

Paleolimnology of Lake Manitoba: the Lithostratigraphic Evidence

Paléolimnologie du lac Manitoba ; les témoins

lithostratigraphiques

Paleolimnología del Lake Manitoba basada en datos litoestratigráficos

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Article abstract

Lake Manitoba, the largest lake in the prairie region of North America, is one of the most intensively studied lacustrine basins in western Canada. New AMS ^{14}C dating, together with mineralogical, geochemical, and lithostratigraphic analyses of the 14-m-thick, offshore sediment sequence, document a complex Holocene history in which water levels and limnological conditions were controlled by the interplay of changing climate, variable river and groundwater inflow, and differential isostatic rebound. Varves, ice-rafted debris, and clast-rich laminated sediment record deposition in the lake when the basin was part of proglacial Lake Agassiz. As Agassiz retreated northward, Lake Manitoba became isolated by about 8500 ^{14}C yrs BP, and for the next 800 years was characterized by mainly shallow water to dry conditions. Deeper and more stable water conditions returned to the Lake Manitoba basin by 7700 ^{14}C yrs BP probably due to the damming effect of differential isostatic rebound and decreasing aridity. For the next 3000 years, relatively stable lake levels and water compositions were maintained, reflecting a delicate balance between differential isostatic rebound, climate, inflow of the Assiniboine River, and groundwater contribution. At ~4500 ^{14}C yrs BP the Assiniboine River was rerouted to its present easterly path, by-passing Lake Manitoba, and resulting in loss of a significant component of the lake's hydrologic budget. Water levels dropped and the offshore sediments were once again subaerially exposed. By 3700 ^{14}C yrs BP, a cooler and wetter climate, together with continued southward transgression of water, compensated for the loss of fluvial input, resulting in reflooding of the basin. By about 2000 years ago the lake had evolved from a shallow, saline, and alkaline pool to its present depth and extent.

PALEOLIMNOLOGY OF LAKE MANITOBA: THE LITHOSTRATIGRAPHIC EVIDENCE

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ABSTRACT Lake Manitoba, the largest lake in the prairie region of North America, is one of the most intensively studied lacustrine basins in western Canada. New AMS ^{14}C dating, together with mineralogical, geochemical, and lithostratigraphic analyses of the 14-m-thick, offshore sediment sequence, document a complex Holocene history in which water levels and limnological conditions were controlled by the interplay of changing climate, variable river and groundwater inflow, and differential isostatic rebound. Varves, ice-rafted debris, and clast-rich laminated sediment record deposition in the lake when the basin was part of proglacial Lake Agassiz. As Agassiz retreated northward, Lake Manitoba became isolated by about 8500 ^{14}C yrs BP, and for the next 800 years was characterized by mainly shallow water to dry conditions. Deeper and more stable water conditions returned to the Lake Manitoba basin by 7700 ^{14}C yrs BP probably due to the damming effect of differential isostatic rebound and decreasing aridity. For the next 3000 years, relatively stable lake levels and water compositions were maintained, reflecting a delicate balance between differential isostatic rebound, climate, inflow of the Assiniboine River, and groundwater contribution. At ~4500 ^{14}C yrs BP the Assiniboine River was rerouted to its present easterly path, by-passing Lake Manitoba, and resulting in loss of a significant component of the lake's hydrologic budget. Water levels dropped and the offshore sediments were once again subaerially exposed. By 3700 ^{14}C yrs BP, a cooler and wetter climate, together with continued southward transgression of water, compensated for the loss of fluvial input, resulting in reflooding of the basin. By about 2000 years ago the lake had evolved from a shallow, saline, and alkaline pool to its present depth and extent.

RÉSUMÉ *Paléolimnologie du lac Manitoba ; les témoins lithostratigraphiques.* Le lac Manitoba, le plus grand lac des Grandes Plaines de l'Amérique du Nord, est l'un des bassins lacustres le plus intensément étudiés de l'Ouest du Canada. De nouvelles dates ^{14}C SMA, ainsi que des analyses minéralogiques, géochimiques et lithostratigraphiques de la séquence sédimentaire de 24 m d'épaisseur au large du rivage témoignent d'une évolution complexe du lac, à l'Holocène. Au cours de cette période, les niveaux lacustres et les conditions limnologiques ont été influencés par les effets combinés des changements climatiques, de la variation des apports d'eaux lacustre et souterraine et d'un relèvement isostatique différentiel. Les varves, les débris glaciels et les sédiments en lamines riches en éléments détritiques ont constitué l'apport sédimentaire au lac lorsque le bassin faisait partie du Lac glaciaire Agassiz. Après la vidange du lac glaciaire vers le nord, le lac Manitoba a été isolé vers 8500 BP ; pendant les 800 années suivantes, le lac était caractérisé par des eaux peu profondes et un climat sec. Des eaux plus profondes et plus stables ont caractérisé le lac vers 7700 BP, probablement en raison de l'endiguement qu'a entraîné le relèvement isostatique différentiel et une moins grande aridité. Pendant les 3000 années qui ont suivi, le niveau lacustre et la composition de l'eau sont demeurés relativement stables, reflétant ainsi le délicat équilibre entre le relèvement isostatique différentiel, le climat, la venue d'eau de la rivière Assiniboine et l'apport d'eau souterraine. Vers 4500 BP, la rivière Assiniboine a été redirigée vers l'est dans son cours actuel, évitant ainsi le lac Manitoba et réduisant grandement son apport sédimentaire au lac. Le niveau lacustre s'est alors abaissé et les sédiments au large du rivage ont de nouveau été mis à découvert. En 3700 BP, un climat plus frais et plus humide et une transgression lacustre continue ont compensé la perte d'arrivée d'eau et provoqué la submersion du bassin. Il y a environ 2000 BP, le lac est passé d'une mare peu profonde, salée et alcaline au lac profond et étendu actuel.

RESUMEN *Paleolimnología del Lake Manitoba basada en datos litoestratigráficos.* El Lake Manitoba, el mayor de los situados en las praderas de Norteamérica, es uno de los sistemas lacustres canadienses de los más estudiados. Datos recientes de datación con ^{14}C unidos a análisis mineralógicos, geoquímicos y litoestratigráficos de una secuencia sedimentaria de 24 m de grosor a lo largo de la ribera dan cuenta de una historia compleja durante el Holoceno. Durante este periodo el nivel de agua y las condiciones limnológicas fueron controladas por un efecto conjunto de cambios climáticos, flujo variable de la corriente y del agua del subsuelo además de un elevamiento diferencial isoestático. El conjunto de varvas, restos de hielo de sobreescurreamiento y los numerosos clastos laminares evidencian el momento en que la cuenca formaba parte del Lake proglacial Agassiz. La datación con ^{14}C sitúa hace unos 8500 años el retiro del Lake Agassiz hacia el norte y la separación del Lake Manitoba. Durante los siguientes 800 años este último sufrió una disminución del nivel de agua hacia condiciones de sequía. Posteriormente, hace unos 7700 años (^{14}C) la cuenca lacustre del Manitoba recobró niveles más profundos y estables, probablemente debido a un efecto de contención del agua causado por un elevamiento diferencial isostático y a una aridez decreciente. Durante los siguientes 3000 años, se mantuvieron una composición y un nivel del agua relativamente estables reflejando un balance frágil entre la elevación diferencial isostática, el clima, el aporte del cauce del Assiniboine River y del agua subterránea. Hace aproximadamente unos 4500 años (^{14}C) el Assiniboine River cambió su curso adoptando el patrón actual desplazado hacia el este, desviándose del Lake Manitoba y resultando en una pérdida de un componente importante del suministro hídrico del lago. El nivel de agua disminuyó y los sedimentos a lo largo de la ribera fueron nuevamente expuestos. La datación de radiocarbono correspondiente a hace unos 3700 años, revela un régimen climático más frío, unido a la transgresión continua del agua en dirección sur que compensó la pérdida del aporte fluvial, y que llevó a una nueva inundación de la cuenca. Finalmente hace unos 2000 años el lago pasó de ser una charca salina y alcalina hasta adoptar su tamaño y profundidad actuales.

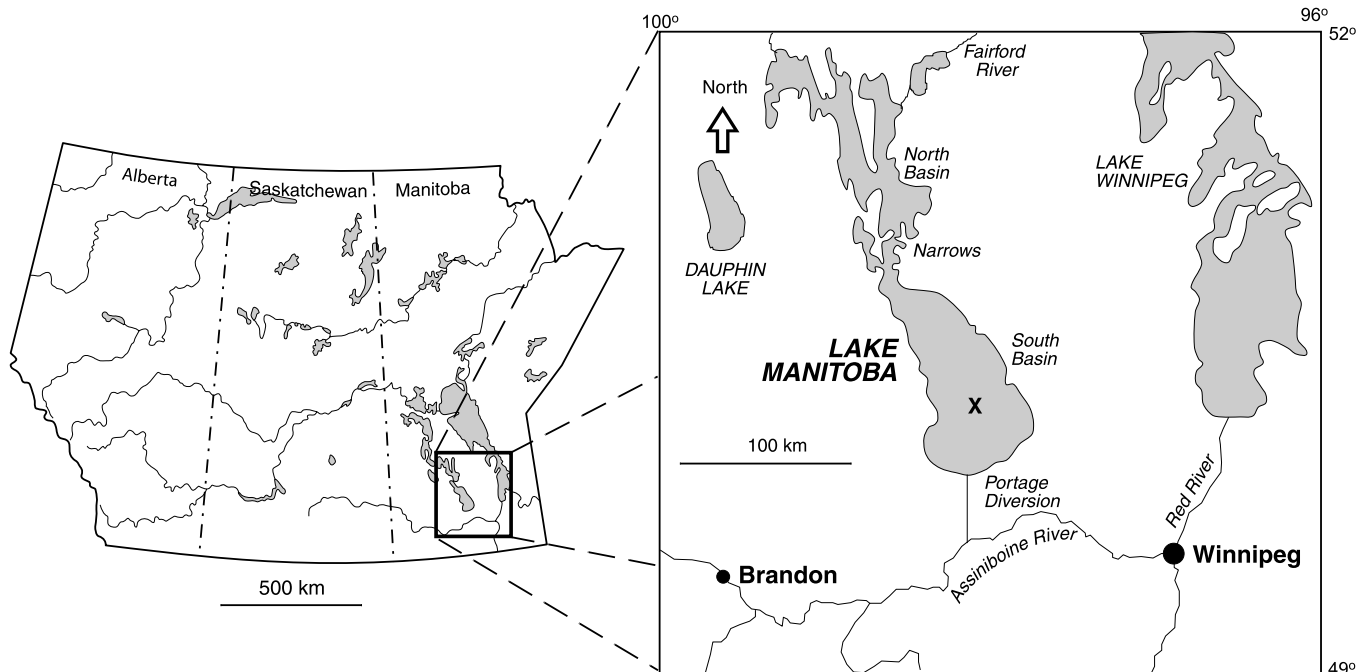


FIGURE 1. Map showing the location of Lake Manitoba in the northern Great Plains of western Canada, and the new long core (X).

Localisation du lac Manitoba, dans les Grandes Plaines du Nord, et site du carottage (X).

INTRODUCTION AND PREVIOUS WORK

The northern Great Plains of western Canada is a large (400 000 km²), semi-arid region that contains millions of lakes (Last, 1989). Most of these lakes are small and ephemeral prairie potholes or "sloughs", but the region also contains several of the largest permanent water bodies in western North America. The late Pleistocene and Holocene sediments preserved in these lakes collectively offer an exceptional opportunity to unravel the marked regional climatic and hydrologic variability that is inherent to this important agricultural area. Considerable recent effort has been made to decipher past regional environmental changes on the basis of multiple proxy investigations of these lacustrine records (Lemmen *et al.*, 1993; Vance and Last, 1994; Lemmen, 1996; Vance, 1997; Lemmen and Vance, 1999a), however only a few of the lakes in the northern Great Plains of Canada have provided complete, uninterrupted Holocene sequences. As discussed by others (*e.g.*, Schweger and Hickman, 1989; Yansa, 1995; Last, 1995, 2002), fewer than a dozen continuous lacustrine stratigraphic sections in the entire interior plains region extend back to the early Holocene.

Lake Manitoba, located on the eastern margin of the Great Plains (Fig. 1), is the largest lake in the Prairie region of North America. Because of its location astride the prairie-forest ecosystem boundary, it is ideally suited for paleoenvironmental investigation. Lakes in the more arid western part of the Plains region to the west of the Lake Manitoba basin are generally more saline, often ephemeral, and frequently contain incomplete Holocene stratigraphic records. Conversely, lake records from the freshwater basins lying to the east in the rel-

atively humid Precambrian Shield area of Manitoba and northwestern Ontario are generally characterized by little stratigraphic variability and thin Holocene sequences.

Relative to other large lakes in western Canada, our knowledge of modern Lake Manitoba is extensive. Numerous biological and geolimnological surveys have been carried out over the past fifty years (Kennedy, 1949; Lakes Winnipeg and Manitoba Board, 1958; Boyd, 1972; Crowe, 1974a; Tudorancea, 1975; Tudorancea *et al.*, 1979; Derksen, 1978; Last, 1982, 1984). The modern hydrological setting of the basin is also well documented (Galay, 1964; Hochbaum, 1967; Burrows, 1970; Crowe, 1974b; Jenkins, 1974; International Garrison Diversion Study Board, 1976; Kenny, 1978, 1985), and the lake has a long record of water chemistry monitoring (Cober, 1968; van Everdingen, 1971; Crowe, 1972; Williamson, 1996).

With nearly 120 m of sediment core collected from 61 locations in the main south basin of the lake, the stratigraphic record of Lake Manitoba has also been the subject of considerable study (Teller and Last, 1979, 1981, 1982, 1990; Last and Teller, 1983; Nambudiri and Shay, 1986; Pip, 1990; Last *et al.*, 1994). These previous stratigraphic studies, while based on conventional radiocarbon dating of bulk lake sediment samples, which may have produced an unreliable chronology (Nambudiri *et al.*, 1980), all indicate that the late Pleistocene and Holocene history of the lake is exceedingly complex due to the interplay of differential isostatic crustal rebound, fluctuating climate, and variable river inflow. As well, the early history of the Lake Manitoba basin was controlled by variations in glacial Lake Agassiz because it was part of this extensive proglacial

water body. In an effort to better resolve the details of this history, and to provide a more accurate radiocarbon chronology for this large lake, a new coring program was initiated.

The objectives of this paper are to report the results of lithostratigraphic studies of these new cores and to integrate them with previous studies. Physical, mineralogical, geochemical, and selected biological studies, as well as AMS radiocarbon dating now provide a more substantial basis from which past hydrologic fluctuations, drainage basin characteristics, and regional climatic changes are inferred. Further complementary investigations directed toward reconstructing late Pleistocene and Holocene lake-level and water quality parameters from biostratigraphic and stable isotope geochemical analyses of these new cores are found in Curry *et al.* (1995), Curry (1996, 1997), Ito *et al.* (1996), and Risberg *et al.* (1999).

SETTING

Lake Manitoba is located at the eastern margin of the northern Great Plains of Canada, approximately 100 km from Winnipeg, Manitoba (Fig. 1). This region experiences a cold, semi-arid, continental climate, with an average annual precipitation of 410 mm and a mean annual temperature of 2.1 °C. Evaporation exceeds precipitation by a factor of about 2 (CNC/IHD, 1978). The lake occupies a shallow glacier-eroded, NW-SE oriented trough and is underlain by a thin sequence of Paleozoic carbonates and evaporites. Mesozoic and Tertiary shales, sandstones, and coals outcrop in the Manitoba Escarpment a short distance to the west. The bedrock is mantled with a variable thickness of unconsolidated Pleistocene glacial and glaciolacustrine sediments reaching thicknesses of greater than 100 m just south of the basin (Teller, 1976a). At the north end of the lake, Pleistocene deposits are thin and irregular.

Lake Manitoba covers an area of 4 706 km², and is divided into a North Basin and a South Basin separated by a kilometre-wide constricted area termed the Narrows. The shoreline and bathymetry of the relatively small North Basin are very irregular and bedrock controlled, whereas the large South Basin has a smooth shoreline and flat bottom topography. Despite its large size, the South Basin has a mean depth of only 4.5 m and a maximum depth of 6.3 m.

The natural watershed of the basin is large (~80 000 km²) and drains a sparsely populated area of mainly aspen parkland to the northwest of the lake. The hydrologic budget is dominated by river inflow from the Waterhen River, which enters the North Basin, and by direct precipitation. Several smaller streams, including the Portage Diversion, a flood control structure designed to carry water from the Assiniboine River northward into Lake Manitoba, contribute water to the South Basin. Groundwater inflow to the lake probably comprises less than 5 % of the total influx (Last, 1984). Water leaves the lake mainly by evaporation and by overflow to the northeast via the Fairford River to the northern Lake Winnipeg basin. Lake Manitoba water is alkaline (pH=9) and hyposaline (850-7000 ppm total dissolved solids). Water composition is dominated by Na⁺ and Cl⁻ ions, with secondary abundances of Mg²⁺ and HCO₃⁻. The modern offshore sediments in the main

South Basin of the lake consist of calcareous and organic-rich clayey silt and silty clay. Seasonally high levels of organic productivity, combined with an elevated Mg/Ca ratio in the lake water, result in the addition of primary, inorganically precipitated magnesian calcite (Last, 1982).

METHODS

Long cores were previously collected and studied from three sites in the Lake Manitoba basin using Shelby tube hollow stem augering techniques (Teller and Last, 1979). A new, 14.5 m long core (S-1; located at 50° 26' 42" N, 98° 15' 43" W) was collected in 5.7 m of water during the winter season from a location near the centre of the South Basin (Fig. 1) using a combination of split spoons and Shelby tubes. Overall, core recovery was good except in the upper metre and between about 7 and 9 m depth where less than 40 % of the section was retrieved. The coring site was located within 5 km of the D-1 core site reported by Teller and Last (1981).

Because of poor recovery in the very soft upper few metres of core S-1, a second, 5 m long core (V-1) was collected from the same location using a 7.6-cm (3-inch) diameter vibracorer. The vibracoring technique normally compacts the sediment by about 20-25 % (Glew *et al.*, 2001). Thus, to assemble a composite section from the two cores, the depths of core V-1 were adjusted on the basis of detailed correlation with core S-1 using moisture content, organic matter content, grain size, and mineralogy. Figure 2 shows the correlation between cores S-1, V-1, and D-1.

After collection and extrusion, the cores were split longitudinally, described, and subsampled for various physical, geochemical, and biological analyses. The vibracore was also photographed (visible and X-radiography) before subsampling. Samples for moisture content, organic matter content, total carbonate content, particle size, and mineralogy were taken at approximately 5 cm intervals from V-1 and 10 cm intervals from S-1. Where bedding or other sedimentary features dictated, closer sample spacing was used. Moisture, organic matter, and total carbonate mineral contents were evaluated by weight loss on heating to temperatures of 85 °C, 500 °C, and 1 000 °C, respectively. Particle size spectra for each subsample were determined using an automated laser-optical particle size analyser (Galai CIS-1; Last, 2001a) after removal of organic matter by hydrogen peroxide treatment; duplicate samples were prepared and analyzed every 25 samples and a standard run every 50 samples. These replicate analyses indicate precision of the particle size data is approximately ±4 %.

All samples analyzed for mineralogy were air-dried at room temperature, disaggregated in a mortar and pestle, and passed through a 62.5 µm sieve. Bulk mineralogy, clay mineralogy, and detailed carbonate and evaporite mineralogy were determined using standard X-ray diffraction techniques. Percentages of the various minerals were estimated from the bulk mineral diffractograms using the intensity of the strongest peak for each mineral as outlined by Last (2001b). Non-stoichiometry of the dolomite and calcite was determined by examining the displacement of the d₁₀₄ peak on a detailed (slow) XRD scan and calculated according to Hardy and Tucker (1988). Duplicate

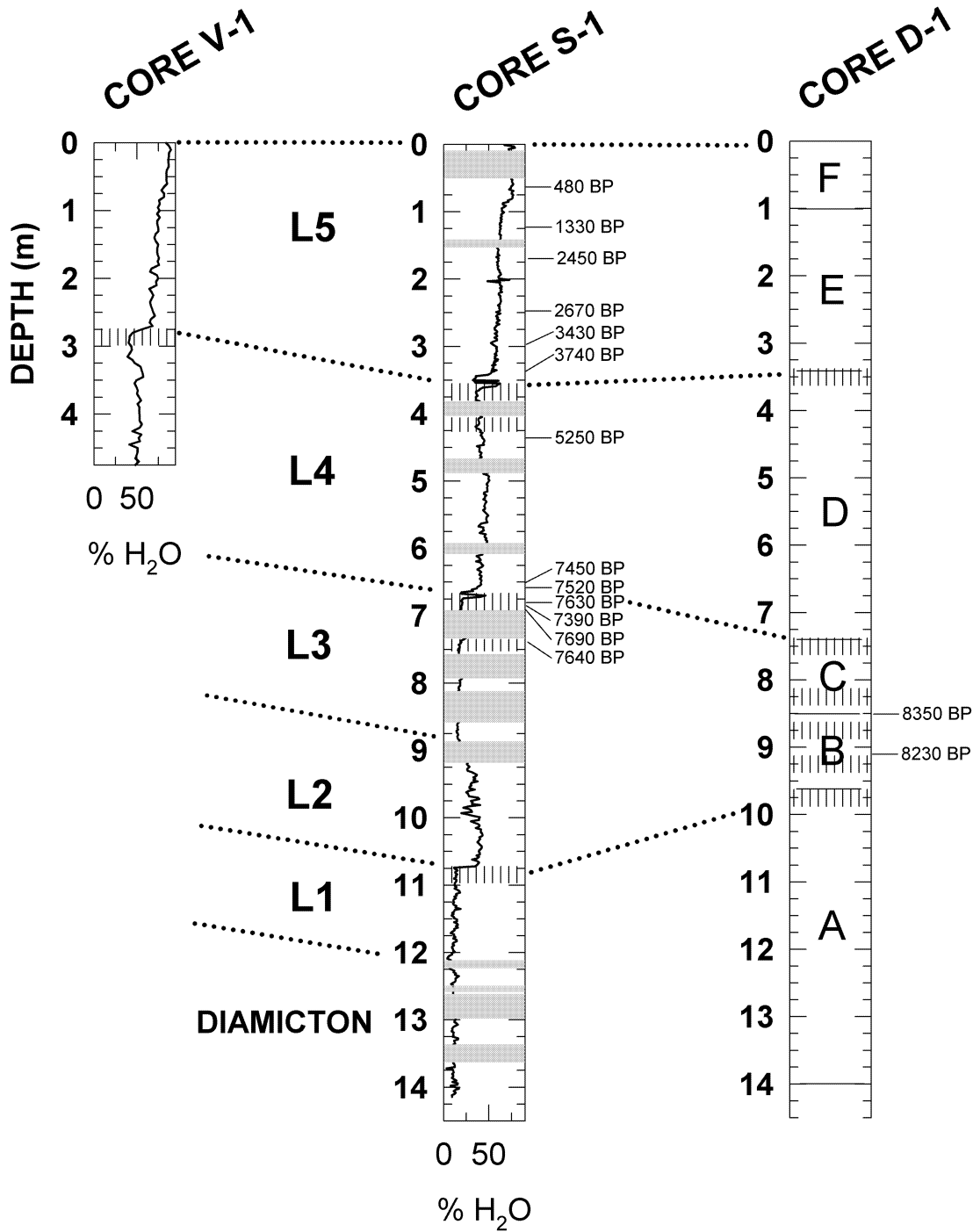


FIGURE 2. Stratigraphic sections from Lake Manitoba showing the lithostratigraphic correlation between core V-1 (vibracore), S-1 (Shelby-tube supplemented by split spoon core) and D-1 (Shelby-tube core, reported by Teller and Last, 1981). Correlations were made on the basis of moisture content, organic matter content, grain size, and mineralogy, however, only the variation in moisture content is shown here for V-1 and S-1. New AMS radiocarbon dates are also shown. The shaded sections in S-1 are missing core sections; the vertically-lined sections in D-1 and S-1 represent basin-wide dry pedogenic zones (see text for discussion).

Coupes stratigraphiques faites au lac Manitoba montrant les corrélations lithostratigraphiques entre les carottes V-1 (carottier à vibrations), S-1 (tube Shelby et carottier à cuiller) et D-1 (tube Shelby, dans Teller et Last, 1981). Les corrélations sont fondées sur la teneur en humidité et en matière organique, la granulométrie et la minéralogie (pour V-1 et S-1, seule la variation de la teneur en humidité apparaît). Les nouvelles dates ¹⁴C SMA sont également données. Les bandes tramées avec un grisé en S-1 représentent des parties de carotte manquantes ; les bandes tramées avec des lignes verticales en D-1 et S-1 identifient les zones pédogénétiques sèches présentes à la grandeur du bassin (voir le texte).

samples were prepared and analyzed for bulk mineralogy every 10 samples. These replicate analyses indicate precision of the mineralogical data is approximately $\pm 8\%$.

The $\delta^{13}\text{C}$ stable isotope composition of organic matter was measured for the finer than $62.5\ \mu\text{m}$ fraction of 29 samples (approximately 20 cm sample spacing) from core V-1 using a VG PRISM mass spectrometer and standard preparation methods (Ito, 2001). The same samples were also analyzed for organic carbon (OC) content and Rock-Eval pyrolysis using a Rock-Eval III analytical unit (Peters, 1986). The isotopic data are reported as per mil (‰) deviation relative to Pee Dee belemnite (PDB) marine-carbonate standard. The Rock-Eval pyrolysis data reported here are the Hydrogen Index (HI; S_1 pyrolysis peak normalized to the organic carbon content), Oxygen Index (OI; S_3 pyrolysis peak normalized to the organic carbon content), and Tmax (temperature at which the maximum hydrocarbon yield occurs). The HI and OI are broadly correlative with the atomic H/C and O/C ratios (Tissot and Welte, 1984).

Ostracode shells (mostly *Candona rawsoni*) from 12 samples and charcoal from one sample of core S-1 were radiocarbon dated. In addition, to help establish a basis of correlation with previously collected cores, three samples of ostracods and mollusks from core D-1 of Teller and Last (1981) were dated. In an effort to evaluate the magnitude of possible errors associated with the "hard water" effect, a serious concern in the prairie environment (Mott, 1973; Barnosky *et al.*, 1987; Vance, 1991) and to avoid the contaminating effect of atomic

bomb activity, a sample of mollusc shells (*Andonta grandis simpsonia*) collected in 1897 from the lake was also dated.

RESULTS

RADIOCARBON DATES

The results of ^{14}C analysis of samples from core S-1 and D-1 are shown in Table I and Figure 2. All dates except those from core D-1 are AMS dates. The mollusk shell collected from the modern lake in 1897 yielded a ^{14}C date of 170 ± 60 BP, indicating that the hard water effect on carbonate radiocarbon dates in the modern lake is about 120 years. Because of the paucity of identifiable woody or vegetal matter in the Lake Manitoba cores (needed to minimize the problem of dating "old" detrital organic material; Nambudiri *et al.*, 1980), we chose to date ostracode shells, acknowledging the potential for contamination by the hard water effect. A ^{14}C date of 7450 ± 680 on charcoal, however, is similar to a date of 7520 ± 90 on ostracode calcite in the same interval, suggesting a minimal hard water effect at this time. The base of our new AMS dating was, therefore, limited by the presence of ostracodes (*cf.* Curry, 1997). The date of 4040 from 1 052-1 060 cm in D-1 is rejected because it is so clearly out of stratigraphic sequence. Similarly, the date of 4730 at 552-562 cm in core S-1 is about a metre below a date of 5250 (Table I), so it too is rejected (see also Risberg *et al.*, 1999). Although not

TABLE I
Lake Manitoba AMS radiocarbon age determinations

Depth (cm)	Lab No.	Material	^{14}C age (BP)
Modern (collected 1897)	TO-4289	mollusks	170 ± 60
53	TO-5820	ostracodes	480 ± 50
124-126	TO-4242	ostracodes	1330 ± 60
173	TO-5819	ostracodes	2450 ± 50
248-50	TO-4243	ostracodes	2670 ± 70
297	TO-5818	ostracodes	3430 ± 80
330	TO-5817	ostracodes	3740 ± 50
425-435	TO-5879	ostracodes	5250 ± 80
552-562	TO-5878	ostracodes	4730 ± 80
648-660	TO-4244	ostracodes	7520 ± 90
649-653	TO-5816	charcoal	7450 ± 680
678	TO-5815	ostracodes	7630 ± 130
682	TO-5814	ostracodes	7390 ± 90
690-694	TO-5813	ostracodes	7690 ± 70
730-734	TO-5877	ostracodes	7640 ± 60
848-850 (from core D1)	OS-02658	ostracodes	8350 ± 50
900-913 (from core D1)	OS-00063	mollusks	8230 ± 100
1 052-1 060 (from core D1)	OS-02659	ostracodes & mollusks	4040 ± 40

specifically dated, the base of the lacustrine sequence in the core is assumed to reflect the time when the Laurentide Ice Sheet last retreated from the basin.

CORE DESCRIPTION

Physical Properties

The postglacial sedimentary sequence recovered in cores S-1 and V-1 consists mainly of massive, calcareous, dark grayish brown to olive gray, clayey silt. The uppermost 3 m is soft to gelatinous, with relatively high moisture and organic matter contents (Fig. 3). The sediment becomes firmer with depth corresponding to a general decrease in moisture content. The lower 2 m of the section is a firm, dry, dark brown (Munsell: 10YR4/2 to 10YR5/3), stony diamicton that is very poorly bedded. Small clasts and pebbles are common to abundant throughout the lower 5 m but absent above about 9 m depth. In addition, the interval between about 11 and 12 m consists of silt and clay rhythmites averaging about half a centimetre thick and composed of alternating clast-rich and clast-poor clayey laminae. Faint light-dark banding and indistinct laminae occur at 6.0-6.5 m and 3.0-3.5 m. Overall, there is little systematic variation in mean grain size, however, above 3 m depth the core shows a slight coarsening upward and an increase in silt content.

As discussed by Teller and Last (1981) for the older cores (e.g., D-1), superposed on the gradual trend of decreasing moisture content with depth are several intervals characterized by dramatic drops in moisture over very short stratigraphic distances. For example, within the 5 cm interval between 345 cm and 350 cm depth, moisture content decreases downward from over 60 % to about 40 %. Sharp decreases of similar magnitude occur at depths of 664 cm and 1 093 cm. Corresponding to each dry zone, the sediment exhibits a distinct fine angular blocky to granular structure, a mottled and gleyed colour, and a sharp upper contact and gradational lower contact.

Mineralogy

The inorganic fraction of sediment is dominated by clay minerals (average: 53 %) and carbonate minerals (31 %), with lower but subequal proportions of quartz (8 %) and feldspar minerals (8 %) (Fig. 4, Table II). Gypsum, pyrite, and various amphibole minerals also occur sporadically through the sequence. Although not common, where present, gypsum can comprise as much as 20 % of the sediment sample.

As can be seen in Figure 4, carbonate minerals that occur in the Lake Manitoba stratigraphic sequence are surprisingly diverse. Stoichiometric, well-crystalline dolomite dominates throughout the entire section, making up about 20 % of the sediment. Normal (low-Mg) calcite occurs in most samples below about 9 m depth and sporadically in the upper half of the section. Magnesian calcite (calcite with more than 4 mol % MgCO_3 incorporated into the crystal), nonstoichiometric, poorly-ordered dolomite ("protodolomite"), aragonite, and magnesite are also present in the upper 10 m. The Mg-calcite shows a broad range of composition, from about 4 to 16 mol % MgCO_3 , whereas the disordered dolomite has a narrow composition, averaging about 15 mol % excess CaCO_3 .

The clay mineral assemblage (Fig. 5) is dominated by illite (59 % of clay minerals), with lesser proportions of expandable lattice and mixed layer clays (18 %), chlorite (17 %) and kaolinite (6 %). These relative proportions show little stratigraphic variation except in the uppermost ~3 m in which the clays have a higher content of expandable minerals and a concurrent decrease in other clay mineral types.

The mineral suite in Lake Manitoba sediment comprises three *genetic* types of inorganic components. The detrital (allo-genic) fraction, which dominates the sedimentary sequence, consists of quartz, feldspars, clay minerals, amphiboles, low-Mg calcite, and dolomite (Fig. 4). Most of this material is derived from erosion of the surrounding glacial deposits and soils, and was transported into the basin by fluvial and sheet-wash processes. The endogenic component of the sediment is that material which is generated within the water column of the lake by either inorganic or bio-induced precipitation. Magnesian calcite dominates this fraction (Fig. 4). Aragonite, as well as a small amount of biologically-precipitated low-Mg calcite, can also be present either as bioclastic shell material or as inorganically precipitated minerals. Finally, the authigenic fraction of the sediment, originating as diagenetic products of reactions within the muds themselves or at the sediment-water interface, consists of pyrite, gypsum, protodolomite and magnesite.

There are several stratigraphic trends in these mineralogical constituents over the length of the Holocene section. Abundances of the various detrital carbonate (dolomite, calcite) and siliciclastic (quartz, K-feldspar, plagioclase) components all tend to decrease upward in the section and are significantly correlated with one another (linear correlation coefficients significant at 0.99 confidence level). The endogenic magnesian calcite, organic matter, and clay minerals covary and are inversely correlated with variations in quartz, feldspars, calcite, and dolomite. Within the detrital components, the ratios of quartz to total siliciclastics (the siliciclastic weathering index in Fig. 3) and plagioclase to total feldspars (the feldspar weathering index in Fig. 3) both show a general increase (*i.e.*, greater weathering intensity) upward in the section.

Organic and Isotope Geochemistry

Similar to the trend in organic matter, the organic carbon content of the upper half of the stratigraphic sequence in Lake Manitoba increases upward (Fig. 6). The $\delta^{13}\text{C}$ composition of this C_{org} ranges from -34.7 ‰ to -30.4 ‰ (mean: -32.8 ‰). Below about 3.5 m depth, the organic matter is depleted with respect to ^{13}C while above 3.5 m the organics are relatively enriched but show a gradual decreasing upward trend. The stratigraphic trends in Hydrogen Index (HI) and Oxygen Index (OI) are inversely related, with the HI showing a general decrease upward in the section to 3.5 m depth and an increase upward to the top of the core. The minimum HI and maximum OI occur in the dry pedogenic zone at 3.46-3.6 m. This zone also shows strongly depleted $\delta^{13}\text{C}$ values for C_{org} . Finally, T_{max} is low (<425 °C) and unvarying throughout the section, except for somewhat elevated temperatures in samples from the low-moisture zones.

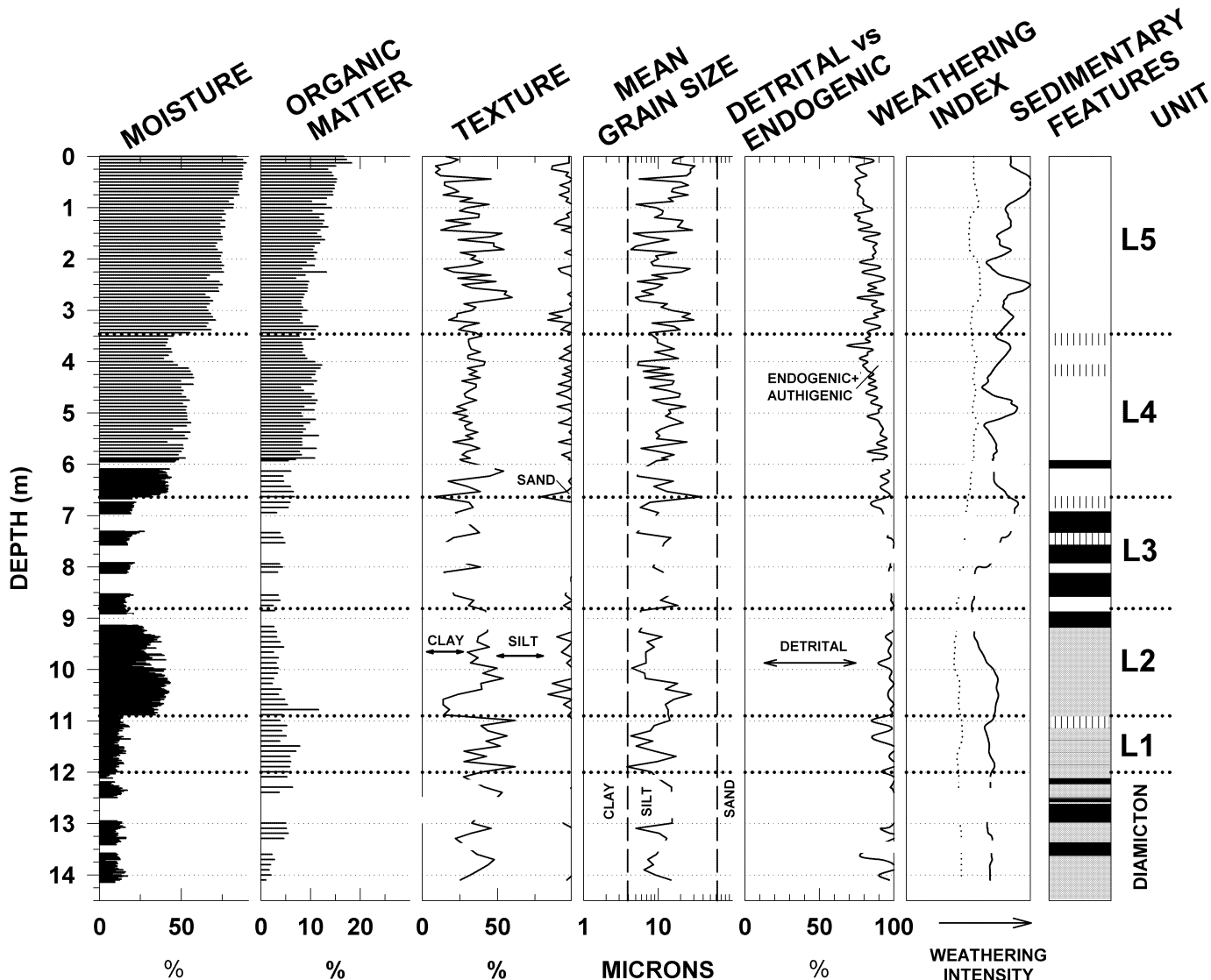


FIGURE 3. Stratigraphic variation in moisture content, organic matter content, texture and mean grain size, proportion of detrital versus endogenic+authigenic mineral components, weathering indices, and sedimentary structures in cores S-1 and V-1; see text for specific definitions of parameters measured. Also shown are the lithostratigraphic units recognized in the cores. Gaps and spaces in the profiles indicate missing samples and the solid black shaded areas in the Sedimentary Features column indicate missing core sections. Vertical hash-marks in the Sedimentary Features column indicate dry, pedogenic zones; sections with horizontal lines indicate rhythmic bedding; grey shading indicates the occurrence of oversized pebbles and granules; no symbol or shading indicates the core is structureless or massive. The Weathering Indices shown are: siliciclastic index (ratio of quartz to total siliciclastic content; solid line) and feldspar index (ratio of plagioclase to total feldspar content; dotted line).

Variations stratigraphiques de la teneur en humidité et en matière organique, de la texture et de la granulométrie, de la proportion entre composants minéraux détritiques et endogènes+authigènes, des indicateurs d'altération et des structures sédimentaires dans les carottes S-1 et V-1 (caractéristiques des paramètres dans le texte). Apparaissent aussi les unités lithostratigraphiques observées dans les carottes. Les espaces vides dans les profils correspondent à des échantillons manquants et les bandes noires dans la colonne des Sedimentary Features identifient des parties de carottes manquantes. Les bandes tramées avec des lignes verticales, dans la même colonne, correspondent aux zones pédogénétiques sèches. Les lignes horizontales dans certaines coupes indiquent une stratification rythmique. Les trames avec un grisé indiquent la présence de cailloux et de granules qui ne passent pas au tamis. Aucun symbole ou trame n'indique que le matériel d'une carotte est massif ou non structuré. Les Weathering Indices illustrés sont l'indice siliciclastique (taux de quartz sur la teneur siliciclastique totale ; ligne pleine) et l'indice feldspathique (taux de plagioclase sur la teneur feldspathique totale ; pointillé).

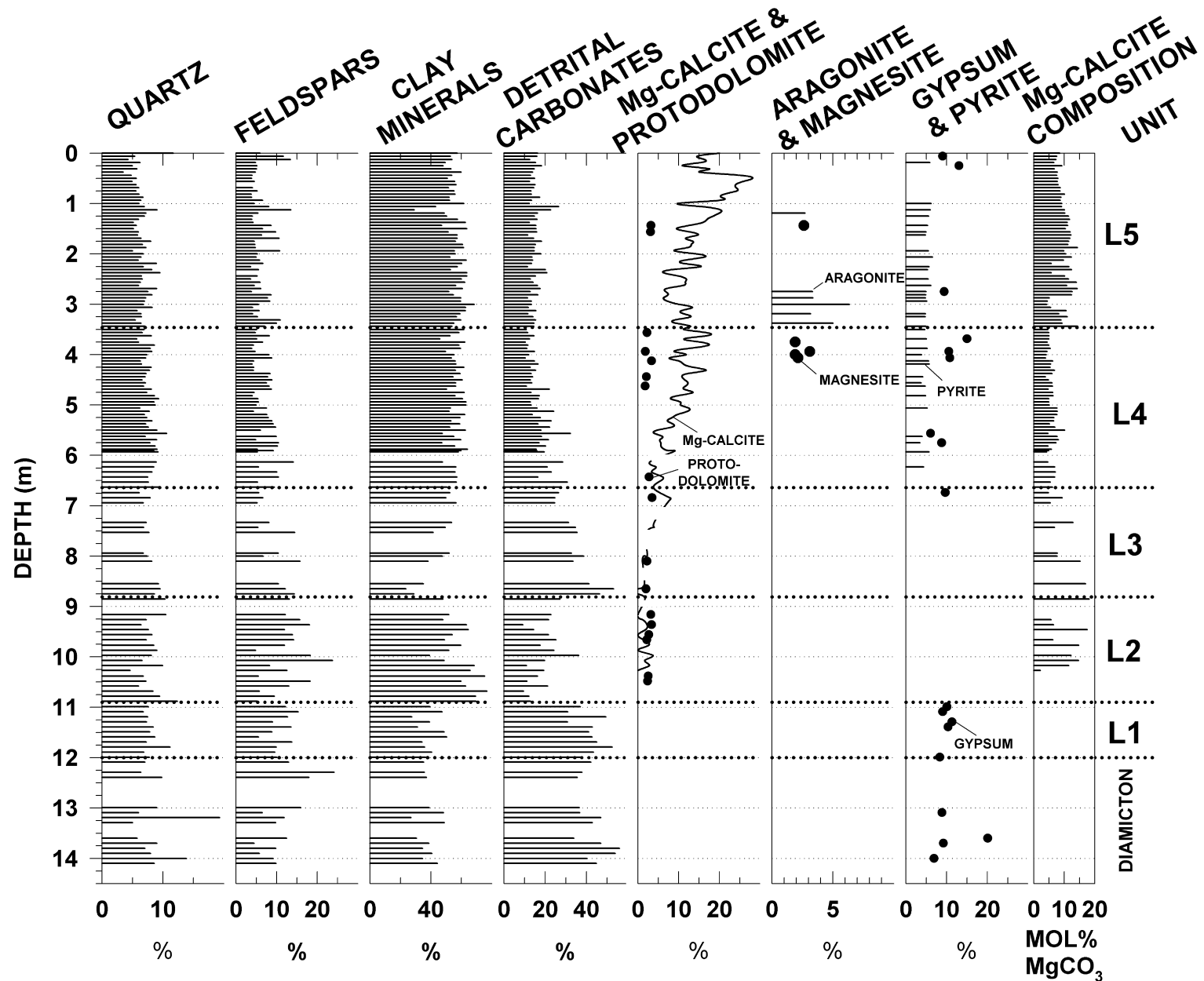


FIGURE 4. Stratigraphic variation in abundance of quartz, total feldspar minerals, total clay minerals, detrital carbonate minerals (*i.e.*, stoichiometric dolomite and calcite), protodolomite, Mg-calcite, aragonite, magnesite, gypsum, pyrite and composition (mol % $MgCO_3$) of the Mg-calcite in cores S-1 and V-1. Also shown are the lithostratigraphic units recognized in the cores. Gaps and spaces in the profiles indicate no recovery.

Variations stratigraphiques entre les quantités de quartz, de minéraux de feldspath total, de minéraux d'argile total, de minéraux détritiques de carbonate (dolomite stœchiométrique et calcite), de protodolomite, de calcite magnésienne, d'aragonite, de magnésite, de gypse, de pyrite et la composition en calcite magnésienne (mol % $MgCO_3$) dans les carottes S-1 et V-1. Apparaissent aussi les unités lithostratigraphiques observées dans les carottes. Les espaces vides correspondent à des lacunes.

TABLE II

Summary of average mineralogical and grain size characteristics of lithostratigraphic units. nd = not determined; np = not present

	Lithostratigraphic Unit						Core Avg.
	L5	L4	L3	L2	L1	Diamicton	
% Total Clay Minerals	55.8	56.3	43.9	59	38.1	37.4	52.8
% Quartz	6.5	7.8	7.7	8.1	7.9	9.1	7.5
% Total Feldspar Minerals	5.9	6.8	9.6	12.3	10.1	9.7	8.1
% Plagioclase	4.4	4.6	5.9	7.6	6.7	6.1	5.4
% K-feldspars	1.5	2.2	3.7	4.7	3.4	3.6	2.7
% Amphibole Minerals	np	np	np	0.1	0.1	0.2	<0.1
% Total Calcite	14.1	9.8	4.3	3.8	9.1	10.9	10.2
% Low-Mg Calcite	np	0.2	1.4	2.8	9.1	10.9	2
% Magnesian Calcite	14.1	9.6	2.9	1	np	np	8.2
Mol% MgCO ₃ in Magnesian Calcite	9.2	5.7	8.5	11.2	15.5	np	7.1
δ ¹³ C of Magnesian Calcite	1.17	-0.23	nd	nd	nd	nd	nd
% Total Dolomite	15.1	16.9	34.3	16.7	30.3	32.7	19.9
% Well-ordered Dolomite	14.9	16.7	33.7	15.8	30.3	32.7	19.6
% Disordered Dolomite	0.2	0.2	0.6	0.9	np	np	0.3
Mol% CaCO ₃ in Protodolomite	65.8	64.6	65.3	65.9	np	np	65.4
% Magnesite	<0.1	<0.1	np	<0.1	<0.1	np	<0.1
% Aragonite	0.4	np	np	np	np	np	<0.1
% Gypsum	0.6	1.1	0.8	np	3.6	3.2	1.2
% Pyrite	1.9	1.5	np	np	np	np	1.1
% Detrital Fraction	83.1	87.8	96.3	98.1	96.4	96.8	90.1
% Endogenic + Authigenic Fraction	16.9	12.2	3.7	1.9	3.6	3.2	9.9
Feldspar Weathering Index	0.54	0.54	0.46	0.42	0.41	0.4	0.51
Plagioclase Weathering Index	0.82	0.74	0.72	0.67	0.65	0.65	0.72
Carbonate Weathering Index	0.45	0.47	0.33	0.53	0.33	0.26	0.44
Calcite Weathering Index	1	0.99	0.95	0.82	0.78	0.73	0.94
% Moisture	75.2	49	37.4	22.3	23.2	12.8	49.9
% Organic Carbon	4.8	3.4	nd	nd	nd	nd	nd
% Organic Matter	11.5	8.6	4.1	3.9	5.8	0.9	8.1
Mean Particle Size (μm)	14.6	12.9	10.7	11.9	8.1	10.2	12.1
Standard Deviation of Mean Size	15.4	15.6	10.7	14.2	11.8	21	14.4
Median Particle Size (μm)	8.9	6.3	7.1	6.2	5.3	17.6	7.1
% Sand	3.5	3.1	0.9	3.4	<0.1	1.9	2.7
% Silt	66.2	65.5	71.6	58.5	60.4	57.7	64.4
% Clay	30.3	31.4	27.5	38.1	39.5	40.4	32.9
δ ¹³ C of Organic Carbon	-32.14	-33.59	nd	nd	nd	nd	nd
H-Index	286	139	nd	nd	nd	nd	nd
O-Index	85	113	nd	nd	nd	nd	nd

LITHOSTRATIGRAPHIC UNITS

Based on the mineralogical composition, bedding features, particle size characteristics, organic and moisture contents, this 14.5-m-long sedimentary sequence recovered from Lake Manitoba can be subdivided into six lithostratigraphic units (Table II, Figs. 2-7). The upper five units (L1 to L5) are broadly similar to the postglacial lacustrine stratigraphic units previous-

ly identified in Lake Manitoba (*e.g.*, Teller and Last, 1981; Last *et al.*, 1994).

The lowermost unit penetrated, from the base of the core to 12 m depth, is a firm, dry, carbonate-rich diamicton. In addition to the high proportions of detrital dolomite, calcite, and siliciclastics, this lower 2.2 m also contains high levels of secondary gypsum. This unit is interpreted as being deposited

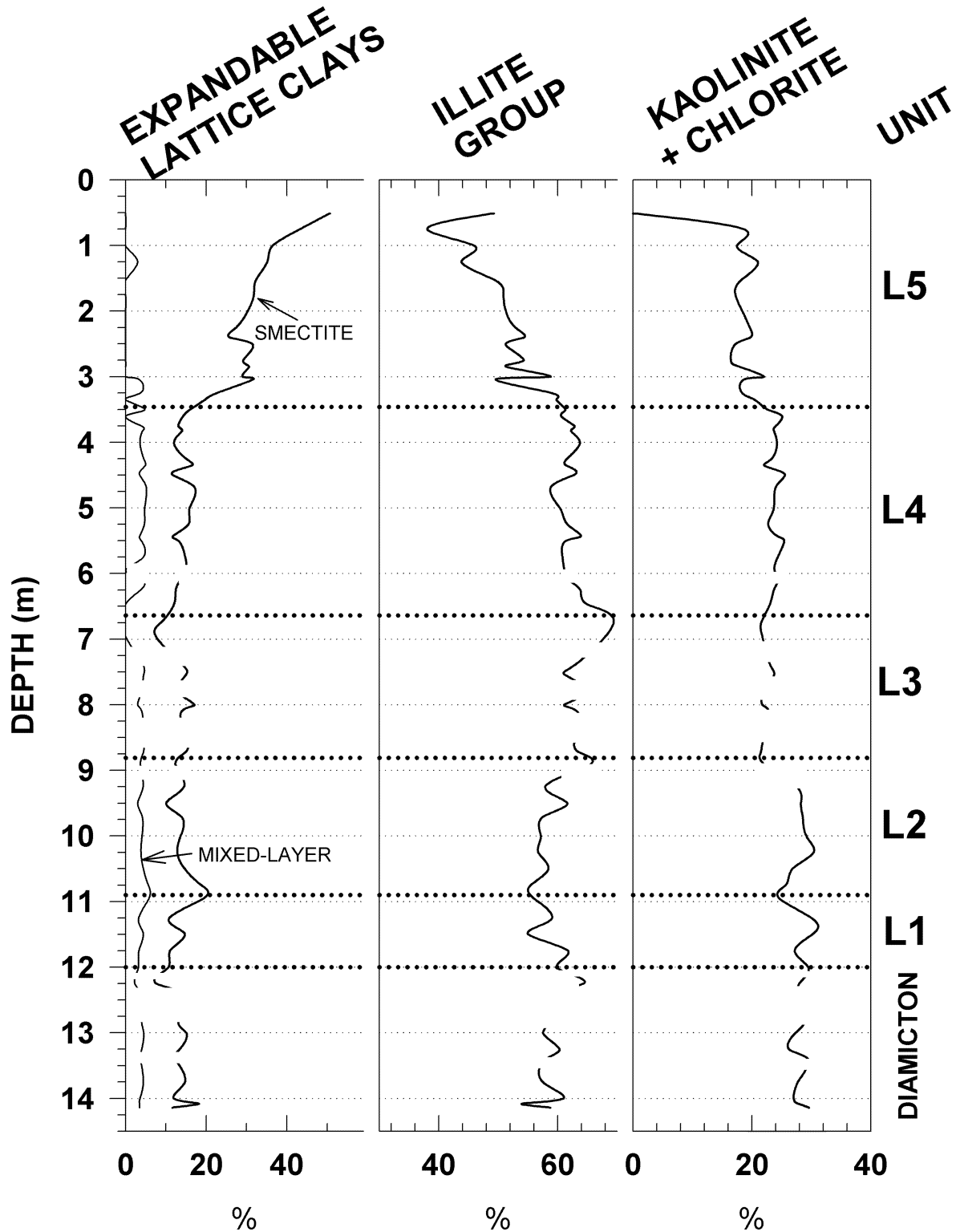


FIGURE 5. Stratigraphic variation in relative abundance of clay minerals in cores S-1 and V-1. Also shown are the lithostratigraphic units recognized in the cores. Gaps and spaces in the profiles indicate no recovery.

Variations stratigraphiques entre les quantités relatives de minéraux argileux dans les carottes S-1 et V-1. Apparaissent aussi les unités lithostratigraphiques observées dans les carottes. Les espaces vides correspondent à des lacunes.

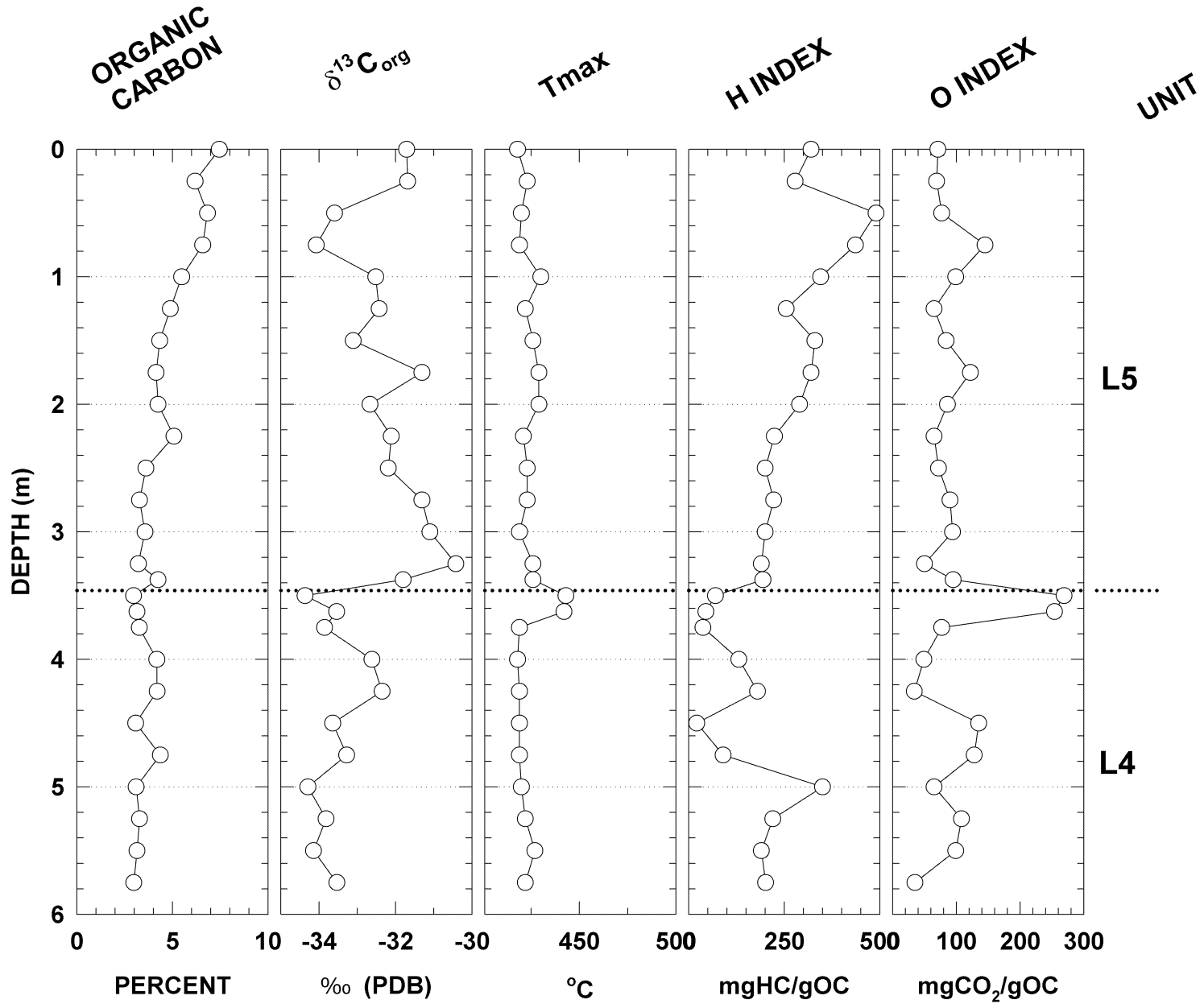


FIGURE 6. Stratigraphic variation in organic carbon, $\delta^{13}C_{org}$, Tmax, Hydrogen Index (H Index) and Oxygen Index (O Index) in core V-1. Also shown are the lithostratigraphic units recognized in the core.

Variations stratigraphiques du carbone organique, de $\delta^{13}C_{org}$, de la température maximale et des teneurs en hydrogène et en oxygène dans la carotte V-1. Apparaissent aussi les unités lithostratigraphiques observées dans les carottes.

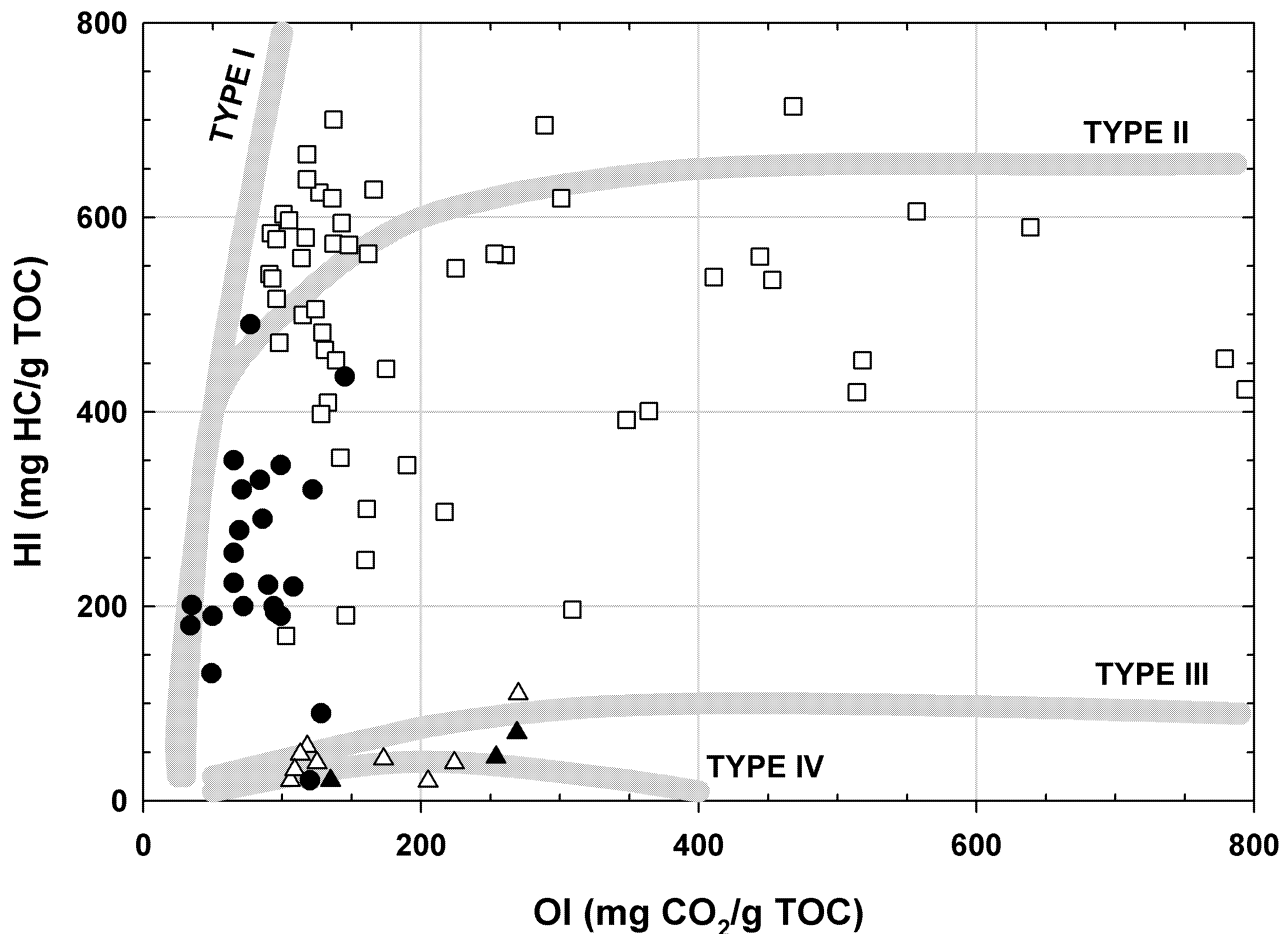


FIGURE 7. Plot of Hydrogen Index (HI) versus Oxygen Index (OI) values for Lake Manitoba (closed symbols) and other lakes from the northern Great Plains of Canada (open symbols). The closed triangles are samples from the dry pedogenic zone at the contact between units L4 and L5. The open triangles are samples from playa environments; the open squares are samples from deep, perennial lakes.

Valeurs des teneurs en hydrogène (HI) et en oxygène (OI) pour le lac Manitoba (symboles en noir) et d'autres lacs des Grandes Plaines (symboles en blanc). Les triangles noirs représentent des échantillons de la zone pédogénétique sèche au contact entre les unités L4 et L5. Les triangles blancs représentent les échantillons de playas ; les carrés blancs représentent des échantillons provenant de lacs permanents profonds.

either directly by the Laurentide Ice Sheet (*i.e.*, till) or by icebergs from a nearby ice margin rafting debris into the lacustrine sequence.

Overlying this basal diamicton is about a metre of calcareous, clay-rich, rhythmically bedded and laminated lacustrine sediment (Unit L1) containing abundant ice-rafted granules and pebbles. Mineralogically, L1 is very similar to the underlying diamicton, with relatively high proportions of detrital carbonates, quartz, feldspars, and authigenic gypsum, and a relatively low content of clay minerals (Fig. 4). Interestingly, the overall grain size of this and the underlying diamicton is finer than the younger part of the sequence. The lower contact is gradational over several tens of centimetres whereas the upper contact is sharp and recognized by abrupt changes in moisture, texture, carbonate, and clay mineral contents at 11 m depth.

Unit L2, extending from 11 m to 8.8 m depth in the composite core, is recognized by low carbonate and high clay min-

eral contents relative to L1. The proportions of sand and silt decrease upward and the upper half of the unit is relatively fine grained. L2 also marks the first appearance of magnesian calcite and protodolomite, and there is an absence of gypsum. Although minor in abundance, the Mg-calcite shows high levels of $MgCO_3$. There are scattered ice-rafted clasts in unit L2, but not in the overlying units.

The contact between L2 and L3 is identified by a sharp increase in carbonate content above 8.8 m (Fig. 4). Upward in L3 the abundance of detrital carbonates gradually decreases from over 50 % at the base to about 20 % at the top of the unit. In contrast, Mg-calcite continues to increase upward in the core. Unlike units above and below, L3 contains no sand. Although poor recovery throughout this part of the core prevents more complete characterization of the sedimentary structures of L3, the unit is indistinctly laminated in the lower metre and contains at least one interval of dry, blocky-structured

sediment in the upper part. The contact between L3 and L4 is marked by a dry, blocky-structure zone.

Overlying the dry zone at 6.6 m is about 3 m of laminated to structureless, calcareous, clayey silt. In contrast to the underlying stratigraphic units in which the dominant carbonate minerals are detrital dolomite and calcite, the carbonate fraction of unit L4 is dominated by magnesian calcite. The abundance of this endogenic calcite increases upward in the unit from 5 % at the base to almost 20 % at the top, paralleling an upward increase in organic matter content (Figs. 3 and 4). However, the MgCO_3 content of the calcite shows little fluctuation as it does in the underlying units, and averages about 5 mol %, considerably lower than that of L3 and L2 (Table II). Normal (low-Mg) calcite is very low to absent in L4. Unit L4 is also distinguished by the first appearance of pyrite. Similar to L3, the upper contact of unit L4 is very sharp and marked by a distinctive dry, blocky structured zone at 3.46 m depth, which is correlated with the uppermost dry zone in the basin that Teller and Last (1981; Fig. 6) showed to be very extensive.

The uppermost Holocene lithostratigraphic unit, L5, is a slightly coarser grained, structureless to indistinctly laminated, calcareous, organic-rich clayey silt. Like the underlying L4, the endogenic carbonate content of unit L5 is dominated by Mg-calcite and pyrite is present (Fig. 4). Above about 3 m depth the Mg-calcite increases upward from less than 10 % to nearly 30 % at 50 cm. The MgCO_3 content of the calcite increases abruptly from 4.5 mol % in the top of L4 to 12 mol % in the sediment immediately overlying the dry zone at the base of L5. Above about 1.5 m depth the composition of the Mg-calcite gradually returns to more moderate values of 6-7 mol % MgCO_3 , characteristic of the modern lake. Aragonite also occurs in the lowermost metre of the unit.

DISCUSSION

BASIS FOR PALEOENVIRONMENTAL INTERPRETATIONS

Bedding Features

The physical stratigraphy, mineralogy, and geochemical nature of the Lake Manitoba sequence contain a wealth of environmental information that can help to interpret the Holocene history of the basin. Although most of the 14.5 m of core retrieved at the site is structureless, massive, or very faintly laminated, the most distinctive visual feature of the record is the presence of numerous zones in which the sediment is dry and crumbly to granular. These zones are easily identified by their lower moisture contents relative to overlying and underlying sediment, and fine to coarse, blocky to pelletal, nodular, prismatic, and columnar structure. They occasionally contain abundant root fibres and exhibit gleyed dark greenish grey (5GY4/1) colours. Sharp upper contacts but gradational lower contacts also characterize these zones. While several possible hypotheses can be suggested for the formation of these zones (Teller and Last, 1982; Last and Vance, 1997; Risberg *et al.*, 1999), their characteristics are best

explained by desiccation and pedogenesis during periods of subaerial exposure of the lake bottom muds. Thus, these dry, structured zones record brief episodes in which the Lake Manitoba basin experienced extremely low, to seasonally dry, water conditions (Teller and Last, 1982).

Rhythmically bedded, half-centimetre-thick couplets of clast-rich and clayey clast-poor laminae between 11-12 m in core S-1 suggest the repetitive nature of annual accumulation and probably are varves. If these are varves, the interval represents about two centuries of sediment accumulation during a time when icebergs regularly contributed sediment to the Lake Manitoba basin, presumably during the phase when it was part of glacial Lake Agassiz.

Grain Size

Changes in the texture (grain size, sorting) of lacustrine sediments are often used to help paleolimnologists deduce water level fluctuations in a basin (Håkanson and Jansson, 1983; Digerfeldt, 1986). Coarse grained detrital sediments are usually interpreted to be associated with relatively high energy and shallow water conditions, whereas deposition of fine grained sediment (clay) requires low energy, deep water settings. However, as pointed out by Teller and Last (1990) and Last (2001a), this simple, intuitive texture-water depth relationship must be used with caution. Many other factors, such as varying runoff (climate, seasonality, weather events), source material, drainage basin characteristics, organic activity, and diagenesis, can make it difficult to interpret water level changes from textural parameters.

Except for a slight upward increase in mean grain size from about 8 μm at the base of the lacustrine section to ~10 μm at the top, and the presence of "outsized" clasts related to iceberg rafting below 8.8 m, there are few systematic variations in the texture of the sediment in S-1 and V-1 cores (Fig. 3). However, this lack of significant textural variation is not surprising because the core site is located in the offshore area of the basin, presently over 20 km from shore and nearly 60 km from the nearest point of river influx.

One important additional grain size relationship in the sequence, as shown in Figure 3, is the consistently (slightly) coarser grain size in the sediment immediately overlying the dry, structured pedogenic zones. This coarser texture most likely reflects the relatively high energy conditions present during the rising water levels associated with reflooding of the basin after each drying event.

Mineralogy

Some of the most noteworthy variations within the Lake Manitoba stratigraphic section occur in the mineralogical parameters. The detrital, or allogenic, fraction of the sediment, comprising siliciclastics, as well as calcite and dolomite, is derived from fluvial and eolian erosion and transport of the surrounding bedrock, Quaternary sediments, and soils. Thus, stratigraphic fluctuations in the abundance of these detrital components may offer valuable insight into past basin hydrology,

source areas, transport mechanisms, and watershed weathering processes.

Unfortunately, interpretation of these paleoenvironmental conditions from the allogenic record in lakes is rarely unambiguous. The size of Lake Manitoba's drainage basin, presently >80 000 km² and considerably larger during much of the Holocene, means that the allogenic sediments delivered to the lake have integrated a vast source area from western Canada, spanning a significant range of climatic and weathering conditions. Similarly, in a lake as shallow as Manitoba, it is likely that significant within-basin erosion, transport, and redeposition by wave and current action occurs, which further blurs stratigraphic interpretations. Finally, it must be emphasized that relative abundance of the various allogenic components is controlled, to a major degree, by the texture of the sediment. For example, clay minerals tend to occur as fine, clay-sized clastic particles and, therefore, dominate in finer grained sediments. In contrast, allogenic carbonate material is usually coarser and dominates silt-rich sediment, whereas feldspars and quartz, whose glacier-comminuted terminal grade is >30 µm, dominates sandy sediment.

It is clear from Figures 3 and 4 that Lake Manitoba has been a detrital-dominated lake throughout its Holocene history. The proportion of allogenic components shows a slight decrease upward in the core above ~7 m depth, reflecting a gradual increase in the importance of endogenic and authigenic mineral formation processes. These latter processes are most likely related to increasing organic productivity in the lake during the late Holocene. The two weathering indices (Fig. 3) also show a gradual upward trend toward higher intensities, and the abundance of detrital carbonate minerals decreases upward in the core, reflecting the progressive removal by chemical weathering of less stable minerals from the tills and soils of the watershed.

Figure 5 shows that the clay minerals, consisting mainly of illite with lesser proportions of expandable layer clays, chlorite, and kaolinite, exhibit little overall stratigraphic variation except in the uppermost 3.5 m. In unit L5, the expandable-lattice clays average over 30 % of the total clay mineral fraction versus only about 10 in the lower units. Furthermore, the clay mineral suite above ~3.5 m contains almost no mixed layer clay minerals, in striking contrast to the sediments of the lower units. These dramatic changes in clay mineralogy most likely indicate a change in source area. Although complex, most of the Jurassic and Lower Cretaceous shale units in the outcrop areas west and north of Lake Manitoba contain mainly illite, smectite, and kaolinite, with little mixed layer clays, whereas the Upper Cretaceous and Tertiary shales, as well as the Glacial Lake Agassiz sediments surrounding Lake Manitoba, contain abundant mixed layer species and relatively lower proportions of illite and kaolinite/chlorite groups (Bannatyne, 1970; Teller, 1976b; Kovac and Last, 1991). Thus, the clay mineral fraction shows that sediment throughout much of Lake Manitoba's history was probably derived from a variety of source areas, but beginning after the most recent drying event in the basin recorded by the pedogenic zone at 3.5 m depth, the relative contribution of fine grained material from Upper Cretaceous/Tertiary bedrock and previously deposited Lake

Agassiz sediments declined. As we discuss later, this shift was coincident with the final diversion of the Assiniboine River from Lake Manitoba to the Red River.

Endogenic and authigenic minerals in lake sediments are important because they provide unequivocal information about the chemical nature of the lake and, in some cases, the pore fluids. For example, calcite that is being precipitated in modern Lake Manitoba is forming by inorganic precipitation in the water column in response to supersaturation brought about by high levels of organic productivity (Last, 1982). The fact that this endogenic carbonate mineral is a magnesium-enriched species of CaCO₃ (magnesian calcite) reflects the elevated level of Mg²⁺ in solution. The average Mg/Ca molar ratio of ~3 in today's lake results in the endogenic calcite having about 7 mol % MgCO₃ in its lattice.

Similarly, in the stratigraphic record, the presence of Mg-calcite indicates not only that the lake water was supersaturated with respect to CaCO₃ throughout the mid- to late Holocene (Fig. 4), but also that the precipitating solution contained high levels of Mg²⁺. Likewise, the occurrence of other Mg-bearing carbonates (magnesite and protodolomite) support this mid to late Holocene enrichment in magnesium. Based mainly on observational evidence provided by Müller *et al.* (1972), Eugster and Kelts (1983), Last (1999) and others, it is generally held that (1) Mg-calcite forms in saturated solutions having Mg/Ca ratios of about 1-5, (2) aragonite in solutions with ratios of 5-50, (3) dolomite (protodolomite) in 50-100, and (4) magnesite in solutions with ratios >100. In addition to elevated Mg/Ca ratios, protodolomite also indicates that carbonate alkalinity levels were, at least periodically, very high in the lake (Fig. 4).

Endogenic precipitation of CaCO₃ (calcite, aragonite, or Mg-calcite) in a closed basin lake will lead to depletion of Ca²⁺ and increased Mg/Ca ratios. Because most freshwater lakes and dilute inflowing water to lakes have low Mg/Ca ratios (<1), the presence of Mg-bearing endogenic carbonates is often used as evidence of elevated salinities. However, it must be emphasized that this relationship between Mg/Ca ratio in the precipitating solution and the lake's salinity is not well-defined and should not necessarily be accepted without corroborating evidence. For example, although dolomite formation is generally associated with saline and hypersaline lakes, considerable thermodynamic evidence suggests that the formation of CaMg(CO₃)₂ is encouraged by *decreased* salinities (see Folk and Land, 1975; Hardie, 1987). Dolomite, aragonite, and Mg-calcite have all been reported as endogenic minerals from fresh water (<3 000 mg/L TDS) lakes (Last, 1990a).

Lake Manitoba sediments contain some salts that indicate elevated salinity. The lowermost lacustrine unit (L1) and the underlying diamicton both contain substantial quantities of CaSO₄·2H₂O, and gypsum also occurs sporadically in the upper 7 m of the core. This evaporitic mineral is most likely secondary in origin, forming authigenically in the lacustrine muds in response to supersaturated pore fluids. The occurrence of secondary gypsum is widespread in sediments of the Lake Agassiz basin and Pleistocene deposits in southern Manitoba, and is also present in the Holocene deposits of Lake Winnipeg (Henderson and Last, 1998). Using δ³⁴S and

$\delta^{18}\text{O}$ data from secondary gypsum in Agassiz sediments near Winnipeg, Young *et al.* (2000) and McDonald (1999) demonstrated that $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ formation is due to downward percolating, slightly acidic, Ca-enriched meteoric waters interacting with SO_4^{2-} from oxidized organic matter in the muds. However, the presence of sulfate-rich saline to hypersaline groundwaters in the vicinity of Lake Manitoba (Last, 1984; van Everdingen, 1971) suggest that saturation of the pore fluids with respect to gypsum is more likely attributed to upward movement of groundwater from the underlying Paleozoic strata, perhaps combined with further evaporative concentration of the fluids in the shallow subsurface during the periodic desiccation events in the basin.

Sulfide minerals are common authigenic components in fine grained lacustrine and marine sediments that are high in organic matter (Jones and Bowser, 1978). In fact, bacterial degradation of the organic matter under anaerobic conditions can generate a variety of metastable and stable metal sulfides, including amorphous to cryptocrystalline and euhedral species (Snowball and Torii, 1999). Pyrite, usually occurring as euhedral framboids and spheres in the Lake Manitoba sequence (Last and Teller, 1983), is favoured by low Eh and pS^{2-} conditions in the presence of dissolved iron (Ehrlich, 1996). The occurrence of pyrite in the upper 7 m of core and its absence below this level (Fig. 4) is most likely related to the low levels of organic matter in the sediments at depth, which preclude formation of the pyrite. As well, during the early phases of the lake, the sediment-water interface and shallow subsurface probably were well oxygenated, whereas during the later Holocene anoxic conditions were more common. It is also possible that, rather than a diagenetic origin, the pyrite may be syngenetically formed in an isolated, anoxic lower stratum of the water column of a chemically stratified (meromictic) lake (*cf.* Last, 1993; Suits and Wilkin, 1998); however, given the size of Lake Manitoba and its shallow depth, this seems unlikely.

Organic Matter Pyrolysis

Rock-Eval pyrolysis has gained widespread use during the past decade as a rapid method of characterizing the type and origin of organic matter in lacustrine sediments (*e.g.*, Meyers and Teranes, 2001; Ariztegui *et al.*, 1996). The Hydrogen Index, HI (the amount of hydrocarbon per gram of organic carbon) is generally considered to be a proxy for the hydrogen content (or H/C ratio) of organic matter in the sediment, whereas the Oxygen Index, OI (the amount of CO_2 per gram of organic carbon) reflects the oxygen content (O/C ratio) of the organics. Because most organic matter is made up of mainly C, H, and O, organic matter types are usually defined by plotting HI versus OI on a pseudo-van Krevelen diagram (Fig. 7). Hydrogen-rich Type I and Type II organic matter are both derived mainly from algal and other microbial biomass in the water (autochthonous organic matter), whereas Type III is humic organic matter, derived mainly from terrestrial and woody land-plant sources (*i.e.*, allochthonous organic matter; Meyers and Teranes, 2001). Type IV organics are viewed as recycled or strongly oxidized material. In addition to organic matter typing by HI versus OI, the Tmax data (temperature at which the maximum hydrocarbon yield occurs) in Quaternary sediments can sometimes be

used to indicate the presence of organic matter derived from bedrock sources (*e.g.*, Manalt *et al.*, 2001). Relatively high Tmax values (greater than $\sim 430^\circ\text{C}$) indicate the organic matter has undergone some degree of thermochemical maturation, which would imply a bedrock source.

Figures 6 and 7 show that most of the organic matter in the upper 6 m of the section is moderately H-rich and, thus, is interpreted to be mainly derived from planktonic sources. Two samples within the dry, pedogenic zone at the contact between units L5 and L4 both have high OI and very low HI which confirms the interpretation that these dry zones represent periods of subaerial exposure and oxidation, or, alternatively, a mainly terrestrial provenance for the organic matter. The somewhat elevated Tmax values at the top of unit L4 further points toward a possible significant bedrock detrital organic matter component within these sediments.

The upward increasing trend of the HI in unit L5, coupled with the trend toward more depleted $\delta^{13}\text{C}$ values, suggests a gradual increase in autochthonous sources, probably associated with increasing lake productivity as evidenced by the trend in organic matter and TOC content. In Minnesota lakes, Dean and Stuiver (1993) showed that ^{13}C -depleted organic carbon and hydrogen-rich organic matter are characteristic of lakes having high algal productivity.

SUMMARY OF PALEOLIMNOLOGY OF LAKE MANITOBA

INTRODUCTION

Modern Lake Manitoba, together with lakes Winnipeg, Winnipegosis, and many smaller basins in the region, are remnants of larger Lake Agassiz that covered most of Manitoba and portions of the adjacent provinces and states. The history of this large proglacial lake, as well as many of the other ice-marginal lakes that occupied basins formed by the retreating Laurentide Ice Sheet, has been summarized by Teller (1987, 1995, 2003), Teller and Clayton (1983) and Teller and Kehew (1994). Fluctuations in the retreat of the ice margin controlled the outlets from the lake and, hence, the water level in the basin (*e.g.*, Leverington *et al.*, 2002; Teller *et al.* 2002).

THE GLACIAL PHASE

The diamicton below lacustrine unit L1 is very clayey and varies vertically in abundance of coarse clasts. Even though not bedded, it is possible that this sediment was deposited in water, perhaps below or just beyond the margin of a floating ice shelf in Lake Agassiz; as shown by Leverington *et al.* (2000), this would have been in about 150 m of water.

Above the diamicton, sediments become laminated, with a weakly displayed rhythmic nature (unit L1) suggesting annual variations between a high and low influx of ice-rafted clasts. The roughly 200 couplets in L1 may reflect that these ice-proximal conditions persisted for about 200 years. The absence of varves in the overlying unit (L2) may indicate that waters in Lake Agassiz became more shallow; the small amount of

ice-rafted detritus in L2 suggests that the ice margin had retreated northward.

The diamicton in core S-1 may be related to the readvance of the Laurentide Ice Sheet (LIS) about 10 100 ¹⁴C yr BP, which probably invaded the Lake Manitoba basin (Thorleifson, 1996; Leverington *et al.*, 2000; Teller, 2001). In this scenario, the couplets with ice-rafted clasts (unit L1) and the overlying clast-containing laminated sediment of unit L2 would have been deposited in Lake Agassiz after the 10 100 ¹⁴C yr BP readvance, ending when the level of Agassiz declined enough to either isolate the Lake Manitoba basin or to keep icebergs out. Alternatively, if the 10 100 ¹⁴C yr BP readvance of the LIS did not reach the south basin of Lake Manitoba, the diamicton in core S-1 would have been deposited before about 10 800 ¹⁴C yr BP, and unit L1 reflects the first appearance of Lake Agassiz in the basin. In both scenarios, Lake Manitoba would have become completely independent of ice-marginal Lake Agassiz some time after unit L2 was deposited, perhaps as late as after L3 was deposited. Based on computer modeling that used isostatically-adjusted DEM topography to map the changing bathymetry of Lake Agassiz, this isolation would have occurred shortly after the Burnside beach phase of Lake Agassiz, which occurred about 8500 ¹⁴C yr BP (see Leverington *et al.*, 2002, Fig. 2).

Throughout the Lake Agassiz controlled phase of Lake Manitoba, the level of the lake fluctuated frequently and substantially in response to the interplay between differential isostatic rebound, ice-marginal changes, and outlet elevation (*e.g.*, Teller *et al.*, 2002). Overall, the lake became increasingly shallow, although this occurred in a series of abrupt declines (regressions) and intervening slower rises (transgressions), each of which fell short of the previous lake level (Teller, 2001). During the later regressive phases, the Lake Manitoba basin probably was periodically cut off from Lake Agassiz for a few decades or centuries at a time. When isolated from Agassiz, and dominated by a warming interglacial climate, limnological conditions in the basin appear to have changed, with deposition of small amounts of endogenic Mg-calcite and protodolomite in units L2 and L3. Mineral magnetic parameters are quite variable, but distinctly higher below the top of unit L3 (Risberg *et al.*, 1999). This magnetic signature and the increase in mean grain size suggest agitated conditions on the lake floor. Although units L1, L2, and L3 are largely barren of fossils, with few siliceous microfossils (Risberg *et al.*, 1999), few mollusks (Pip, 1990), and little pollen (Nambudiri and Shay, 1986), fresh water ostracodes that prefer cold waters are present in some zones (Curry, 1997); a sparse assemblage of both fresh water and brackish water diatoms are present in unit L1, but absent in units L2 and L3 (Risberg *et al.*, 1999).

After complete isolation of the basin from Lake Agassiz, shortly after 8500 ¹⁴C yr BP, isostatic depression of the northern end of the Lake Manitoba basin and erosion of the Fairford River outlet probably left the south end of the basin dry, or only locally filled by water. Some or most of unit L3 may have been deposited after this isolation, although it is also possible that it represents the last phase of Lake Agassiz sediment accumulation in the basin. Although poor recovery in this inter-

val prevents a detailed evaluation of environmental conditions, shallow water to dry conditions in the South Basin are suggested by the presence of Mg-calcite with high mole % MgCO₃, protodolomite, a reduced moisture content, low organic matter content, and the presence of several pedogenic horizons. The absence of diatoms and of ostracodes in all but a few thin intervals support the conclusion that the Lake Manitoba basin was either an unfavourable environment for fresh or even brackish water organisms and/or an unfavourable setting for the preservation of organisms due to subaerial weathering. Based on new AMS dates in both S-1 and D-1 cores, unit L3 was deposited after about 8400 and before 7700 ¹⁴C yr BP, which according to Leverington *et al.* (2002), was the period immediately following separation of lakes Manitoba and Agassiz. Nielsen *et al.* (1993) conclude, based on dated alluvium, that drainage had developed on the floor of the Red River Valley by 7500 ¹⁴C yr BP.

THE MID-HOLOCENE PHASE

After formation of the pedogenic horizon at the top of unit L3, the basin entered a long period marked by shallow but relatively stable water levels. Based on six new AMS dates, two in the lower part of unit L4 and four in the upper part of L3, reflooding began about 7700 ¹⁴C yr BP. Many physical, mineralogical, and biological parameters abruptly change at the base of unit L4. Although mid-Holocene Lake Manitoba was still dominated by detrital sedimentation, the increasing proportion of endogenic carbonates upward in the section indicates a greater importance of chemical sedimentation. This carbonate mineral assemblage points toward high but constant Mg/Ca ratios (~3-4) and moderate carbonate alkalinities. The lack of distinct bedding in the sediment suggests that the lake was shallow enough to allow at least storm waves to periodically agitate the bottom muds. Conversely, pyrite, which forms and is stable only under reducing conditions, indicates that the lake was deep enough to prevent complete oxygenation at the sediment-water interface for extended periods of time. Risberg *et al.* (1999) and Curry (1997) suggest the lake varied substantially from fresh (1 000 mg/L TDS) to saline (up to ~10 g/L), with generally elevated HCO₃⁻/Ca²⁺ ratios. Based on ostracode assemblages, Curry (1997) related varying water chemistry in Lake Manitoba to relative proportions of groundwater versus surface runoff.

The gradual change to more negative δ¹⁸O values for inorganic, endogenic calcite (Last *et al.*, 1994) suggests either cooler, less saline waters or, more likely, a change in source of waters, perhaps to a hydrologic budget that was dominated by groundwater. For example, groundwater in carbonate aquifers that immediately underlie Lake Manitoba today have strongly negative δ¹⁸O values (in the -14 to -20 ‰ SMOW range; Grasby and Betcher, 2002). Smith *et al.* (1997) suggest that groundwater inflow "mediated" the isotopic signatures in some middle Holocene lakes in the northern Great Plains.

The period of relatively stable water levels in the lake suggests a positive hydrologic budget existed in the basin during 7700-4500 ¹⁴C yrs BP. Only near the top and in the top of this unit are there any pedogenic horizons, indicating lower water

levels. Although the mid-Holocene in the northern Great Plains is generally viewed as a period of aridity (e.g., Fritz, 1996; Lemmen and Vance, 1999b), the actual timing of peak aridity is enigmatic. There is considerable evidence suggesting that maximum aridity occurred early in the Holocene and, thus, the onset of a more positive hydrologic budget in Lake Manitoba after 7700 ¹⁴C yrs BP corresponds with many paleolimnological records from the region (e.g., Radle *et al.*, 1989; Dean and Stuiver, 1993; Haskell *et al.*, 1996; Last *et al.*, 1998; Yansa, 1998; Aitken *et al.*, 1999; Last and Vance, 2002). In contrast, other paleoclimatic reconstructions in the northern Great Plains point toward much later aridity maximums (Last, 1990b; Valero-Garcés and Kelts, 1995; Smith *et al.*, 1997; Xia *et al.*, 1997; Teller *et al.*, 2000; Lewis *et al.*, 2001; see also Schwab, 2003).

Part of this uncertainty is undoubtedly due to equivocal radiocarbon chronologies as suggested by some researchers (e.g., Whitlock *et al.*, 1993; Dean *et al.*, 2002) or, alternatively, the onset of maximum aridity was time transgressive. In addition, in some basins such as Lake Manitoba, transgressing waters related to differential rebound may have offset a trend toward greater aridity during the mid-Holocene. Thus, it is likely that the specific hydrological setting of individual watersheds and drainage basins dictated, to a major degree, how climatic changes, such as increased aridity, were recorded in the lacustrine sediments.

In the Lake Manitoba basin, relatively stable water levels and compositions were maintained during much of the middle Holocene through the interaction of four main mechanisms: (1) a relatively dry climate; (2) continuing differential isostatic rebound, which resulted in uplift of the northern outlet of the lake and progressive southward transgression and deepening of the waters; (3) the discharge of groundwater into the basin; and (4) the influx of runoff from the Assiniboine River, which today bypasses the basin to the south. Evidence for this is the presence of coarse-grained fluvial and deltaic deposits at the south end of the basin (Teller and Last, 1981) and now-abandoned fluvial channels south of the lake (Rannie *et al.*, 1989). The addition of the Assiniboine-Qu'Appelle system, which began about 7500 ¹⁴C yrs BP (Nielsen *et al.*, 1996), may have more than doubled the catchment area of the lake.

THE LATE HOLOCENE PHASE

At about 4500 ¹⁴C yrs BP, the Assiniboine-Qu'Appelle River was diverted out of the Lake Manitoba drainage basin, removing about 80 000 km² of catchment drainage. This rerouting of the river to its present easterly path was due to the combined affects of (i) gradual channel avulsion caused by sediment accumulation plugging the northward-flowing channels leading to the lake, and (ii) continued differential tilting of the basin. As discussed by Rannie *et al.* (1989) and Nielson *et al.* (1993, 1996), the diversion was probably not abrupt nor complete because the channel system south of the lake was still periodically active as recent as ~4000 ¹⁴C yrs BP. Nonetheless, with the gradual loss of this significant component of the lake's hydrologic budget, possibly compounded by the warm and dry climatic conditions, water levels in the basin dropped and the uppermost pedogenic horizon developed at the contact between units L4 and L5.

The duration of this most recent dry episode in Lake Manitoba has not been established with certainty, but by about 3700 ¹⁴C yrs BP lacustrine sediment accumulation was once again occurring in the offshore areas of the basin. The clay mineralogy of unit L5 suggests a change in provenance of the offshore sediments that is consistent with the diversion of the Assiniboine River. The lake was initially shallow and saline, with high Mg/Ca ratios (5/50). Risberg *et al.* (1999) interpret the highest and most variable salinity of the past 7000 years as occurring in the lowermost sediments of unit L5. Curry (1997) concludes on the basis of ostracodes that salinity was high but extremely variable at this time. Dissolution of efflorescent salts and some of the secondary intrasedimentary minerals that precipitated within the exposed lake bottom muds during the dry phase probably caused these initial high salinities and elevated Mg/Ca ratios in unit L5. The high salinities probably also curtailed organic productivity and much of the organic matter in the lower part of unit L5 was derived from woody and herbaceous terrestrial plants as indicated by the enriched $\delta^{13}\text{C}$. However, as the climate gradually became wetter and cooler, giving rise to an increasingly more positive hydrologic budget, and as continued differential rebound caused water in the north to transgress southward, fresher and likely deeper water conditions prevailed. Ostracodes, diatoms, and pelecypods support the conclusion that, although variable, the waters were generally brackish (Pip, 1990; Curry, 1997; Risberg *et al.*, 1999).

The lake reached its present-day level at about 2000 ¹⁴C yrs BP. Since then, it has continued to increase in organic productivity, which has further enhanced the inorganic carbonate mineral genesis. The high productivity, combined with loss of Assiniboine River inflow, also results in a dominance of autochthonous organic matter in the most recent record, in contrast to more mixed terrestrial and autochthonous sources prior to 4000 ¹⁴C yrs BP.

The physical and mineralogical data recorded at the S-1/V-1 core site do not suggest significant fluctuations in limnological conditions during the past several thousand years. Similarly, on the basis of the siliceous microfossil content and ostracode stratigraphy, Risberg *et al.* (1999) and Curry (1997) indicate generally stable hydrologic conditions, with few water quality changes, over the past two millennia. Last *et al.* (1994) interpret trends in the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ of inorganic endogenic calcite in the most recent sediment as reflecting increasing levels of organic productivity and minor fluctuations in water levels resulting in repeated alternations from closed basin evaporitic conditions to an open system.

CONCLUSION

Previous investigations of the paleolimnology of Lake Manitoba (e.g., Teller and Last, 1981; Last *et al.*, 1994) illustrated the complexity of changing postglacial and Holocene conditions in this large basin, but were restrained by relatively low resolution sampling and problematic chronology. This paper, based on much higher resolution stratigraphic analyses of new cores and more accurate AMS ¹⁴C-based chronology, offers a more detailed paleolimnological interpretation of this important basin.

The basal clayey and clast-rich diamicton probably was deposited by the Laurentide Ice Sheet, but may have been deposited in deep water near or below the glacier margin in Lake Agassiz. This oldest sediment in Lake Manitoba likely reflects the readvance of the Laurentide Ice Sheet into the region about 10 100 ¹⁴C yr BP, or, alternatively, may record the first appearance of Lake Agassiz before 10 800 ¹⁴C yr BP. The 3 m-thick sequence of rhythmically-bedded and clast-rich sediment overlying this basal diamicton was also deposited in Lake Agassiz, while it covered the Lake Manitoba basin. Northward retreat of the ice margin eventually resulted in complete separation of the basin from Lake Agassiz, probably shortly after 8500 ¹⁴C yr BP. For the next ~800 years Lake Manitoba fluctuated between shallow water and dry conditions. The influence of differential isostatic rebound, which gradually reflooded the basin, and a more positive hydrologic budget due to inflow of the Assiniboine River, influx of groundwater, and possibly a moderating climate after an early Holocene aridity maximum, resulted in Lake Manitoba experiencing relatively stable levels and limnological conditions between 7700 and 4500 ¹⁴C yrs BP. When the Assiniboine River was diverted away from the basin, assuming its present easterly flow, Lake Manitoba lost a major component of its hydrologic budget and the basin dried completely around 4500 ¹⁴C yrs BP. However, decreasing aridity and continued rebound of the northern end of the basin resulted in reflooding of the basin, and by 3700 years ago it was filled by a shallow, saline and highly alkaline lake. Generally wetter and cooler climatic conditions helped create a more positive hydrologic budget; water levels rose and salinities gradually decreased until about 2000 ¹⁴C yrs BP, at which time the lake reached its present day configuration and depth.

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