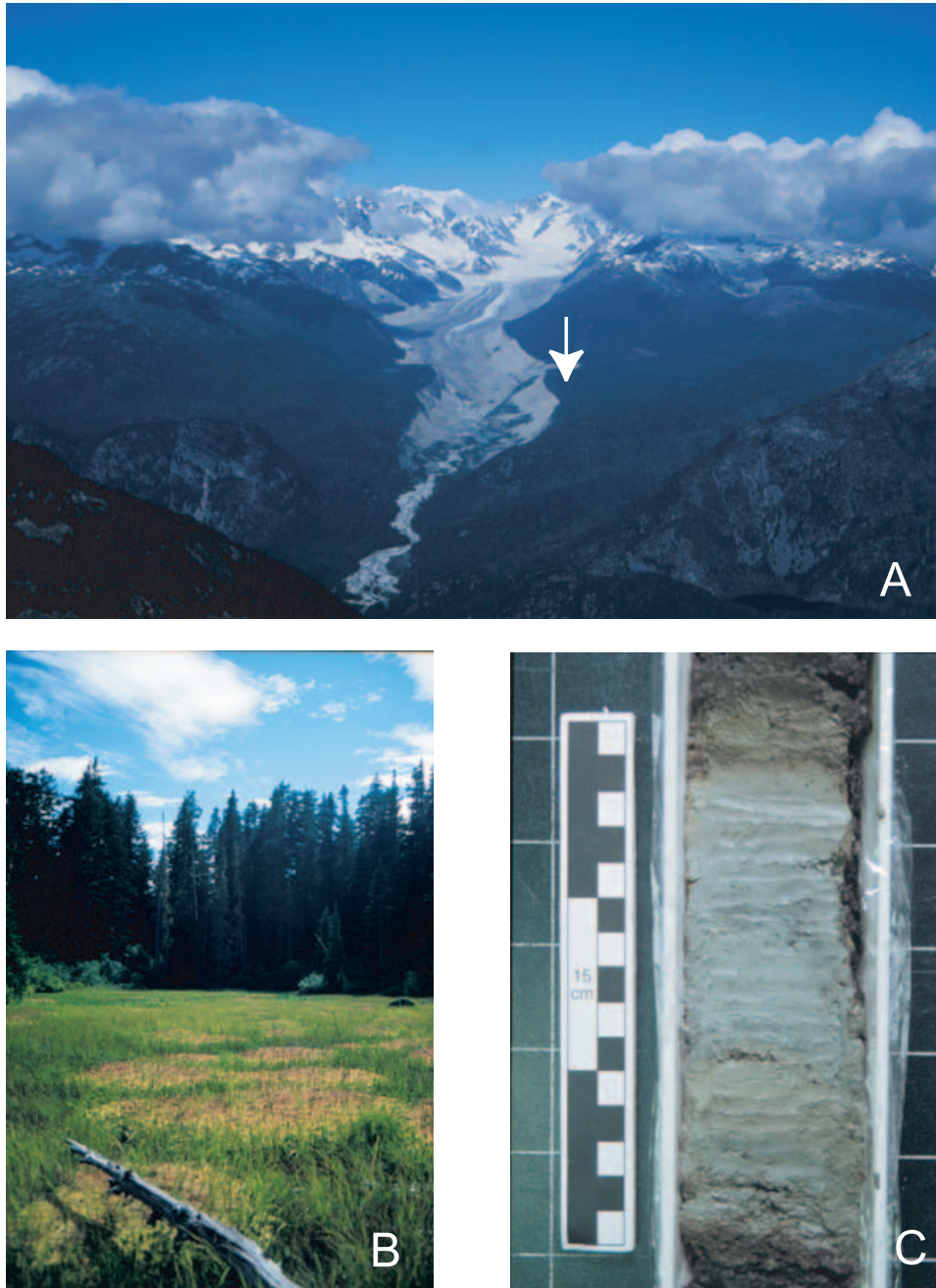

complex and Little Ice Age moraines (Fig. 4) on the east side of Tiedemann Glacier using lichenometry. Their lichen data suggest that the middle moraines were built during still-stands or minor readvances after the Tiedemann Advance. They assigned ages of 1330 calendar years BP (ca. 1400 ^{14}C years BP) to the oldest of the middle moraines and 1025 calendar years BP (ca. 1100 ^{14}C years BP) to the moraine that surrounds North Moraine Lake.

Methods

We visited Tiedemann Glacier in the summer of 2002 to retrieve cores from Moraine Bog, check previously mapped moraines, and perform a brief qualitative vegetation survey of the wetland. Moraines bordering Tiedemann Glacier were mapped using vertical aerial photographs (BCC94039-176, BCC94039-178, BCC94039-179). The mapping was checked in the field and compared with that of Larocque and Smith (2003). Two sediment cores, 372 and 373 cm long, were collected from the centre of a pool of open water in the wetland with a 5 cm diameter, modified Livingstone piston sampler (Wright 1967). Both cores terminated in silt and sand. The boreholes were kept open with a 7 cm diameter, polyvinyl chloride pipe. Maximum measured water depth in the open pool at the time of field work was 39 cm. The uppermost 42 cm of watery sediment were sampled with a

Fig. 3. Topographic map of the area around Moraine Bog. The contour interval is 20 m (Map 92N 036, scale 1 : 20 000, modified with permission of the Province of British Columbia).
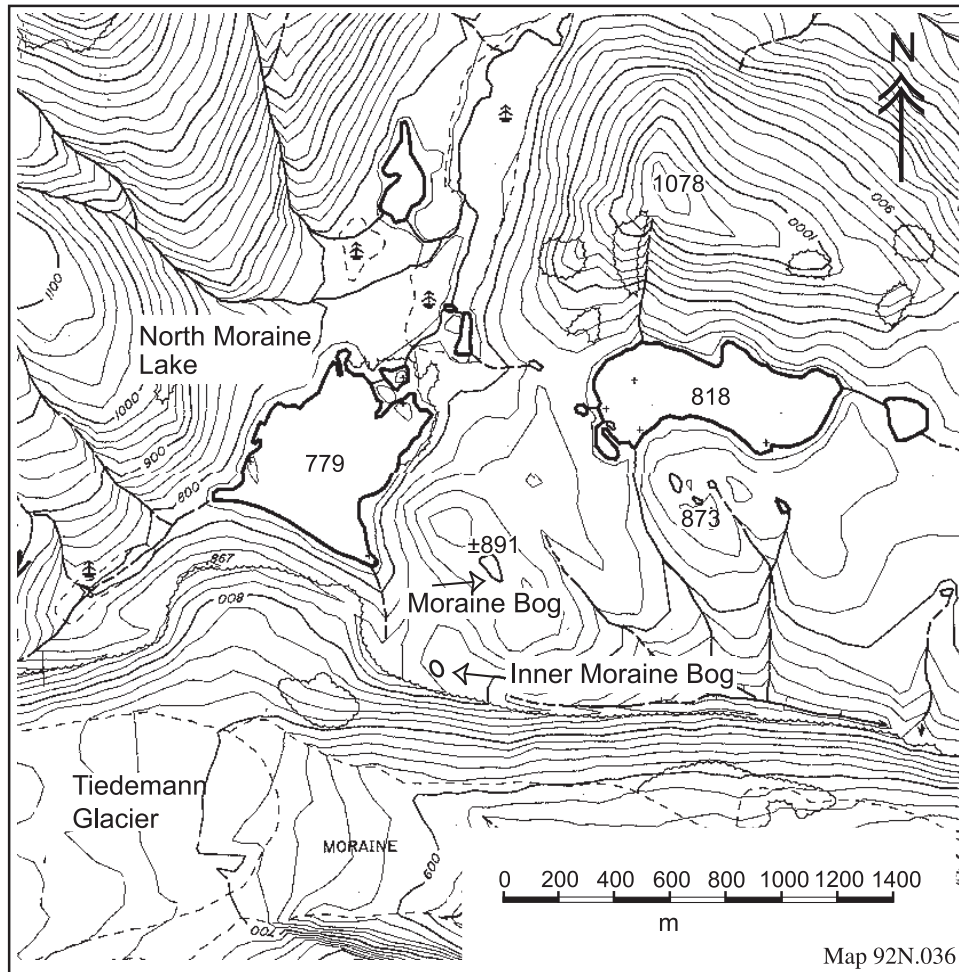

Brown corer. The loose sediments from the Brown core were siphoned into labelled plastic bags at 1 cm intervals. Segments of the Livingstone cores were extruded onto plastic wrap surrounded by aluminium foil, wrapped, and labelled. Cores were transported to Simon Fraser University, Burnaby, in a core box and stored in a cold room at 4 °C until analyzed.

Cores were split in the laboratory and photographed. One of the two cores was selected for analysis and the other was archived. The former was scraped with a clean spatula to remove possible surface contaminants. Munsell colour, texture, and sedimentary features were recorded. Wet mounts and grit tests established the type and texture of sediment. Sediment was described using a modified version of the Troels-Smith classification (Troels-Smith 1955; Aaby and Berglund 1986). Specifically, we classified sediment using four broad categories: (1) peat (humic organic sediment), (2) peaty gyttja (organic sediments of terrestrial and limnic origins), (3) gyttja (organic sediment of limnic origin), and (4) silt and clay. Samples of 1 cm³ each were extracted for measurement of organic content at 2 cm intervals using a calibrated brass sampler. Organic carbon was determined through loss on ignition following the procedure given by

Bengtsson and Enell (1986). Samples were heated in dry ceramic crucibles for 12 h at 105 °C (Heiri et al. 2001), followed by heating at 550 °C for 2.5 h (Smith 2003). Measurements of magnetic susceptibility were taken at 2 cm intervals along the core using a 60 mm diameter loop connected to the Bartington Instruments Multisus® system (King and Channell 1991; Bartington Instruments Ltd. 2002).

Volumetric subsamples (1 cm³) for pollen analysis were collected from the core at 2 cm intervals from 0 to 220 cm with a calibrated brass sampler (Birks 1976). Samples were placed in labelled, sealed glass vials, and the remaining core was archived in a cold room at 4 °C. A known concentration of *Lycopodium* marker spores (11 300 ± 400, Batch # 201890) was added to each sample prior to processing (Stockmarr 1971). Samples were processed using standard procedures (Faegri and Iversen 1989), including treatment in 10% HCl, 10% KOH in a hot water bath for 10 min, concentrated HF in a hot water bath for 12 min, followed by acetolysis (9:1 acetic anhydride: sulphuric acid). All treated samples were then screened through a 500 μm sieve. Mineral-rich samples were filtered through a 7 μm Nitex screen to remove clay (Cwynar 1978). Residues were dehydrated with ethanol, stained with safranin, and stored in silicone oil (2000 cs) in

Fig. 4. Aerial photograph of the area around Moraine Bog showing the outer, middle, and inner moraines (Aerial photograph 30BCC94064-164 reproduced with permission of the Province of British Columbia).
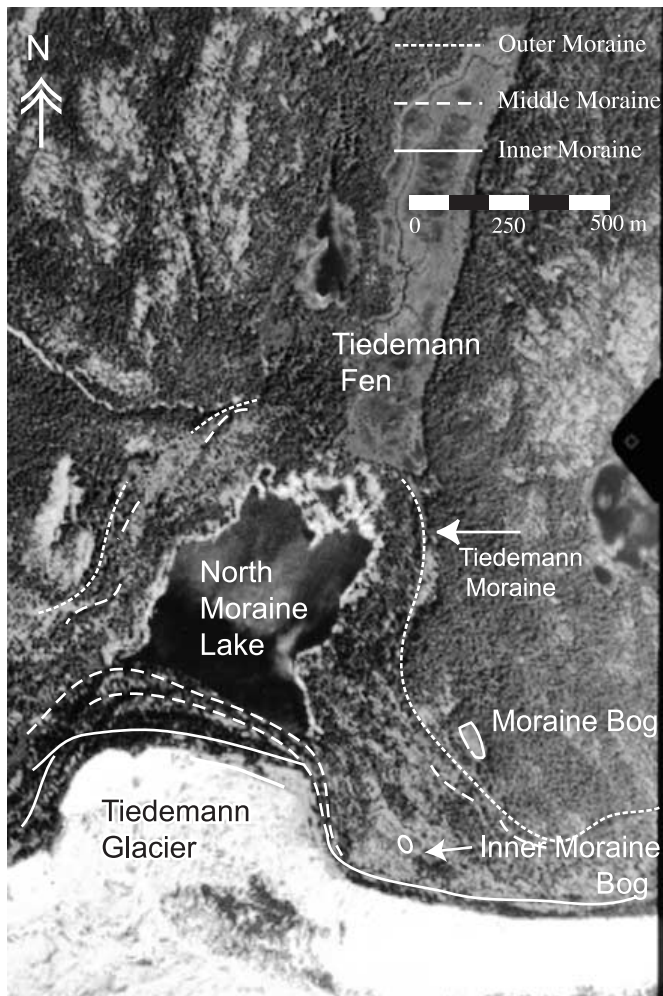
1 mL plastic vials. All cores and remaining residues are stored in a cold room in the Department of Biological Sciences at Simon Fraser University.

Pollen identification and counting were performed at 400 × magnification. Critical identifications were made under oil immersion at 1000× magnification using a Zeiss binocular microscope. A minimum of 500 terrestrial pollen grains were counted in each sample along regularly spaced traverses. Counts were terminated at 300 terrestrial grains for samples with low pollen concentrations (<30 000 grains/cm^3) and poor preservation. Identifications were made using Richard (1970), McAndrews et al. (1973), and Kapp (2000), and by comparison with the reference collection at Simon Fraser University. Some non-pollen fossils were identified using Warner (1990).

Microscopic sclereids (stellate leaf support cells) of yellow water lily (*Nuphar lutea*) were used to estimate the past abundance of this aquatic plant (Warner 1990; Arsenault 2004). Variations in abundance of sclereids may provide an estimate of past changes in water level (Larmola et al. 2003) where supported by other indicators, such as sediment lithology. *Nuphar* and other macrophytes commonly become more

abundant as water levels decrease, driven by increased concentration of nutrients (Charman 2002; Larmola et al. 2003). Studies have also shown *Nuphar* will grow only in water depths < 2 m; in deeper water, their leaves are no longer able to reach the surface (Warrington 1980). Using this reasoning, water levels were interpreted by zone, as lower or higher, in comparison to other zones. More work on modern distributions of sclereids in lakes and other wetlands is needed to strengthen this interpretation.

Counts were processed and the pollen diagram plotted using PSIMPOLL (Bennett 2002). Zonation of pollen diagrams was done using constrained cluster analysis by sum of squares (CONISS) (Grimm 1987) of percentage data. The "broken-stick" model (MacArthur 1957) was applied to determine, objectively, the number of numerically recognizable zones (Bennett 1996). Pollen taxa were divided into trees and shrubs, herbs, aquatics, and spores for graphing and discussion. The terrestrial sum includes trees, shrubs, and herbs. Aquatics and spores form a separate sum. Taxa with frequencies of more than 5% are included in the summary diagram (Fig. 5). A total of 38 taxa and morphotypes were found in the Moraine Bog core.

Well-preserved conifer needles and wood fragments from six levels in the core were radiocarbon dated by accelerator mass spectrometry at IsoTrace Laboratory, University of Toronto, Toronto, and the Center for Accelerator Mass Spectrometry (CAMS), Lawrence Livermore National Laboratory, Livermore, California. Two samples at 138–139 cm were dated by CAMS to provide a check on the precision of the laboratory. Uncalibrated radiocarbon ages are expressed as ^{14}C years BP. Radiocarbon ages were calibrated using the probability distribution calculation in the software program CALIB 4.3, with a 95.4% (2σ) confidence interval (Stuiver et al. 1998*a*, 1998*b*). Calibrated ages are expressed as calendar years BP. Median probability values were used as inputs to the age–depth model and are plotted in Fig. 5. Sedimentation rates were determined using the age–depth modelling function in PSIMPOLL (Bennett 2002). The average pollen accumulation rate (PAR) (grains/cm^2/years) for each pollen assemblage zone was calculated, and the data are presented in Tables 1 and 2.

Results

Stratigraphy

The 373 cm long core consists primarily of dark brown gyttja intercalated with brown, rooty, decomposed peat, peaty gyttja, and gyttja. Coarse detritus and macrofossils are abundant throughout the core. A silty clay layer is present at 158–171 cm (Fig. 2). A silt and sand layer at the base of the core lies on impenetrable material, which is possibly late Pleistocene till. The stratigraphy of the upper 220 cm of the core, which is the focus of this study, is shown in Fig. 5. A three-term, polynomial, age–depth model, based on five radiocarbon ages (Table 1) from the upper 220 cm of sediment, suggests that sedimentation rates over the last 3500 years are relatively uniform. Radiocarbon ages for the two samples from 138–139 cm (1880 ± 40 and 1850 ± 35 ^{14}C years BP) overlap at 2σ, indicating high laboratory precision.

Loss on ignition (Fig. 5) is high (>90% organic content) for most of the record. Lower organic values occur between

Fig. 5. Moraine Bog pollen diagram showing pollen percentages (>5%), loss-on-ignition values, magnetic susceptibility, and concentrations of *Nuphar* sclereids. Unfilled curves are percentages at 10× exaggeration. Lithology and radiocarbon ages are shown at the left. Pollen zones and CONISS dendrogram are shown at the right. Horizontal lines in the *Nuphar* plot indicate sample depths.
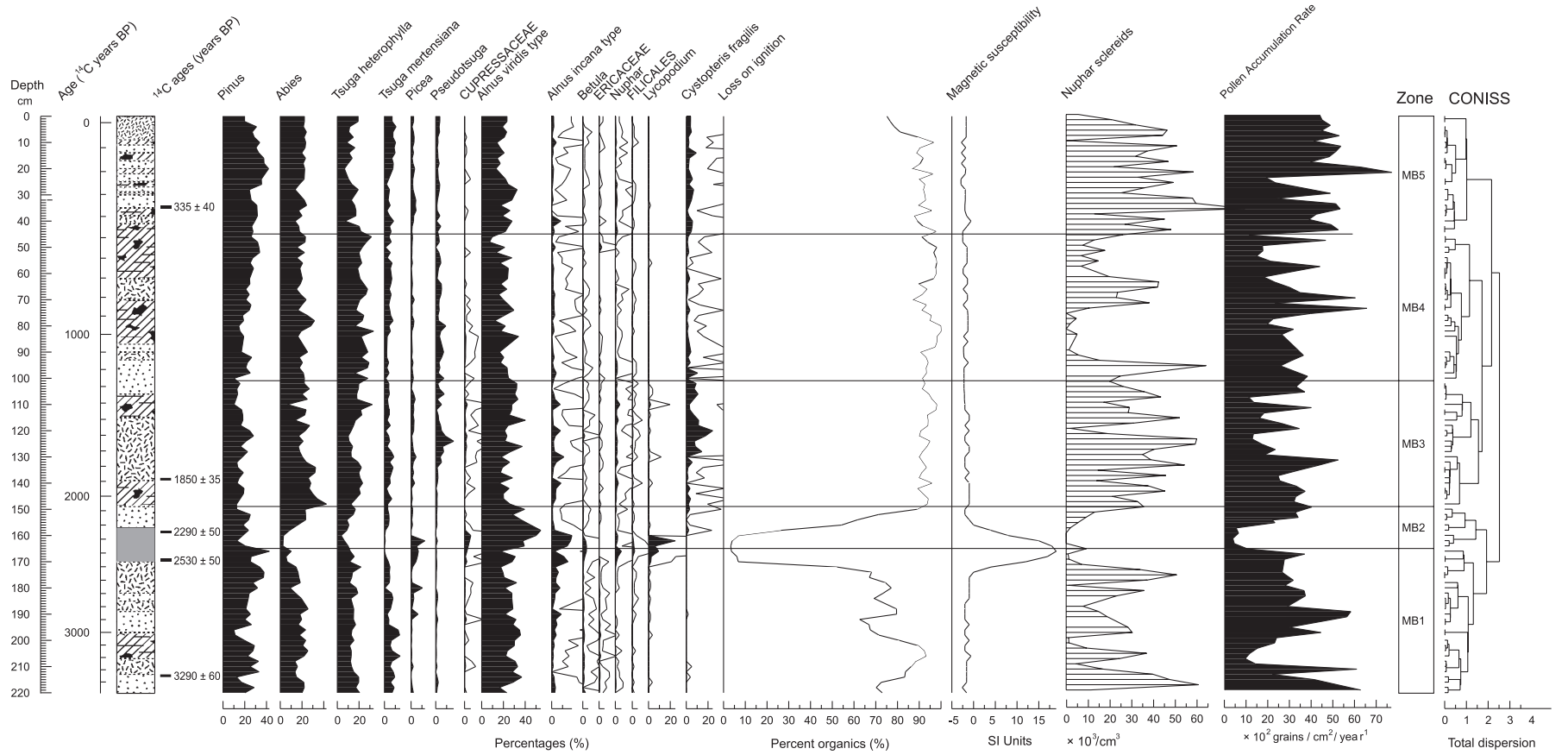
Analyst: T. Arsenault

Table 1. Accelerator mass spectrometry ^{14}C ages on macrofossils from Moraine Bog.

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

Note: CAMS, Center for Accelerator Mass Spectrometry (Lawrence Livermore National Laboratory, Livermore, California); TO, IsoTrace Laboratory (University of Toronto, Toronto).

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

[b]Upper and lower age range with intercept ages in parentheses. Ages calibrated using CALIB 4.3 (Stuiver et al. 1998*a*, 1998*b*).

[c]Calendar years BP denotes years before 1950.

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

0 and 10 cm (75% organic content), 154 and 174 cm (~6%), 188 and 194 cm (~62%), and 210 and 220 cm (75%). Magnetic susceptibility values are low throughout the core, except between 158 and 172 cm (Fig. 5), which is coincident with the silty clay layer.

Pollen zonation

Five local pollen assemblage zones are defined for Moraine Bog (Table 2; Fig. 5). Average sedimentation rates, pollen percentages, pollen concentration, and PARs are presented for each assemblage zone in Table 2. Pollen percentage and *Nuphar* sclereid data are summarized in Fig. 5. Pollen from Moraine Bog is generally well preserved, although the preservation in some samples is poor.

Zone MB-1

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

Alnus viridis-type pollen (~30%) dominates the base of zone MB-1. Shrub alder likely formed the forest understorey around the wetland at this time. The forest cover is mainly *Abies* (~17%) and *Tsuga heterophylla* (15%). *Pinus* is also a component of the pollen rain, but pine values fluctuate markedly through this zone. *Tsuga mertensiana* pollen briefly achieves its highest values (14%) in zone MB-1. The assemblage suggests a local mixed-species conifer forest. PARs (2640 grains/cm^2/years) are low compared with values in the other zones. *Nuphar* pollen values are very low (~1%) throughout the zone, and sclereid concentrations fluctuate between 15 000 and 40 000 sclereids/cm^3.

Zone MB-2

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

Zone MB-2 spans the silty clay layer and exhibits the largest changes in pollen percentages in the Moraine Bog record. *Alnus viridis*-type pollen continues to dominate, increasing to a mid-late Holocene maximum (~45%). At the base of the zone, *Alnus incana* increases to about 10%, and *Abies*, *Tsuga mertensiana*, *Tsuga heterophylla*, and *Pinus* decrease rapidly in abundance. *Abies* increases midway through the zone. *Tsuga heterophylla* and *Tsuga mertensiana* increase simultaneously, but more gradually. *Picea* increases slightly,

reaching its highest values (~12%) in the lower half of the zone before declining to about 1% at the top. Monolete fern spores, *Lycopodium* spores, and *Equisetum* spores reach their highest levels in zone MB-2. *Nuphar* pollen decreases and *Nuphar* sclereids reach their lowest values in this zone. PARs are low, averaging 1760 grains/cm^2/years, with values of only 840 grains/cm^2/years in the silty clay layer.

Zone MB-3

(Abies – Tsuga heterophylla – Pseudotsuga, 149–101 cm, ca. 2100–1300 ^{14}C years BP, ca. 2100–1250 calendar years BP)

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

Zone MB-4

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

Abies and *A. viridis* percentages (20%) change little in zone MB-4. *Pinus* pollen values increase slightly to 23%, *Cystopteris fragilis* decreases to about 2%, *Pseudotsuga* decreases to 4%, and *T. heterophylla* increases to 23%. *Nuphar* sclereids and pollen decrease at two levels in zone MB-4. Values drop to almost zero in the lower part of the zone, increase to about 30 000 sclereids/cm^3 in the middle of the zone, then decrease to about 5000 sclereids/cm^3 near the top. PARs increase to 3180 grains/cm^2/years.

Zone MB-5

(Abies – Tsuga heterophylla – Pinus – Tsuga mertensiana, 45–0 cm, ca. 500 ^{14}C years BP – present, ca. 525–0 calendar years BP)

Pinus pollen is abundant (30%) in the middle of zone MB-5, but decreases gradually to about 20% at the top. *Tsuga mertensiana* values increase to about 6% in this zone.

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Table 2. Pollen zones, pollen and spore percentages, sedimentation rates, pollen concentrations, and pollen accumulation rates for the Moraine Bog core.

Zone description	Depth (cm)	Age (ca. calendar years BP)	Pollen and spore percentages	Sedimentation rate (cm²/years)	Pollen concentration (grains/cm³)	Pollen influx (grains/cm²/years)
MB-1: *Abies – Tsuga heterophylla – Tsuga mertensiana*	220–165	3750–2425	*Alnus viridis*-type 27%, *Pinus* 26%, *Abies* 17%, *Tsuga heterophylla* 15%, *Tsuga mertensiana* 6%, *Alnus incana*-type 3%, *Picea* 2%	0.085	52738	2638
MB-2: *Alnus viridis – Alnus incana – Picea – Lycopodium*	165–149	2425–2100	*Alnus viridis*-type 41%, *Pinus* 19%, *Abies* 13%, *Tsuga heterophylla* 10%, *Alnus incana*type 7%, *Lycopodium* 4%, *Picea* 3%, *Tsuga mertensiana* 2%	0.070	46287	1763
MB-3: *Abies – Tsuga heterophylla – Pseudotsuga – Cystopteris fragilis*	149–101	2100–1250	*Alnus viridis*-type 26%, *Abies* 24%, *Tsuga heterophylla* 18%, *Pinus* 17%, *Cystopteris fragilis* 7%, *Tsuga mertensiana* 4%, *Pseudotsuga* 4%, *Alnus incana*-type 3%, *Picea* 2%	0.060	46931	2548
MB-4: *Tsuga heterophylla – Abies – Alnus viridis*	101–45	1250–550	*Tsuga heterophylla* 24%, *Pinus* 23%, *Abies* 21%, *Alnus viridis*-type 20%, *Tsuga mertensiana* 4%, *Pseudotsuga* 4%, *Cysopteris fragilis* 2%, *Picea* 1%	0.055	37159	3178
MB-5: *Abies –Tsuga heterophylla – Pinus – Tsuga mertensiana*	45–0	525–0	*Pinus* 30%, *Alnus viridis*-type 21%, *Abies* 20%, *Tsuga heterophylla* 14%, *Tsuga mertensiana* 7%, *Cystopteris fragilis* 4%, *Pseudotsuga* 3%, *Picea* 2%	0.05	63655	4392

Abies and *Alnus viridis*-type pollen are constant at about 20%. *Nuphar* sclereid concentrations are about 30 000 sclereids/cm³ throughout the zone. PARs (4390 grains/cm²/years) are the highest of the last 3500 years.

Discussion

Moraine Bog core synthesis

The Moraine Bog core provides evidence for a period of cooler and wetter climate from about 3200 to 1900 ^{14}C years BP, followed by warmer drier conditions between ca. 1900 and 1500 ^{14}C years BP. The transition from MB-1 to MB-2 coincides with deposition of the silty clay layer, when Tiedemann Glacier achieved its maximum extent during the Tiedemann Advance. A decrease in *Abies* pollen and increases in fern and clubmoss spores at this time likely result from inwash of soil (cf. Mathewes 1973, 1985). Both *Alnus viridis* and *Alnus incana* are indicators of disturbed environments (Pojar and MacKinnon 1994). They serve as indicator taxa for the onset of environmental conditions associated with cooler climate and glacier advance (Heusser 1985; Mayle et al. 1993; Brown and Hebda 2003; Walker 2003) and increased avalanche activity (Gavin et al. 2001). The largest increase in *Alnus* at Moraine Bog coincides with deposition of the silty clay layer. Newly exposed minerogenic soils, likely created during glacier advance, would have provided habitat for this Pacific Northwest pioneer genus. The proximity of Tiedemann Glacier to Moraine Bog at the peak of the Tiedemann Advance (2500–2200 ^{14}C years BP) likely had an impact on the microclimate and vegetation of the wetland. However, climate around the wetland, which is reflected in local vegetation, probably responded in a similar manner to the regional climate that controlled the regimen of the glacier. We thus infer that regional climate change is responsible for coeval changes to Tiedemann Glacier and the vegetation surrounding Moraine Bog during the Tiedemann Advance. Little change in vegetation is recorded until ca. 1900 ^{14}C years BP (zone MB-3), suggesting that the period of cool wet climate that triggered the glacial advance persisted until that time.

Zone MB-3 is marked by an increase in *Pseudotsuga* pollen and decrease in *Tsuga heterophylla* pollen, suggesting reduced precipitation and more frequent drought between about 1900 and 1500 ^{14}C years BP. *Tsuga heterophylla* typically occurs in mesic areas in the Coast Mountains, but it is replaced by *Pseudotsuga* on dry rocky sites or in areas subject to fire disturbance (Pojar and MacKinnon 1994). *Pseudotsuga* pollen percentages exceed 5% at Moraine Bog in nine samples in zone MB-3, suggesting that the taxon was common around the wetland during this period. *Pseudotsuga* pollen grains are relatively large and do not disperse far from their source (McLennan and Mathewes 1984); values as low as 10% have been recorded within *Pseudotsuga* stands in southern British Columbia (Mathewes and King 1989).

The *Nuphar* sclereid record likely provides additional evidence for a dry period at Moraine Bog during the late Holocene. Sclereids are abundant from 1900 to 1600 ^{14}C years BP, likely indicating water levels similar to or lower than today. Sediment that accumulated in the wetland during this interval is peat and peaty gyttja, which is consistent with relatively low water levels. Increases in spores of the fern *Cystopteris*

fragilis likely reflect colonization of exposed rocky substrates (Pojar and MacKinnon 1994), such as the nearby blocky moraine.

About 1350 ^{14}C years BP, cooler wetter conditions returned to Moraine Bog. The transition from zone MB-3 to MB-4 is characterized by a decrease in *Pseudotsuga* pollen and an increase in *Tsuga heterophylla* pollen to its highest late Holocene level. A shift from peaty vegetation to gyttja suggests a return to wetter conditions and higher water levels. A decrease in *Nuphar lutea* sclereids possibly reflects an increase in water depth, with *Nuphar* unable to extend its leaves to the surface.

The change from zone MB-4 to MB-5 is subtle, but it marks the establishment of the present vegetation and climate. Although the vegetation indicated by zone MB-5 is consistent with a cool wet climate during the last 500 years, lack of chronological resolution precludes examination of centennial-scale variation during this period. However, high *Picea* and *Tsuga mertensiana* pollen values and low *Tsuga heterophylla* ones during the last 500 years are likely the result of thicker winter snowpacks and lower summer temperatures (Gagan et al. 1998). *Nuphar* sclereid values are similar to those of the dry period in zone MB-3, suggesting that water levels were likely lower than those reached during the wettest period of the record. Cooler and wetter conditions likely established the present Mountain Hemlock zone forest at Moraine Bog.

The present mixed assemblage forest at Moraine Bog is likely a unique mid-elevation climax forest adapted to a transitional coastal-interior climate.

Regional synthesis

The vegetation record and inferred climate trends derived from Tiedemann Glacier study site are consistent with other late Holocene records from the coastal Pacific Northwest. Most published studies report the establishment of the modern climate in southern British Columbia around 3000 ^{14}C years BP (Mathewes and Heusser 1981; Mathewes 1985; Wainman and Mathewes 1987; Mathewes and King 1989; Hebda 1995; Pellatt and Mathewes 1997; Pellatt et al. 1998, 2000, 2001; Gavin et al. 2001). These studies, however, are based on relatively coarse sampling, and some of the study sites are insensitive to minor changes in climate.

Tiedemann Advance

Analysis of pollen from Moraine Bog suggests that relatively temperate intervals during Neoglaciation were punctuated by periods of cooling and increased moisture and by periods of drought (Fig. 6) (Mathewes 1985; Hebda 1995). The Moraine Bog pollen record is compatible with records of glacier fluctuations in British Columbia. The Tiedemann Advance, one of the most significant of the cool periods, is documented at several sites in the Coast Mountains (Ryder and Thomson 1986; Ryder 1989; Desloges and Ryder 1990; Clague and Mathews 1992, 1996; Koch et al. 2003; Reyes 2003; Reyes and Clague 2004). Work at Moraine Bog suggests that Tiedemann Glacier reached its maximum extent during the Tiedemann Advance between 2500 and 2200 ^{14}C years BP (ca. 2700–2300 calendar years BP). However, the term "Tiedemann Advance" is somewhat of a misnomer; it is a period of cool wet climate from ca. 3300 to 1900 ^{14}C years BP, not simply a single glacier advance.

Tiedemann-age glacier advances have been documented

Fig. 6. Previously reported climate events during the last 3500 ^{14}C years BP in the Coast Mountains and Moraine Bog pollen zones.
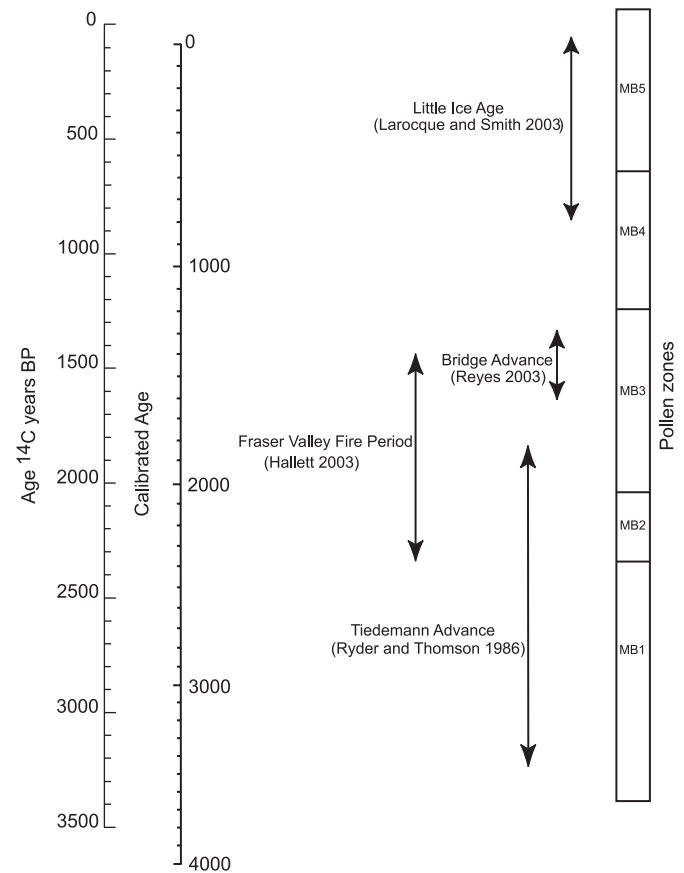
elsewhere in western North America: at Berendon and Frank Mackie glaciers in the northern Coast Mountains (2870–2220 ^{14}C years BP) (Clague and Mathewes 1996), Gilbert Glacier in the middle Coast Mountains (2200–1900 ^{14}C years BP) (Ryder and Thomson 1986), Jacobsen Glacier near Bella Coola (2500 ^{14}C years BP) (Desloges and Ryder 1990), and at Mount Rainier in the Cascade Ranges (2980 ^{14}C years BP) (Crandell 1965; Crandell and Miller 1974). Two separate Tiedemann advances are recorded at Lillooet Glacier: one at ca. 3000 ^{14}C years BP and another at ca. 2500 ^{14}C years BP (Reyes and Clague 2004). Sediment records from Black Tusk Lake in the southern Coast Mountains suggest a glacier advance beginning about 2650 ^{14}C years BP (ca. 2750 calendar years BP) (Cashman et al. 2002). A correlative glacier advance between 3300 and 2500 ^{14}C years BP, termed the Peyto Advance, has also been documented at several sites in the Canadian Rocky Mountains, including Peyto and Robson glaciers (Luckman et al. 1993), Saskatchewan Glacier (Smith and Wood 2000), and Yoho Glacier (Luckman et al. 1993). The Peyto Advance culminated at Stutfield Glacier prior to the deposition of the Bridge River tephra, 2400 ^{14}C years BP (2400 calendar years BP) (Osborn et al. 2001). High sedimentation rates in lakes in Banff National Park, Alberta, between 3000 and 2350 ^{14}C years BP have also been interpreted as indicating glacier advance at that time (Leonard 1986).

Fraser Valley Fire Period

The Moraine Bog pollen record suggests that the Tiedemann Advance was followed by dry warmer conditions from about 1900 to 1500 ^{14}C years BP (ca. 1800–1350 calendar years BP). A relatively warm dry interval at this time has been termed the Fraser Valley Fire Period by Hallett et al. (2003a, 2003b) on the basis of an increase in macroscopic charcoal accumulation in high-elevation lakes 300 km southeast of Moraine Bog between 2400 and 1400 ^{14}C years BP (2400–1300 calendar years BP).

Tiedemann Glacier retreated during the Fraser Valley Fire Period (Ryder and Thomson 1986). The retreat is evidence for ablation owing to higher summer temperatures, decreased winter precipitation, or both. Larocque and Smith (2003) found no evidence for a readvance of Tiedemann Glacier until the end of the Fraser Valley Fire Period (ca. 1300 calendar years BP).

Hallett (2003a) attributed the warmer climate of the Fraser Valley Fire Period to a long-term increase in the intensity of the Pacific High. Evidence for similar drought at Tiedemann Glacier suggests that an intensified Pacific High affected latitudes up to at least 51°N, which is farther north than previously inferred.

Bridge Advance

Evidence from Moraine Bog suggests cooler wetter conditions returned about 1350 ^{14}C years BP. Lichen data from Tiedemann Glacier moraines, reported by Larocque and Smith (2003), suggest two pre-Little Ice Age advances, the first before 1330 calendar years BP (ca. 1400 ^{14}C years BP) and the second prior to 1025 calendar years BP (ca. 1100 ^{14}C years BP).

A short-lived, pre-Little Ice Age advance has been dated to between 1700 and 1400 ^{14}C years BP at Lillooet Glacier (Reyes and Clague 2004). Similar advances between 1500 and 1200 ^{14}C years BP have been documented in the mountains throughout western North America (Reyes et al. 2006).

Little Ice Age

The Moraine Bog record indicates cool wet conditions over the past 500 years, with little change in vegetation during this time. The Little Ice Age, the last of the major Neoglacial cool intervals, is well documented in the western Canadian Cordillera (Clague and Rampton 1982; Ryder and Thomson 1986; Osborn and Luckman 1988; Ryder 1989; Desloges and Ryder 1990; Clague and Mathewes 1992, 1996; Smith and Desloges 2000, Larocque and Smith 2003, Reyes and Clague 2004). Radiocarbon ages from the southern Coast Mountains suggest that the Little Ice Age began about 900 ^{14}C years BP and persisted until about 100 years ago (Mathews 1951; Ryder and Thomson 1986; Ryder 1989).

Global perspective

Pollen analysis and paleobotany in general have a long and well-documented history of using plant communities and taxon distributions to interpret changes in climatic conditions. Many of the references cited in this paper illustrate the value of paleobotanical approaches as proxies for climatic change (i.e., Mathewes and Heusser 1981; Mayle et al. 1993; Hebda 1995; Pellatt and Mathewes 1997; Hallett et al. 2003a, 2003b). When plant evidence is combined with geological data, past changes in climate and glacier dynamics can be reconstructed with greater confidence than using these data independently.

Evidence for climatic deterioration coinciding with the Tiedemann Advance and possibly linked to a change in ocean temperatures has been found in many parts of the world (Bond et al. 1997; de Menocal et al. 2000), and is typically reflected in local vegetation records. Glacier advances in the Brooks Range in Alaska culminated about 3500, 2800, and 2300 ^{14}C years BP, and glaciers in the Alaska Range also advanced during this interval (Calkin et al. 2001). In the European Alps, the lower Grindelwald Glacier advanced twice, between 2800 and 2600 ^{14}C years BP and between 2300 and 2100 ^{14}C years BP (Holzhauser and Zumbühl 1996); the Gorner Glacier advanced around 2300 ^{14}C years BP (Holzhauser 1997); advances of the Gepatschferener culminated about 3400, 3300, 2950, 2450, and 2000 ^{14}C years BP (Nicolussi and Patzelt 2000); and the Great Aletsch Glacier expanded around 3200–3100, 2800–2700, and again between 2400 and 2300 ^{14}C years BP (Holzhauser 1997). Shifts in treeline in the Italian and Swiss Central Alps have been correlated with periods of glacier advance, increased solifluction, and vegetation change (Wick and Tinner 1997). Treeline fluctuations indicate two distinct cooling phases between 3500–3200 and 2600–2350 ^{14}C years BP in this region (Haas et al. 1998). A cold phase with relatively high precipitation began around 3000 ^{14}C years BP in Patagonia, and glacier advances have been documented between 2700 and 2000 ^{14}C years BP and at 2300 ^{14}C years BP (Wenzens 1999; Glasser et al. 2004). Paleoclimate records from this area indicate a shift to grass–shrub steppe vegetation around 3500 ^{14}C years BP and development of more extensive late Holocene forests, reflecting an increase in effective moisture and cooler conditions (Glasser et al. 2004). Glaciers in New Zealand advanced about 3700 ^{14}C years BP, between 3500–3000 ^{14}C years BP, and between 2700–2200 ^{14}C years BP (Gellatly et al. 1988). Forest at treeline in central New Zealand was replaced by subalpine scrub between about 3500 and 1100 ^{14}C years BP, which is consistent with the glacial record (Horrocks and Ogden 2000). Scandinavian glaciers advanced between 3200 and 2800 ^{14}C years BP and again at about 2500 and 2000 ^{14}C years BP (Karlén 1988; Bakke et al. 2005). Vegetation records from Sweden indicate a shift to a cooler more humid climate after about 5600 ^{14}C years BP (Barnekow 2000). Further evidence of a major change in climate at the time of the Tiedemann Advance is the appearance of wind-blown Saharan diatoms in West Africa at about 2800 ^{14}C years BP, marking a shift in the Intertropical Convergence Zone (Nguetsopa et al. 2004).

Conclusions

Pollen and sediment records from Moraine Bog provide evidence for four centennial-scale climate phases over the last 3500 years. The Tiedemann Advance, a period of cool wet climate and glacier advance occurred from ca. 3300 to 1900 ^{14}C years BP. A warmer dry interval from ca. 1900 to 1500 ^{14}C years BP is inferred from high *Nuphar* sclereid abundance and an increase in *Pseudotsuga* pollen. A return to cool wet conditions around 1350 ^{14}C years BP is coeval with the Bridge Advance documented at Lillooet and Bridge

glaciers to the south. Cool moist conditions characterize much of the last millennium.

Tiedemann Glacier achieved its maximum extent during the Tiedemann Advance between ca. 2500 and 2200 years ^{14}C BP. Several advances between ca. 3300 and 1900 ^{14}C years BP have been inferred by others from moraines, but are not evident in the Moraine Bog vegetation record.

The record of inferred climate change at Moraine Bog is consistent with paleoecological and paleoclimate records from other parts of the Coast Mountains. The Moraine Bog record is unique, however, in one important respect—most previous palynological studies in the Coast Mountains establish the onset of modern conditions around 3000 ^{14}C years BP and show little vegetation change after that. The Moraine Bog record provides more detail on vegetation change over the last 3500 years, and highlights the importance of sampling at a short interval and selection of a site that is sensitive to climate change.

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