Géographie physique et Quaternaire

Holocene chironomid-inferred salinity and paleovegetation reconstruction from Kilpoola Lake, British Columbia

La salinité (déterminée par les chironomides) et la reconstitution paléovégétale du Kilpoola Lake (Colombie-Britannique) à l'Holocène

Salzgehalt, bestimmt durch die Chironomidae, und Rekonstruktion der Paläovegetation des Kilpoola-Sees, British Columbia

Mark L. Heinrichs, Ian R. Walker, Rolf W. Mathewes et Richard J. Hebda

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Résumé de l'article

Les fluctuations de la salinité dans les lacs des régions semi arides ont été considérées comme étant des indicateurs de changements paléoclimatiques et en ont facilité la reconstitution. Toutefois, certains facteurs autres que climatiques, y compris certains événements sédimentologiques, peuvent aussi modifier la salinité. Au Kilpoola Lake, les chironomides d'eau douce du début du postglaciaire (*Microtendipes*, *Sergentia* et *Heterotrissocladius*), trouvés dans les sédiments de la base, laissent présumer une salinité de <0,03 g/l. Des salinités plus élevées, de 1,0 à 3,5 g/l, avec *Cricotopus/Orthocladius* et *Tanypus* (chironomides caractéristiques des mileux salins) ont suivi et se sont maintenues presque tout le reste de l'Holocène. Les sédiments au-dessus du tephra du mont Mazama ont enregistré une augmentation de la salinité de 450 % (de 1,6 à 7,3 g/l), puis une diminution jusqu'à la salinité d'avant l'éruption du mont Mazama. Les spectres polliniques de l'Holocène inférieur sont caractéristiques de la steppe ouverte, mais les pourcentages d'*Artemisia* après l'éruption sont exceptionnellement élevés et sont associés aux argiles silteuses. Les spectres polliniques qui suivent le maximum d'*Artemisia* représen- tent les communautés de la steppe et concordent avec les tendances régionales. Les auteurs croient que les changements observés dans la communauté des chironomides et la végétation après le dépôt de la cendre de Mazama ne reflète pas un changement rapide vers un climat plus chaud et plus sec, mais plutôt une augmentation de la concentration ionique en raison de la présence de produits en solution issus de la couche de tephra nouvellement déposée.

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HOLOCENE CHIRONOMID-INFERRED SALINITY AND PALEOVEGETATION RECONSTRUCTION FROM KILPOOLA LAKE, BRITISH COLUMBIA

Mark L. HEINRICHS*[1,2,3,4], Ian R. WALKER[1,2], Rolf W. MATHEWES[2], and Richard J. HEBDA[3,4,5]: [1] Department of Biology, Okanagan University College, 3333 College Way, Kelowna, British Columbia V1V 1V7 (address for correspondence); [2] Department of Biological Sciences, Simon Fraser University, Burnaby, British Columbia V5A 1S6; [3] Department of Biology, University of Victoria, P.O. Box 3020, Victoria, British Columbia V8W 2Y2; [4] Royal British Columbia Museum, Box 9815, Stn. Prov. Gov't., Victoria, British Columbia, V8N 9W1; [5] School of Earth and Ocean Sciences, University of Victoria, P.O. Box 3020, Victoria, British Columbia V8W 2Y2.

ABSTRACT Salinity fluctuations in lakes of semi-arid regions have been recognised as indicators of paleoclimatic change and have provided a valuable line of evidence in paleoclimatic reconstruction. However, factors other than climate, including sedimentologic events, may also affect salinity. At Kilpoola Lake, early postglacial freshwater chironomids (*Microtendipes*, *Sergentia*, and *Heterotrissocladius)* occur in the basal sediments and yield a chironomid-inferred salinity of <0.03 g/l. Higher salinities, ranging from 1.0 to 3.5 g/l, with *Cricotopus*/*Orthocladius* and *Tanypus* (chironomids typical of saline environments) follow and, persist for most of the remainder of the Holocene. An inferred 450% salinity increase (from 1.6 to 7.3 g/l) occurred in the sediment above the Mount Mazama tephra, followed by a return to the pre- Mount Mazama salinity. The early Holocene pollen spectra are typical of open steppe, but the post- Mazama *Artemisia* pollen percentages are exceptionally high and are associated with silty clays. Pollen spectra following this *Artemisia* peak represent steppe communities and are consistent with regional trends. We suggest that the changes in chironomid communities and vegetation after deposition of the Mazama ash do not reflect a rapid shift to warmer or drier climate and evaporation, but rather an increased ionic concentration due to solutes derived from the freshly deposited tephra and perhaps inwashed silts and clays.

RÉSUMÉ *La salinité (déterminée par les chironomides) et la reconstitution paléovégétale du Kilpoola Lake (Colombie-Britannique) à l'Holocène*. Les fluctuations de la salinité dans les lacs des régions semi arides ont été considérées comme étant des indicateurs de changements paléoclimatiques et en ont facilité la reconstitution. Toutefois, certains facteurs autres que climatiques, y compris certains événements sédimentologiques, peuvent aussi modifier la salinité. Au Kilpoola Lake, les chironomides d'eau douce du début du postglaciaire (*Microtendipes*, *Sergentia* et *Heterotrissocladius*), trouvés dans les sédiments de la base, laissent présumer une salinité de < 0,03 g/l. Des salinités plus élevées, de 1,0 à 3,5 g/l, avec *Cricotopus*/*Orthocladius* et *Tanypus* (chironomides caractéristiques des mileux salins) ont suivi et se sont maintenues presque tout le reste de l'Holocène. Les sédiments au-dessus du tephra du mont Mazama ont enregistré une augmentation de la salinité de 450 % (de 1,6 à 7,3 g/l), puis une diminution jusqu'à la salinité d'avant l'éruption du mont Mazama. Les spectres polliniques de l'Holocène inférieur sont caractéristiques de la steppe ouverte, mais les pourcentages d'*Artemisia* après l'éruption sont exceptionnellement élevés et sont associés aux argiles silteuses. Les spectres polliniques qui suivent le maximum d'*Artemisia* représentent les communautés de la steppe et concordent avec les tendances régionales. Les auteurs croient que les changements observés dans la communauté des chironomides et la végétation après le dépôt de la cendre de Mazama ne reflète pas un changement rapide vers un climat plus chaud et plus sec, mais plutôt une augmentation de la concentration ionique en raison de la présence de produits en solution issus de la couche de tephra nouvellement déposée.

ZUSAMMENFASSUNG *Salzgehalt, bestimmt durch die Chironomidae, und Rekonstruktion der Paläovegetation des Kilpoola-Sees, British Columbia.* Die Salzgehalt-Fluktuationen in den Seen halbtrockener Gebiete sind als Indikatoren für paläoklimatische Veränderungen erkannt worden und haben wertvolles Beweismaterial bei der paläoklimatischen Rekonstruktion geliefert. Indessen könnten auch andere als klimatische Faktoren einschließlich sedimentologischer Ereignisse den Salzgehalt beeinflussen. Am Kilpoola-See treten frühe postglaziale Frischwasser-Chironomidae (*Microtendipes, Sergentia* und *Heterotrissocladius)* in den Basal-Sedimenten auf, und ergeben einen durch Chironomidae herbeigeführten Salzgehalt von <0.03 g/l. Höhere Salzgehalte, von 1.0 bis 3.5 g/l mit *Cricotopus/Orthocladius* und *Tanypus* (für salzhaltige Umwelt typische Chironomidae) folgen und dauern während des größten Teils der übrigen Holozän-Zeit. In den Sedimenten über dem Tephra von Mount Mazama kam es zu einem Salzgehaltanstieg um 450 % (von 1.6 bis 7.3 g/l), worauf eine Senkung auf den Vor-Mount Mazama-Salzgehalt folgte. Die Pollen-Spektren aus dem frühen Holozän sind typisch für die offene Steppe, jedoch ist der Nach-Mazama *Artemisia* Pollen-Gehalt außerordentlich hoch und wird mit schlammigem Lehm in Verbindung gebracht. Die auf das *Artemisia* -Maximum folgenden Pollen-Spektren sind Steppen-Einheiten und stimmen mit den regionalen Tendenzen überein. Wir glauben, dass die Wechsel in den Chironomidae-Einheiten und in der Vegetation nach der Ablagerung der Mazama-Asche keinen schnellen Wechsel zu einem wärmeren oder trockeneren Klima und Verdunstung spiegeln, sondern vielmehr eine Zunahme der Ionen-Konzentration aufgrund von aufgelösten Elementen aus dem neu abgelagerten Tephra und vielleicht ausgewaschenem Schlamm und Lehm.

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* E-mail for corresponding author: markus.heinrichs@ans.kiruna.se

INTRODUCTION

Recent investigations have used multiproxy approaches to investigate glacial recession, the evolution of limnic systems, vegetation succession and response, and the timing and severity of climate change in the south-central interior of British Columbia (Cumming *et al.*, 1995; Evans, 1997; Hebda, 1982, 1995, 1996; Heinrichs *et al.*, 1997; Rück *et al.*, 1998; Smith, 1997). Elsewhere, chironomid analysis of saline lake sediments has been demonstrated as a reliable method in reconstructing climate change (Mees *et al.*, 1991; Vershuren 1994). Many saline lakes in British Columbia have diverse chironomid communities (Cannings and Scudder, 1978) so we have been investigating their potential as indicators of paleosalinity and paleoclimate in British Columbia (Heinrichs, 1995; Heinrichs *et al.*, 1997; Smith, 1997; Walker *et al.*, 1995).

Factors other than climate, such as mineral influx and biotic characteristics, affect lake chemistry (Wetzel, 1975). An often overlooked source of minerals in an aquatic system are the tephras derived from volcanic events. Several volcanic eruptions are recorded in the sediments of many British Columbia lakes (Clague, 1991). Volcanic activity is still evident in western North America today, and the eruption of Mount St. Helens in 1980 has prompted several studies of volcanic influences on the biology and chemistry of aquatic and terrestrial environments (Antos and Zobel, 1986; Baross *et al.*, 1982; Mack, 1981; Wissmar *et al.*, 1982a,b). Similar studies have been conducted elsewhere, for example, following the eruption of Mount Besymjanny, in Kamchatka, Russia (Kurenkov, 1966). Each study shows that the fallout from these volcanic events has severe and prolonged influences on the biota of nearby lakes and watersheds; the magnitude of the impact being dependent upon the nature of the tephra and proximity of the lake to the volcano. It is not surprising, therefore, that effects of past volcanic events are often recorded by the remains of biota preserved in lake sediment (Birks and Lotter, 1994; Lotter and Birks, 1993; Lotter *et al.*, 1995).

In this study, we document postglacial changes at Kilpoola Lake, British Columbia, focussing especially on the impact of the Mount Mazama tephra within the lake's drainage basin and on the lake's salinity and fauna. A few investigations have considered the impact of tephra deposition on chironomid communities (Boubée, 1983; Pienitz *et al.*, 1992; Tsukada, 1967; Walker and Mathewes, 1987a, 1987b, 1989a, 1989b; Warwick, 1989), but none has examined these changes in relation to salinity. Although Heinrichs *et al.* (1997) have examined salinity changes at Mahoney Lake, in southern British Columbia, sampling resolution was insufficient to associate any faunal changes with deposition of an ash layer. We include reconnaissance level palynological analysis to assist in understanding the role of climatic *vs.* other factors on the aquatic ecosystem.

STUDY AREA

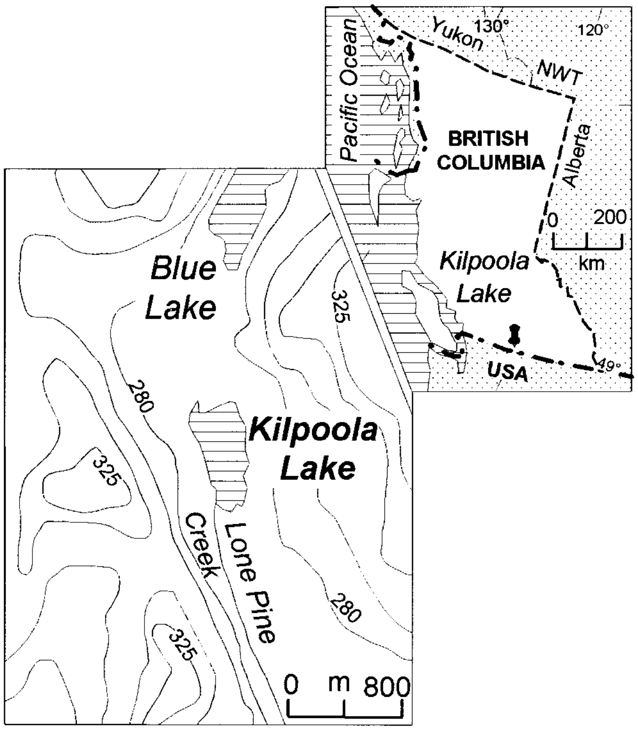

FIGURE 1. Study site map indicating the location of Kilpoola Lake within the Okanagan valley region.

Carte de localisation du Kilpoola Lake, dans la vallée de l'Okanagan, en Colombie-Britannique.

Kilpoola Lake, approximately 10 km west of Osoyoos, is located adjacent to the Okanagan Valley of the south-central interior of British Columbia, Canada, at 49° 01' N, 119° 33' W and an elevation of 815 m above sea level (Fig. 1). The climate is typically semi-arid with a mean annual precipitation not exceeding 350 mm, with an annual average temperature of 14 °C, and summer daytime temperatures often exceeding 30 °C (Environment Canada, 1993). The regional vegetation is typical of Ponderosa Pine and Bunchgrass biogeoclimatic zones, British Columbia's two warmest and driest zones (Meidinger and Pojar, 1991). The underlying rock formations are composed of sedimentary and volcanic rocks of Cretaceous and Tertiary age (British Columbia Department of Mines and Petroleum Resources, 1976).

Kilpoola Lake is a 21 ha saline lake with a maximum depth of 7.9 m, an average depth of 3.0 m, and a shoreline perimeter of 1920 m (surveyed by S. Hawthorne, May 29, 1969). The present salinity is approximately 9 g/l (August 17, 1993, B.F. Cumming, pers. com.). The lake is essentially a closed-drainage basin with the surrounding hills reaching elevations over 325 m. Kilpoola Lake had no visible inlet or outlet streams in April 1995, although the 1: 50,000 topographical map (Canada Centre for Mapping, 1988) indicates a seasonal outlet stream (Lone Pine Creek) at the south end of the lake, and two ephemeral input streams—one from the north-west and the other from the east. The surrounding vegetation consists primarily of bunchgrass (*Agropyron spicatum* (Pursh) Scribn. and Smith) and sagebrush (*Artemisia* spp.) communities, however open Ponderosa Pine (*Pinus ponderosa* Dougl.) woodland occurs on the valley slopes and along moist draws.

METHODS

FIELD METHODS

Kilpoola Lake was cored in the early spring of 1993, at which time a 4.9 m core (Kilpoola core 1) was obtained using a modified Livingstone piston corer with an internal diameter of 2.5 cm. The core was taken to the Paleoecological Environmental Assessment and Research Laboratory (PEARL) at Queen's University where it was photographed, sectioned into 1 cm intervals, and stored in plastic sampling bags. The sections were then stored at 4 °C.

Because suitable material for radiocarbon dating could not be found in core 1, we re-cored the lake in June, 1996 using a 5 cm diameter modified Livingstone piston corer in the deepest part of the lake. The 7.9 m core (Kilpoola core 2) was taken to the cold storage facility of Okanagan University College (North Kelowna Campus) where it was stored until subsampling and screening for macrofossils could be completed.

LABORATORY METHODS

Dating

No macrofossils suitable for accelerator mass spectrometry (AMS) radiocarbon dating were found in Kilpoola core 1. Kilpoola core 2 was screened for macro- remains. Charcoal fragments derived from organic-debris-rich clay at 624 and 665 cm were submitted to Beta Analytic in Miami, Florida, USA for AMS radiocarbon dating.

Chironomid analysis

Chironomid head capsules were extracted from the sediment using the methods described by Walker *et al.* (1995). Sediment was deflocculated with hot 10% KOH, followed by a water rinse, and then treated with 5 % HCl to remove carbonates. The sediment was sieved on a 95 µm Nitex® screen and the residue retained on the sieve was backwashed into a beaker. The residue was later hand sorted for head capsules in a Bogorov counting tray under a Wild M5 dissecting microscope. A magnification of 12 to 25x was used for head capsules floating on the water surface and 25 to 50x magnification was used when removing head capsules from the bottom. Individual, complete and partial remains were extracted with #4 forceps and placed onto coverslips, which were air dried and later mounted with Permount® medium.

Chironomids were identified with the aid of a Zeiss Universal compound microscope and identifications were made at 200 to 500x according to keys and descriptions prepared by Walker (1988), Wiederholm (1983), and Oliver and Roussel (1983).

Pollen Analysis

Selected sediment samples, 1 cm^3 in volume, were extracted from Kilpoola core 2 and later processed at the Royal British Columbia Museum for pollen analysis using the technique described by Faegri and Iversen (1989) and Hebda and Whitlock (1997). Samples were first deflocculated with 5 % KOH solution, and then neutralized using a 5 % K_2CO_3 solution. Hydrochloric and hydrofluoric acids were used to dissolve carbonates and silicates respectively. The resultant residue was treated with a 9: 1 mixture of acetic anhydride: concentrated H_2SO_4 to remove non-sporopollenin organic material. Following filtration on a 10 µm screen, the residue was mounted on microscope slides in glycerin jelly. Pollen and spores were identified and counted with a compound microscope under magnifications ranging from 400 to 1000 x. Identifications were established using McAndrews *et al.* (1973), a key of British Columbia Quaternary pollen and spores (Hebda *et al.,* unpublished), and the reference collection of the Royal British Columbia Museum.

Data Analysis

Data were compiled and graphed using TILIA, version 2.0 (Grimm, 1991-1993) and TILIA-GRAPH, version 1.25 (Grimm,1991). Stratigraphically constrained sum-of-squares (CONISS) cluster analysis (Grimm, 1987) was applied to the percentages of identified pollen and chironomids. Zonation of Kilpoola core 1 was based upon the examination of major differences in the CONISS groupings.

Chironomid inferred salinities were determined from Kilpoola core 1 using the weighted averaging inference model developed by Walker *et al.* (1995) from surface sample analyses on 86 British Columbia lakes. The lowest bootstrapped RMSE for this model was 0.518 and the $r^2_{adjusted}$ was 0.723. Only samples with a minimum of 30 headcapsules were included in all calculations. Shannon-Wiener diversity index values and species richness values were calculated according to Lesveque *et al.* (1996). Inferred salinity computations and graphs were prepared using Microsoft Excel 5.0 (Microsoft Corporation, 1985-1995).

RESULTS

Core Chronology and Stratigraphy

KILPOOLA CORE 1

Kilpoola core 1 has a similar stratigraphy to Kilpoola core 2 (Fig. 2). It includes 33 cm of basal clay resembling that obtained from the earliest postglacial sediments (10 000 yr BP) of other British Columbia lakes. As in Kilpoola core 2, numerous, complex laminations were apparent within the marly gyttja above and below an ash layer, located between 290 and 304 cm. Contained within the laminations below the ash layer were several large mollusc shells.

Based on relative depth and colour, the ash layer in Kilpoola core 1 is believed to represent the Mount Mazama tephra, deposited 6730 ± 40 yr BP (Hallett *et al.*, 1997). The Mount Mazama ash is the thickest and most widespread of all of the tephras to be deposited in southern British Columbia, and is often the only tephra visible in cores from this region (Clague, 1991).

KILPOOLA CORE 2

Approximately 1.3 m of late-glacial clay were recovered from the base (7.9 to 6.6 m) of Kilpoola core 2. Much of the basal clay contained thin, banded laminations of darker sediment. The clay to gyttja transition occurred over approximately 10 cm, and at 657 cm gyttja was the primary material.

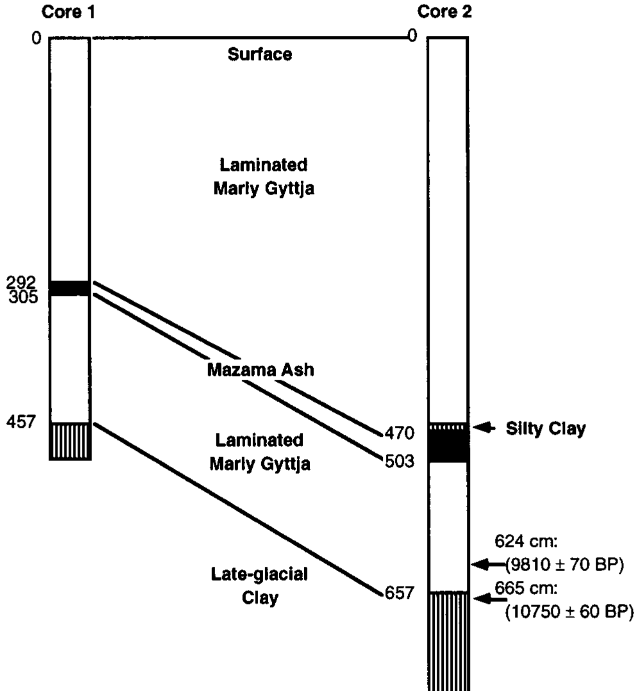

FIGURE 2. Lithology and stratigraphic correlation for Kilpoola cores 1 and 2.

Corrélation entre la lithologie et la stratigraphie des carotes 1 et 2.

AMS radiocarbon dates on charcoal at 665 cm (BETA-102867: 10750 ± 60 yr BP) and 624 cm (BETA-102868: 9810 ± 70 yr BP) revealed that the clay/gyttja transition lay near the Pleistocene/Holocene boundary (Fig. 2).

The overlying marly gyttja, from 650 to 503 cm, contains many laminations, ranging from dark brown black to light cream or grey, and from millimetres to centimetres thick. Infilled burrows through many of the laminations suggest that the sediment was weakly bioturbated. Numerous mollusc shells were removed during the macrofossil screening process in the lower portion of the laminated sequences.

An abrupt change in the sediment to dense tephra occurs at 503 cm and extends to 470 cm. Based on relative depth and colour, this tephra is believed to be the Mazama Ash. Dense, grey silty clay rests on top of the ash from 470 cm to 455 cm.

From 455 to 6 cm, the sediment consists of marly gyttja containing fine to coarse distinct laminations, with a similar diversity of colour and size to those formed prior to deposition of the ash. Some laminations appear to be lens-like or folded, and inclusions of lighter coloured material were present. However, bioturbation was not observed. The top 6 cm of the core consisted of an olive to brown undifferentiated organic mud.

Chironomid Analysis

Detailed chironomid analysis was initially performed on Kilpoola core 1. Parallel analyses of Kilpoola core 2 facilitate correlation between the two cores and provide clearer chronological control.

KILPOOLA CORE 1 (Fig. 3a)

Subzone Ia: 473 cm to 453 cm

Subzone Ia was distinguished by the presence of freshwater indicator taxa including *Microtendipes* and *Heterotrissocladius* in the basal sample (473 cm) (Fig. 3a). In the following sample (463 cm), there were no remains of *Heterotrissocladius*, but a sharp increase in *Chironomus* was recorded coincidentally with a decrease in subtribe Tanytarsina. Other chironomids such as *Dicrotendipes*, *Glyptotendipes*, *Procladius* and *Psectrocladius* (subgenus *Psectrocladius*) were present, which was reflected by near average chironomid richness values (Fig. 4d); however, diversity was low (Fig. 4c). A chironomid-inferred salinity of <0.05 g/l (Fig. 4b) was calculated for the basal sample, however it increased towards the end of this subzone to approximately 1.5 g/l.

Subzone Ib: 453 cm to 412 cm

The early portion of subzone Ib is characterised by an increase in *Chironomus* and a decrease in subtribe Tanytarsina (Fig. 3a). Both diversity and richness values are low in comparison with other zones (Fig. 4c and Fig. 4d). The inferred salinity is approximately 2 g/l, however this value decreases to less than 0.05 g/l towards the latter portion of this subzone (Fig. 4b). The appearance of *Sergentia* and reappearance of *Chironomus,* coincident with a decrease in subtribe Tanytarsina, was noted towards the end of the subzone (Fig. 3a). Chironomid diversity remained approximately 0.6 (Fig. 4c), however an increase in richness values was observed (Fig. 4d).

Zone II: 412 cm to 277 cm

Zone II was relatively complex in terms of its chironomid assemblages. Large shifts in the percentages of subtribe Tanytarsina and *Chironomus*, intermittent appearances of *Cryptochironomus*, *Cladopelma*, *Psectrocladius* (subgenus *Psectrocladius*), *Cricotopus*/*Orthocladius* and *Glyptotendipes* occurred in this zone (Fig. 3a). At 367 cm *Procladius* decreased and increases in *Cricotopus*/ *Orthocladius*, *Tanypus* and *Psectrocladius* (subgenus *Monopsectrocladius*) were observed. *Labrundinia*, *Derotanypus*, and tribe Pentaneurini first appeared within this zone (Fig. 3a). This zone had nearly as low chironomid richness values as the preceding zone (Fig. 4d), although diversity had increased significantly (Fig 4c.). Zone II ended with deposition of the Mount Mazama ash. Zone II had a nearly constant salinity, ranging between 1 and 2 g/l (Fig. 4b). The presence of *Procladius* also suggested moderate salinities.

Subzone IIIa: 277 cm to 246 cm

The chironomid fauna changed abruptly at 267 cm, after the eruption of Mount Mazama, as seen by a rapid increase in the relative abundance of *Cricotopus*/*Orthocladius*, and a slower increase with respect to *Psectrocladius* (subgenera *Monopsectrocladius* and *Psectrocladius*). Corresponding decreases in *Chironomus*, *Cladopelma* and *Glyptotendipes* were also observed (Fig. 3a). No significant change in chironomid head capsule concentrations was observed (Fig. 4a), and chironomid richness values remained near average (Fig. 4d). Chironomid diversity values continued to increase

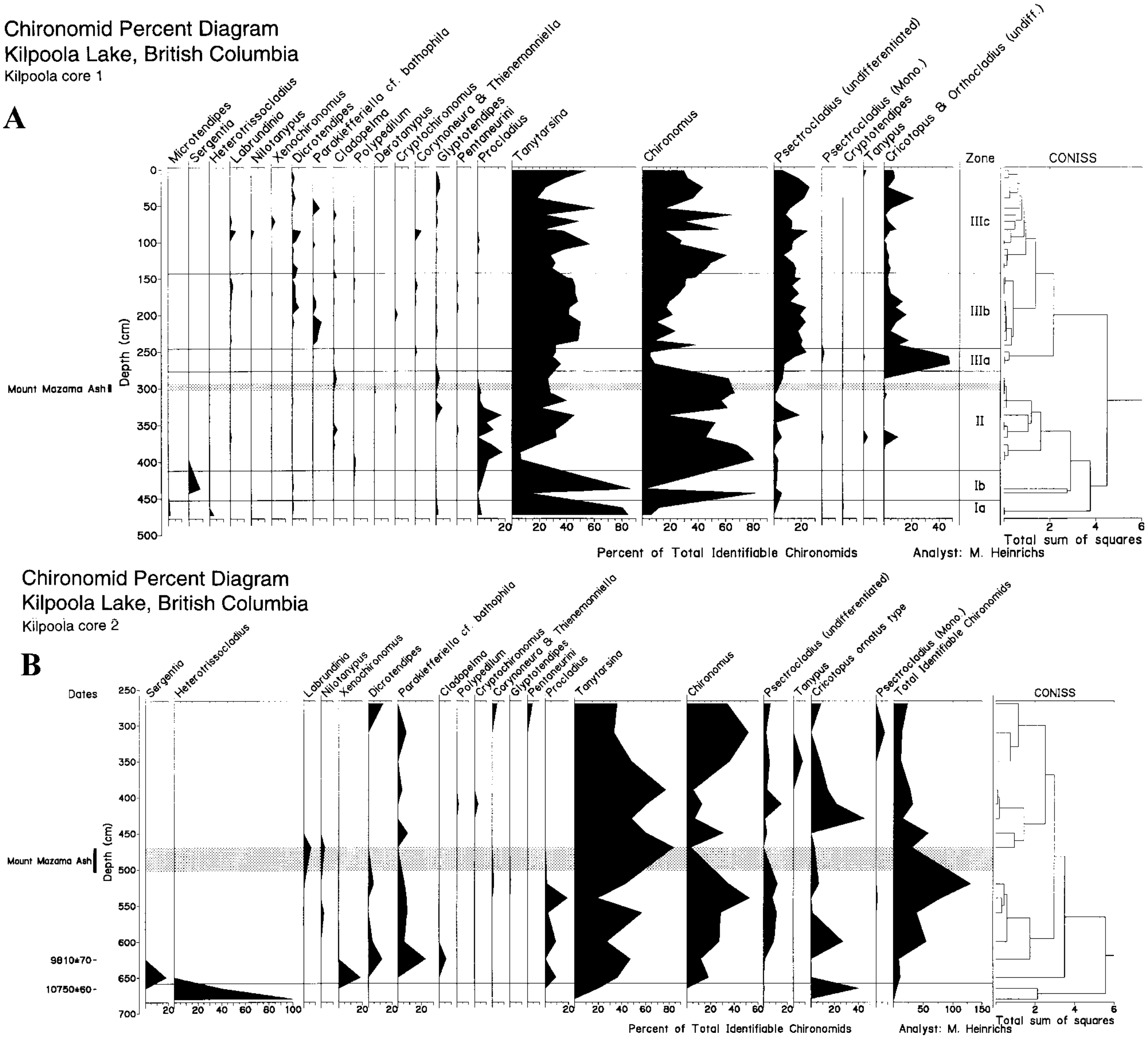

FIGURE 3. Chironomid stratigraphies. Chironomids are arranged in the figures in order of increasing salinity optima from left to right, with the exception of *Nilotanypus*, *Psectrocladius* (subgenus *Monopsectrocladius*), and *Xenochironomus*, for which no salinity optima are available (Walker *et al.*, 1995). a) Kilpoola core 1. b) Kilpoola core 2.

Stratigraphie des chironomides. Les chironomides sont classés selon un ordre d'optimum de salinité croissante, de gauche à droite, sauf pour Nilotanypus, Psectrocladius *(sous-genre* Monopsectrocladius*), et* Xenochironomus, *pour lesquels il n'y a pas d'optimum (Walker* et al., *1995). a) Carotte de Kilpoola 1. b) Carotte de Kilpoola 2.*

in this subzone (Fig. 4c). The chironomid-inferred salinity during this period reflects the dramatic change in assemblage, increasing from 1.5 g/l to approximately 8 g/l, followed by a decrease to approximately 2 g/l (Fig. 4b). The deposition of Mount Mazama ash appears to have had an effect in increasing the salinity of Kilpoola Lake.

Subzone IIIb: 246 cm to 143 cm

The percentage of *Cricotopus*/*Orthocladius* decreased around 246 cm, with corresponding increases in both *Chironomus* and subtribe Tanytarsina. Overall diversity increased (Fig. 4c), with *Nilotanypus*, *Corynoneura*/*Thienemaniella, Xenochironomus* and *Parakiefferiella* cf. *bathophila* appearing for the first time, and the reappearance of *Dicrotendipes*, *Labrundinia*, *Cryptochironomus*, *Cladopelma*, *Glyptotendipes*, tribe Pentaneurini, and *Procladius* (Fig. 3a). The assemblage appeared to remain relatively unchanged throughout this subzone. The chironomid-inferred salinity ranged from 1 to 3 g/l (Fig. 4b) and diversity values varied between 1.3 and 1.6 (Fig. 4c). Chironomid richness reached its highest value in this subzone, at 182 cm (Fig. 4d).

Subzone IIIc: 143 cm to 0 cm

Subzone IIIc was characterised by large oscillations in subtribe Tanytarsina and *Chironomus* percentages, and relatively rapid and large concurrent diversity fluctuations

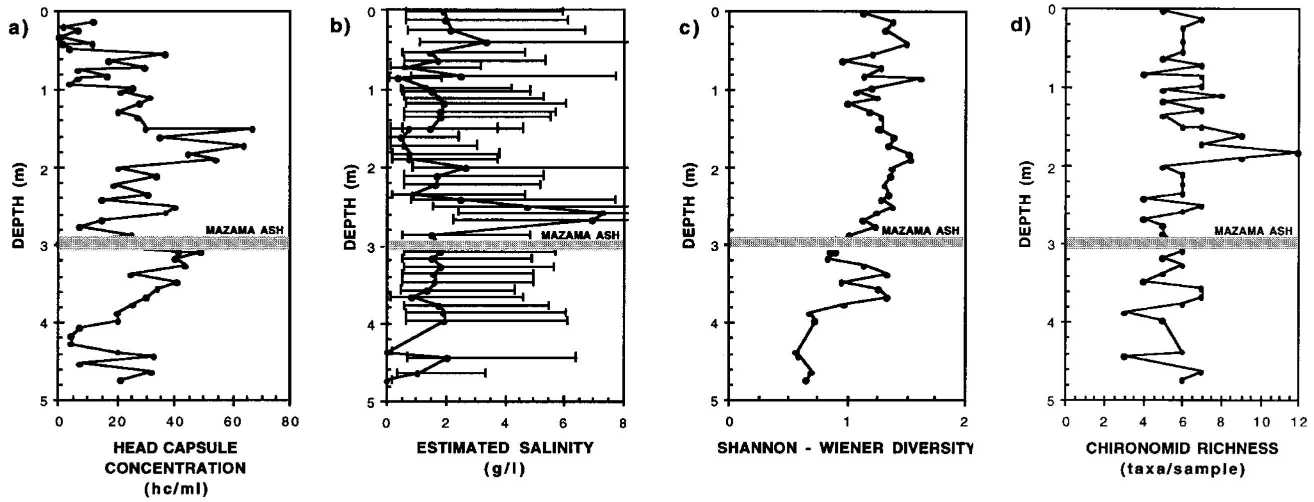

FIGURE 4. a) Head capsule concentration with depth in Kilpoola core 1. b) Chironomid-inferred salinity record for Kilpoola core 1. c) Shannon-Wiener diversity index values for Kilpoola Lake core 1. d) Chironomid richness values for Kilpoola Lake core 1.

a) Concentration de têtes de chironomides selon la profondeur dans la carotte de Kilpoola 1 ; b) le registre de salinité déterminée par les chironomides (carotte 1) ; c) indice de diversité de Shannon-Wiener (carotte 1) ; d) les quantités de chironomides (carotte 1).

(Fig. 3a, 4c). *Cryptochironomus* and tribe Pentaneurini were not observed in this subzone. Small increases in *Cricotopus*/*Orthocladius* and *Psectrocladius* (subgenus *Psectrocladius*) occurred at approximately 50 cm, and *Tanypus* was observed in the most recent sediments (Fig. 3a). Chironomid richness values returned to near average values (Fig. 4d). The chironomid-inferred salinity varied, decreasing to 0.7 g/l at 85 cm, and immediately increasing to 2.5 g/l at 83 cm. Further increases raised the salinity to 3.5 g/l at 40 cm. However towards 0 cm, the salinity returned to approximately 2 g/l (Fig. 4b). These apparent salinity changes in zone IIIc are probably well within the errors inherent in chironomid-salinity inferences, and may not reflect real salinity changes.

Kilpoola Core 2 (Fig. 3b)

Similarities between Kilpoola core 1 and core 2 with respect to the depth distributions of several key indicator taxa are apparent (Fig. 3b), although the numbers of total identifiable midges in some intervals of Kilpoola core 2 were low. *Heterotrissocladius* and *Sergentia* were found in basal and near-basal sediments of both cores. A *Chironomus* peak at 530 cm in Kilpoola core 2 correlates with one at 332 cm in core 1. The large *Cricotopus*/*Orthocladius* (most likely *Cricotopus ornatus*) peak at 430 cm in Kilpoola core 2 was observed in core 1 at 269 cm. *Dicrotendipes* peaks at 270 and 624 cm of Kilpoola core 2 correlated with peaks at 170 and 424 cm in core 1. *Psectrocladius, Procladius*, and subtribe Tanytarsina patterns, and those of most other midges of core 2, fit the general depth distribution patterns described for core 1 (Fig. 3b).

CONISS dendrograms differed somewhat between cores 1 and 2 in the major zonation divisions between cores. However, the early freshwater period and Mount Mazama ash related intervals were clearly revealed in Kilpoola core 2 as well as core 1. We conclude that both Kilpoola cores extend from the late-glacial to the present and include the early Holocene. Correlation on the basis of both lithology and chironomid fauna permits the AMS dates obtained on core 2 to be applied to the core 1 stratigraphy. The AMS dates obtained at 624 cm (9810 ± 70) and 665 cm (10750 ± 60 yr BP) from Kilpoola core 2 were estimated to correlate with core 1 depths of 427 and 465 cm respectively.

POLLEN ANALYSIS

KILPOOLA CORE 2

The skeleton pollen diagram shows three broad zones and one prominent feature, an *Artemisia* peak associated with Mazama Ash (Fig. 5). The first interval spans the lower third of the core from 710 to about 550 cm, or approximately 12,000 to 7500 yr BP. *Pinus* pollen dominated (40 to 60 %), but *Artemisia* was also abundant (5 to 15 %). Poaceae (grass) pollen occurs at 10 to 15 % in the upper part of the interval. A relatively high *Picea* value of 20 % and the Cupressaceae peak at 665 cm are notable (Fig. 5).

High *Artemisia* pollen values characterise the second interval from 550 to 450 cm, spanning approximately 7500 to 6000 yr BP. The *Pinus* values are exceptionally low for the south-central interior of British Columbia (Hebda, 1995). The *Artemisia* values of 20 to 30 % at 540 and 520 cm are very high. The prominent peak of 75 % *Artemisia* near the top of the Mazama ash represents the greatest abundance of this genus ever recorded in this region (Fig. 5).

The third interval from about 450 to 270 cm, or approximately 6000 to 3500 yr BP, is characterised by modest *Pinus* pollen values of 30 to 40 %, 10 to 20 % *Alnus* pollen, 5 to 10 % *Betula*, nearly 10 % grasses, 10 to 15 % *Artemisia,* and 5 to 10 % Cyperaceae (Fig. 5).

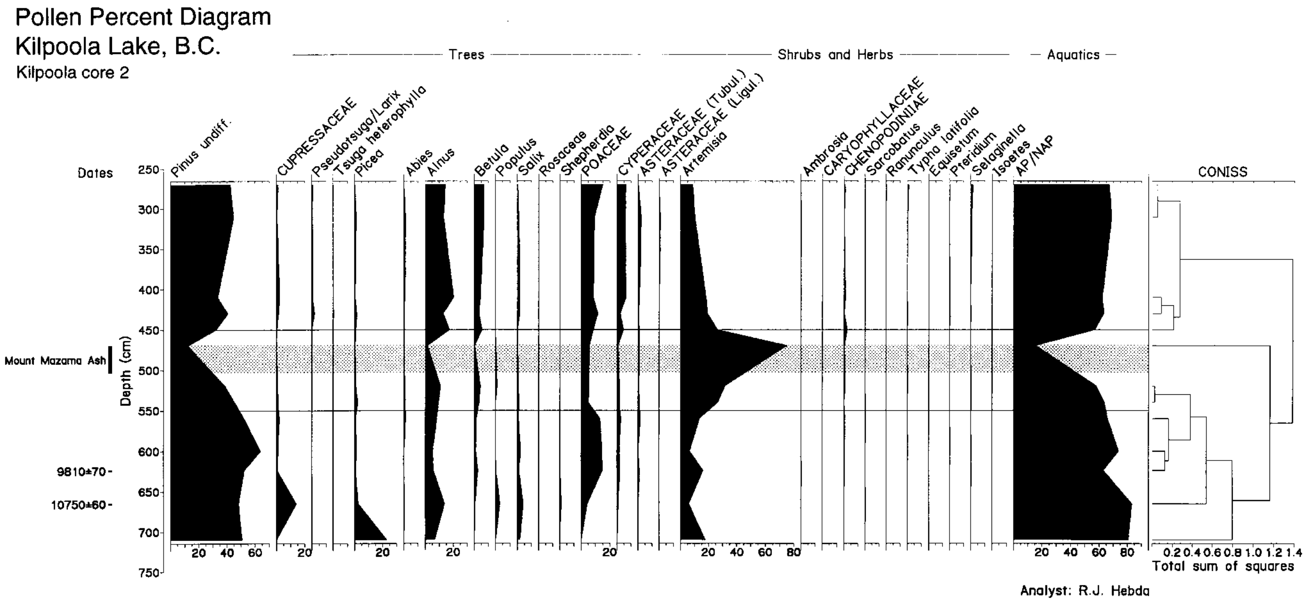

FIGURE 5. Pollen percentage diagram for Kilpoola Lake core 2.

Diagramme pollinique en pourcentages de la carotte du Kilpoola Lake 2.

INTERPRETATION AND DISCUSSION

FRESHWATER STAGE AND EARLY HOLOCENE CONDITIONS

The earliest sediments of Kilpoola Lake core 1, were distinguished by the presence of several stenohaline freshwater midges, including *Heterotrissocladius* and *Microtendipes; Heterotrissocladius* is considered to be cold-stenothermous, and is often abundant in the late-glacial sediments of temperate lakes (Levesque, 1995; Wilson *et al.*, 1993). The massive grey clay at the base of Kilpoola core 1 also resembles the earliest, late-glacial sediments deposited in other British Columbia lakes. Given the AMS dates obtained from Kilpoola core 2, it seems very likely that the initial freshwater conditions at Kilpoola Lake were the product of the cold late-glacial climate that characterised this time in southern British Columbia. The temporary influence of glacial meltwater may also have contributed to the maintenance of these initial cold, freshwater conditions. Low chironomid richness and diversity values in the early sediments confirm observations made by Levesque *et al.* (1996) who suggested low values were correlated with cold water.

Following the initial freshwater stage, the disappearance of those taxa characteristic of cold, fresh waters, and the increase in chironomid inferred salinity suggests a decrease in P-E (Precipitation minus Evaporation). This may represent the rapid climatic warming that is well known to have occurred at the beginning of the Holocene (Hebda, 1995; Hebda and Whitlock, 1997; Mathewes, 1985). A similar, rapid salinity increase is evident in Mahoney Lake at this time (Heinrichs *et al.*, 1997).

The subsequent return to freshwater conditions at 437 cm is intriguing, as it suggests a climatic oscillation. However, this possibility requires further evaluation since the chironomid sample sizes are low, and the inferred salinity calculations are strongly influenced by the presence/absence of a few uncommon, but important freshwater indicator taxa. Similar oscillations have been observed at Cabin Lake (Smith, 1997) and at Lake of the Woods (Palmer, 1998). Following this event, the chironomid-inferred salinities increase again, and remain relatively constant (1.5 to 2.0 g/l) throughout the remaining early Holocene sediments. These constant salinities suggest stable climatic conditions throughout most of the early Holocene.

The late-glacial and early Holocene pollen assemblages reflect relatively open vegetation. Pine, probably lodgepole pine (*Pinus contorta* Dougl.), grew in the region, but the percentage values are too low to suggest local stands (see Hebda and Allen, 1993). Spruce, presumably *Picea engelmannii* Parry, grew locally in the late-glacial but disappeared before 10,750 ± 60 radiocarbon years BP. The Cupressaceae peak may represent local *Juniperus* stands (Hebda, 1995) but macrofossils are needed to verify this interpretation. A community of *Artemisia*, followed shortly by *Artemisia* and grasses, occupied the valley bottom and lower slopes, based on comparison with surface sample values in the region (Hebda, 1982).

INFLUENCE OF THE TEPHRA

Above the tephra, the increased abundance of *Cricotopus/ Orthocladius* (likely primarily *Crictopus ornatus;* see Walker *et al.*, 1995) and the character of the chironomid assemblages indicate an abrupt salinity peak. The chironomid-salinity inference of 1.6 g/l obtained at 287 cm, 7 cm above the ash, is very similar to the inferred salinity of 1.8 g/l obtained 4 cm below the tephra. However, the highest inferred salinities for the entire core, 7.4 and 7.7 g/l, occur only slightly higher in the core (at 267 and 257 cm respectively).

Ash deposition had another effect on the landscape. Immediately after the volcanic event, a layer of grey silty clay was deposited, suggesting substantively increased erosion of the basin landscape. Clearly the blanket of ash on the ground somehow contributed to instability and erosion of underlying mineral horizons, presumably through some effect on the vegetative and lichen crust cover. The sudden impact of fresh mineral sediment, perhaps rich in salts because of arid climate soil-forming processes, in addition to salts derived from the ash itself, raised lake water ionic concentrations. The chironomid communities responded accordingly.

We interpret the pronounced increase in salinity as a direct result of volcanic ash deposition on the landscape. The dense tephra deposits sank towards the bottom perhaps displacing flocculent organic ooze that commonly forms the uppermost few centimetres of lake deposits (Anderson *et al.*, 1984). There was a brief lag effect perhaps because of the vertical displacement of some of this ooze. Nevertheless, the increase in *Cricotopus*/*Orthocladius* percentages and the high salinity inferences occur in silty clays or sediment derived from local erosion immediately following the tephra.

Prior to ash deposition the soils of the Kilpoola Lake basin had been exposed to several thousand years of weathering, but had been stabilised by plant cover. The processes of chemical weathering can gradually deplete soils of labile elements, including base cations and other constituents which contribute to the solute load of water enroute to lakes and streams. For example, the natural pH decline evident during the early Holocene at many temperate lakes has been attributed to the gradual leaching of these materials from soils (Whitehead *et al.*, 1989). In these situations an equilibrium pH is later established, and tends to persist throughout the Holocene, until the impact of recent increases in acidic precipitation become apparent (Whitehead *et al.*, 1989).

No major regional climatic changes are known to have occurred shortly after the eruption of Mount Mazama (Hebda, 1995). We conclude therefore, that ash deposition was likely the direct or indirect causal factor of the Kilpoola lake salinity event. The geology and composition of catchment soils have a tremendous influence on the chemical composition and salinity of closed basin brines (Eugster and Hardie, 1978; Renaut, 1990; Topping and Scudder, 1977). Deposition of a fresh (unweathered) tephra over the weathered, pre-existing soils would be expected to influence the ionic strength and composition of Kilpoola Lakes water. Leaching of salts may have been greatly enhanced because of the large surface area provided by a fine-grained tephra. Consequently, an abrupt, but temporary increase in the solute and nutrient loads of water feeding Kilpoola Lake would be expected from the ash itself. This, in turn, would favour biota tolerant of higher ionic concentrations.

The changes in the character of pollen assemblages seem to support this interpretation. Preceeding ash deposition, a dense cover of sagebrush, presumably big sagebrush (*Artemisia tridentata* Nutt) covered the landscape. This steppe assemblage contained fewer grasses than in the early Holocene interval. The *Artemisia* peak after deposition of the Mazama ash represents an exceptional and abnormal situation and may have occurred for two reasons. First, the extremely low relative values of pine pollen suggest that pollen production in the regional forests was suppressed following ash deposition. Comparison to surface spectra (Hebda and Allen, 1993) suggests that at least briefly, little or no pine grew in the region. Second, the abundance of *Artemisia* grains suggests that they may have been washed in from the soil surface rather than blown into the lake basin, consistent with the sediment which encloses them. The four-fold rise in *Alnus* at the end of the pollen zone may indicate pioneer species colonization of moist habitats on the ash- covered and raw, eroded soils.

Other studies have recorded the impact of past tephra accumulations on aquatic and terrestrial biota. Birks and Lotter (1994), Lotter *et al*. (1995), and Lotter and Birks (1993) performed statistical analysis on terrestrial vegetation and diatom fossil records, derived from sites near the Laachersee Volcano, Germany. They found that the diversity and accumulation rates of some taxa of both terrestrial vegetation and diatoms, at some sites, were affected after tephra deposition. Hickman and Reasoner (1994) examined diatom remains in Mary and Opabin lakes, Yoho National Park, British Columbia, and observed that tephra deposition had a great effect on diatom production, but less effect on diversity. Hebda (1995) suggested middle Holocene diatom blooms may have resulted from the deposition of volcanic ash. These conclusions contrast with those of Abella (1988), whose examination of diatoms in Lake Washington, Washington, U.S.A. showed little change in abundance, but a dramatic shift in diversity. Blinman *et al*.'s study (1979) of the impact of the Mount Mazama ash showed profound sedimentologic effects but little or no extended impact on terrestrial and aquatic ecosystems.

Drainage basin and lake sizes, together with tephra volume, affect the character of tephra deposition, sometimes resulting in the break-up and sinking of tephra in larger pieces (Anderson *et al*., 1984) or formation of a continuous muffling "blanket" (Barsdate and Dugdale, 1972). Basin lithology and the chemical composition of the tephra also may interact, thereby regulating the nature of the biotic change or, in the case of diatoms, preservation (Hickman and Reasoner, 1994).

Walker (1995) reviewed the chironomid paleoecological literature, and noted that studies by Boubée (1983) and Tsukada (1967) were particularly interesting with regard to the possible impacts of tephra. Although Boubée's (1983) core from Lake Maratoto, New Zealand contains many tephra layers, he makes no reference to the possible effect of volcanic ash on the fauna. If the ash layers did have a significant effect, it is not easily recognisable in the chironomid stratigraphy. It is probable that the 5 cm (*ca.* 500 yr) sampling interval was too coarse to resolve any effect. In contrast, Tsukada (1967) noted that *Tanytarsus genuinus* abundance decreased temporarily after two volcanic ashfalls in Lake Nojiri, Japan.

The effects of tephra deposition on aquatic biota and terrestrial vegetation may be only short term (decades) at some sites (Lotter *et al*., 1995; Wissmar *et al*., 1982a, b) but, at other sites, the impact may persist for centuries (Hickman and Reasoner, 1994). Very long water renewal times are an important characteristic of saline lakes (Langbein, 1961).

This slow renewal is responsible for hysteresis (a significant lag between the time of an environmental event, such as ash deposition or climatic change, and its apparent impact within the basin). The lake may also be slow in returning to the pre-impact condition, or in attaining a new equilibrium condition (Langbein, 1961; Richardson, 1969; Street-Perrot and Harrison, 1985). Thus, Kilpoola Lake, and other saline lakes might be slow to respond to an ashfall, but the impact might also persist longer than at other sites.

LATE HOLOCENE CONDITIONS

By 222 cm depth, the chironomid salinity inferences had decreased to values as low as those recorded prior to the deposition of the tephra, and thus no further effect from this event is apparent. Chironomid-inferred salinities through the remainder of the core range between a minimum salinity of 0.7 g/l recorded at 85 cm depth, to a maximum of 3.5 g/l recorded at 40 cm. Despite this variation, the salinity record suggests stable conditions throughout the late Holocene. This limited variation might be considered indicative of climatic stability, but there is abundant evidence from chironomids and other indicators for a gradual late Holocene cooling at other sites in British Columbia (Hebda, 1995; Mathewes, 1985; Smith, 1997).

The uppermost pollen interval indicates that forest cover returned to the region but few trees grew on the valley bottom. The low values of *Pseudotsuga* suggest that this species with poorly dispersed pollen (Hebda and Allen, 1993) probably grew on the valley slopes. The valley bottom continued to support sagebrush and grass communities which, as indicated by the Tubuliflorae and Liguliflorae pollen values, were more diverse than in the preceding interval. The relatively high *Betula* pollen values suggest that western birch (*Betula occidentalis* Hook.) may have grown in suitable moist habitats at the lake's edge, and/or that paper birch (*B. papyrifera* Marsh) expanded in regional forests. Almost certainly, well developed *Scirpus* and *Carex* communities grew in the lake's shallow shoreline zone, as they do today.

CONCLUSIONS

Sediment from Kilpoola Lake in the south-central interior of British Columbia was analysed for pollen and chironomid remains, and a postglacial paleosalinity record was inferred. The shift from freshwater to saline conditions early in the Holocene, may be related to glacial retreat and rapid climatic warming. The surrounding area was characterised by steppe communities but the regional landscape was drier than later in the record, as suggested by relatively low birch, alder and Cyperaceae pollen values. The chironomids and inferred salinities appear to have been remarkably stable throughout most of the subsequent record except for a period following input of the Mount Mazama tephra. The dramatic increase in salinity following this event appears not to be climate driven, but was rather the by-product, directly or indirectly, of a random volcanic event. The 7500 to 6000 yr BP interval, clearly characterised by *Artemisia* steppe, occurs during a regionally recognised moistening phase (Hebda, 1995). High *Artemisia* values have been used in the past as an indicator of arid conditions (Hebda, 1982, 1995) so reconstruction of the past climate remains unclear. The increased moisture and implied higher lake levels after 6000 BP are consistent with regional trends (Hebda, 1995). The pollen record demonstrates that the landscape around the lake has never been covered in forest.

The apparent severity of salinity and community change after the deposition of the tephra provides a unique insight into the effect of volcanic ash on vegetation, soil processes and aquatic invertebrates. Diversity was affected, probably due to an increased lakewater salinity, and perhaps also by the ash blanketing previously deposited sediment. Why ash deposition seems to have had a profound effect on aquatic and terrestrial ecosystems at Kilpoola lake but not in adjacent regions (Blinman *et al*., 1979) is a puzzle which merits further study.

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