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Multi-proxy Holocene palaeoclimatic record from a saline lake in the Canadian Subarctic

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Abstract: Multi-proxy palaeolimnological analyses of a postglacial sedimentary sequence at a centennial-scale resolution from an athalassic saline lake in the Yukon were conducted to infer patterns of Holocene climatic change in the Canadian Subarctic, using sediment mineralogy and biostratigraphy (diatoms, pigments). Diatom-inferred quantitative estimates of palaeosalinity were obtained by use of transfer functions developed from a calibration set of 219 lakes from western North America. The sediment mineralogy and fossil pigments at the base of the core indicated a moderately deep non-stratified lake dominated by clastic influx, probably in a basin fed by glacial meltwater. The early-Holocene history (*c.* 11 000–8100 ^{14}C yr BP) was characterized by a relatively deep mesosaline lake with diatom-inferred salinities approximating 20 g L^{-1}. The occurrence of both aragonite and dolomite, as well as elevated concentrations of chlorophyll and carotenoid pigments, support the interpretation of deepwater anoxia and possibly strong chemical stratification. High concentrations of the chemically stable β-carotene suggest that total algal abundance was particularly high during the early Holocene, when planktonic *Cyclotella* cf. *choctawhatcheeana* and *Chaetoceros muelleri* were the most common diatom taxa. Relatively fresh (2–15 g L^{-1}) eutrophic conditions prevailed during the mid-Holocene period (*c.* 8000–2000 yr BP), with four periods of alternating fresh and saline conditions. The diatom-inferred salinity profile reveals significant fluctuations within these cycles, but overall they indicate humid climatic conditions compared to today. Algal abundance is inferred to have declined three-fold relative to the early Holocene, particularly in the case of eukaryotic algae (e.g., diatoms, cryptophytes, chlorophytes). The recent history of the lake (about 2000 years BP until the present day) was marked by important changes in ionic composition (e.g., occurrence of gypsum and Mg-carbonates) and hydrologic conditions. The lakewater composition during the last two millennia was characterized by hypersaline Mg-SO$_4$ brines. The palaeolimnological evidence from most proxies indicates a trend towards drier conditions during the past 2000 years. The various indicators reveal a complex history of frequent and rapid shifts in palaeosalinity and lake palaeoproductivity during the Holocene, and the effects of the Younger Dryas and 'Little Ice Age' episodes may be recorded in the palaeoclimate proxy data. The palaeoclimatic interpretation emerging from this high-latitude lake corroborates existing broad trends based on palynological studies in this region but provides evidence for more dynamic climatic change during the mid- and late Holocene.

Key words: Saline lakes, palaeoclimate, palaeolimnology, diatoms, pigments, mineralogy, multi-proxy approach, Yukon, Subarctic, Holocene.

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Introduction

Most saline lakes lie within endorheic drainages and are sensitive to the hydrologic balance between inputs (precipitation and inflows) and outputs (evaporation and out-seepage) (Langbein, 1961). Small variations in the hydrologic budget may therefore produce large changes in the chemical nature of these lakes. Saline lakes are of special interest to palaeoclimatologists (Williams, 1996), as many of the aquatic organisms that respond to fluctuations in salinity leave identifiable fossils in the sedimentary record that can be interpreted in terms of past climatic conditions. For example, the abundance and species composition of diatoms is strongly related to lakewater ionic concentration and composition, and changes in diatom communities can be used to infer past salinities by the use of quantitative models (reviewed in Fritz *et al.*, 1999). Similarly, biogeochemical remains (e.g., pigments) of past phototrophic communities are often preserved in sediments of saline lakes and offer evidence of past algal abundance and community composition (reviewed in Sanger, 1988), grazing by invertebrates (Carpenter and Bergquist, 1985), and the penetration of visible and ultraviolet radiation (Leavitt *et al.*, 1997). Because endogenic and authigenic minerals found in these saline lakes are generated in direct response to the salinity and ionic composition of the brine, the composition and petrography of the preserved salts in the stratigraphic sequence can provide an unambiguous record of changes in chemical composition, salinity, atmospheric relative humidity and water-column stratification of the lake. The allogenic or detrital component of the sediment provides information about weathering conditions within the watershed and about provenance, water depth and lake level.

Inland (athalassic *sensu* Bayly, 1967) saline lakes in Subarctic and Arctic regions are rare and remain largely unknown to the scientific community (Pienitz *et al.*, 1992). As part of a project investigating diatom distributions across northern tree-line in the Yukon-Mackenzie Delta region of the Canadian Subarctic (Pienitz *et al.*, 1995), we found a region containing at least four saline lakes (Veres *et al.*, 1995) in the Pelly Crossing area of the central Yukon (Figure 1). The initial palaeolimnologic work completed on a short core from one of these lakes (Pienitz *et al.*, 1992) showed significant floristic and faunistic changes indicative of substantial changes in lakewater salinity in its recent history. With the promising results from this reconnaissance study, we returned to the area to re-examine these saline lakes in more detail in order to assess their suitability as reference sites for palaeolimnologic and palaeoclimatic studies. The results obtained thus far suggest that these lakes have considerable potential for providing high-resolution proxy data of past climatic changes in high-latitude regions.

Long-term, high-resolution palaeoenvironmental data from the Subarctic region of the Canadian Northwest are rare. In the Yukon, reconstructions of Holocene palaeoclimate are based mainly on analyses of fossil pollen and tree rings (e.g., Cwynar and Spear, 1995; Szeicz, 1998). This paper presents new palaeoclimatic data for this region that have been obtained from other sources of proxy climatic information, combining evidence from diatom, pigment and mineralogical analyses conducted on the uninterrupted Holocene stratigraphic sequence from a saline lake. The main purpose for this multi-disciplinary research was to provide detailed information on lake ontogeny in relation to palaeoenvironmental changes in the immediate watershed, thereby allowing palaeolimnologic inferences in the central Yukon that are related to climate. Such palaeoclimate proxy data are especially important because simulations of most General Circulation Models (GCMs) suggest that the effects of global changes on climate are going to be amplified in these high-latitude regions (e.g., Houghton *et al.*, 1990; Riewe and Oakes, 1994). In addition, we compare our results with other palaeoecological and palaeoclimatic data from surrounding regions in an attempt to identify the broader forcing mechanisms leading to Holocene climatic change.

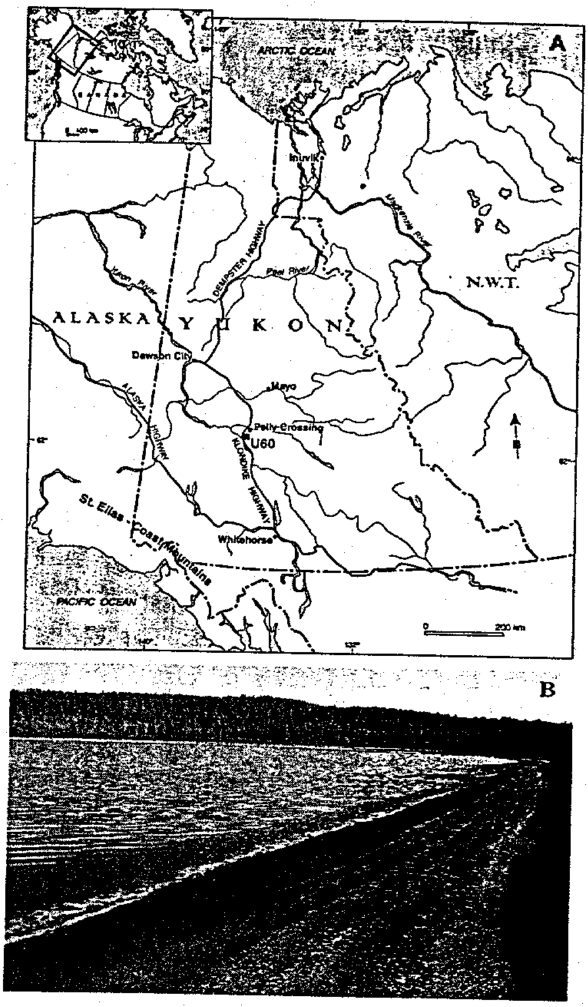

Figure 1 (A) Map showing the location of U60 near Pelly Crossing, Yukon Territory, as well as other study sites referred to in the text. (B) Photo showing the modern lake and local setting.

Description of study site

Lake U60 (unofficial name), which among members of the Selkirk First Nation's people is known as 'Stinky Lake', is located *c.* 150 m from the Klondike Highway near Pelly Crossing (62°45′N; 136°38′W) (Figure 1A). This topographically closed-basin lake has a surface area of about 9.5 ha (highly variable depending on season and year; Pienitz *et al.*, 1992; Veres *et al.*, 1995) and is located at an elevation of 600 m above sea level. The surrounding area belongs to the Yukon River Basin physiographic region, a 500–1000 m high plateau that occupies the central part of the interior Yukon Territory. The salt lakes of this region of low relative humidity and precipitation (<300 mm yr^{-1}; Wahl *et al.*, 1987) fall within the large rain shadow of the coastal St Elias-Coast Mountains.

Precambrian metamorphic bedrock is composed mainly of amphibolite, greenschist, muscovite and chlorite schist and is overlain by glacial till. Maps showing the distribution of glacial deposits (Duk-Rodkin *et al.*, 1986; Klassen *et al.*, 1987) indicate that our study site lies just beyond the limits of the Late Wisconsinan McConnell glacial advance.

The catchment vegetation of Lake U60 displays a distinct pattern of concentric zonation (Figure 1B), with an inner ring composed of grasses and sedges dominated by *Triglochin palustris*, a panarctic arrowgrass commonly growing on alkaline soils. The surrounding Boreal forest is composed predominantly of white spruce (*Picea glauca*), trembling aspen (*Populus tremuloides*) and some balsam poplar (*Populus balsamifera*).

Materials and methods

Sediment sampling and dating techniques

On 4 August 1993, a sediment core 4.13 m long was taken from the deepest part ($Z_{max} = 1.8$ m) of the study site using a modified Livingstone piston corer and a coring platform mounted on two canoes. Sediment core sections (1 m) were extruded in the field, wrapped in plastic and aluminum foil, and then stored in the dark at 4°C until analysis. Limnological characteristics measured included depth profiles of water temperature, conductivity, salinity, pH and Secchi disk transparency. Surface water samples were collected for analyses of nutrients, major ions, trace metals, and chlorophyll *a* at the National Water Research Institute (Burlington, Ontario).

Sediment cores were sectioned into 1 cm slices in the laboratory. Mineralogical and biological analyses were conducted at 2 cm and 4 cm intervals, respectively. The outermost sediment was removed to reduce contamination between adjacent stratigraphic levels. Macrofossil remains, including plant stems, moss fragments and gastropod shell fragments, were isolated and dated by accelerator-mass spectrometry (AMS) ^{14}C techniques.

Mineralogical and lithostratigraphic analyses

Samples for moisture content, organic matter content, total carbonate content, bulk mineralogy, evaporite or carbonate mineralogy and chemical composition were taken at 2 cm intervals. Moisture and organic matter contents were evaluated by weight loss on heating to temperatures of 45°C and 500°C, respectively (Dean, 1974). All samples analysed for mineralogy were air-dried at room temperature, disaggregated in a mortar and pestle, and passed through a 62.5 μm sieve. Bulk mineralogy and detailed carbonate, phosphate and evaporite mineralogy were determined by standard x-ray diffraction techniques (Chen, 1977; Hardy and Tucker, 1988) using a nonaqueous mounting medium. Mineral identification was aided by the use of an automated search-match computer program (Marquart, 1986). Percentages of the various minerals were estimated from the diffractograms using the weighted intensity of the strongest peak for each mineral (Schultz, 1964; Shang and Last, 2000). Non-stochiometry of the dolomite and calcite was determined by examining the displacement of the d104 peak on a detailed (slow) XRD scan (Goldsmith and Graf, 1958). Duplicate samples were prepared and analysed for mineralogy every 10 samples. These replicate analyses indicate precision of the mineralogical data is approximately ±8%. Molalities and activities of the chemical species in the brine and the saturation state of the water with respect to various mineral components were calculated by use of WATEQF (Truesdell and Jones, 1974; Rollins, 1989). A modified version of PHRQPITZ (Plummer *et al.*, 1988) was used to reconstruct the major ion brine composition based on the preserved endogenic mineral suite.

Diatom analyses

Siliceous algal microfossils were isolated and identified using standard techniques (Pienitz *et al.*, 1992). A minimum of 300 diatom valves was enumerated in each sample from which relative abundances were calculated (% diatom sum). Species identifications were based mainly on Archibald and Schoeman (1984), Bérard-Therriault *et al.* (1986), Cumming *et al.* (1995), Germain (1981), Krammer and Lange-Bertalot (1986; 1988; 1991a; 1991b), and Schoeman and Archibald (1987).

Quantitative reconstructions of salinity are based on a simple weighted-averaging model (bootstrapped $r^2 = 0.87$, $P < 0.001$) developed from a modern data set of 219 lakes primarily from central British Columbia (Wilson *et al.*, 1996). Unconstrained correspondence analysis (CA), with downweighting of rare taxa but no species transformation, was used to summarize the main directions of variation in the diatom assemblages during the past 10 000 years when lake U60 was saline. Prior assemblages characteristic of glacio-lacustrine conditions were eliminated from the CA ordinations in order to quantify the variability in the species assemblages over this period.

To determine whether fossil assemblages were adequately represented in modern training sets, the species composition of each sample was compared to modern assemblages from the 219 lake set using squared chord distance as a measure of dissimilarity between samples in the computer program ANALOG (H.J.B. Birks and J.M. Line, unpublished program). A sample was deemed to have a poor analogue when the chord distance with the best fit modern sample was >90% of all distances among modern samples, and to have no analogue when the chord distance was greater than all observed distances.

Fossil pigment analyses

Pigments were extracted (18 h, 4°C, dark, under N_2) from freeze-dried sediments (24 h, 0.01 Pascals) using standard techniques (Vinebrooke *et al.*, 1998). Dried extracts were filtered (0.22 μm), dried under N_2, and stored at –20°C in the dark until pigment analysis. Pigments were dissolved in an injection solvent containing 3.2 mg L^{-1} Sudan II (Sigma Chemical Co.) as an internal standard (Vinebrooke *et al.*, 1998). Concentrations of fossil carotenoids, chlorophylls (Chls), and their derivatives were quantified using a Hewlett Packard (HP) model 1050 high performance liquid chromatography (HPLC) system equipped with an HP Model 1050 photo-diode array (PDA) spectrophotometer and an HP model 1046A fluorescence detector. Pigments isolated from sediments were tentatively identified by comparison of spectral characteristics and chromatographic mobility with authentic standards provided by the US-EPA. Acid and methyl derivatives of chlorophyllous pigments were created either by aqueous-alcohol extraction (chlorophyllides) or by acidification following the procedures of Leavitt *et al.* (1989) and Leavitt and Findlay (1994).

Analysis of fossil pigments was restricted to carotenoids characteristic of cryptophytes (alloxanthin), mainly diatoms (diatoxanthin), siliceous algae (diatoms, chrysophytes) and some dinoflagellates (fucoxanthin), dinoflagellates (peridinin), chlorophytes and cyanobacteria (lutein-zeaxanthin), cyanobacteria (echinenone), filamentous cyanobacteria (myxoxanthophyll), N_2-fixing cyanobacteria (aphanizophyll), purple (okenone) and green sulphur bacteria (isorenieratene), as well as the major *a*, *b* and *c*-phorbins. Chl *b* and pheopigment derivatives (mainly pheophytin *b*) were used to distinguish green algae from cyanobacteria, whose carotenoid zeaxanthin was not separated from the chlorophyte pigment lutein on our HPLC system. Similarly, chromatographic peaks from aphanizophyll (*Aphanizomenon*), oscillaxanthin (Oscillatoriaceae) and 4-keto-myxoxanthophyll (*Anabaena*) were incompletely resolved and were reported as aphanizophyll.

Sediments of Lake U60 also contained algal-derived pigments capable of absorbing ultraviolet radiation (UVR). As described by Leavitt *et al.* (1997), these non-fluorescent compounds are produced by benthic cyanobacteria in response to exposure to damaging levels of UVR and can be used to reconstruct past penetration of high energy irradiance into shallow aquatic environments. Preliminary analysis by mass spectrometry suggests that the UVR-absorbing pigments are derivatives of scytonemin (Leavitt and Hodgson, unpublished data), a photo-protective compound

Table 1 Summary of limnological and water chemistry data measured in Lake U60 in August 1993

Maximum water depth (m)	1.8
Secchi disc reading (m)	1.0
Surface temperature (°C)	20.0
Bottom temperature (°C)	28.0
Specific conductance at surface (μS cm^{-1})	17,000
Specific conductance at bottom (μS cm^{-1})	43,000
Salinity at surface (g L^{-1})	11.0
Salinity at bottom (g L^{-1})	26.0
pH (mid-lake)	9.0
Chlorophyll *a* (μg L^{-1})	5.3
Particulate organic carbon (mg L^{-1})	3.73
Particulate organic nitrogen (mg L^{-1})	0.60
Dissolved inorganic carbon (mg L^{-1})	82.8
Dissolved organic carbon (mg L^{-1})	20.4
Total phosphorus (μg L^{-1})	107.5
Soluble reactive phosphorus (μg L^{-1})	20.2
Nitrite (μg L^{-1})	3.0
Nitrate (μg L^{-1})	10.0
Ammonia (μg L^{-1})	1080
Silica (mg L^{-1})	6.18
Chloride (mg L^{-1})	659.0
Sulphate (mg L^{-1})	20,483
Calcium (mg L^{-1})	265.0
Potassium (mg L^{-1})	229.0
Magnesium (mg L^{-1})	5890.0
Sodium (mg L^{-1})	827.0
Barium (mg L^{-1})	0.027
Cobalt (mg L^{-1})	0.003
Copper (mg L^{-1})	0.007
Iron (mg L^{-1})	0.015
Lithium (mg L^{-1})	0.907
Manganese (mg L^{-1})	0.012
Strontium (mg L^{-1})	8.69

characteristic of the Nostocales. When expressed as a % fraction of the sum of biomarker carotenoids alloxanthin, lutein-zeaxanthin and diatoxanthin, the proportion of these compounds is linearly correlated with the maximum depth of penetration of damaging UV-B radiation (Leavitt *et al.*, 1997). This UVR index takes values of >100% in highly transparent alpine and Arctic lakes, ~15% in acidified boreal systems with low levels of dissolved organic carbon, and 0% in optically deep lakes.

Results

Modern limnology

The limnological and water chemistry data for 4 August 1993 are summarized in Table 1. Lake U60 is alkaline (pH = 9.0–9.3), highly conductive (17 000 μS cm^{-1} at surface; 43 000 μS cm^{-1} at 1.8 m), and composed predominantly of Mg^{2+} and SO_4^{2-} ions. Despite its shallow nature, a stable chemocline existed at 1.0 m depth. Deeper waters were anoxic and significantly warmer (28°C at 1.8 m) than were surface waters (20°C). The Secchi depth of only 1.0 m reflected the high concentration of algae and bacteria at the time of sampling. In warm years, the evaporative concentration of the lake water causes epsomite to crystallize around the margin of the lake (Figure 2 in Pienitz *et al.*, 1992). Cyanobacterial mats develop during the summer along the shoreline and floating on the lake surface (Gerry Whitley, personal communication). Additional limnological data from July 1990 were presented in Pienitz *et al.* (1992), and Veres *et al.* (1995) provided seasonal trends of conductivity, salinity, temperature and pH for U60 between May and August 1992.

Table 2 AMS radiocarbon dates (^{13}C-corrected) from Lake U60 sediments, Yukon Territory. Depth corresponds to the core depth from the surface sediments at which the sample for dating was taken. The calibrated dates in calendar years (cal. BP) represent the probability range of dates calculated by the computer program CALIB 3.03 (Stuiver and Reimer, 1993). AMS radiocarbon dates provided by IsoTrace Laboratories (University of Toronto, Ontario)

Depth (cm)	Material	Age (yr BP ± 1δ)	Age (cal. BP)	Lab. number
78–80	stem	1560 ± 140	1571–1302	TO-4326
122–124	stem	2020 ± 100	2159–1717	TO-4327
200–202	moss fragment	2400 ± 180	2801–1994	TO-4328
264–266	moss fragment	6040 ± 160	7220–6507	TO-4329
296–298	moss fragment	7850 ± 240	8974–8406	TO-4330
376–378	macro fossils	10 020 ± 170	11 740–11008	TO-4331
394–413	gastropod shells	10 870 ± 100	12 904–12685	TO-4332

Sediment chronology

Seven AMS ^{14}C dates were used to construct a depth-time profile for the core (Table 2; Figure 2). Fragments of gastropod shells preserved in the lowest clay unit revealed a maximum age of 10 870 ± 100 yr BP (12 904–12 685 cal. BP; Stuiver and Reimer, 1993). Ages of other levels were interpolated or extrapolated from AMS dates by assuming constant depth-age relationships. For samples falling between the sediment surface (zero years BP) and the first radiocarbon date, sediment ages were extrapolated from a Pb^{210} profile (data not shown) indicating that 8 cm represented *c.* 150 years of sedimentation. Such estimates of sediment age for the 80–90 cm interval fell within that measured from ^{14}C (1560 ± 140 yr BP) at 80 cm depth, suggesting that inferences of sediment ages were reasonably accurate in the upper sections of the core.

The high linear sedimentation rates in the upper half of the stratigraphic section, although exaggerated due to the higher moisture content relative to the more compact basal sediments, suggest changing environmental conditions within the watershed. As noted by numerous studies (e.g., Schumm, 1968; Wilson, 1973; Allen, 1997) highest sediment accumulations generally

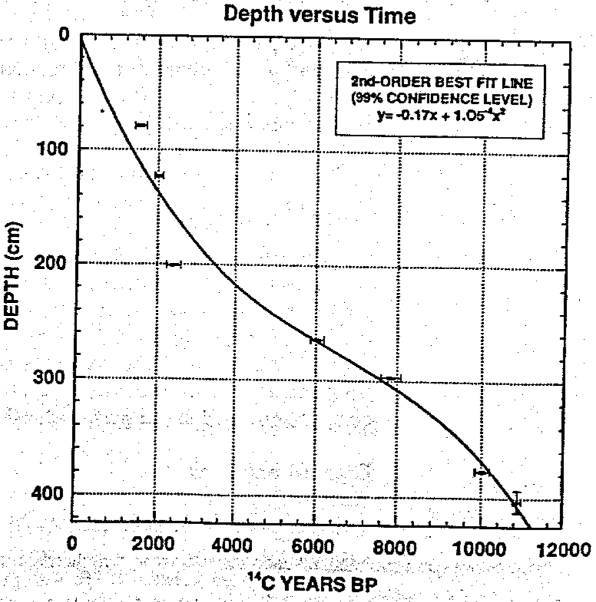

Figure 2 Lake U60 chronostratigraphy: ^{14}C-inferred age versus depth in the sediment core.

occur in basins in semi-arid climatic regimes. Relatively sparse vegetation cover combined with elevated lakewater salinities provided optimum conditions for sediment yield and endogenic deposition after about 4000 yr BP. More humid conditions earlier in the Holocene afforded watershed stability and relatively lower inorganic endogenic mineral precipitation rates.

Lithostratigraphy and mineralogy

The sedimentary sequence recovered from Lake U60 consists mainly of dark grey, indistinctly laminated to non-bedded, soft, fine-grained organic mud and gyttja. Light-coloured thin beds are common throughout the sequence and thin to very thin, horizontal, parallel laminae are present near the base of the core (383–390 cm). Moisture content gradually decreases downward in the core from >75% at the surface to about 50% at 390 cm depth (Figure 3). The sediment below 391 cm is dry (<30% moisture content), firm and compact. The organic matter content is uniformly high throughout most of the core (~50%), but it decreases abruptly to less than 10% below 391 cm.

The inorganic fraction of the sediment consists of a complex mixture of soluble and sparingly soluble salts, with minor amounts of clay minerals, quartz and feldspars. The diverse suite of soluble endogenic and authigenic minerals, including hydrated and anhydrous magnesium, sodium, and calcium sulphates, carbonates and chlorides, occur in moderate to high proportions throughout the core except in the lower 25 cm. Hydrated iron and manganese sulphates, iron and magnesium phosphates, and various nitrate and borate minerals also occur in low to trace abundances.

The basal sediments (391–413 cm) consist mainly of allogenic clay minerals, feldspars and quartz with minor detrital ferromagnesian silicates and carbonates. With the exception of depth intervals 141–145 cm and 250–255 cm, these allogenic components comprise <10% of the total inorganic fraction above 391 cm. Soluble evaporitic sulphates dominate the sequence above 391 cm, averaging about 80% of the inorganic material. Carbonate minerals make up the remaining *c.* 10% of the inorganic fraction, and are mainly aragonite and dolomite. Phosphates, nitrates, borates and halides comprise <5% of the mineral fraction but form considerably higher proportions in selected sections of the core (Figure 3).

Five lithostratigraphic units can be identified based on the mineralogical composition, organic and moisture contents, and bedding features (Figures 3 and 4; Table 3). The lowermost unit (391–413 cm) is a firm, compact, structureless, siliciclastic-rich, grey clay with very low moisture and organic matter contents. The mineral suite comprises mainly clay minerals (~60%), with subequal proportions of quartz, feldspar and carbonate. The carbonate fraction of the sediment consists entirely of stoichiometric well-ordered dolomite and calcite of detrital origin. Endogenic and authigenic minerals, which dominate the overlying sediment, are absent from lithostratigraphic unit 1.

Calcareous, organic-rich salts comprise lithostratigraphic unit 2 (309–391 cm). The carbonate mineral fraction, dominated by aragonite and dolomite, is greatest in the finely laminated lower half of the unit and decreases upward. The sulphate mineral content shows a complementary increase upward from about 50% at

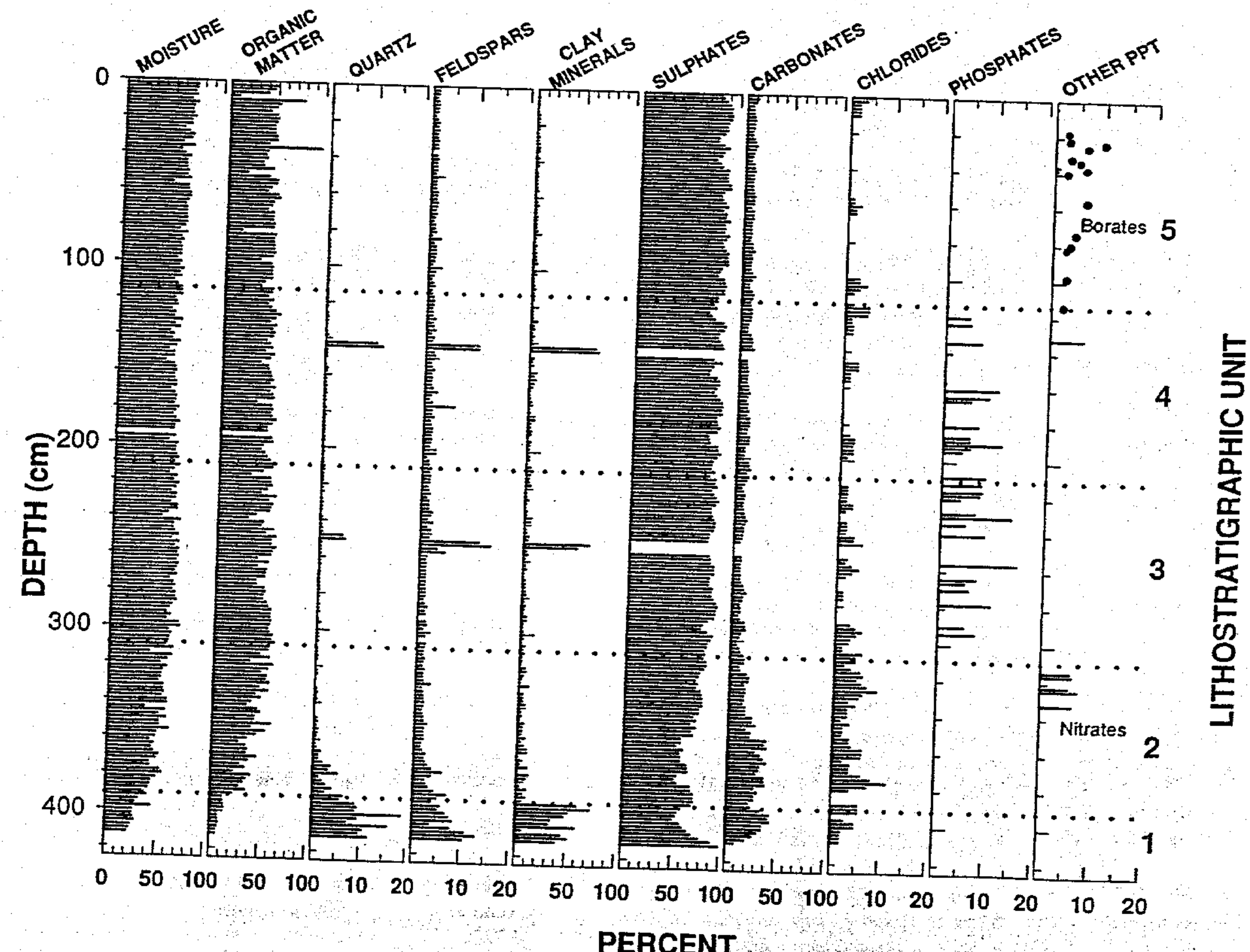

Figure 3 Summary diagram of sediment mineralogy and lithostratigraphy. Lithostratigraphic units are shown on the right.

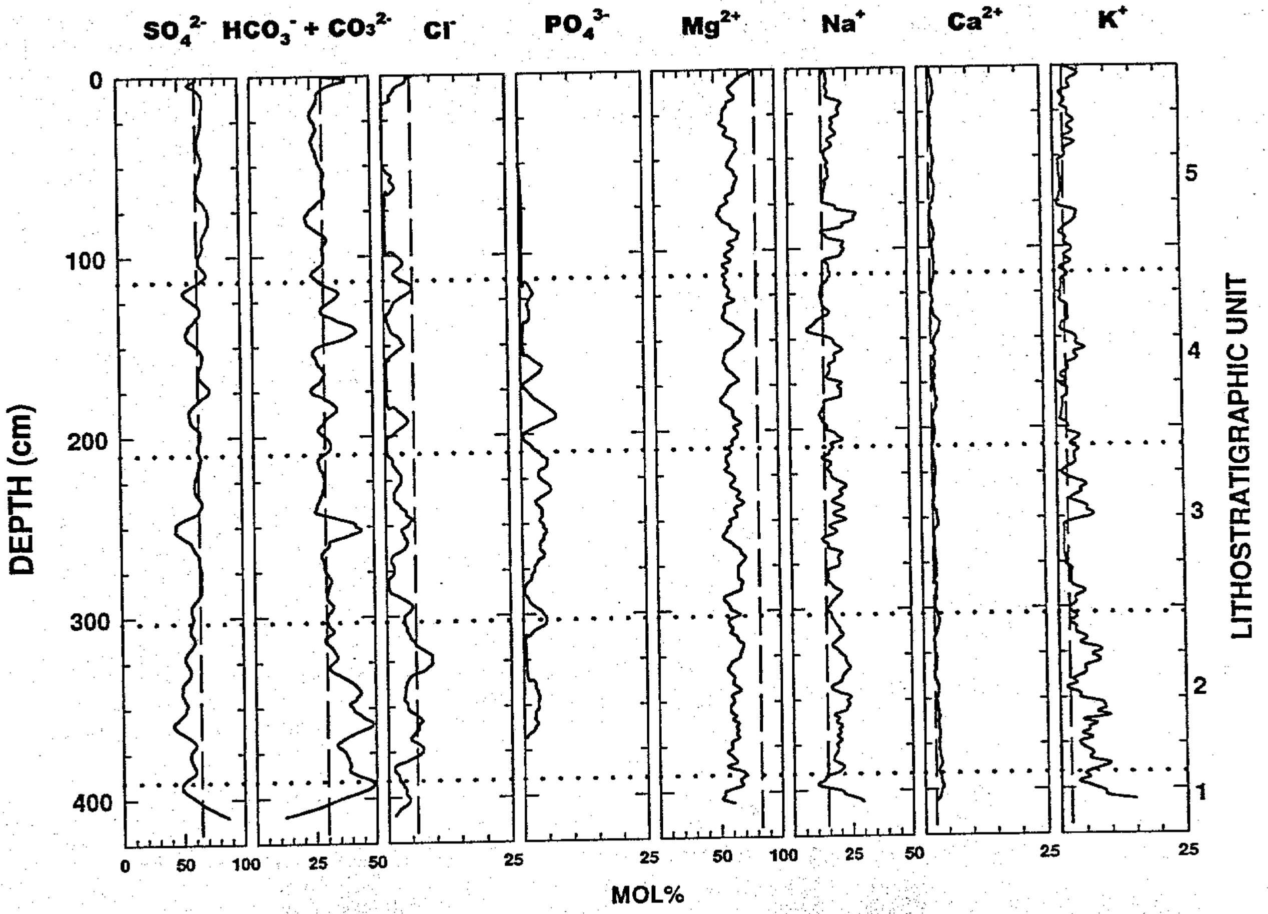

Figure 4 Relative mole ratios of major ionic components in Lake U60 brine interpreted from the endogenic and authigenic mineral suite. The vertical dashed line on each graph is the modern lakewater composition. Lithostratigraphic units are shown on the right.

the base to 90% at the top of the unit. Dolomite in unit 2 is nonstoichiometric and poorly ordered, whereas the small amount of calcite (<1%) is normal, low-Mg $CaCO_3$. Unit 2 is further characterized by Mg and Na carbonates, halides and, in the uppermost 30 cm, nitrate salts.

Lithostratigraphic unit 3 (210–309 cm) and unit 4 (114–210 cm) are distinguished from the underlying sediment mainly by the presence of phosphate minerals, low proportions of carbonates and few halides. Although both units averaged nearly 60% Mg-sulphate precipitates, unit 3 marks the earliest occurrence of iron sulphates in the U60 record, and unit 4 contains the earliest occurrence of gypsum. Both units also contain thin zones in which clastic sediments predominate (e.g., 250–255 cm and 141–145 cm) and exhibit centimetre-scale banding.

The uppermost lithostratigraphic unit 5 is characterized by an absence of phosphate minerals, sporadic occurrences of borate salts, and high content of gypsum, bloedite, and Fe and Mg+K sulphate salt. The lower contact of unit 5 with unit 4 is delineated by a sharp increase in gypsum at about 1.1 m (Figures 3 and 4).

One of the most striking features of the Holocene record recovered from Lake U60 is that nearly all of the inorganic sediment was formed within the lake. Detrital sediment influx by streamflow, sheetflood and other clastic sedimentary processes has been very small for nearly 11 000 years. Maximum clastic influx occurred during the earliest stage of sedimentation in the basin (prior to 10 000 yr BP) and, with the exception of several short periods of non-evaporite deposition at about 5500 and 2200 BP, sedimentation has been dominated by chemical precipitation processes throughout the entire Holocene (Figure 4).

Diatoms

Diatoms were well preserved except in the lowermost section of the core (392 to 413 cm), where only a few frustule fragments were observed among clay particles. Assemblages were composed mainly of euryhaline freshwater or saline taxa (total of 74 species) typical of lakes with fluctuations in hydrology and salinity. Interestingly, several of the species identified from the sediment record of Lake U60 are also known to occur in marine environments (e.g., *Amphora acutiuscula, A. coffeaeformis, Chaetoceros muelleri*).

The CA axis 1 core samples were highly correlated with diatom-inferred salinity ($r = 0.93$, $P < 0.001$), indicating that this variable accurately reflects the dominant patterns of diatom variation in this core. This statistical interpretation was further supported by an examination of the distribution of the dominant taxa in the U60 core along gradients of salinity, dissolved inorganic carbon (DIC) and lake depth. Overall, two-thirds of the core samples had analogues among the 219 modern diatom assemblages, whereas those with poor (32) or no analogues (2) usually contained taxa whose maximum abundance (MA) was greater than those in the modern training set, including *Amphora acutiuscula* (MA in modern data set = 28%), *Chaetoceros muelleri* (MA = 63%), and *Cyclotella* cf. *choctawhatcheeana* (MA = 22%). Chrysophyte cysts were present in the sediments of U60, but were rare compared to the diatoms.

The five diatom zones shown in Figure 5 are based on major transitions in diatom species composition. Zone 1 is defined by the absence of whole diatom frustules prior to about 10 500 yr BP. Assemblages in zone 2 correspond to the period following

Table 3 Summary of average mineralogical characteristics of lithostratigraphic units (nd = not determined; np = not present)

	Unit 1	Unit 2	Unit 3	Unit 4	Unit 5	Core average
% Total clay minerals	56.2	4.4	2.5	3.8	1.5	4.9
% Quartz	13.6	1.1	0.3	0.9	0.1	1
% Total feldspar minerals	10.3	2.4	1.6	2.6	1.2	1.9
% Plagioclase	7.2	2.2	1.5	2.5	1.1	1.8
% K-feldspars	3.1	0.2	<0.1	<0.1	<0.1	0.1
% Amphibole minerals	1.1	<0.1	np	np	np	<0.1
% Total carbonate minerals	18.5	20.2	7.2	8.3	6.2	9.6
% Total calcite	5.3	0.9	0.6	1.7	0.6	0.9
% Low-Mg calcite	5.3	0.9	0.6	1.6	0.6	0.8
% Magnesian calcite	np	np	np	<0.1	np	<0.1
% Total dolomite	13.2	3.9	3.6	4.3	3.9	3.8
% Well-ordered dolomite	13.2	np	0.1	1.3	1.1	0.7
% Disordered dolomite	np	3.9	3.5	3	2.8	3.1
% Aragonite	np	14.8	3	2.2	1.3	4.6
% Total Mg carbonate minerals	np	0.3	np	0.1	0.2	0.2
% Total Na carbonate minerals	np	0.3	np	np	0.2	<0.1
% Total sulphate minerals	np	67.1	84.1	79	88.3	79.6
% Gypsum	np	np	np	4.8	7.7	3.4
% Total Mg sulphate minerals	np	50.9	62.5	56.9	59.7	57.3
% Total Mg + Na sulphate minerals	np	0.4	0.4	0.2	0.7	0.4
% Total Mg + K sulphate minerals	np	0.5	0.2	0.7	1.4	0.6
% Total Na sulphate minerals	np	0.1	0.4	0.4	0.5	0.3
% Total Na + Ca sulphate minerals	np	11.9	12.1	11.1	10.6	11.1
% Total Fe sulphate minerals	np	np	1.6	0.7	2.2	1.2
% Total other sulphate minerals	np	3.3	6.9	4.2	5.5	5.3
% Total phosphate minerals	np	np	3.5	2.7	<0.1	1
% Total chloride minerals	np	4.1	<0.1	1	0.6	1.6
% Total nitrate minerals	np	0.8	<0.1	0.1	<0.1	0.1
% Total borate minerals	np	np	np	1.5	1.9	0.1
% Allogenic mineral components	81.2	8.0	4.4	7.3	2.8	7.9
% Endogenic + authigenic fraction	18.5	92.2	95	92.6	97.2	92.0
% Moisture	29.9	50.6	61.4	58	63.7	57.1
% Organic matter	9.8	43.6	51.5	49.8	51.8	50.1
Sedimentation rate[1] (cm 100 yr^{-1})	1.9	2.1	3.6	3.7	7.2	3.4

[1] Calculated on the basis of a best fit line of depth versus time using the seven ^{14}C dates and assuming no interruption in deposition.

lake inception and are composed mainly of the centric diatom *Cyclotella* cf. *choctawhatcheeana* (5–87% of diatom sum). Valves and cysts (29–86%) of planktonic *Chaetoceros muelleri* form the main component within zone 3, but are accompanied by the salt-tolerant periphytic taxa *Cymbella pusilla* (3–31%) and *Amphora coffeaeformis* (2–22%).

Diatom zone 4 includes three subzones, the first of which is defined by the loss or decline of salt-tolerant taxa (e.g., *Chaetoceros*, *A. coffeaeformis*) and an increase in the diversity of less salt-tolerant diatoms (Figure 5). Both periphytic freshwater diatoms (e.g., *Achnanthes minutissima*, *Cocconeis placentula* var. *euglypta*) and halophilous species (e.g., *Cymbella pusilla*, *Craticula halophila* fo. 3 PISCES, *Navicula veneta*, *Nitzschia paleacea* and *Cyclotella meneghiniana*) are common in zone 4a. *N. paleacea* predominates throughout this zone (2–75%), along with isolated peaks of *C. meneghiniana* (41%; 300 cm) and *Amphora acutiuscula* (55%, 240 cm; 36%, 280 cm).

Subtle changes occur in diatom subzone 4b, with *Nitzschia paleacea* (4–70%), *Cymbella pusilla* (1–84%) and *Amphora acutiuscula* (1–64%) being the three principal taxa. *Cyclotella meneghiniana* is reduced to trace abundance within this subzone, whereas *A. acutiuscula* is more continuously represented in the sediment record. Irregular occurrences of the freshwater taxa within this subzone (e.g., *Gomphonema* cf. *clavatum*, *Cymbella angustata*, *Achnanthes minutissima*, *Fragilaria construens* var. *venter*) contribute to periods of low diatom-inferred salinity (Figure 5).

The boundary of diatom subzones 4b and 4c is marked by an abrupt increase in the relative abundance of *Amphora acutiuscula* (7–100%), which remains the predominant diatom throughout the last 2000 years in Lake U60. Other abundant diatoms include *Nitzschia paleacea* (1–73%) and *Cymbella pusilla* (1–65%). Periphytic freshwater taxa decline and occur only sporadically during zone 4c.

Uppermost diatom zone 5 is defined by a depauperate flora, consisting of few halophilous and freshwater diatoms and an overwhelming abundance of periphytic saline taxa (*Amphora acutiuscula*, *Cymbella pusilla*).

Fossil pigments

Carotenoids and chlorophylls are well preserved through most of the postglacial sequence of U60 (Figure 6). Undegraded labile pigments (Chl *a*, Chl *b*, fucoxanthin) were recovered from most intervals, while carotenoids characteristic of lakes with strong chemical stratification and deepwater anoxia were common. For example, pigments tentatively identified as okenone (purple sulphur bacteria) and isorenieratene (green sulphur bacteria) were abundant during much of the Holocene. Sediments from Lake U60 are also characterized by a high number of unidentified carotenoids and Chl derivatives (ex. X1, X2), a state also characteristic of a strongly stratified water column.

Organic matter-specific concentrations of ubiquitous pigments (Chl *a*, pheophytin *a*, β-carotene) decline five-fold from maxima in sediments 300–375 cm (pigment zone 1) to historical minima in the uppermost 90 cm of sediment (pigment zone 4; Figure 6). Changes in fossil concentrations do not arise from alterations in

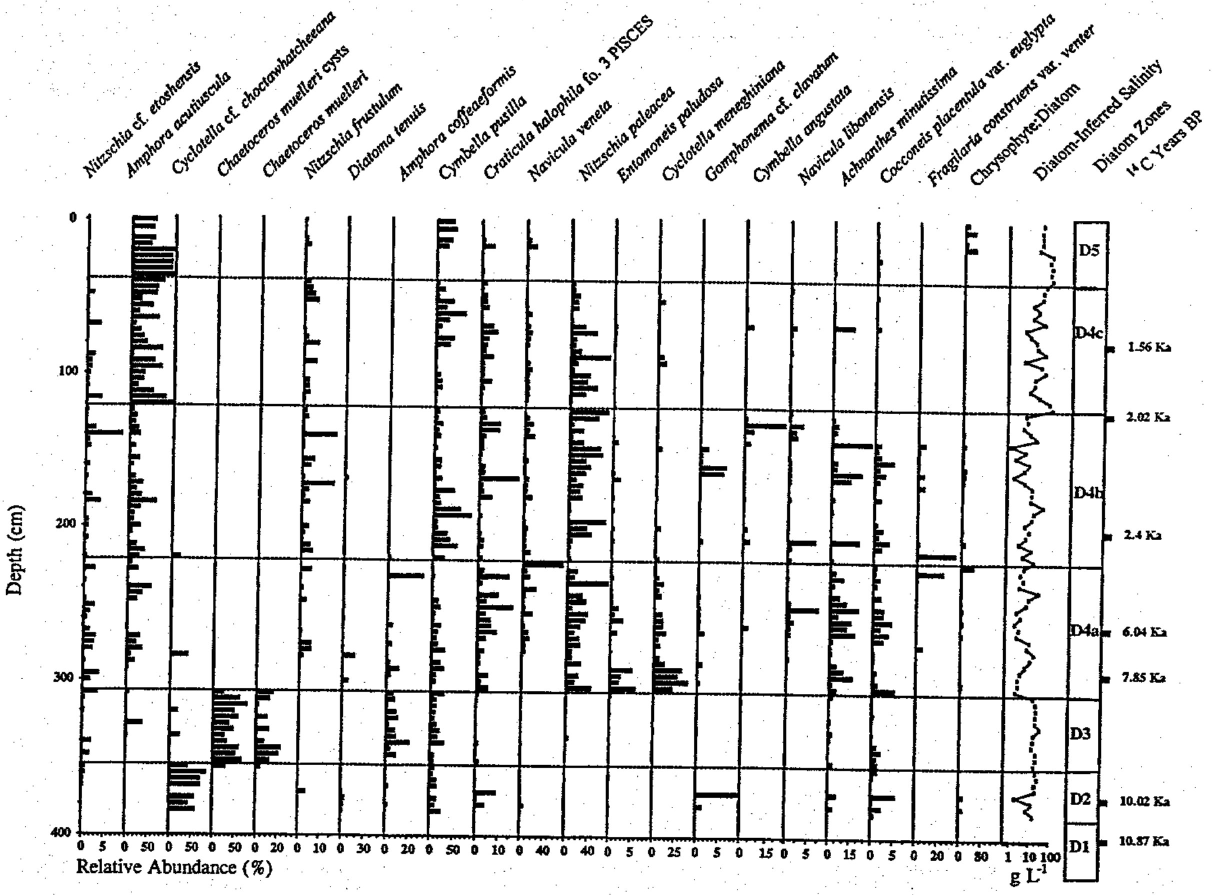

Figure 5 Summary diagram of the relative abundances (%) of the common diatom taxa in the Lake U60 sediment core. Diatom taxa are arranged, from left to right, in order of decreasing salinity optima as estimated by Wilson *et al.* (1996). Diatom-inferred lakewater salinity is shown to the right (using the Wilson *et al.*, 1996, transfer function). Diatom zones, shown on the right, are based on chord-distance constrained cluster analysis, based on diatom species assemblages (Grimm, 1987).

sedimentary organic content, which remained comparatively stable over the same period (52.46 ± 6.9%). Instead, reductions in concentrations of widely distributed pigments suggest that total algal abundance declined, particularly in the upper 200 cm of the core (pigment zones 2–4). Total algal abundance is inferred to be greatest during diatom zones 2 and 3, when planktonic *Cyclotella* cf. *choctawhatcheeana* and *Chaetoceros muelleri* are common (Figures 5 and 6).

Concentrations of most indicator carotenoids and Chl *b* show fossil profiles similar to those of ubiquitous pigments with core-wide maxima between 300 and 360 cm (pigment zone 1), declines to near-baseline levels during 260–290 cm (zone 3), and briefly elevated abundance (200–260 cm) before low concentrations in the uppermost 90 cm (Figure 6; zone 4). Pigments from cyanobacteria (myxoxanthophyll, lutein-zeaxanthin) decline less during the Holocene than do those of cryptophytes (alloxanthin), diatoms (diatoxanthin), chlorophytes (Chl *b*), sulphur bacteria (okenone, isorenieratene) and total algae (β-carotene). These patterns are consistent with the presence of abundant benthic mats of cyanobacteria within the lake at the present time (Pienitz *et al.*, 1992). Overall, pigments from N_2-fixing cyanobacteria (e.g., aphanizophyll) were rare through most of the Holocene record.

UVR-indicator compounds exhibit disjunct distributions within the sediments of Lake U60 (Figure 6). Photoprotective compounds produced by benthic algae (C_a, C_b) are present in detectable quantities only during the three intervals, 95–150 cm, 175–250 cm and 290–350 cm. When expressed as a fraction of the sum of chemically stable indicator carotenoids (alloxanthin, diatoxanthin, lutein-zeaxanthin), UVR-specific pigments are always <20%, suggesting that, while UVR may penetrate into Lake U60, irradiances were less than those typical of highly transparent lakes. Discontinuous changes in photoprotective pigments in Lake U60 suggest that the UVR environment of the lake has been highly variable during the past 10 000 years. In general, UVR penetration is inferred to be greatest in pigment zone 3 when ratios of C_a/carotenoids range between 5 and 15%.

Discussion

The application of diatom transfer functions, thermodynamic calculations and lake productivity inferences allow quantitative and qualitative reconstructions of past variations in lakewater salinity, ionic composition and physical characteristics. The almost continuous occurrence of salt-tolerant diatom taxa (e.g., *Amphora acutiuscula*, *Cymbella pusilla*) and soluble evaporite minerals throughout the sequence suggests that saline conditions prevailed during most of the Holocene. We believe this is primarily due to the hydrologic and climatic setting of the lake. However, the diatom-inferred palaeosalinity profile illustrated in Figure 7 in conjunction with sediment mineralogy and pigments reveal that, despite overall saline conditions during its 11 000-year history, Lake U60 had experienced frequent, rapid and synchronous fluctuations in salinity and brine composition, from which we infer four limnologic intervals driven by changes in climatic conditions, as follows.

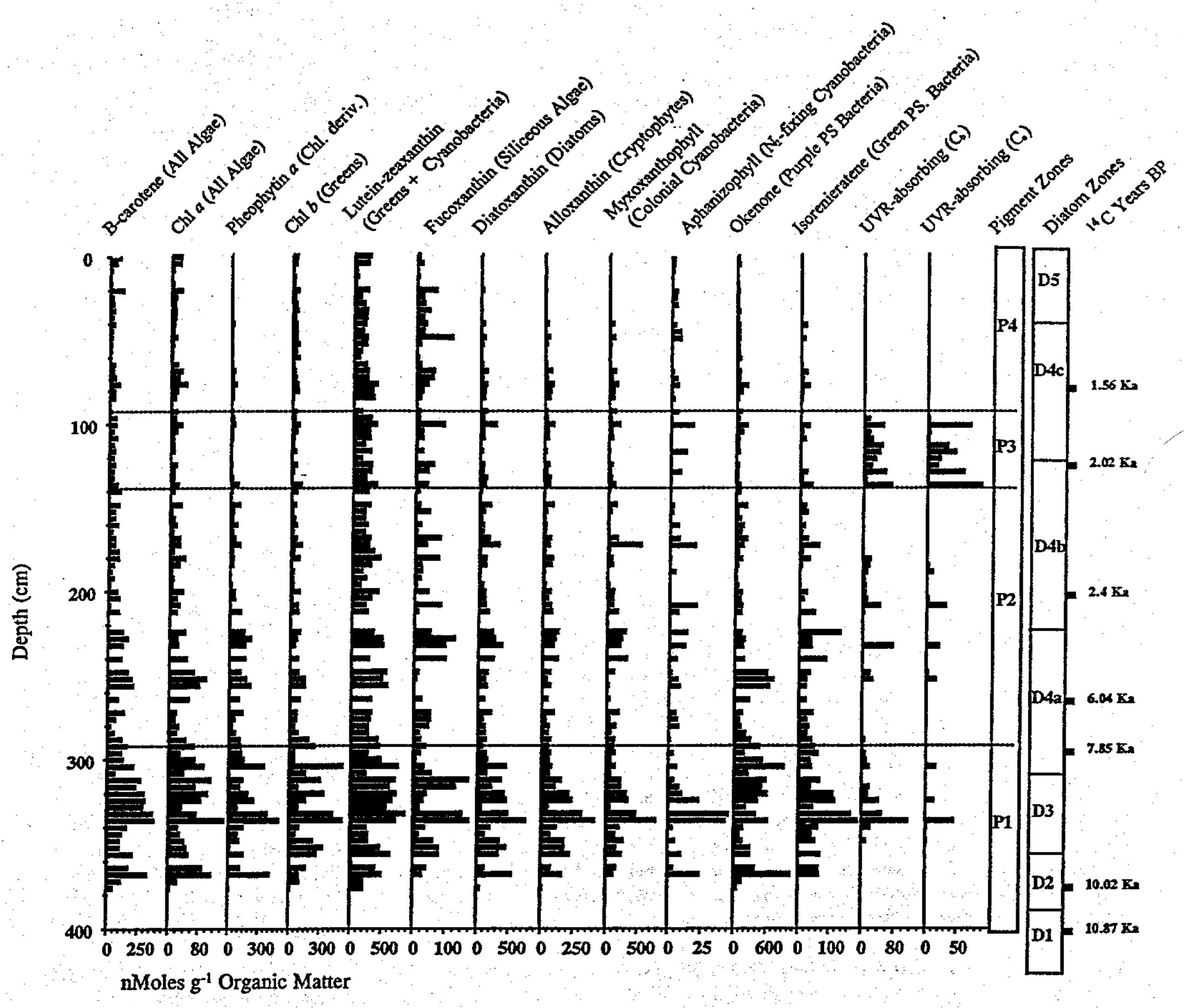

Figure 6 Summary diagram of fossil carotenoid, chlorophyll and pigment derivatives. All compounds expressed as nmol pigment g^{-1} organic matter. Organic content as weight loss-on-ignition. See text for taxonomic affinities. Pigment zones, shown on the right, are based on a chord-distance constrained cluster analysis, based on pigment assemblages (Grimm, 1987).

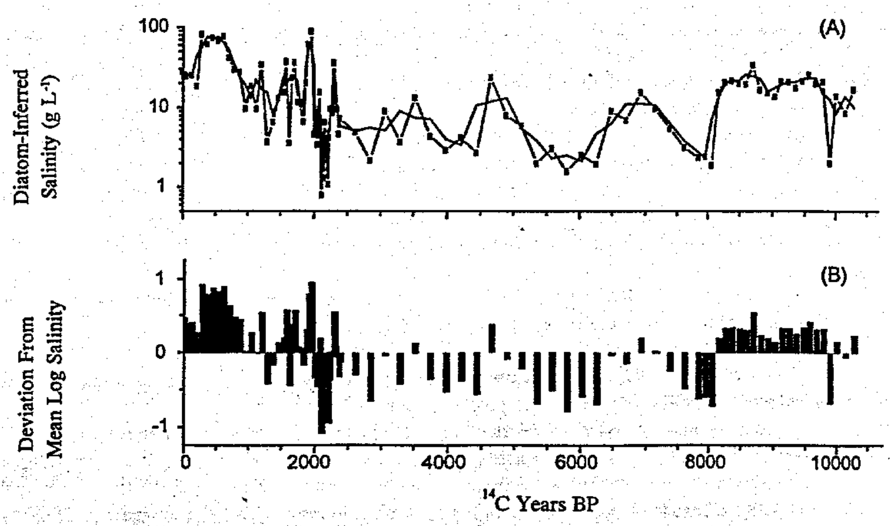

Figure 7 Diatom-inferred salinity (A) in Lake U60 presented on logarithmic scales owing to the logarithm-based derivation of the transfer functions (Wilson *et al.*, 1996). Average temporal resolution between samples in the mid-Holocene is 200 years. The solid line represents a three-point running average. (B) The deviation from mean log salinity (mean log salinity is 0.99 g L^{-1}) over the past 10 500 years.

Limnologic intervals

Interval I (c. 11 000–10 500 yr BP)

During this interval, Lake U60 was characterized as a moderately deep freshwater lake receiving high levels of clastic material, as indicated by the absence of soluble salts, abundant detrital minerals, low organic matter content, and fine particle sizes in this lowermost lithostratigraphic unit (392–413 cm). The absence of diatoms is consistent with strongly turbid, cool and nutrient-poor limnic conditions characteristic of this time interval at other western Canadian sites (e.g., Hickman and Reasoner, 1998; Bennett *et al.*, 2000). The combined evidence from all stratigraphic markers suggests either deposition in a basin fed by glacial meltwaters from the receding Laurentide Ice Sheet or deposition during a cool and dry climatic episode corresponding to the Younger Dryas (*c.* 10 800–10 000 yr BP) reported from Alaskan sites (Engstrom *et al.*, 1990; Peteet and Mann, 1994).

Interval II (c. 10 500–8100 yr BP)

The early Holocene period showed initially high diatom-inferred salinity values (~20 g L^{-1}), probably driven by low effective moisture and higher temperatures. For example, development of the Mg-Na-SO_4 brines and deposits of epsomite recorded here are known to occur in other hydrologically closed basins where evaporation exceeds inflow (e.g., Hawkins, 1985; Renaut, 1994). Dominant diatom species during this interval included *Cyclotella* cf. *choctawhatcheeana* and *Chaetoceros muelleri*, two planktonic taxa adapted for high salinity (optima = 20.3 and 17.9 g L^{-1}; Wilson *et al.*, 1996). According to Fritz *et al.* (1993; 1999), diatom assemblages dominated by *Cyclotella choctawhatcheeana* reflect mesosaline and meromictic conditions with specific conductivities ranging between 3 to 50 mS cm^{-1} and sulphate-chloride waters. The cause for the replacement of *Cyclotella* cf. *choctawhatcheeana* by *Chaetoceros muelleri* at the transition from diatom zone 2 to 3 (Figure 5) remains uncertain but may be related to changes in lake level or to variability in nutrient supply (cf. Saros, 1999) and/or ionic composition (see below) independent of salinity.

Fossil pigment concentrations exhibited maxima early in the Holocene (*c.* 10 000–8000 yr BP), suggesting that primary production was greatest shortly after the retreat of Wisconsin glaciers (Figure 6). In particular, concentrations of widespread pigments and their derivatives (β-carotene, Chl *a*, pheophytin *a*) were greatest *c.* 9000 yr BP, during the period of diatom-inferred hypersalinity and predominance by planktonic taxa. Elevated production early in the Holocene is known from other western Canadian saline (Bennett *et al.*, 2000), alpine (Hickman and Reasoner, 1998; Leavitt *et al.*, unpublished data), and temperate lakes (Hickman and Schweger, 1993). In particular, abundances of chlorophytes and cyanobacteria were great (as lutein-zeaxanthin), similar to patterns seen in other saline lakes (e.g., Vinebrooke *et al.*, 1998). Such patterns have been attributed to lake fertilization following mineralization of glacial tills (e.g., Brown *et al.*, 1984), although such a mechanism is unlikely to be important for Lake U60, as local tills are derived from the more ancient Reid Glaciation (*c.* 80 ka yr BP).

The presence of high concentrations of pigments tentatively identified as originating from phototrophic bacteria (e.g., okenone, isorenieratene) suggests that Lake U60 was strongly stratified between 10 000 and 8000 yr BP (Figure 6). These carotenoids are characteristic of obligately anaerobic purple (okenone) and green (isorenieratene) sulphur bacteria (Brown *et al.*, 1984) and are common in fresh and saline lakes where light penetrates to anoxic waters (Leavitt *et al.*, 1989; Hurley and Watras, 1991; Vinebrooke *et al.*, 1998). Because both okenone and isorenieratene were consistently present until about 2000 yr BP, and because organic content varies little, we infer that stratification and preservation characteristics remained relatively constant, and that changes in algal pigment concentration during the early and mid-Holocene mainly recorded changes in algal abundance rather than variability in pigment preservation.

The predominance of very soluble sulphate, halide and nitrate salts in lithostratigraphic unit 2 clearly indicated deposition in a hypersaline environment and was consistent with strong chemical stratification. The high diversity and range of evaporites supports an interpretation of a fluctuating brine composition during this interval, whereas the gradual increase in sulphate minerals at the expense of carbonates is a reflection of decreasing carbonate alkalinity (Figure 4), probably associated with increased salinity between 11 000 and 8000 yr BP. Similarly, the fine parallel lamination within this region (364–391 cm) suggests either relatively deep water or a meromictic water column, while the presence of aragonite and dolomite is consistent with chemical stratification of the water column (Last and Slezak, 1986; Last, 1993).

Interval III (c. 8100–2000 yr BP)

The mid-Holocene was characterized by a ten-fold reduction in lakewater salinity (2 to 15 g L^{-1}) as inferred from fossil diatoms (Figure 7). Inferred salinities also exhibited four major cycles of alternating fresh and saline conditions due to variations in the proportion of freshwater (e.g., *Nitzschia paleacea*) and euryhaline (*Cymbella pusilla* and *Amphora acutiuscula*) taxa. The calculated sedimentation rates varied by an order of magnitude within this interval, possibly reflecting variable sediment and organic matter inputs from catchment due to a more humid climate.

Mean concentrations of pigments from eukaryotic algae (alloxanthin, diatoxanthin, Chl *b*) declined more than those from cyanobacteria (lutein-zeaxanthin, myxoxanthophyll, aphanizophyll) following 8000 yr BP. However, community changes do not appear to have resulted solely from declines in salinity (Figure 7), as fresher waters generally favour fucoxanthin-containing algae (diatoms, chrysophytes) over cyanobacteria (Hammer, 1986; Evans and Prepas, 1996; Vinebrooke *et al.*, 1998). While abundance and diversity of grazing invertebrates are also known to increase in fresher waters (Williams *et al.*, 1990), concentrations of the grazing indicator pheophorbide *a* (Carpenter and Bergquist, 1985) were uniformly low and suggest that herbivores had little impact on primary producers in Lake U60.

Salinity values increased during four periods within the otherwise fresh interval of the mid-Holocene. In general, these diatom-inferred episodes correspond to the variations in the concentrations of the two photoprotective pigments (C_a and C_b; Figure 6) known to be produced by benthic algae in response to exposure to damaging levels of UVR (Leavitt *et al.*, 1997). Increased UVR exposure during saline episodes would be consistent with low water levels due to evaporative concentrations of U60. However, the relative abundance of UVR-specific pigments (<20%) was lower than values recorded for highly UVR-transparent lakes in alpine, Arctic, boreal and prairie lakes (Leavitt *et al.*, 1994; 1997) despite the shallow nature of U60, suggesting that factors other than lake morphometry (UVR path length) regulated UVR receipt by aquatic organisms (e.g., DOC, specific attenuation). Because these compounds are produced in proportion to the degree to which UVR penetrates a lake, changes in their fossil abundance are valuable indicators of past UVR environments in clear lakes (Leavitt *et al.*, 1997).

Mineralogical changes during the mid-Holocene were also consistent with moderate salinities and at least two intervals of fresher water (141–145 cm, 250–255 cm). Iron-phosphate minerals usually arise from diagenetic or hypolimnic reactions involving phosphate ions and poorly crystalline Fe/Mn oxides and hydroxides (Nriagu and Dell, 1974; Jones and Bowser, 1978; Dean, 1993), and are indicative of fresh but productive conditions and low alkalinity relative to the early Holocene. The reconstructed carbonate and calcium relative activity values (Figure 4) are low throughout this mid-Holocene period represented by unit 3 (7000–4200 yr BP). The dominance of Mg-sulphates indicates that high thermodynamic activities of Mg^{2+} and SO_4^{2-} were maintained at the sediment-water interface, whereas the well-bedded nature of the sequence suggests that chemical stratification was maintained during the mid-Holocene. Although the absence of soluble and sparingly soluble salts in the interval 141–145 cm indicates that a freshwater episode occurred at about 2200 yr BP, sedimentation during the last several millennia took place in a lake characterized by hypersaline Mg-SO_4 brines.

Interval IV (c. 2000 yr BP to present)

Unstable limnologic conditions characterize the past 2000 years (Neoglacial). Overall, palaeolimnologic changes imply a trend towards drier climatic conditions during most of the late Holocene, as only salt-tolerant periphytic taxa (e.g., *Amphora acutiuscula*, *Cymbella pusilla*) were present in these sediments. Early in the period salinity increased (Figure 7), culminating *c.* 500 years BP with maximum inferred salinity values of 70 g L^{-1}. This event may be coincident with the onset of the 'Little Ice Age' (about AD 1550–1850; Hughes and Diaz, 1994), cooling of the North Pacific (Jacoby *et al.*, 1994) that caused glacier advances in Alaska (Wiles and Calkin, 1994), timber-line retreats in the North American cordillera (Porter and Denton, 1967) and increased white spruce mortality at alpine tree-line sites in the western Northwest Territories and central Yukon (Szeicz, 1998). The timing of peak salinities in Lake U60 also roughly coincides with palaeoclimatic evidence of the sixteenth-century 'megadrought' that occurred throughout the western United States (reviewed in Woodhouse and Overpeck, 1998). Other lines of evidence also suggest that 'Little Ice Age' climatic conditions were dry and cold in Subarctic northwestern Canada (Bradley *et al.*, 1987; Szeicz, 1998). Palaeolimnologic conditions then reversed after *c.* AD 1500 to present, with sharp reductions in inferred salinity. However, Lake U60 waters remained highly saline relative to the mid-Holocene, and the diatom-inferred salinity for the most recent sediments (23 g L^{-1}) corresponds well with the actual salinity measured during sampling (26 g L^{-1}) and in July 1990 (22 g L^{-1}; Pienitz *et al.*, 1992).

Total algal abundance is inferred to have reached a Holocene minimum during the past 2000 years. Concentrations of most pigments, except those derived in part from chlorophyte (lutein-zeaxanthin, *b*-phorbins) and chromophyte algae (fucoxanthin), declined up to ten-fold, especially following 1000 yr BP (Figure 6). In particular, concentrations of alloxanthin (cryptophytes), diatoxanthin (diatoms), myxoxanthophyll (colonial cyanobacteria) and isorenieratene (Chlorobiaceae) were all reduced to near-undetectable values concomitant with historical maxima in inferred salinity (~70 g L^{-1}) and presumed cool temperatures during the 'Little Ice Age'. Increased abundance of green algae at the expense of filamentous cyanobacteria, flagellates and some diatoms (as fucoxanthin) in saline lakes has also been recorded in a survey of pigments in surficial sediments from 111 saline lakes in central British Columbia (Vinebrooke *et al.*, 1998). However, because concentrations of planktonic and fossil pigments do not vary as a function of lakewater salinity (Hammer, 1986; Evans and Prepas, 1996; Vinebrooke *et al.*, 1998), we believe that overall reductions in inferred biomass did not arise from the chemical influence of salinity but rather may reflect the loss of planktonic habitat following extensive declines in lake depth.

Lithostratigraphic analyses demonstrate that the ionic composition of sediments in U60 changed markedly during the past 2000 years, continuing trends which began *c.* 4200 yr BP. The occurrence of both gypsum and Mg-carbonates in unit 4 indicates that activities of Mg, Na and SO_4 decreased, whereas those of Ca and CO_3 increased, both *c.* 4200 and *c.* 1600 yr BP (Figure 4). Only during the most recent century have carbonate alkalinities and activities increased. In this context it is interesting to note that the inferred changes in brine composition in the history of Lake U60 may provide an explanation for shifts in diatom assemblages, such as the replacement of *Cyclotella* cf. *choctawhatcheeana* and *Chaetoceros muelleri* by *Amphora acutiuscula* and *Cymbella pusilla* in recent sediments (Figure 5).

Palaeoclimatic significance

Analyses of multiple climatic proxies from Lake U60 sediments demonstrate that an early-Holocene warm period was followed by an increase in effective moisture between *c.* 8000–2000 yr BP and the development of the modern semi-arid climate during the last two millennia. In general, such a pattern agrees with other palaeoenvironmental studies from the Yukon (e.g., Burn *et al.*, 1986; Cwynar, 1988; Cwynar and Spear, 1995; Keenan and Cwynar, 1992; Lacourse and Gajewski, 2000) and northern British Columbia (Hebda, 1995). For example, the early-Holocene mesosaline phase (*c.* 10 500 to 8100 yr BP) corresponds well with evidence from northwestern Canada (Ritchie *et al.*, 1983) and Alaska (Barnosky *et al.*, 1987; Anderson and Brubaker, 1993; Elias *et al.*, 1996) of greater summer warmth during the high-latitude insolation maximum, as predicted by the Milankovitch insolation cycles. According to Cwynar (1988), the southern Yukon experienced lower effective moisture and higher summer temperatures than at present, as reflected by the development of xeric (*Artemisia*) communities between 11 030 and 9250 yr BP. This early-Holocene warm summer climate coincides with increased melting of the Devon Island ice cap (Koerner and Fisher, 1990), a reduction in the spatial extent of Arctic sea ice (Dyke *et al.*, 1996) and increased thermokarst activity in northwestern Canada until about 8000 yr BP (Ovenden, 1990; Mackay, 1992; Burn, 1997; Vardy *et al.*, 1997).

The onset of the mid-Holocene freshwater phase (*c.* 8100 yr BP) in Lake U60 corresponds well with palynological and dendrohydrological signals of increased moisture and the development of spruce woodlands (*c.* 9250 yr BP; Cwynar, 1988; Cwynar and Spear, 1995) and forests (8500 to 8200 yr BP; Keenan and Cwynar, 1992; Lacourse and Gajewski, 2000) in the south and southwest Yukon, respectively, as well as in the Mackenzie Mountains of the western Northwest Territories (*c.* 8000 yr BP; Szeicz *et al.*, 1995). The dry period inferred from Lake U60 sediments for the late Holocene also matches similar climatic interpretations from south-central Alaskan lake records, suggesting colder but drier climate than today (Forester *et al.*, 1989). Overall, the more xeric climate during the late Holocene may be due to a decline in the frequency of penetration of coastal air masses into the arid interior plateaus of the Yukon.

Unlike some prior records, climatic interpretations from Lake U60 suggested that humid conditions may have prevailed for *c.* 2000 years longer than at some southwestern Yukon sites (Cwynar, 1988). In those studies, analyses of fossil pollen implied a moist period between 9250 and 4100 yr BP, with prolonged aridity beginning after 4000 yr BP and particularly dry periods after 2000 yr BP (*Pinus contorta* rise; Figure 4 in Cwynar, 1988). To the north of our location, Vardy *et al.* (1997) reported significantly reduced peat accumulation rates in Arctic tundra polygons during the past 4000 years. In contrast, our model of humid conditions until *c.* 2000 yr BP agrees with pollen inferences from central Yukon (Miller and Anderson, 1974), which indicate an initial period of cool and dry conditions from about 11 000 to 8000 BP, followed by a warm and wet 'thermal maximum' between 8000 and 2500 yr BP and a cooler, somewhat drier period (relative to the 'thermal maximum') after 2500 yr BP.

Correspondence between the timing of hydrologic changes reconstructed from the sedimentary record of Lake U60 and those recorded in saline lakes from the interior of British Columbia and Alberta (e.g., Mathewes and King, 1989; Schweger and Hickman, 1989; Heinrichs *et al.*, 1997; Lowe *et al.*, 1997) suggest that broad-scale climatic change produced the inferred limnological variations and that the changes reported from the Yukon through British Columbia to the Prairies may be time-transgressive. The timing of these changes is also consistent with those from western and central North America, suggesting possible climatic teleconnections between regions. In particular, the temporal agreement between the period of inferred effective moisture increase in the Yukon and northwest North America and the period of greater aridity in the central North America (Radle *et al.*, 1989; Fritz *et al.*, 1991; Dean *et al.*, 1996; Laird *et al.*, 1996; Wright, 1996) is consistent with proposed oceanographic and climatic linkages between the North Pacific and the central prairies (Mann and Hamilton, 1995). Specifically, Miller and Anderson (1974) suggest that changes in the position, strength and frequency of westerly cyclonic storms in the region (in particular storm tracks over the Gulf of Alaska) arise from changes in the oceanic influence on continental high pressure events over northern British Columbia and the southern Yukon. These interactions not only determine Yukon climate (Wahl *et al.*, 1987) but also influence the position of the jet stream and the transport of Gulf of Mexico moisture into the Great Plains region (Ting and Wang, 1997).

The frequent fluctuations in diatom-inferred palaeosalinity recorded in Lake U60 provide evidence for highly unstable mid- and late-Holocene climatic conditions in northwestern North America. Recent palaeoclimatic data from western Canada (Case and MacDonald, 1995; Bennett *et al.*, 2000) and Alaska (Eisner and Peterson, 1998) similarly suggest complex climatic patterns during the late Holocene. In this context it is worth pointing out that the pattern of palaeosalinity fluctuations displayed in Figure 7 followed roughly a ~1500- to ~2000-year periodic cycle during the mid-Holocene similar to other low-frequency climatic signals in the northern hemisphere (e.g., Dean, 1997; Mayewski *et al.*, 1997; Campbell *et al.*, 1998). As yet, neither an external forcing mechanism for these cyclic variations nor the climatic teleconnections alluded to above can be clearly defined from the study of U60. Consequently, future research should focus on elucidation of decadal to centennial-scale patterns of climatic variability and their causal mechanisms in studies from a sufficient number of these high-latitude saline sites, in order to improve the temporal and spatial resolution of the palaeorecords. Such high-resolution palaeolimnological data will not only improve our understanding of the extent, timing and causes of past climatic variability in continental parts of northwestern North America but will also help test and evaluate the climate models that are being developed as part of the Mackenzie Basin Impact Study and other research initiatives.

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