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Holocene Climatic Change and Landscape Response at Cathedral Provincial Park, British Columbia, Canada

Changement climatique de l'holocène et conséquences sur le paysage du parc provincial Cathedral, Colombie-Britannique, Canada

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Résumé de l'article

La sensibilité de l'environnement de Lake of the Woods (montagnes Cascades, parc provincial Cathedral, sud de la Colombie-Britannique) face au changement de température de l'Holocène a été établie en mettant en parallèle les données locales de pollen, de macrofossiles de plantes, de charbon de bois macroscopique et d'apports sédimentaires à des données indépendantes provenant d'une banque de paléotempératures déduites à partir de l'étude de moucherons. La végétation de steppe comportant quelques épinettes et sapins qui s'est initialement établie a fait place à des forêts de pins, sous l'influence du climat plus chaud du début de l'Holocène. Ces forêts étaient soumises à de fréquents feux, qui ont entravé la succession des épinettes et des sapins. Une fois établies, celles-ci ont conservé les caractéristiques de la pessière d'Engelmann-sapinière subalpine. Après 8000 BP (années étalonnées), en raison de l'existence de conditions chaudes mais plus humides, la forêt comportait moins de pins et de sapins et les feux y étaient moins fréquents. Vers 4000 ans BP, des températures plus froides ont entraîné la disparition de la pessière d'Engelmann-sapinière subalpine et une réduction continue de la fréquence des feux de forêts. Les niveaux d'apports sédimentaires indiquent un environnement stable durant l'Holocène, découlant principalement du trappage des sédiments dans deux lacs situés en amont. Les températures déduites à partir de l'étude de moucherons concordent avec la reconstitution de températures établie à partir d'un consensus pour le sud de la Colombie-Britannique. Il s'avère que les écosystèmes terrestres du parc provincial Cathedral n'ont pas été aussi sensibles aux variations climatiques passées que d'autres pessières d'Engelmann-sapinières subalpines environnantes.

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HOLOCENE CLIMATIC CHANGE AND LANDSCAPE RESPONSE AT CATHEDRAL PROVINCIAL PARK, BRITISH COLUMBIA, CANADA

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ABSTRACT Environmental sensitivity to temperature change was established by comparing pollen, plant macrofossils, macroscopic charcoal, and sediment yield data from Lake of the Woods, Cathedral Provincial Park in the Cascade Mountains of southern British Columbia, Canada, to an independent record of midge-inferred paleotemperature. Steppe vegetation with some spruce and fir occurred initially, developing into pine forests in the warm early Holocene. These forests burned often, preventing spruce and fir succession. Once established, the forests retained an Engelmann Spruce-Subalpine Fir character. After 8000 cal BP, in warm but wetter conditions, the forest contained less pine and fires burned less frequently. About 4000 cal BP, cooler temperatures resulted in closure of the Engelmann Spruce-Subalpine Fir forests and a further reduction in fire frequency. Sediment yield results suggest a stable environment throughout the Holocene, likely due to sediment trapping in two upstream lakes. Midge-inferred temperatures correspond closely with a consensus reconstruction of temperatures from southern British Columbia, however Cathedral Provincial Park terrestrial ecosystems were not as sensitive to past climate change when compared to other nearby Engelmann Spruce-Subalpine Fir sites.

RÉSUMÉ *Changement climatique de l'Holocène et conséquences sur le paysage du parc provincial Cathedral, Colombie-Britannique, Canada.* La sensibilité de l'environnement de Lake of the Woods (montagnes Cascades, parc provincial Cathedral, sud de la Colombie-Britannique) face au changement de température de l'Holocène a été établie en mettant en parallèle les données locales de pollen, de macrofossiles de plantes, de charbon de bois macroscopique et d'apports sédimentaires à des données indépendantes provenant d'une banque de paléotempératures déduites à partir de l'étude de moucherons. La végétation de steppe comportant quelques épinettes et sapins qui s'est initialement établie a fait place à des forêts de pins, sous l'influence du climat plus chaud du début de l'Holocène. Ces forêts étaient soumises à de fréquents feux, qui ont entravé la succession des épinettes et des sapins. Une fois établies, celles-ci ont conservé les caractéristiques de la pessière d'Engelmann-sapinière subalpine. Après 8000 BP (années étalonnées), en raison de l'existence de conditions chaudes mais plus humides, la forêt comportait moins de pins et de sapins et les feux y étaient moins fréquents. Vers 4000 ans BP, des températures plus froides ont entraîné la disparition de la pessière d'Engelmann-sapinière subalpine et une réduction continue de la fréquence des feux de forêts. Les niveaux d'apports sédimentaires indiquent un environnement stable durant l'Holocène, découlant principalement du trappage des sédiments dans deux lacs situés en amont. Les températures déduites à partir de l'étude de moucherons concordent avec la reconstitution de températures établie à partir d'un consensus pour le sud de la Colombie-Britannique. Il s'avère que les écosystèmes terrestres du parc provincial Cathedral n'ont pas été aussi sensibles aux variations climatiques passées que d'autres pessières d'Engelmann-sapinières subalpines environnantes.

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INTRODUCTION

The postglacial history of mountain forest ecosystems is well documented throughout much of southern British Columbia (Mathewes, 1985; Hebda, 1995). It has generally been assumed that these postglacial dynamics primarily record responses to climatic change. Nevertheless, concerns persist that vegetation changes may have lagged behind climate change (Davis, 1989). Paleotemperature interpretations based on pollen alone have proven problematic in other regions, where megafossils do not necessarily correlate with pollen and macrofossil data (*e.g.*, Barnekow, 1999; Kullman, 1999).

Sub-fossil midges have been accepted as robust paleotemperature indicators (Battarbee, 2000), and we have been using these as a primary tool for reconstructing Holocene paleotemperatures for British Columbia. Our midge-temperature inference model reveals a six degree mean summer temperature range over the last 13 000 years (Palmer *et al.*, 2002; Rosenberg *et al.*, 2004). This use of midges in multi-proxy studies facilitates detailed comparisons of the vegetation record (Williams *et al.*, 2004) with independent paleotemperature estimates (Smith *et al.*, 1998).

Here, we reconstruct vegetation change using pollen, spores, plant macrofossils and charcoal, and examine these changes relative to the midge-inferred paleotemperature record (Palmer *et al.*, 2002; Walker and Pellatt, 2003; Rosenberg *et al.*, 2004). We also support our observations of landscape change via sediment yield analyses, a useful indicator of land surface stability (Brunsden, 1990; Gorham *et al.*, 2001). Used together, landscape stability and vegetation response provide reliable measures of ecological sensitivity. Furthermore, we compare the results from Lake of the Woods with data from several nearby sites in the Engelmann Spruce-Subalpine Fir forest to provide a comprehensive view of landscape sensitivity to climate change, and broaden our knowledge of high elevation forests in the region.

STUDY AREA

Cathedral Provincial Park is a 33 000 ha park situated on the north-eastern slopes of the Cascade Mountains in British Columbia, between the Ashnola River and the International Boundary with the USA (Fig. 1). Much of the park is considered an excellent example of late-successional Engelmann

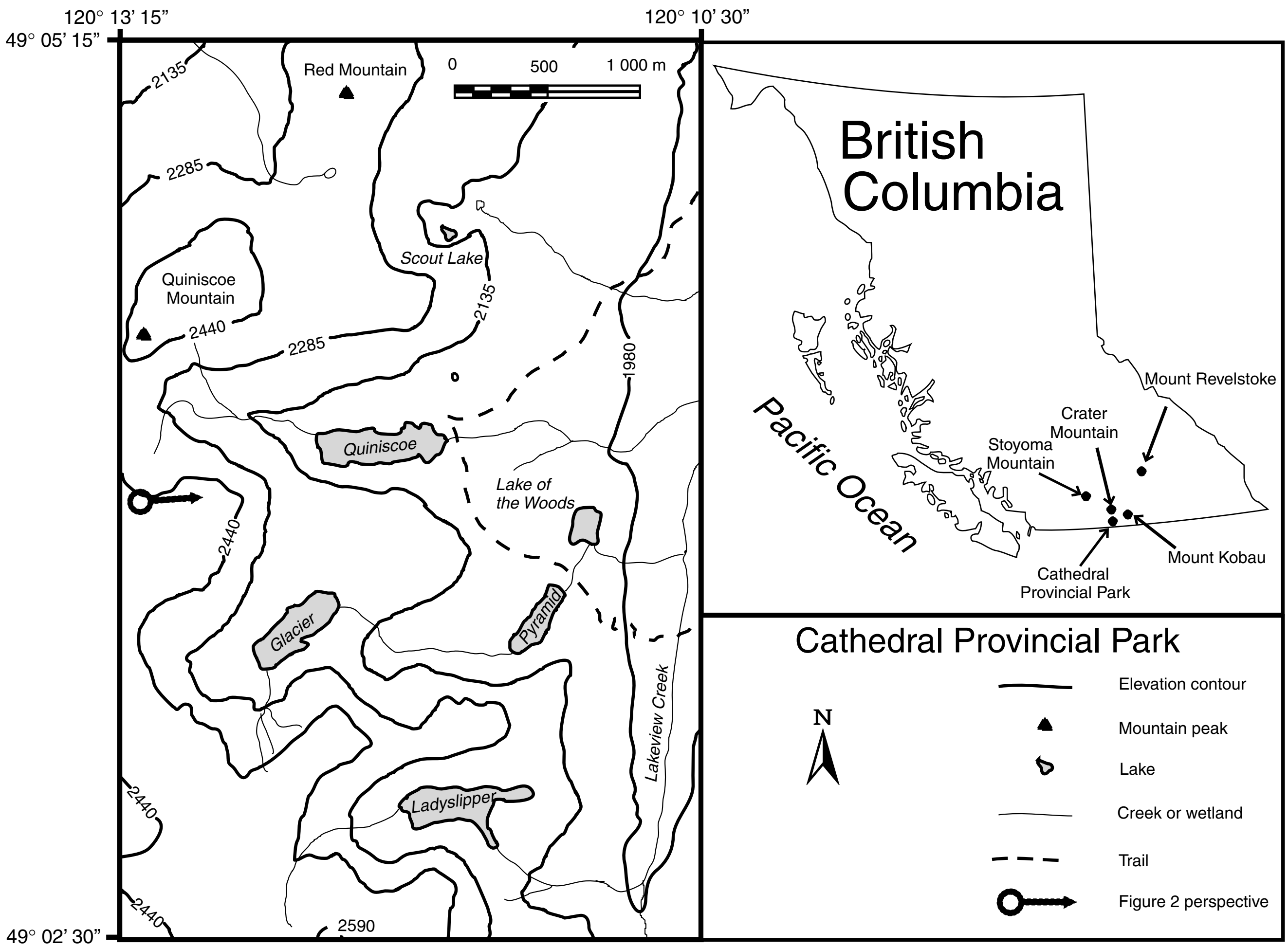

Figure 1. Map showing Lake of the Woods sampling site in Cathedral Provincial Park, as well as the park location relative to other locations mentioned in the text.

Emplacement des sites d'échantillonnage dans le parc provincial Cathedral et localisation du parc par rapport aux autres lieux mentionnés dans le texte.

Spruce-Subalpine Fir (ESSF) forest and alpine-tundra (AT) wilderness, however it extends down valleys into drier Interior Douglas Fir (IDF) and Ponderosa Pine (PP) ecosystems (Meidinger and Pojar, 1991). This site (Fig. 2) was chosen because of the park's limited historical human impact (Ministry of Environment and Parks, 1987) and its location within the main ecological range of a typical ESSF xeric cold (xc) ecosystem (Coupé *et al.*, 1991). Mean annual temperature and precipitation of the ESSFxc are 1.7 °C and 565 mm, respectively (Lloyd *et al.*, 1990). Lake of the Woods (49° 03' N, 120° 11' W), is situated at an elevation of 2 060 m, downstream of Pyramid (2 070 m) and Glacier Lakes (2 200 m), and is approximately 3.6 m deep with a surface area of 2.5 ha. Sediments in the lake are rich in organic matter, unlike the relatively minerogenic sediments of nearby Glacier, Ladyslipper, and Pyramid lakes, and thus are more suitable for our analyses. Underlying geology consists of Permian aged sediments (including limestone), Triassic aged lavas, Jurassic aged granitic plutons, and Eocene aged lavas and sediments (Melcon, 1975).

The surrounding forest consists of a mixture of *Pinus contorta* ex Loud. var. *latifolia* Engelm. (lodgepole pine), *Picea engelmannii* Parry ex Engelm. (Engelmann spruce), and *Abies lasiocarpa* Hook. (Nutt.) (subalpine fir) (Table I). *Larix lyallii* Parl. in DC. (alpine larch) is abundant at higher elevations, forming a parkland between the ESSF and AT. Treeline occurs over a narrow elevation gradient, forest canopy opening at about 2 130 m, and absolute tree limit at 2 290 m. Non-forested areas consist of scattered low shrubs and herbaceous, alpine meadows (Ratcliffe and Turkington, 1987, 1989) shaped by cold temperatures and strong winds (Saunders and Bailey, 1996).

METHODS

SAMPLING

Lake of the Woods was cored during the summer of 1995 using a modified Livingstone piston sampler (Wright, 1967). Ten cores were analysed to determine sediment yield (Evans, 1997a, b; Evans and Slaymaker, 2004). Core A9 (3.86 m long), taken from the deepest part of the lake, was subsampled in intervals of 1 to 5 cm for macro- and micro-fossil analyses.

CHRONOLOGY

We employed the sediment chronology previously established by Palmer *et al.* (2002) for core A9 from Lake of the Woods, which is based upon five radiocarbon dates and two chemically identified tephras (Table II). Calibration of these dates to calendar years was accomplished using CALIB 4.3 (Stuiver and Reimer, 1993). Pollen and charcoal accumulation rates were calculated using only the calibrated ages of the one conifer needle macrofossil and two tephras (Hallett *et al.*, 1997), as an inversion in the early Holocene sediment chronology occurs with respect to the AMS dated macrofossil. Carbonates present in the bulk gyttja samples may have affected the dating (Table III), though the only apparent inaccuracy appears near the carbon plateau at 10 000 ^{14}C BP (Hughen *et al.*, 1998).

POLLEN, CHARCOAL, AND PLANT MACROFOSSIL ANALYSES

Approximately 1 cm^3 of sediment was processed for pollen and spores according to standard methods (Fægri and Iversen, 1989), and mounted on microscope slides in glycerine jelly. *Lycopodium* tablets were added to samples allowing influx determinations (Stockmarr, 1972). Palynomorph identifications were made using an unpublished key to British Columbia pollen and spores, and McAndrews *et al.* (1973). A minimum of 300 terrestrial pollen grains was counted from each sample, which was used as the base sum to calculate percentages. Percent (Fig. 3) and influx (Fig. 4) diagrams were produced using TILIA 2.0.b.4. (Grimm, 1993) and TILIAGRAPH 2.0.b.5.

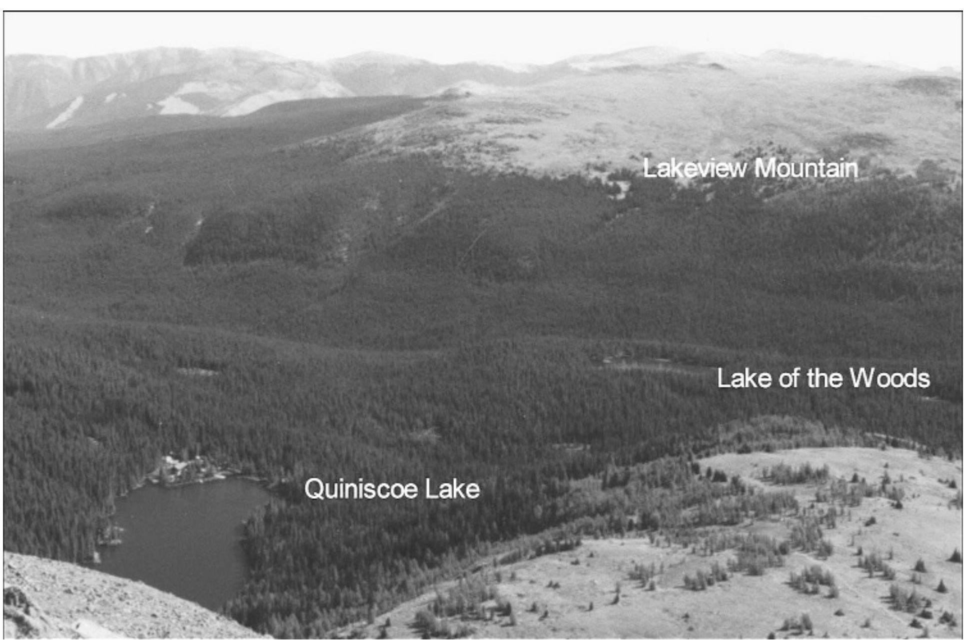

Figure 2. Photograph of the study area, looking east from Quiniscoe Mountain. Quiniscoe Lake is at the bottom left, Lake of the Woods in the centre right, and Lakeview Mountain is in the immediate background.

Photographie de l'aire d'étude vue de l'ouest, depuis le mont Quiniscoe. Le lac Quiniscoe est situé en bas, à gauche, Lake of the Woods, à mi-hauteur, à droite, et le mont Lakeview, en arrière-plan.

TABLE I

Vegetation surrounding Lake of the Woods (percent cover by visual estimation)

Trees	Shrubs	Herbs, forbs and mosses
	Stream outlet, in moist forest, south shore	
Abies lasiocarpa: 5%	*Ledum glandulosum*: 20%	*Valeriana sitchensis*: 5-10%
Picea engelmannii: 25%	*Salix* sp.: 1%	*Veratrum viride*: 10-15%
	Vaccinium scoparium: 25%	*Rubus pedatus*: 5-10%
	Phyllodoce sp.: 2-5%	Poaceae: 1%
		Asteraceae present
		Arnica sp. present
		Senecio triangularis present
		Bryophytes: 100%
	Dry bouldery slope, 5-10% slope on south side of lake	
Abies lasiocarpa: 15-20%	*Phyllodoce* sp. present	*Lupinus* sp.: 1%
Picea engelmannii: 15-20%		*Luzula* sp. present
		Bryophytes: 80%
	Dry boulder field, north side of lake	
Pinus contorta: 25-30%	*Vaccinium scoparium*: 60%	*Lupinus* sp.: 1%
Picea engelmannii: 25-30%	*Phyllodoce* sp.: 1-2%	Bryophytes: 90%
Abies lasiocarpa nearby		

TABLE II

Chronology of Lake of the Woods

Depth intervals (cm)	Age (^{14}C BP)	Calendar age (cal BC) 1σ	Calendar age (cal BP) 1σ	Lab number	Tephra or sample type
82-87	3390 ± 130	1525-1779	3474-3728		St. Helens Yn
140-150	5450 ± 90	4162-4364	6111-6313	Beta-94805	bulk
185-193	6730 ± 40	5620-5703	7514-7652		Mazama
241-250	8580 ± 80	7540-7679	9489-9628	Beta-94806	bulk
304-309	9800 ± 220	8802-9615	10 751-11 564	Beta-104157	bulk
341-350	10 200 ± 70	9739-10 152	11 688-12 101	Beta-94807	bulk
376-377	9650 ± 70	8902-9219	10 789-11 168	To-6051	AMS

TABLE III

Mean organic matter and biogenic silica proportions for correlated zones based on cores A1, A4b, A6, A7, A8, A9, A10, A11, A12 and A13 (Evans, 1997a)

Core A9 interval equivalent (cm)	Mean dry weight/wet volume (kg m^{-3})	Mean loss on ignition (%)	Diatom silica (%)	Carbonate (%)
0-84	202.9	24.9	9.3	2.0
84-145	202.8	27.7	10.2	2.4
145-185	183.5	29.9	10.1	3.4
185-386	209.6	29.8	9.5	3.4
386-439	461.9	13.4	9.5	1.9

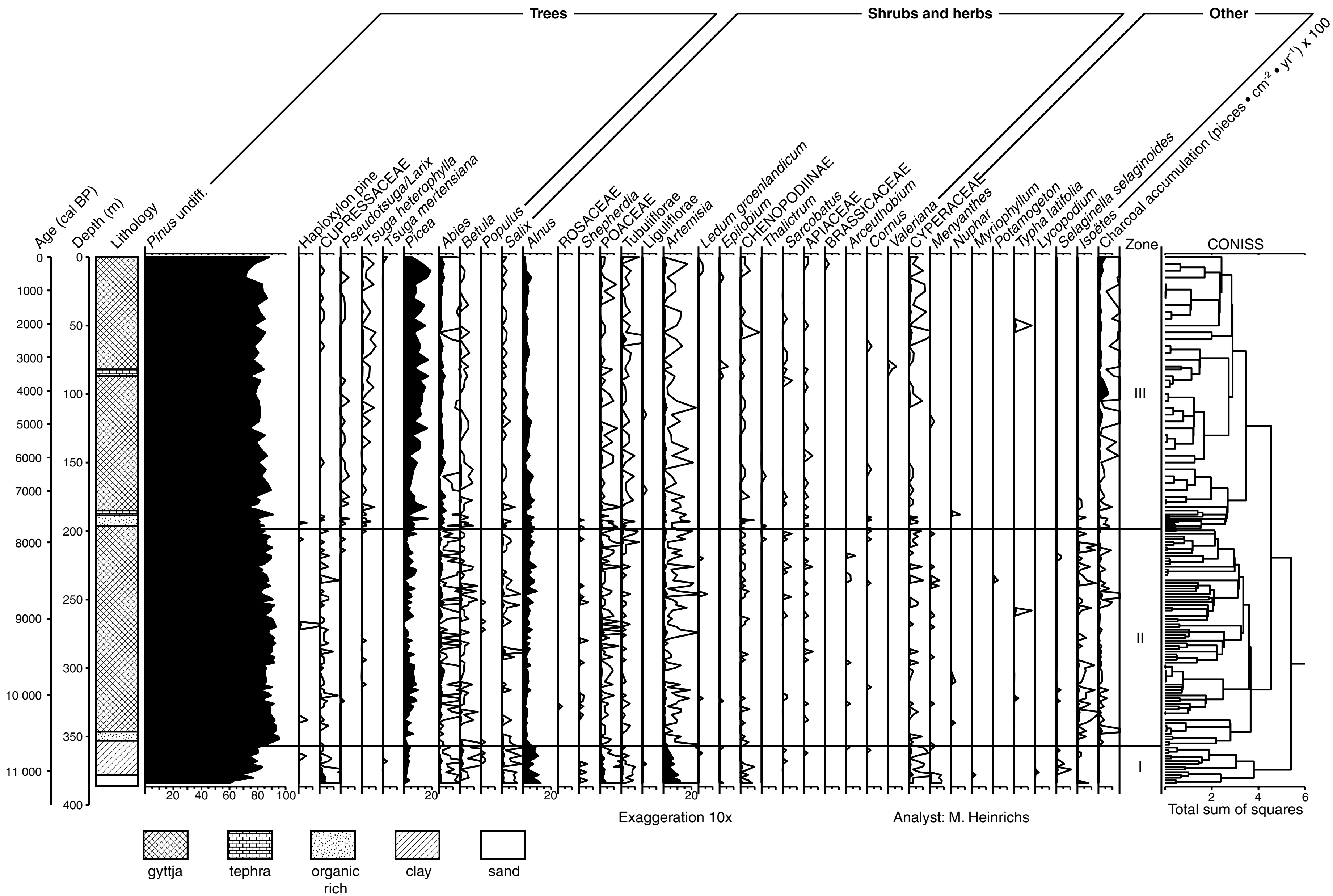

Figure 3. Pollen and spore percent diagram from Lake of the Woods, Cathedral Provincial Park, British Columbia, plotted on a depth scale. Hollow exaggeration curves are X10. Constrained sum of squares (CONISS) analysis on upland taxa is shown on the right.

Diagramme des pourcentages de pollens et de spores de Lake of the Woods, au parc provincial Cathedral, en Colombie-Britannique, en fonction de la profondeur. Les courbes sont exagérées dix fois. La somme contrainte des carrés (CONISS) de l'analyse sur les taxons des hautes terres est présentée à droite.

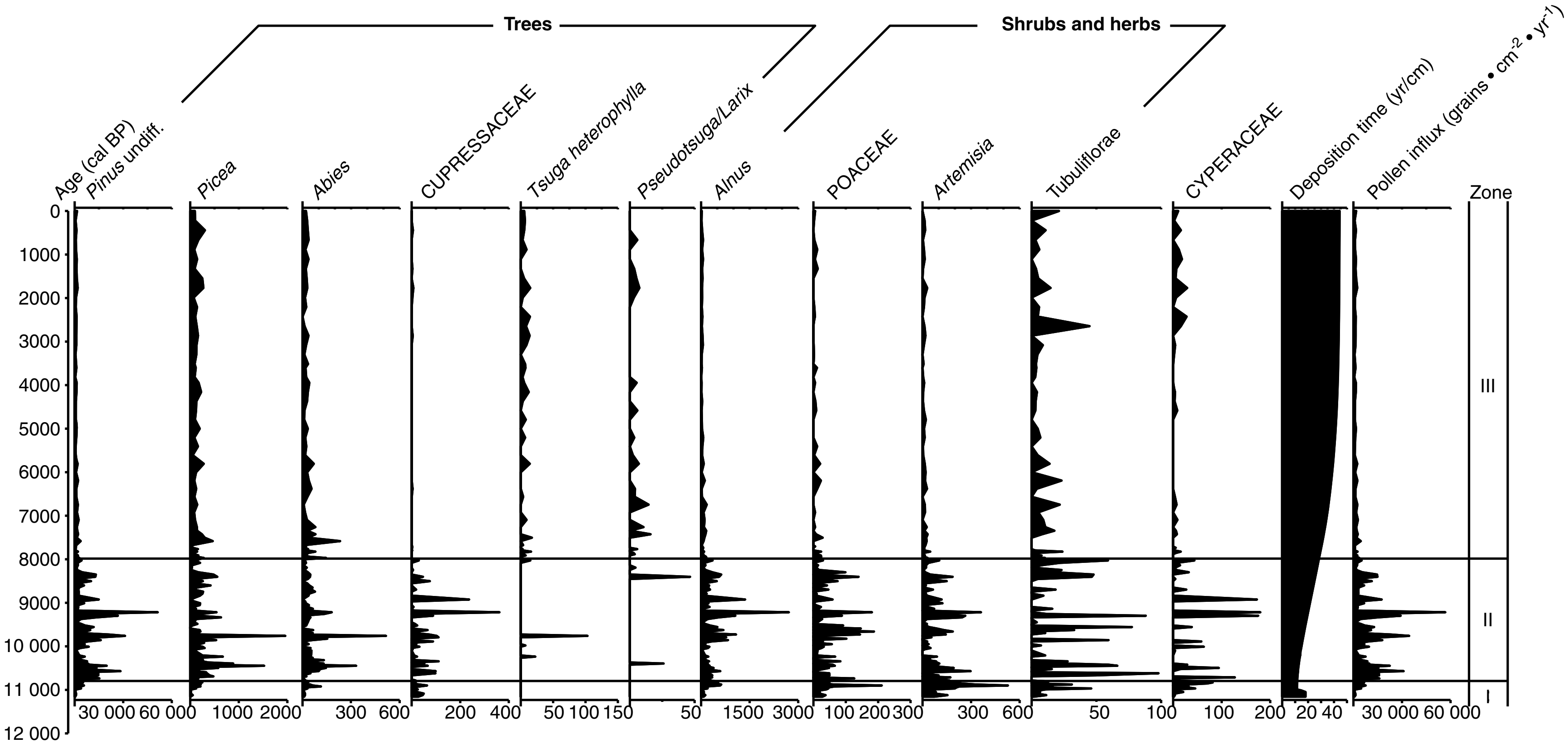

Figure 4. Pollen influx diagram for selected taxa from Lake of the Woods, plotted on a time scale using a smoothed curve based on the one AMS macrofossil date and two tephra ages. Note that the accumulation rate scales differ among taxa.

Diagramme d'influx polliniques de taxons choisis de Lake of the Woods, selon une échelle de temps dont la courbe a été corrigée à l'aide d'un âge de macrofossile (défini par SMA) et deux âges de tephra. Notez que les échelles de taux d'accumulation diffèrent d'un taxon à l'autre.

(Grimm, 1991). Zonation was facilitated by conducting stratigraphically constrained incremental sums-of-squares cluster analysis (CONISS) on square-root transformed percent data (Grimm, 1987).

Charcoal concentrations were determined for each subsample by extracting macroscopic charcoal from 1 cm^3 of sediment that remained on a 180 μm mesh (Millspaugh and Whitlock, 1995; Whitlock and Larsen, 2001). This charcoal-bearing residue was backwashed into a watch-glass and tallied under 4X magnification; concentrations were converted to accumulation rates (pieces cm^{-2} yr^{-1}) based on the chronology established using tephra and AMS dates. Plant macrofossils recovered from the remainder of the sediment in each subsample are presented as whole needles, needle fragments and seeds (Fig. 5). Plant macrofossils were identified using a key prepared by Dunwiddie (1985) and the reference collection of the Royal British Columbia Museum.

Ordination analysis was implemented to objectively determine if patterns of change exist within the pollen data (Fig. 6), as outlined in Heinrichs *et al.* (2002). A pilot detrended correspondence analysis (DCA), using the computer program CANOCO 3.12 (ter Braak, 1991), indicated a principal gradient length of 0.8; thus, principal components analysis (PCA) was selected as an appropriate ordination method for subsequent analysis (Jongman *et al.*, 1987; ter Braak and Prentice, 1988).

MIDGE-INFERRED TEMPERATURES

A detailed description of the midge analysis and paleotemperature inference procedure is found in Palmer *et al.* (2002) and Rosenberg *et al.* (2004). Midge-inferred temperature records are presented for Lake of the Woods and the southern interior region of British Columbia based on five high-elevation lakes, including Lake of the Woods (Fig. 7a).

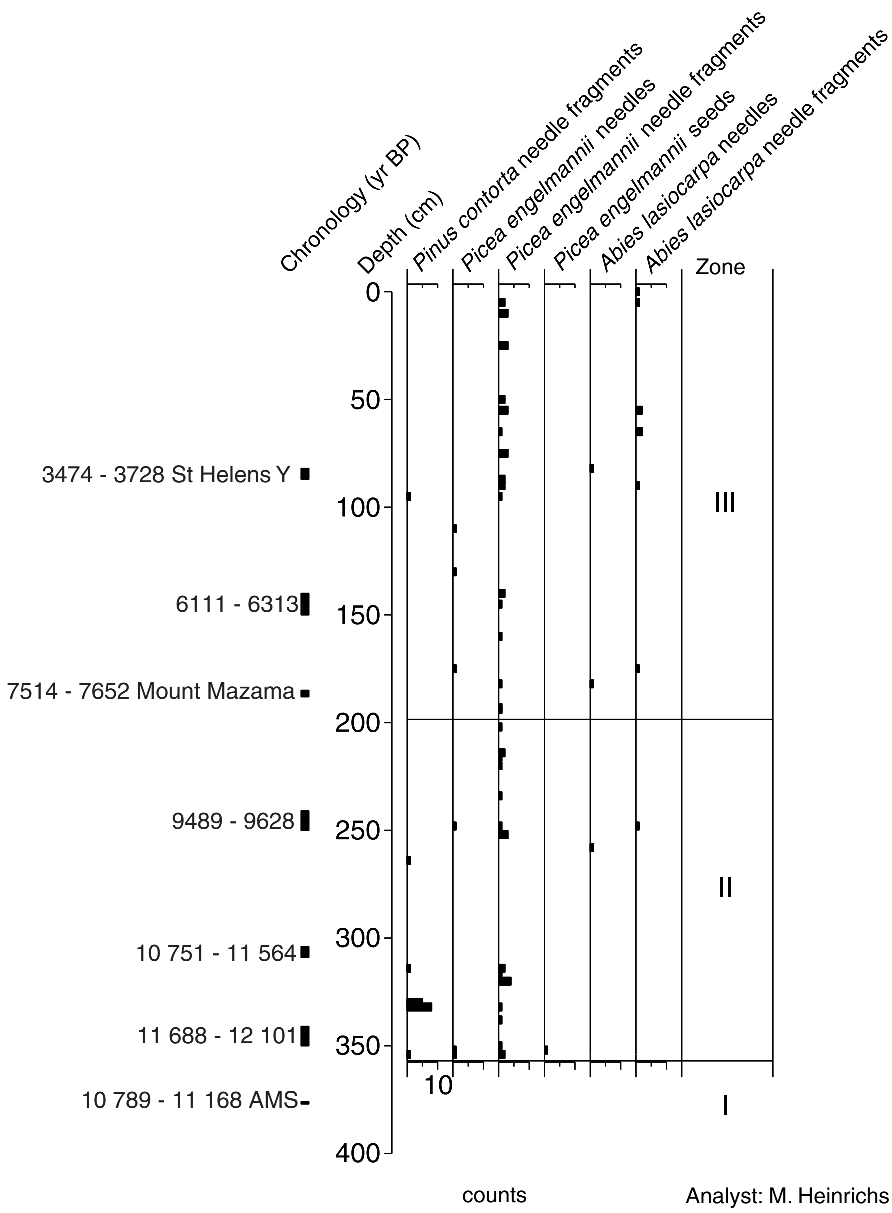

Figure 5. Macrofossil record, composed of needles, needle fragments, and seeds for *Picea engelmannii*, *Pinus contorta*, and *Abies lasiocarpa* from Lake of the Woods.

Relevé de macrofossiles composé d'aiguilles, de fragments d'aiguilles et de graines de Picea engelmannii*, de* Pinus contorta *et d'*Abies lasiocarpa *de Lake of the Woods.*

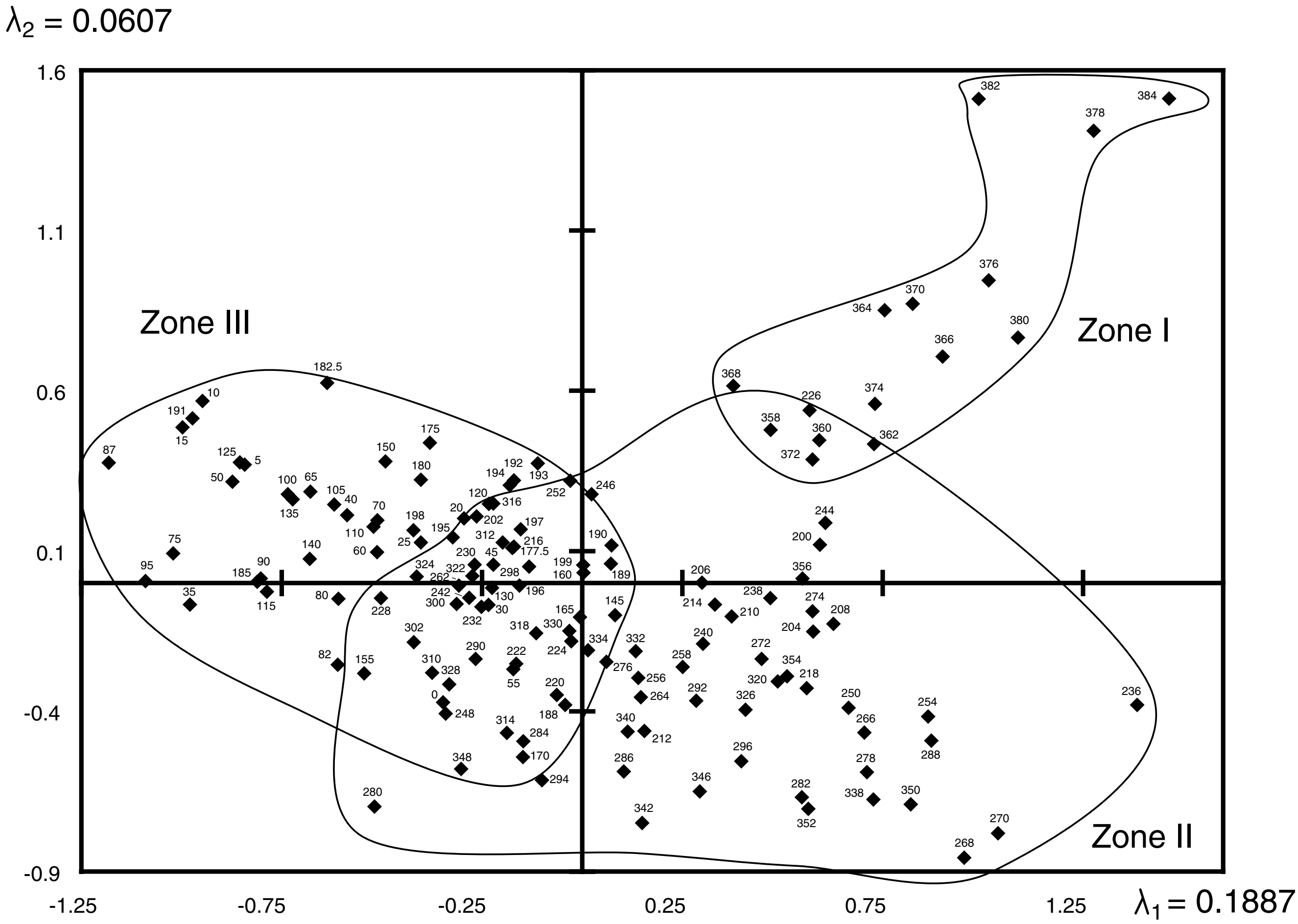

Figure 6. Ecosystem trajectory, composed of axis 1 vs. axis 2 sample scores from a principal components analysis (PCA). Zones are clustered using rounded shapes.

Trajectoire de l'écosystème telle que définie par les axes 1 et 2 de l'analyse en composantes principales (ACP). Les zones sont circonscrites à l'intérieur d'ensembles.

SEDIMENT YIELD

Sediment yield is a quantitative estimate of coarse (>8 mm) and fine (<8 mm) inorganic material generated through weathering and dustfall, deposited or transferred through an aquatic system (Caine, 1974); it provides an indication of landscape sensitivity to climate change (Gerrard, 1990). Sediment yield to Lake of the Woods (Fig. 8) was calculated using ten cores, correlated using volume magnetic susceptibility measurements made by whole core scanning, and with reference to the core stratigraphy (Evans, 1997a; Evans and Church, 2000; Evans and Slaymaker, 2004). Correlated horizons were assigned ages using the radiocarbon dates and two identified tephras. Sediment depth for each of the five correlated units was converted to sediment volume by multiplying by the area of a thiessen polygon constructed around the core site. Sediment volumes were converted to mass using measured sediment densities, corrected for averaged concentrations of organic matter (Bengtsson and Enell, 1986) and biogenic silica (Engstrom and Wright, 1984) (Table III). Sediment yields were normalised by the basin area and expressed as tonnes per kilometre squared per year (t km^{-2} yr^{-1}). Confidence intervals around estimated sediment yields were derived using a regression based technique described in detail in Evans and Church (2000).

RESULTS

STRATIGRAPHY

Bluish clay dominates from 386 to 353 cm; however a distinct coarse-grained (2-3 mm) sand layer was noted from 378.5 to 378 cm. A transition to light brown gyttja begins at 353 cm and extends to 346.5 cm. Gyttja occurs from 346.5 to 196 cm, where it begins to be mixed with tephra. The mixture gradually becomes dominated by tephra, and from 189 to 185 cm consists entirely of tephra. This tephra is attributed to the 6730 ± 40 ^{14}C BP eruption of Mount Mazama, which is widespread throughout southern mainland British Columbia (Nasmith *et al.*, 1967). This tephra layer has been identified in nearby lakes as the Mazama tephra (Evans, 1997a), and is positioned between radiocarbon dates of 5450 ± 90 and 8580 ± 80 ^{14}C BP. Gyttja occurs from 185 cm to the top of the core. A distinct tephra layer interrupts the gyttja from 87 to 82 cm; it is identical in appearance and stratigraphic position

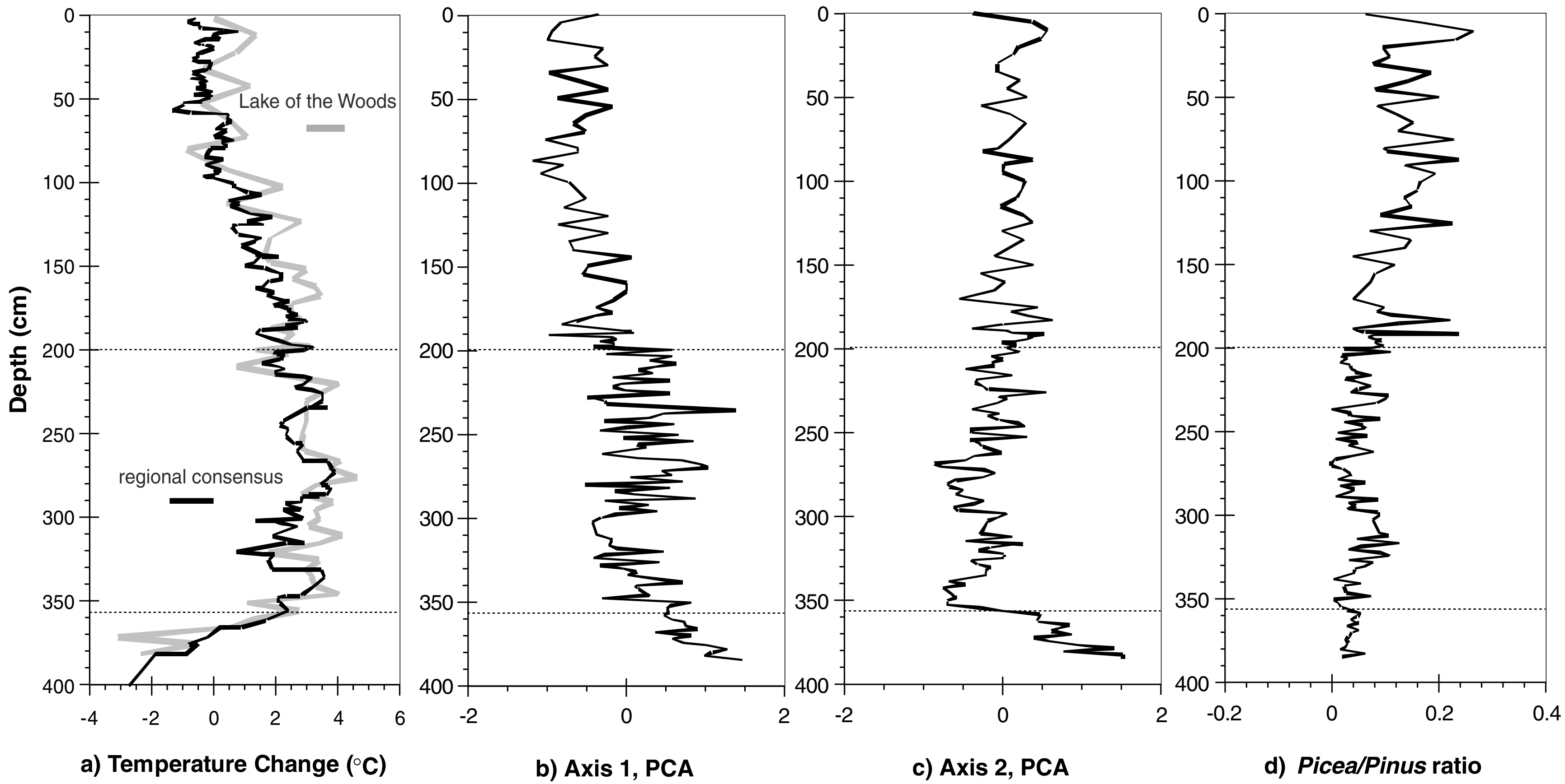

Figure 7. Depth plots for Lake of the Woods of a) midge-inferred temperature changes for Lake of the Woods adapted from Palmer *et al.* (2002) and regional consensus reconstruction modified from Rosenberg *et al.* (2004), b) principal components analysis axis 1 sample scores adapted from Heinrichs *et al.* (2002) c) principal components analysis axis 2 sample scores, and d) *Picea/Pinus* pollen ratios.

Graphiques a) des changements de température déduits à partir de l'étude de moucherons (d'après Palmer et al. *[2002]) et d'une reconstitution des températures régionales issue d'un consensus (modifiée de Rosenberg* et al. *[2004]), b) des résultats de l'axe 1 de l'analyse en composantes principales (adaptés de Heinrichs* et al. *[2002]), c) des résultats de l'axe 2 de l'analyse en composantes principales et d) des ratios de pollen de* Picea/Pinus, *selon la profondeur, à Lake of the Woods*

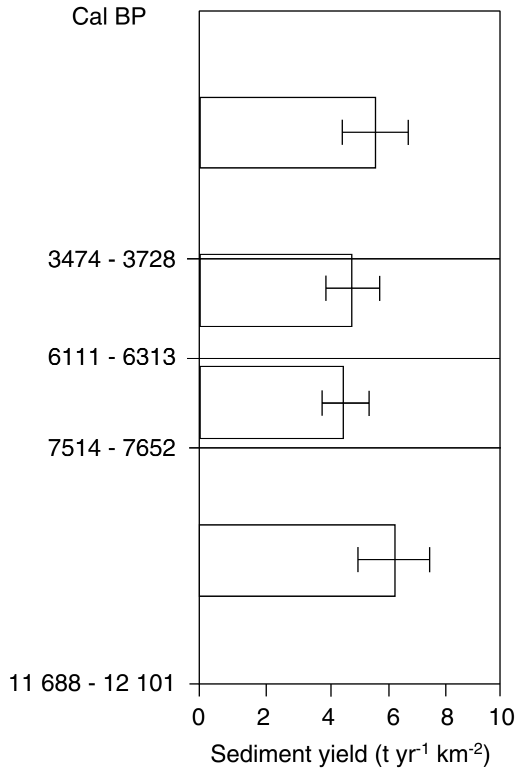

Figure 8. Postglacial changes in sediment yield in Lake of the Woods derived from ten cores, correlated using volume magnetic susceptibility measurements. Error bars were estimated using a regression technique (Evans and Church, 2000).

Variations postglaciaires de la production des sédiments de Lake of de Woods obtenues à partir de l'étude de dix carottes. Les corrélations ont été établies à l'aide de mesures de susceptibilité magnétique. Les intervalles d'erreur ont été estimés par le biais d'analyses de régression (Evans et Church, 2000).

to tephra identified by X-ray fluorescence as Mount St. Helens Yn (3390 ± 130 ^{14}C BP) in Quiniscoe and Glacier Lakes (Evans, 1997a).

POLLEN, CHARCOAL, AND PLANT MACROFOSSILS

Zone I: 386 to 357 cm, 11 200 to 10 800 cal BP, *Pinus*-Cupressaceae-*Picea-Alnus-Artemisia*

This zone is characterised by the highest non-arboreal pollen (NAP) percentage values, beginning at >20 % and decreasing to <10 % by the end of the zone. *Pinus* pollen values increase from 60 % at 386 cm to 80 % at the end of the zone. Pollen derived from the Cupressaceae, *Betula, Alnus, Salix,* Poaceae and *Artemisia* is more common on a percentage basis in Zone I than in all subsequent levels of the Lake of the Woods core. The total pollen accumulation rate increases in this zone from ~650 to 7 600 grains cm^{-2} yr^{-1}. No charcoal was observed. *Picea/Pinus* ratios are <0.10 (Fig. 7d).

Zone II: 357 to 198.5 cm, 10 800 to 8000 cal BP, *Pinus-Picea-Alnus*

The proportion of arboreal pollen (AP) is very high and relatively constant in this zone, around 95 %. *Pinus* values comprise 95 % of the pollen assemblage at the beginning of the zone, but decrease to 85 % by the zone end. *Picea* increases from about 2 to 10 % through the zone, with a period of lower values occurring around 270 cm. Cupressaceae, *Betula*, and *Abies* pollen are present throughout the zone, making up <1, <1, and <5 %, respectively. *Alnus* varies between 5 and 10 %, and Poaceae and *Artemisia* occur at <3 %. *Isoëtes* is more abundant in Zone II than at any other time. Pollen influx is up to ten times greater than in the previous zone, ranging from ~1 300 to 57 000 grains cm^{-2} yr^{-1}. *Picea/Pinus* ratios are slightly higher than in Zone I, as several intervals exceed 0.10.

Charcoal accumulation is low with small peaks observed at 346 and 247 cm. Needle fragments and a seed from *Picea engelmannii* were recovered in this zone, together with needles of *Pinus contorta* and *Abies lasiocarpa*. Increased amounts of organic matter were deposited, as determined by the change in sediment from clay to gyttja and the corresponding increase in loss-on-ignition.

Zone III: 198.5 to 0 cm, 8000 cal BP to present, *Pinus-Picea*

The AP values are >95 % for much of this zone, and *Pinus* values vary between 75 and 90 % of the pollen assemblage. *Picea* values range between 5 and 20 %, generally increasing upwards in the core. *Tsuga heterophylla* and *Pseudotsuga/Larix* pollen is uncommon (<1 %), but is more abundant in Zone III than elsewhere in the record. *Abies* also tends to be more abundant than in Zones I or II. *Isoëtes* spores, and Cupressaceae and *Shepherdia* pollen decline or disappear early in this zone, whereas Cyperaceae pollen becomes increasingly common in late Zone III. Pollen influx in this zone ranges from ~520 to 4 500 grains cm^{-2} yr^{-1}, however, less *Pinus* pollen was deposited than previously. *Picea/Pinus* ratios are significantly higher in this zone, exceeding 0.25. Charcoal accumulation values are also greater than in previous zones. Needle fragments of *Picea engelmannii, Abies lasiocarpa,* and *Pinus contorta* were recovered from the sediments.

MIDGE-INFERRED TEMPERATURES

The midge stratigraphic record for Lake of the Woods has been published in Palmer *et al.* (2002), thus we provide only a brief summary here. The midge-paleotemperature record was incorporated into a consensus record as developed by Rosenberg *et al.* (2004) for southern British Columbia (Fig. 7a).

The basal chironomid zone, containing a mix of cold and warm-adapted midges, has inferred temperatures indicating cold mean July air temperatures initially, *ca.* 8.7 °C, but subsequent warming to 13.1 °C. A major shift to dominance by warm-adapted midges occurs at 357.5 cm, coincident with the pollen zone change. Accumulation of organic material also began at this time, indicating changes in terrestrial and aquatic productivity, likely associated with the warmer temperatures.

Temperate midges, dominating throughout pollen Zone II (Palmer *et al.*, 2002), yielded warm inferred-temperatures ranging between 12.5 and 16.4 °C for this period (Fig. 7a). Increased abundance of cold stenothermous taxa (*i.e.*, *Sergentia*), and decreased abundance of temperate taxa (*i.e.*, *Microtendipes*) in Zone III generated cooler inferred-temperatures than earlier, ranging from 13.1 to 8.7 °C.

ORDINATION ANALYSES

The plot of PCA species scores depicts a strong separation of open vegetation versus closed forest species along axis 1 (Heinrichs *et al.*, 2002). *Artemisia, Alnus*, Poaceae, *Salix*, and Cupressaceae (probably *Juniperus*, based on current Cupressaceae distribution in British Columbia) have high axis 1 species scores whereas species with low (negative) scores include *Picea, Abies* and *Tsuga*. On axis 2, *Artemisia* and *Picea* have high species scores, and *Pinus* and *Potamogeton* have negative scores.

The plot of PCA sample scores provides an ecosystem trajectory (Fig. 6). The three pollen zones identified via cluster analysis (Zones I, II, and III) represent three biogeochrons: 1) an open steppe during the initial revegetation stage, close to the late-glacial/Holocene boundary, 2) open *Pinus* parkland forests and *Abies*- and *Picea*-dominated stands in the early Holocene, and 3) the modern closed ESSF forest in the middle- to late Holocene.

The plot of axis 1 sample scores versus depth (Fig. 7b, reproduced from Heinrichs *et al.*, 2002) potentially provides a reconstruction of "openness" of the vegetation. The high scores in Zone I indicate that the vegetation likely comprised an open steppe or alpine tundra. Somewhat lower scores in Zone II may reflect open forest parkland. The negative scores of Zone III indicate a more closed ESSF forest, perhaps reflecting cooler, moister conditions in the late Holocene. There is a similarity in the shape of this plot to that of the *Picea/Pinus* ratio ($R^2 = 0.74$). This is not surprising, as Beaudoin (1986) found that high *Picea/Pinus* ratios indicate forested vegetation and low ratios more open conditions. We also note an inverse correspondence ($R^2 = 0.32$) between the axis 2 sample scores (Fig. 7c) and the midge-inferred paleotemperature records (Fig. 7a); thus, axis 2 likely relates to the paleotemperature signal.

SEDIMENT YIELD

Average sediment yields to Lake of the Woods range between 4.6 and 6.2 t km^{-2} a^{-1} over the course of the Holocene. The highest yields are recorded for the period preceding the Mazama tephra, corresponding with pollen Zone II. However, the estimated Holocene variance of sediment yield is within the 95 % confidence intervals of the individual points so that statistically, the sediment yield is constant throughout the Holocene.

DISCUSSION

LATE-PLEISTOCENE–HOLOCENE TRANSITION (>10 900 CAL BP)

The high relative abundance of Poaceae, *Artemisia* and other non-arboreal pollen types clearly indicates that the freshly deglaciated landscape near Lake of the Woods was dominated by open vegetation, perhaps an *Artemisia*-Poaceae steppe or tundra, with scattered *Abies* and *Picea* krummholz or distant forested stands. Similar high elevation late-glacial communities have been documented elsewhere in the southern interior (Fig. 9), at Stoyoma Mountain (Pellatt *et al.*, 1998, 2000), Mount Kobau (Heinrichs *et al.*, 2001a), and Crater Mountain (Heinrichs *et al.*, 2002).

High Cupressaceae values in the earliest part of the Lake of the Woods record suggest that *Juniperus communis* may have been a prominent plant in this early landscape. It is currently common on poor, mineral soils with a dry, cold climate, such as exposed mountain ridges (Ringius and Sims, 1997). Why this plant seems to have occurred abundantly around Lake of the Woods, but apparently not at other sites nearby, such as Crater Mountain (Heinrichs *et al.*, 2002), is not clear.

The low pollen influx reflects the open character of the vegetation (Heinrichs, 1999), and the midge-inferred summer temperatures are up to 3 °C colder than today. Low temperatures and drought likely restricted tree growth. Although *Pinus* pollen is abundant, these trees are prolific pollen producers. Much, if not all of the *Pinus* pollen, was likely derived via long-distance transport, creating the illusion of a treed landscape when few, if any, trees were actually present.

The dominance of minerogenic sediments (Table III) reflects the initial unstable, sparsely-vegetated landscape with low aquatic and terrestrial productivity. The coarse sand layer probably represents a single, large sediment pulse, associated with either high discharge or a mass movement in the unstable land surface. Fires were not an important feature of the landscape during the late-glacial period, probably due to a low fuel load and unsuitable weather conditions, which has been documented in boreal forests (Flannigan *et al.*, 2000).

Climate was changing rapidly at this time, with summer insolation approaching its postglacial maximum. The high albedo of the Cordilleran ice sheet would have reinforced the initially cold climate, and an anticyclone over the ice would have promoted an easterly flow of cold, dry air from the continental interior (Bartlein *et al.*, 1998). As the ice-sheet rapidly waned, the decreasing albedo and high summer insolation promoted increasing temperatures, and westerly flows from the Pacific began to dominate the regional climate (Kutzbach and Guetter, 1986; Barnosky *et al.*, 1987; Anderson *et al.*, 1988). This dramatic shift in temperatures is seen in the midge-paleotemperature reconstructions (Fig. 7a). Climate-induced changes in hydrology are also apparent in the shift from freshwater to saline conditions at nearby Kilpoola and Mahoney Lakes (Heinrichs *et al.*, 2001b).

XEROTHERMIC INTERVAL (10 900-8000 CAL BP)

Midge-inferences indicate early Holocene summer temperatures up to 4 °C warmer than present. At this time, the increasing arboreal pollen percentages and influx, reflect the first establishment of forests, with *Pinus*, *Picea* and *Abies* all contributing to the pollen rain. Present-day forests surrounding Lake of the Woods also consist of a mixture of *Pinus contorta* var. *latifolia*, *Picea engelmannii*, and *Abies lasiocarpa*. It therefore appears that this dominant aspect of the vegetation

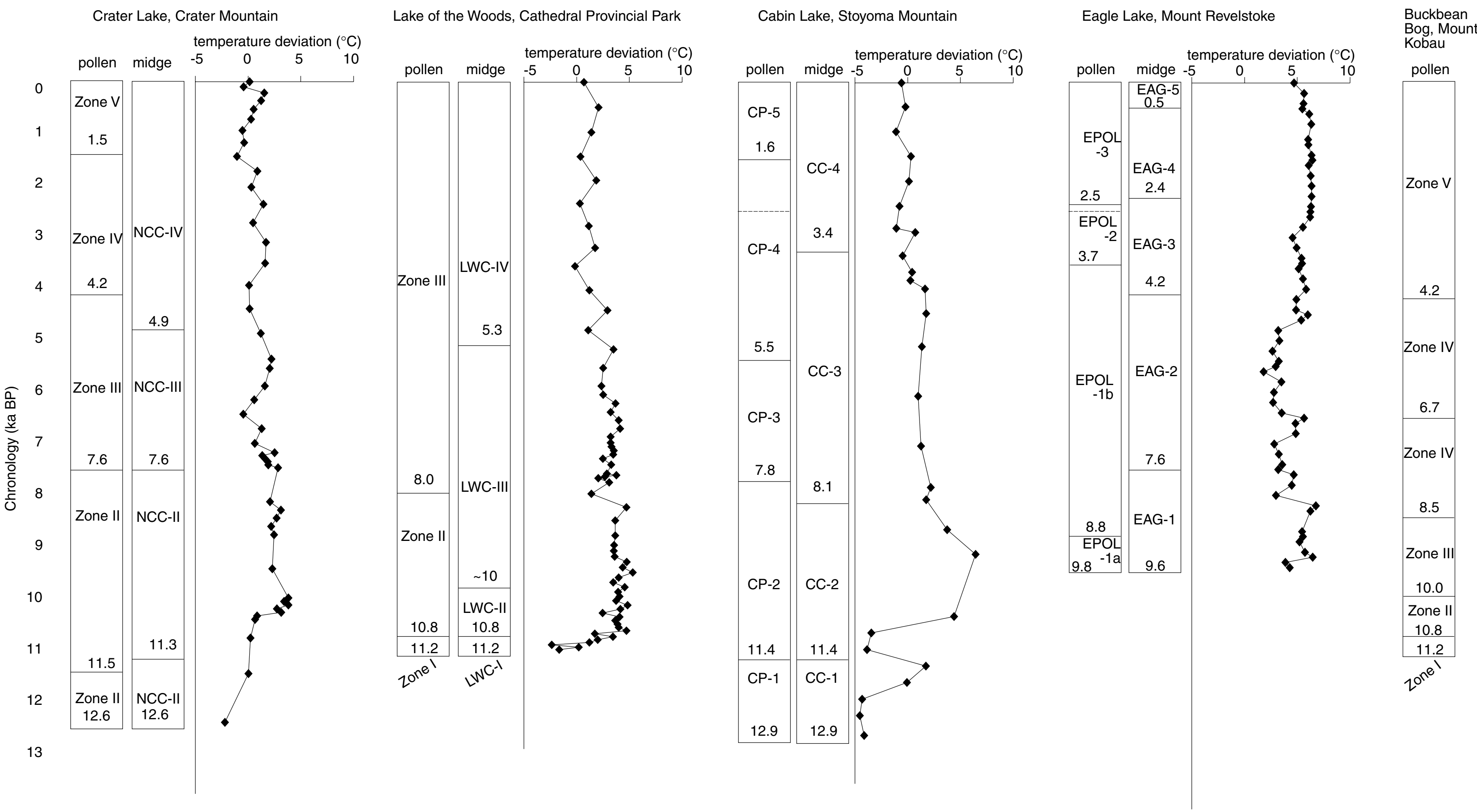

Figure 9. Comparison of pollen and midge zones and midge-inferred mean-July air temperature deviations (where available) from Crater Lake (Heinrichs *et al.*, 2002), Lake of the Woods (this paper), Cabin Lake (Pellatt *et al.*, 1998, 2000; Smith *et al.*, 1998), Eagle Lake (Rosenberg *et al.*, 2004) and Buckbean Bog (Heinrichs *et al.*, 2001a). Calendar year ages were estimated using Calib 4.3 (Stuvier and Reimer, 1993).

Comparaison des zones définies à l'aide des pollens et de celles obtenues par l'étude des moucherons, et variations de la température moyenne de juillet déduite à partir de l'étude des moucherons (là où l'information était disponible) au lac Crater (Heinrichs et al.*, 2002), à Lake of the Woods (présente étude), au lac Cabin (Pellatt* et al.*, 1998, 2000; Smith* et al.*, 1998), au lac Eagle (Rosenberg* et al.*, 2004) et à la tourbière Buckbean (Heinrichs* et al.*, 2001a). Les âges calendaires ont été estimés à l'aide du logiciel Calib 4.3 (Stuvier et Reimer, 1993).*

was already established in the early Holocene. Macrofossils of all three species were recovered from the early Holocene sediments, confirming this inference. *Pinus* percentages were higher in the early Holocene than in surficial sediments at Lake of the Woods, whereas *Picea* and *Abies* percentages were lower. In addition, the influx of important non-arboreal pollen indicators, such as Poaceae, *Artemisia*, *Alnus* and Cupressaceae (probably *Juniperus*), was particularly high in the early Holocene. Thus, the fossil pollen assemblages reflect a more open parkland-type forest.

The charcoal record indicates that fires burned regularly throughout the early Holocene, likely supported by a greater fuel supply and the warmer, drier summer climate. This pattern has been observed in other mountainous forests (Hanson and Weltzin, 2000). These early fires at Lake of the Woods were important determinants of forest structure and composition, maintaining a vegetation mosaic dominated by successional forest stands and favourable for shade-intolerant species (Hebda, 1998).

This early Holocene phase is commonly referred to as the xerothermic interval in British Columbia. The high midge-inferred summer temperatures (Fig. 7a) approximately coincide with the Holocene maximum for summer solar insolation. Winter temperatures are difficult to infer from our records. However, the Holocene winter minimum for insolation also occurred at this time (Berger and Loutre, 1991; Webb and Bartlein, 1992). Thus, it is probable that the hot, dry early Holocene summers alternated with severely cold winters. The implications of such cold winters, in terms of forest structure and composition, are unclear, but severe winters are recognised as a key factor limiting infestations by mountain pine beetle (Bentz and Mullins, 1999) and other forest pathogens in present-day forests of interior British Columbia.

Despite the warm, dry summer conditions, sediment yield upstream in Glacier Lake was at its maximum at this time (Evans, 1997b). This may be in part due to an abundance of unconsolidated material higher in the catchment which was left over from deglaciation and available for transport. In the Coast and Rocky Mountains, sediment yield typically increases while passing through the system, whereas the pattern at Lake of the Woods is more similar to that of low-slope systems (Evans, 2000; Schiefer *et al.*, 2001). In Colorado, the period of maximum sediment yield was also associated with maximum warmth, but much of the sediment was air-borne material (Andrews *et al.*, 1985). At Glacier Lake, particle size determination indicated that most of the material consists of silts and clays and is not eolian (Evans, 1997a). Since Glacier Lake and Lake of the Woods are situated in close proximity, the sediment is also unlikely to be of eolian origin at Lake of the Woods. Furthermore, the warm conditions of the xerothermic allowed trees to establish at Lake of the Woods and stabilize the landscape, limiting overall sediment yield (Evans, 1997a; Evans and Slaymaker, 2004).

MESOTHERMIC INTERVAL (8000-5000 CAL BP)

Midge-inferred summer temperatures gradually declined as summer insolation decreased through the middle Holocene. Hebda (1995) refers to this time as the Mesothermic interval.

The decreasing abundance of Cupressaceae and *Shepherdia* pollen, together with the increases in *Picea* and *Abies*, presumably reflect an increase in effective soil moisture, the development of an ESSF-type forest composed of *Abies lasiocarpa* and *Picea engelmannii*, and generally more mature, closed forest stands. The decreased pollen influx likely reflects the decreased importance of *Pinus*, and increased proportions of *Picea* and *Abies*; *Picea* and *Abies* trees produce much less pollen than *Pinus* (Fægri and Iversen, 1989; Hebda and Allen, 1993).

Middle Holocene increases in *Tsuga heterophylla*, and *Pseudotsuga/Larix* pollen were also noted. *Tsuga heterophylla* is unlikely to have ever grown near this dry interior site; thus, the *Tsuga* pollen probably reflects long-distance transport from coastal forests, >50 km to the west. Rosenberg *et al.* (2003) note *Tsuga heterophylla* pollen normally constitutes at least 5 % of the pollen rain at sites where the trees are actually present.

The pollen of *Pseudotsuga* and *Larix* cannot reliably be distinguished. The increase in *Pseudotsuga/Larix* pollen may date the arrival of *Larix lyalli* at the Cathedral Lakes, but this possibility needs confirmation via plant macrofossil or stomate evidence.

Charcoal accumulation increased during the middle Holocene. We suggest this reflects the greater density of the forests and increased fuel supply, rather than an increase in fire frequency due to the increased effective moisture. It is, however, also possible that increased thunderstorm activity may have accompanied the gradual shift to a moister hydrological regime. Similar middle Holocene increases in charcoal accumulation have been documented nearby at Crater Mountain (Heinrichs *et al.*, 2002), at Dog Lake in the Kootenay region of southeastern British Columbia (Hallett and Walker, 2000) and at Sheep Mountain Bog, Montana (Mehringer, 1996).

These patterns of moisture-related landscape change are similar to those documented at other sites in the dry, southern interior of British Columbia. Increasing moisture during the middle Holocene at Mount Kobau, was accompanied by an increase of *Pinus* on the landscape, rather than *Picea* and *Abies* (Heinrichs *et al.*, 2001a). There, fires may have become more intense, destroying mature *Pinus* trees and/or stands of trees, promoting regrowth of *Pinus*, and generating abundant charcoal. At Crater Lake, only 60 m higher in elevation and <20 km to the north of our study site, *Pinus* remained a dominant tree on the landscape, with true ESSF forest only developing ~4000 years later than at Lake of the Woods (Heinrichs *et al.*, 2002). *Picea* also appears to have been a less important element of the forests at Stoyoma Mountain (Pellatt *et al.*, 1998, 2000), as compared to Lake of the Woods.

The statistically unchanged sediment yield at Lake of the Woods in the middle Holocene is contrary to expectation, since more moisture was available for weathering and transport of material. It is unlikely that exhaustion of sediment sources occurred (Ballantyne, 2002). Evans (1997b) shows an increasing sediment yield at Glacier Lake, which likely intercepted material that otherwise would have been deposited in Lake of the Woods.

NEOGLACIAL INTERVAL (5000 CAL BP TO PRESENT)

By 4000 to 5000 BP summer insolation and midge-inferred temperatures were at, or very close to, modern values, and little subsequent change in the vegetation occurred. *Picea/Pinus* ratios were high, reflecting the cooler climate and moister soils. An increase in Cyperaceae suggests that an extensive marginal sedge fen developed at Lake of the Woods around 4000 cal BP, and provides additional evidence of the increased moisture availability.

Curiously, charcoal accumulation rates were higher during this interval than at any other time. We are not suggesting that fire frequency increased with the decreasing temperatures. The increase may reflect 1) different charcoal fragment preservation characteristics, or number of fragments produced by *Picea* and *Abies* relative to *Pinus*, 2) a change in fire intensity/fuel load, or 3) the influence of first nations (Turner, 1994; Clark and Royall, 1995).

At Mount Revelstoke, Rosenberg *et al*. (2003) note the arrival of *Tsuga heterophylla* and *T. mertensiana* populations after 3500 cal BP, providing additional evidence of the cooler, moister environment. Although late-Holocene glacial advances, and increased sediment yield are evident at many British Columbia sites (*e.g*., Souch, 1994; Desloges, 1999), this is not apparent at Lake of the Woods. The lack of sediment yield response throughout the Holocene, but especially in the neoglacial period, demonstrates how insensitive Lake of the Woods is to climate-driven, landscape weathering.

IMPLICATIONS

Differences in timing and severity of landscape or vegetation response to climate change between Lake of the Woods and other dry ESSF sites in the southern interior are likely the result of differences in aspect, elevation (Lavender, 1990; Stathers *et al*., 1990), relief, and specific landscape features — *e.g*., streams (Schiefer *et al*., 2001). Lake of the Woods is in a large, north-facing basin surrounded by high mountain ridges, thus air mass movement and temperatures at Cathedral Provincial Park are likely affected by cold air drainage, consequently winter snow-packs remain longer and less drying occurs during the summer. Lake of the Woods receives water from a 2.2 km^2 catchment area that includes Pyramid and Glacier Lakes, thus short-term droughts may be mediated by stream inflow, soil moisture, and ground-water seepage (Winter, 1978).

Drier ESSF sites, such as Crater Lake (2 120 m asl), approximately 15 km north of Cathedral Provincial Park, display greater changes in vegetation with Holocene climate change. Fire-dependant *Pinus*-dominated parkland occurred until about 7500 cal BP, and *Abies* and *Picea* were lesser components of a *Pinus* forest until about 4200 cal BP. Increasing moisture during the neoglacial resulted in modern ESSF composition around 1700 cal BP (Heinrichs *et al*., 2002). Mount Kobau (1 830 m asl) also responded later than Lake of the Woods to early Holocene warming, shifting from open grasslands to *Pinus* parkland with increasing mesothermic moisture, and *Pinus* dominated-ESSF forest late in the neoglacial (Heinrichs *et al*., 2001a). Though Mount Kobau, Crater Mountain, and Cathedral Provincial Park are classified into the same variant of the ESSF biogeoclimatic zone (xc, or xeric cold), the sites clearly do not share a similar vegetation history, nor do they respond ecologically in the same manner to climate change. The vegetation at Mount Kobau is highly sensitive to climate change, showing the greatest sensitivity, and therefore should be expected to respond significantly to future climate change and disturbance. The forests at Lake of the Woods were much less sensitive to past climate change, suggesting that they will be more resilient to future climate change. Stoyoma Mountain (ESSFdc - dry cold) and Mount Revelstoke (ESSFvc - very wet cold), were similar to Cathedral Provincial Park in the degree of vegetation change relative to climatic change, suggesting that in the southern interior of British Columbia, differences in precipitation regime at higher elevations may be more important than temperature in regulating vegetation changes. Precipitation was also found to have significant influence on subalpine vegetation in Washington state, United States (Fagre *et al*., 2003).

Site sensitivity to climate change and associated natural disturbance (Parminter, 1998) is relevant to biodiversity and natural resource management, and is critical in selecting sites for habitat preservation. Sites less sensitive to disturbance, including climate change, may be ideal for the preservation of existing ecosystems. These sites may also be suitable for selective forestry, although changes in wildlife habitat may have further implications related to conservation issues or recreational opportunities (Wall, 1998). Since not all sites respond to climate and disturbance in the same manner, better knowledge of the forest history in all parts of the western Cordillera is invaluable in understanding and preserving biodiversity for the future, especially with future climate change (Laprise *et al*., 2003). It is recommended that paleoecological analyses be used routinely to determine vegetation histories of designated park sites and to plan timber harvesting operations. Sensitive sites may require more consideration in terms of current and future anthropogenic impact such as range use, recreational development, or preservation strategies.

CONCLUSIONS

The vegetation history of the Cathedral Provincial Park region consisted of three biogeochrons: open steppe with krummholz spruce and fir occurred during the cool late-glacial interval, pine forest with some spruce and fir and frequent fires occurred in the warm early Holocene, and ESSF forest occurred with increasing moisture after 8000 cal BP, closing after 4000 cal BP under cooler temperatures. Relatively little change in vegetation occurred at this site compared to other dry ESSF sites, such as Mount Kobau or Crater Mountain. Wetter sites, such as Stoyoma Mountain and Mount Revelstoke were also less sensitive than the two drier sites. Midge-inferred temperatures from Lake of the Woods correspond closely with other quantitative records in southern British Columbia. Sediment yield results also suggest a stable environment throughout the Holocene and that Lake of the Woods has a high climatic threshold to geomorphic change. Thus terrestrial ecosystems at Cathedral Provincial Park have a low potential sensitivity to climate change.

The results of this study provide information valuable to site selection for habitat preservation and biodiversity management in the ESSF forests of the southern interior. Low sensitivity to natural disturbance made this site an ideal, and likely fortuitous, choice for the preservation of existing ecosystems and biodiversity, especially under the scenario of future climate change (Zwiers and Kharin, 1998; O'Brien and Leichenko, 2000; Laprise *et al.*, 2003). Conservation strategies in all parts of the Canadian Cordillera should be enhanced by considering vegetation history and aquatic faunal responses to disturbance, including future climate change, because, as this study shows, these responses differ at sites within the same biogeoclimatic zone. This proposal is likely applicable to other geographically diverse regions that are facing increasing pressure of development or tourism. It is recommended that paleoecological analyses be routinely used to determine site-specific vegetation histories. These should be incorporated into the planning for designated park sites, timber harvesting operations, fire management strategies, range use, recreational development, and other important resource management decisions. Sites sensitive to natural disturbance may require more consideration of current and future anthropogenic impacts to ensure biodiversity conservation.

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