Hydrobiologia 158: 301–316 (1988)
J. M. Melack (ed.). Saline Lakes
© Dr W. Junk Publishers, Dordrecht – Printed in the Netherlands

The salt lakes of western Canada: A paleolimnological overview

William M. Last & Laurie A. Slezak
Department of Geological Sciences, University of Manitoba, Winnipeg, Manitoba, Canada, R3T 2N2

Abstract

The northern Great Plains of western Canada contain many saline and hypersaline lakes. Deadmoose and Waldsea Lakes in south-central Saskatchewan are meromictic, with saline Mg-Na-SO_4-Cl waters overlying denser brines of similar composition. Mineralogical, chemical, palynological, and stable isotope analyses of the sediments in the Waldsea basin indicate the lake was much shallower about 4000 years ago in response to a warmer and drier climate. Since that time water levels have generally increased in the basin giving rise to higher organic productivity and greater inorganic carbonate precipitation. Within this overall trend there is also evidence of several lower water stages during the last 3000 years. The stratigraphy preserved in the Deadmoose basin suggests considerably lower water levels about 1000 years ago.

Ceylon Lake, located about 350 km south of the Waldsea-Deadmoose area, is presently a shallow, saline playa. The basin originated about 15000 years ago as a glacial meltwater spillway. Stratigraphic variation in evaporite and carbonate mineralogy shows that the basin evolved from a relatively low salinity, riverine lake to one in which initially Na-rich and then Mg-rich hypersaline brines dominated.

Lake Manitoba is a large, hyposaline lake located in the eastern Great Plains about 700 km from the Deadmoose-Waldsea area. Stable oxygen and carbon isotope analyses of the endogenic carbonates in the basin indicate gradually increasing levels of organic productivity but decreasing temperatures between 9000 and 5000 years B.P. Between about 4000 and 2000 years ago the isotope ratios suggest relatively stable temperatures followed by a strong decrease during the most recent 2000 year period.

Introduction

Salt lakes often respond dramatically to environmental change, and, consequently, offer an excellent opportunity to evaluate fluctuations in water chemistry, hydrology, organic productivity, drainage basin characteristics, and climate. The Great Plains of western Canada and northern United States contain thousands of brackish, saline, and hypersaline lakes. Many of these lakes are small (<1 km^2); the region also contains several of North America's largest inland saline waters. Because these high salinity lakes are frequently the only surface water present in the region, they have attracted considerable attention (e.g., Rawson & Moore, 1944; Rutherford, 1970; Whiting, 1977; Hammer, 1978a, b; Hammer & Haynes, 1978; Haynes & Hammer, 1978; Lieffers & Shay, 1983; Hammer *et al.*, 1983). Due to the presence of thick deposits of evaporitic salts and commercially extractable brines, the mineral resources of the lakes have been actively investigated (Cole, 1926; Grossman, 1949, 1968; Tomkins, 1953, 1954; Carlson, 1956; Carlson & Babey, 1955; Govett, 1958; Rueffel, 1968; Broughton, 1984; Slezak & Last, 1985a). Recently, attention is being directed toward the stratigraphic records in these basins in an effort to interpret the past hydrologic, chemical and climatic conditions of the lakes and watersheds. The purposes of this paper are to review some of the recently published historical studies of saline lakes in the northern Great Plains and summarize the results of paleolimnological investigations by the authors.

Regional setting

The saline lakes discussed in this paper are located in the Great Plains physiographic province of North

America (Fig. 1). This region is characterized by hummocky to gently rolling topography interspersed with numerous deep, often terraced valleys cut by glacial meltwater. The region experiences a cold continental steppe climate. Mean daily temperature during January over the area is about −18 °C; during July it is 19 °C. The natural vegetation of much of the area is prairie grassland which grades into aspen parkland and pine-spruce forests to the north and east. Most of the natural vegetation cover has been cleared for agricultural purposes, and much of the area is cultivated or rangeland.

The northern Great Plains region is underlain by up to 5000 m of nearly horizontal Phanerozoic clastic, carbonate and evaporitic sedimentary rocks. Unconsolidated ice laid, fluvial, and lacustrine Quaternary sediment now blankets the area, in places reaching over 300 m in thickness. The numerous salt lakes of the area fill local depressions or kettles in the Pleistocene sediment, or occupy dammed glacial meltwater channels.

Most of the groundwater in the surficial deposits is of low to moderate salinity (<3000 mg l^{-1} total dissolved solids (TDS)) and dominated by Ca, Mg, and HCO_3. The shallow bedrock aquifers (Upper Cretaceous and younger rocks) are mainly Na-HCO_3 in the west, grading to Ca-Mg-Na-HCO_3 in the east. The deeper Cenozoic and Paleozoic bedrock contains higher salinity water (up to 300 g l^{-1} TDS) that is usually dominated by Na and Cl.

The lakes of the northern Great Plains show considerable variability in ionic composition and concentration. The waters range in salinity from relatively dilute (100 mg l^{-1} TDS) to brines ten times more concentrated than normal sea water. Sulfate and carbonate-rich lakes are most common, while lakes dominated by either Ca, Mg, or Na + K are about equally abundant. There is a distinct trend toward higher relative proportions of Na and SO_4 and lower percentages of Ca and HCO_3 with increasing salinity.

Synopsis of paleolimnological studies

Alberta

Several hyposaline lakes in central Alberta have at-

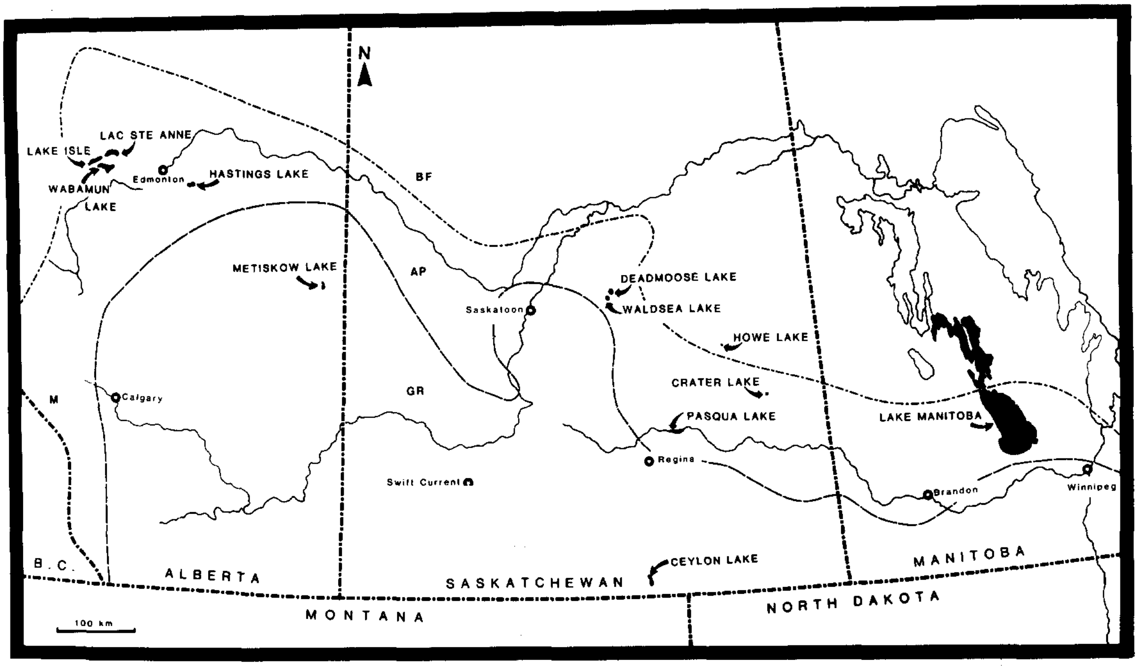

Fig. 1. Map of the northern Great Plains showing the locations of the lakes discussed in this paper and the modern vegetation regions (GR = grassland; AP = aspen parkland; BF = boreal forest; M = montane).

tracted considerable paleolimnological attention. Hickman *et al.* (1984), Holloway *et al.* (1981), and Fritz & Krouse (1973) supply some of the most detailed analyses of a postglacial lacustrine sequence in western Canada for Lake Wabamun. Cores from this 82 km^2 closed basin lake located west of Edmonton have been examined for major and nutrient elements, organic pigment, diatom and pollen stratigraphy, and $^{18}O/^{16}O$ content. Using these data in conjunction with both radiocarbon analyses and dated tephra layer chronology, Hickman *et al.* (1984) recognize an initial (early Holocene) shallow and turbid lake of moderate salinity. With the onset of warmer and possibly more arid conditions during the mid-Holocene Hypsithermal, the lake became more saline, with lower organic productivity and higher sedimentation rates. During the past 5000 years Lake Wabamun gradually returned to lower salinity and eutrophic conditions. The stable isotope data collected from endogenic carbonates of Wabamun cores (Fritz & Krouse, 1973), confirms the overall evaporitic regime of the basin during the last 12000 years, and points toward an increase in evaporation/precipitation ratio during the mid-Holocene.

Lake Isle and Lac Ste. Anne are two shallow, alkaline-brackish water lakes near Lake Wabamun (Hickman & Klarer, 1981; Forbes & Hickman, 1978, 1981). Lake Isle became eutrophic immediately after its inception about 10000 years ago. For the 4000 year period from 8000 – 4000 B.P. a warmer and drier climate resulted in increased evaporation/precipitation ratios in the basin, a lower lake level, increased salinity, and abundant carbonate precipitation. Productivity and sedimentation rates also increased substantially during this period. The most recent 4000 years in Lake Isle were uneventful except for a gradual increase in water levels, decrease in salinity and a slight decrease in productivity. The 6400 year geochemical and biostratigraphic sequence recovered from Lac Ste. Anne is complacent with no major water level or productivity changes during the post-Hypsithermal period.

In contrast, the mid to late Holocene sediments recovered from Hastings Lake, a closed basin lake 30 km east of Edmonton, indicate much more pronounced water level fluctuations and concomitant changes in organic productivity and sedimentation rates (Forbes & Hickman, 1981). High but irregular Fe/Mn ratios, low organic matter and carbonate contents, low total α pigments to total carotenoid ratios, and high sedimentation rates between about 5500 and 4000 B.P. lead the authors to suggest an early unstable phase of a much shallower lake that was dominated by allochthonous deposition. Subsequently, a gradual increase in water depth and generally more stable watershed conditions gave rise to higher levels of organic productivity, increased endogenic carbonate precipitation and lower overall sedimentation rates. A change from an open parkland vegetation to more closed forest conditions about 4000 years ago further suggests the onset of cooler, moister conditions (Vance *et al.*, 1983).

Wallick (1981) and Wallick & Krouse (1977) examined the Holocene evolution of the groundwater system of the Metiskow Lake (Horseshoe Lake) basin in eastern Alberta. Metiskow Lake is a shallow, hypersaline playa whose thick sulfate and carbonate salts are being commercially exploited. While not concentrating on the paleolimnology of the deposit *per se*, these studies do stress the importance of deciphering the reaction details of the dynamic groundwater-sediment system through time, and also provide some important quantitative data regarding the ultimate source(s) of the salts in lakes such as Metiskow.

Saskatchewan

Several small, circular, closed basins in eastern Saskatchewan have been studied because of their unusual morphologies, sediment records, and origins. Christiansen (1971) and Gendzwill & Hajnal (1971) have shown that Crater Lake occupies a surface expression of a deep collapse structure that originated from dissolution of Devonian evaporites nearly 1000 m below the surface. Howe Lake occupies a similar nearly circular but deeper basin near Crater Lake. The postglacial fill in this small (0.07 km^2) basin consists of over 120 m of coarse-grained colluvium and finer-grained lacustrine sediment (Christiansen *et al.*, 1982). Seismic and gravity surveys show that the most plausible explanation for the origin of this basin is a hydrodynamic blowout. During deglaciation groundwater recharge from the nearby melting ice front gave rise to extremely high hydrostatic pressures in the underlying Cretaceous bedrock aquifer. This pressure exploited, possibly in an explosive manner, local irregularities or fractures in the overlying Tertiary and Quarternary sediment to form an elutriation cone and pipe from the aquifer to the surface.

Several researchers have attempted to use invertebrate remains to decipher the developmental history of salt lakes in southern Saskatchewan. Guliov (1963) studied the mollusc stratigraphy in conjuction with the palynology and physical and chemical characteristics of a 6 m section from a small ephemeral pond near Regina. Using primarily the ostracode remains, the 10000 year sediment record was interpreted in terms of temperature, water depth, alkalinity, redox potential, salinity, and abundance of vegetation. Temperatures were initially relatively low but gradually warmed to averages well above that of the present between 7000 and 4000 B.P. A gradual decrease in water depth and increasing oxidation of the sediment accompanied this rise in temperature. Surprisingly, the salinity of the lake was greatest early in the lake's history and gradually decreased with time. The presence of gypsum, Fe-oxide stained concretions, and an oxidized hardpan within the sequence indicate that the lake dried sometime in the mid-Holocene. After about 4000 years ago a short predominance of cold water ostracodes marks a brief period of lower temperatures, but a subsequent gradual increase of warm water species indicates a return to higher (present-day) temperatures.

Delorme (1965, 1970a, b, c, d, 1971a) has accumulated a wealth of information on the ecology of ostracodes in many of the lakes of Saskatchewan. Although the use of these data in association with other paleobiological and sedimentological information can yield very precise estimates of a variety of paleoecological factors (Delorme, 1969, 1971b; Delorme *et al.,* 1977), it has not yet been applied to saline lacustrine sequences in southern Saskatchewan.

Pasqua Lake in eastern Saskatchewan is one of a series of shallow, eutrophic, riverine lakes that occupy a late Pleistocene glacial spillway. Warwick (1979, 1982) attempted to evaluate historical changes in the trophic status by analyzing the fossil chironomid remains in a series of 2 m cores from the basin. Although precise chronological control was not achieved, the chironomid communities indicate that the lake had been shallow and eutrophic for a considerable time before European settlement in the area.

Manitoba

Of the many lakes in the plains portion of southern Manitoba, few are saline. Lake Manitoba, a remnant of glacial Lake Agassiz and one of the largest lakes in western Canada, is alkaline and moderately saline with up to 3500 mg l^{-1} TDS (Last, 1984a). In recent years the lake has been the subject of considerable geolimnological research centered on the paleoenvironmental record which can be deduced from the 15 m, 12000 year old stratigraphic sequence recovered from the basin (Teller & Last, 1979, 1981, 1982; Last, 1982; Last & Teller, 1983; Nambudiri & Shay, 1986; Nambudiri *et al.,* 1980; Sproule, 1972). Several weakly developed soil horizons in the cores suggest that the lake's level has fluctuated significantly, with the last major period of desiccation occurring about 5500–4500 B.P. The amount and type of endogenic carbonate precipitated in the lake varied in conjunction with these fluctuations. After each period of desiccation, elevated Mg/Ca ratios in the reflooded lake were brought about by dissolution of efflorescent crusts that formed during previous arid episodes. The high Mg/Ca ratio brines are recorded in the sediment by the presence of magnesian calcite. Stratigraphic variation in pyrite from the cores reflects changing chemical conditions of the near-surface, very early diagenetic environment. High amounts of authigenic pyrite and kaolinite in the mid-Holocene sediment reflect low Eh and probably slightly acidic conditions. In contrast, the near absence of pyrite in sediment immediately overlying each of the soil zones suggests an aerated water column caused by wave mixing and the influx of oxygenated river water. Finally, the occurrence of fluvial and deltaic sediments in the offshore portion of the basin further points to substantially lower water levels about 4500–3500 years ago.

Current paleolimnological investigations

General

It is evident from the foregoing review that there are relatively few comprehensive paleolimnological studies of saline lakes in the Canadian Great Plains. This is surprising considering the large geographic area (130000 km^2), the large number of saline lakes and closed basins, and the likely sensitivity of the region to Pleistocene and Holocene climatic fluctuations. Similarly, there has been little past effort to integrate observational and experimental studies of modern sediment-water interaction with the paleoenvironmental investigations. The studies described below are a summary of the authors' ongoing paleolimnological efforts on the salt lakes of the region. As the objective of this discussion is to provide an overview of salt lake paleolimnology, the many important sedimentological and geochemical details are left to other presentations. Table 1 summarizes the main features of the four lakes discussed.

Waldsea Lake

Waldsea Lake, located about 100 km east of Saskatoon, has an area of about 5 km^2 and a mean depth of 8.1 m. The lake is now saline and meromictic with the mixolimnion averaging 29 g l^{-1} TDS and the monimolimnion about 53 g l^{-1}. Both water masses are dominated by Na and SO_4 and have secondary abundances of Mg and Cl ions. Because the chemocline also contains a bacterial plate composed of a green sulfur bacteria, *Chlorobium*, modern Waldsea Lake has received considerable attention (e.g., Hammer *et al.*, 1978; Lawrence *et al.*, 1978; Parker *et al.*, 1983; Swanson & Hammer, 1983). The entire water column is saturated or supersaturated with respect to various carbonate minerals at all times of the year, and, because of the high Mg/Ca ratio of the brine, aragonite precipitation occurs. The monimolimnion is also at or near saturation with respect to gypsum (Last & Schweyen, 1983). During the cold winter season, the surface waters can approach saturation with respect to mirabilite (Na_2SO_4 $10H_2O$).

The modern sediment and the mid to late Holocene deposits of the basin have been intensively sampled with cores from 40 sites (Fig. 2) and surficial samples from 60 locations. The modern sediments can be divided into three broad genetic groups: shallow and nearshore coarse clastics; fine-grained, organic-rich carbonates and clastics; and deep basinal, highly anoxic, fine-grained clastics and carbonates. Details regarding the genesis and distribution of these modern sediments are presented elsewhere (Schweyen, 1984; Last & Slezak, 1986). This relatively simple modern facies assemblage does not persist throughout the Holocene record. Rather, the stratigraphic sequence preserved in the basin reflects significantly differing lacustrine environmental conditions (Fig. 3).

The lowermost sediment recovered (mid-Holocene) consists of black, faintly laminated,

Table 1. Characteristics of the four lakes discussed in this paper.

	Waldsea lake	Deadmoose lake	Ceylon lake	Lake Manitoba
Basin type	Perennial	Perennial	Playa	Perennial
Basin area (km^2)	4.7	10.5	3.0	4706
Mean depth (m)	8.1	9.7	-	3.6
Basin morphology	Smooth	Irregular	Riverine	Smooth
Brine type	Na-SO_4 (Mg, Cl)	Na-SO_4 (Mg, Cl)	Mg-SO_4 (Na, Cl)	Na-Cl (HCO_3)
Stratification	Meromictic	Meromictic	-	Monomictic
Sediment type	Allogenic	Allogenic	Endogenic	Allogenic

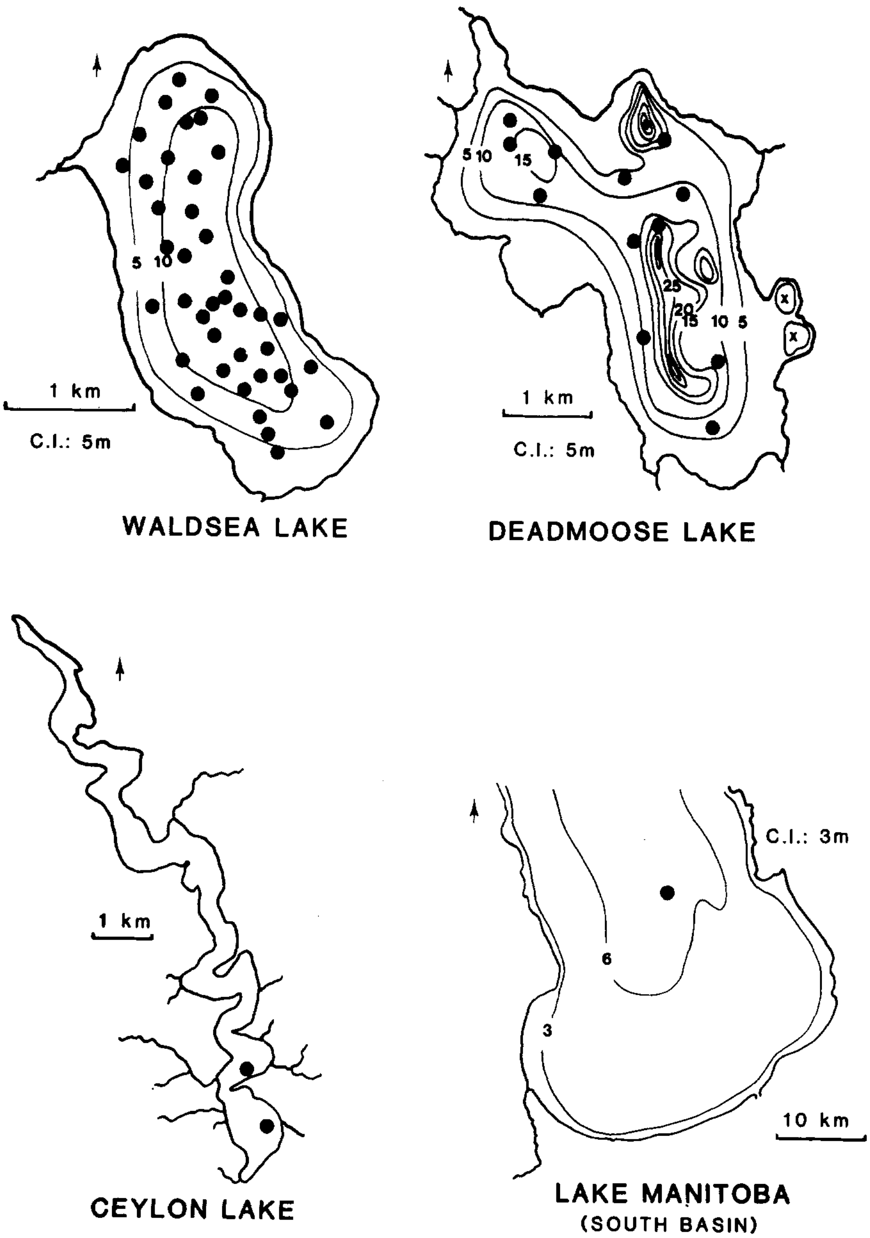

Fig. 2. Bathymetric maps of the four lakes discussed in this paper. Black circles indicate core locations. C.I. is contour interval. Ceylon Lake is a playa basin and no bathymetric contours are shown.

organic-rich silty clay that is characterized by an abundance of disseminated plant fibers and fiber mats, and the presence of large, euhedral crystals of mirabilite. This sediment intercalates with and grades laterally into a laminated, greenish grey, gypsiferous, clayey and sandy silt. This latter material also contains magnesite, dolomite-cemented hardgrounds and beds of calcareous intraclasts. Upsection, the sediment grades into a finely laminated, dark grey, silty clay characterized by abundant aragonite-clay couplets, a relatively low gypsum content, and much organic matter. Overlying this is another laminated, gypsum-rich clayey silt with dolomite hardgrounds which grades upward into a

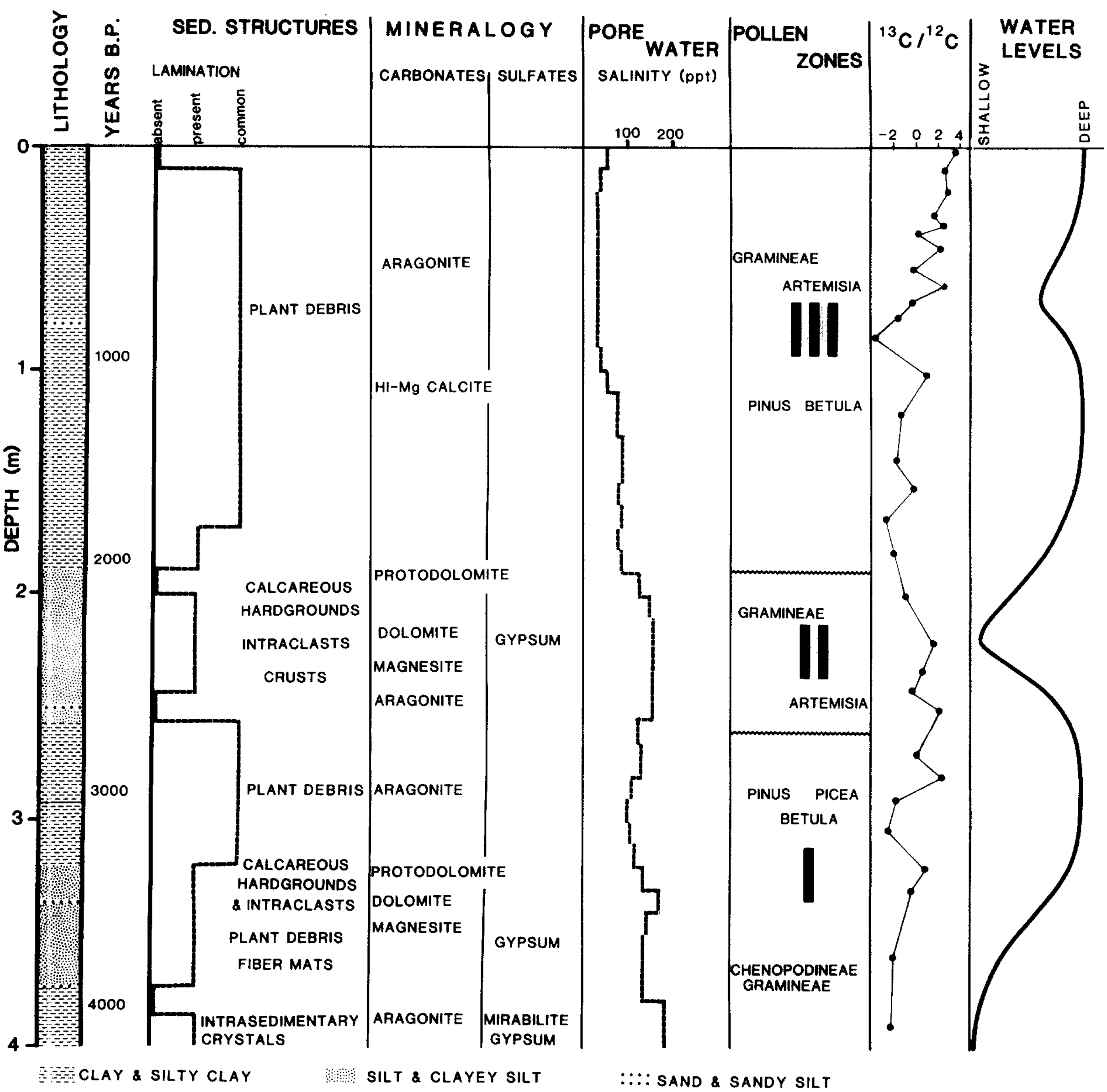

Fig. 3. Composite stratigraphic section from Waldsea Lake showing interpreted water level changes. The carbon isotope ratios are from endogenic carbonates in the sediment and are reported in δppt (PDB).

rhythmically laminated, organic-rich carbonate mud and, finally at the top of the sequence, a non-laminated, calcareous silty clay.

The distinctive mineral suite (gypsum, dolomite, mirabilite), and the morphologies and textures of these components in the lower-most sediment indicate that deposition occurred in a saline, clastic-dominated playa. Water levels fluctuated significantly, probably on a seasonal basis. When there was ponded water in the basin, it was dominated by Na and SO_4 ions. Concentrations in the lake probably exceeded 200 g l^{-1} and seasonal precipitation of mirabilite and other evaporitic salts occurred. The mudflats surrounding this shallow lake were sites of abundant gypsum and organic and inorganic carbonate precipitation. The intense evaporation on the mudflats created a dynamic diagenetic environment and much of the original calcium carbonate was quickly altered to dolomite in response to the high Mg/Ca ratios of the pore water. When water levels were even lower, algal mudflats and vegetation mats covered most of the basin.

As climatic conditions moderated and the hydrologic budget became increasingly more positive, lake levels rose. Fine, undisturbed carbonate laminae alternating with organic-rich muds suggest deposition in a relatively deep, stratified lake. Although high pore water salinities indicate that the lake was still saline during this high water phase, it cannot be unequivocally established that the basin was also meromictic. Deposition of the pure aragonite laminae is most likely related to sporadic influx and mixing of water of a composition different from the lake brine. As dilute inflow, probably associated with periods of increased streamflow and surface runoff, entered and mixed with the highly alkaline and Mg-rich saline brines, basin-wide inorganic precipitation would occur in the form of carbonate whitings. In addition to this endogenic precipitation of aragonite, fluctuating Mg/Ca ratios in the lake or within the pore water gave rise to a complex assemblage of early diagenetic carbonates including calcite, high-Mg calcite, protodolomite, and magnesite.

The lake became shallow once more and mudflat-playa conditions returned to the basin between 2800 and 2000 B.P. as evidenced by gypsum laminae, dolomite crusts, organic fiber mats, and high pore water salinities. Finally, deposition of finely laminated sediment (aragonite-clay couplets) in a relatively deep water, stratified basin dominated the most recent 2000 years of Waldsea. Except for a slight lowering of the lake about 1000–700 B.P. indicated by the occurrence of a relatively coarse silt-sand facies, water levels, brine chemistries, and ionic ratios have been stable.

The vegetation history of the region, determined from the pollen content of the sediment, and the paleoproductivity, deduced from stable carbon isotope studies, further help describe the paleoenvironmental conditions of Waldsea Lake. Last & Schweyen (1985) present a palynological sequence from the center of the basin which accords closely with the conditions deduced from sedimentological data. The lowermost pollen zone, dominated by grasses at the base and pine, spruce and other boreal elements at the top, indicates a transition from warmth and aridity to cooler and moister conditions. A middle zone shows a decrease in pine and spruce and a corresponding increase in herbaceous pollen types. This suggests the return to more open prairie vegetation conditions and supplies additional confirmation of a lowering of the lake at about 2800 years ago. The uppermost pollen zone in Waldsea indicates no major natural vegetation changes during the last 2000 years.

As shown by McKenzie (1982), stable carbon isotope data collected from endogenic precipitates in a lacustrine basin can be used as a general guide to the paleoproductivity of the lake. Greater primary productivity should preferentially extract more of the lighter ^{12}C isotope from the water, therefore enriching the lake with respect to ^{13}C. Assuming isotopic equilibrium, the endogenic carbonates originating in the upper layers of the lake should faithfully record any carbon isotopic changes in the water and, thus, be a guide to the fluctuations of organic productivity. The $^{13}C/^{12}C$ values for aragonite from Waldsea Lake sediment (Fig. 3) suggests initially low productivity (low $^{13}C/^{12}C$) grading upsection to higher productivity levels. There is a reversal in this trend with decreased productivity indicated about 2200 years ago. Finally, the upper 1.5 m of sediment shows a trend toward increasing productivity.

Deadmoose Lake

Deadmoose Lake, a 10 km^2 saline lake, is also presently meromictic with a monimolimnion of about 61 g l^{-1} TDS and a mixolimnion of 29 g l^{-1}. Both water masses of Deadmoose are dominated by Na and SO_4 with secondary abundances of Mg and Cl, and are at or near saturation with respect to calcium and magnesium carbonates and gypsum (Last & Slezak, 1986). A total of 25 m of sediment cores have been retrieved from 12 sites in the basin (Fig. 2). The modern sediments being deposited in Deadmoose are generally similar to those of nearby Waldsea. Because of the strikingly irregular morphology of the basin, the stratigraphic sequence in Deadmoose Lake is rather complex. Cores from relatively shallow portions of the basin (<15 m water depth) exhibit a rather intricate facies assemblage (Fig. 4). In the southern part of the lake in water depths less than about 7 m, a light grey, poorly sorted, pebbly sandy clay (till) underlies a thin veneer (2–5 cm) of finely laminated, black, organic-rich, calcareous clay.

The sequences recovered from the northern and

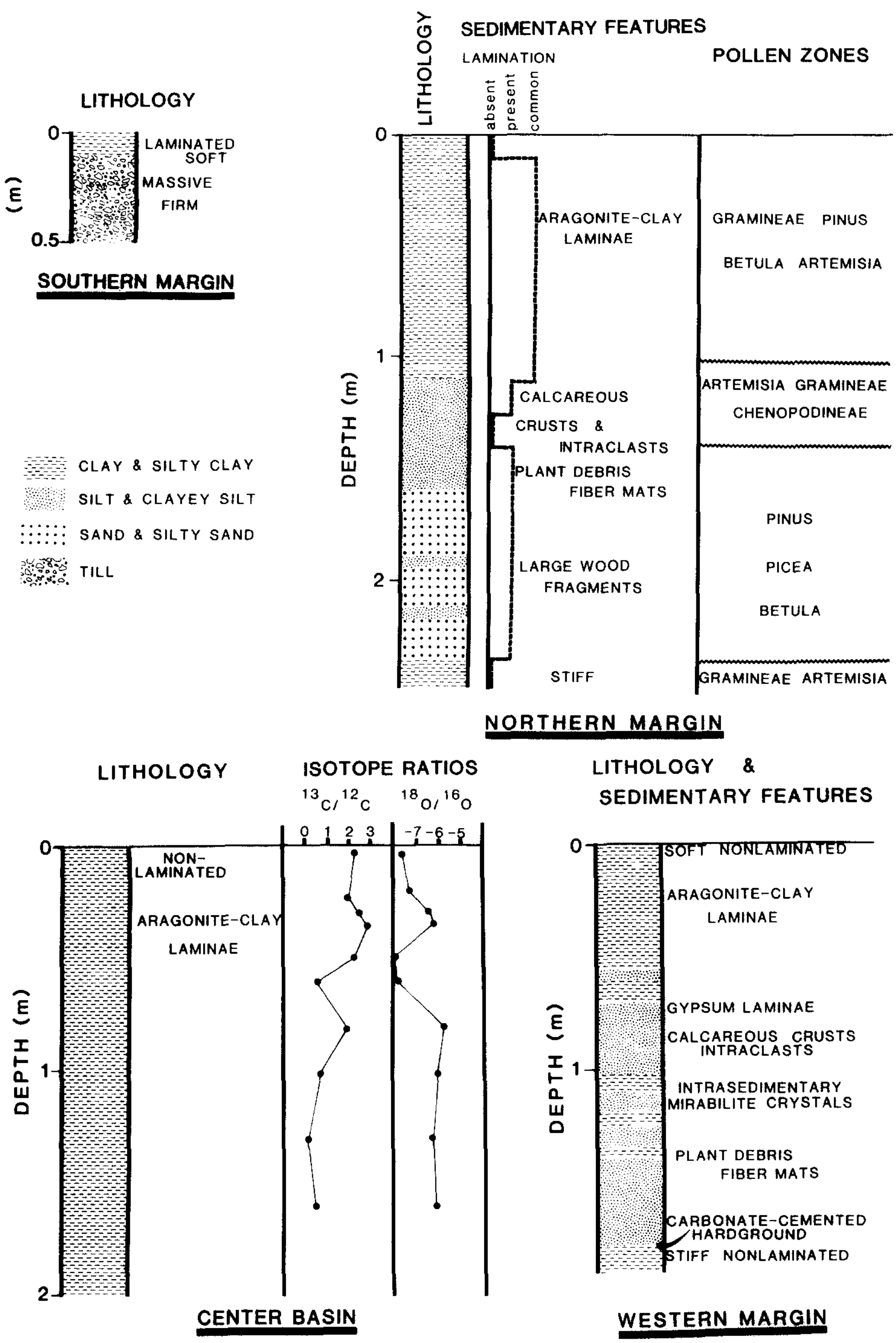

Fig. 4. Representative stratigraphic sections from Deadmoose Lake. The stable isotope data are from endogenic carbonates in the sediment and are reported in δppt (PDB).

western sides of the basin are much more diverse. In the north, the available stratigraphic section consists of a very stiff, homogeneous basal clay which is overlain by 50–100 cm of fine grained sand. This is overlain by up to 75 cm of faintly laminated, gypsiferous, greyish green mud containing abundant vegetation debris and carbonate cemented crusts. The upper meter of section consists of alternating aragonite-clay couplets grading upward to non-laminated, calcareous organic mud. Wood fragments from the sand overlying the stiff basal clay in the north have be dated at 1080 +/–110 B.P. (Beta 9888).

In the western part of the basin the stiff basal clay is capped by a thin carbonate cemented hardground. Overlying this sharp contact is a dark gray, organic-rich, gypsiferous mud which contains carbonate intraclasts, fragments of carbonate crust, vegetation mats and debris, and mirabilite crystals. As in the northern part of the basin, the upper part of the section consists of well-laminated, aragonite-clay couplets grading upward to homogeneous mud at the top. The stratigraphic sequence recovered from relatively deep portions of Deadmoose Lake (15–30 m water depth) consists only of well laminated, black, organic-rich clay with abundant, irregularly spaced aragonite laminae. In water depths greater than about 30 m, the sediment consists of mirabilite salt of undetermined thickness.

The presence of coarse clastics, carbonate cemented hardgrounds and crusts, vegetation mats, and gypsum laminae in the relatively shallow margins of Deadmoose indicate considerably lower lake levels (Fig. 5). Several satellite basins, which are now part of Deadmoose, were probably separate lakes during this low water phase. The sandy facies in the northern end of the basin was part of a shoreline/delta complex that was active about 1200 years ago. This sediment was deposited in a lake about 10 m lower and considerably smaller than that of today. Mudflats covered with vegetation debris and carbonate cemented hardgrounds and crusts surrounded the nearshore wedges of coarse clastics. To the south the presence of till within centimeters of the present-day sediment-water interface suggests that erosion of any previously deposited lacustrine sediment occurred during this lower water phase. Despite substantially lowered lake levels, there is no evidence to date that the basin dried completely. Conditions within the main (deep) part of the basin were probably roughly similar to that of today. Fine, undisturbed lamination and the lack of crusts, intraclasts and fiber mats confirm the existence of a relatively deep, stratified water body. The presence of aragonite points toward elevated but probably stable Mg/Ca ratios. The occurrence of mirabilite in the deepest part of the basin indicates strongly saline bottom water conditions.

With higher water levels and a transgressing shoreline, the nearshore coarse clastics and mudflat deposits were drowned, and deeper water (aragonite laminated) sediment was deposited. The homogeneous uppermost 5–15 cm of sediment in the basin suggests that conditions responsible for the periodic aragonite whitings have not occurred for some time.

The pollen sequence identified from a 2 m core on the northern edge of the basin consists of three zones (Fig. 4). The basal zone is characterized by high *Artemisia* and Gramineae and relatively low *Pinus* values. This changes upward to a zone of increased arboreal pollen at the expense of the grasses and shrubs. The upper meter of sediment shows a complacent pollen assemblage except for increases in *Chenopodiineae, Cruciferae, Ambrosia,* and *Selaginella,* which can all be related to cultivation of the drainage basin during the last century. This pollen stratigraphy suggests a change from a warm, dry period at the base of the section to a cooler and wetter episode after about 1000 B.P.

Stable oxygen isotope information collected from calcareous sediment has been widely used as a paleothermometer (e.g., Hendy & Wilson, 1968; Stuiver, 1970; Savin, 1977). $^{18}O/^{16}O$ data on the endogenic carbonates from a relatively deep water (14 m) portion of the basin (Fig. 4) confirms a warmer, more evaporitic regime at the base of the core grading upward to cooler conditions at the top of the section. Likewise, $^{13}C/^{12}C$ data on these carbonates imply generally increasing levels of organic productivity upward in the section.

Ceylon Lake

Ceylon Lake occupies a 7 km long riverine basin in-

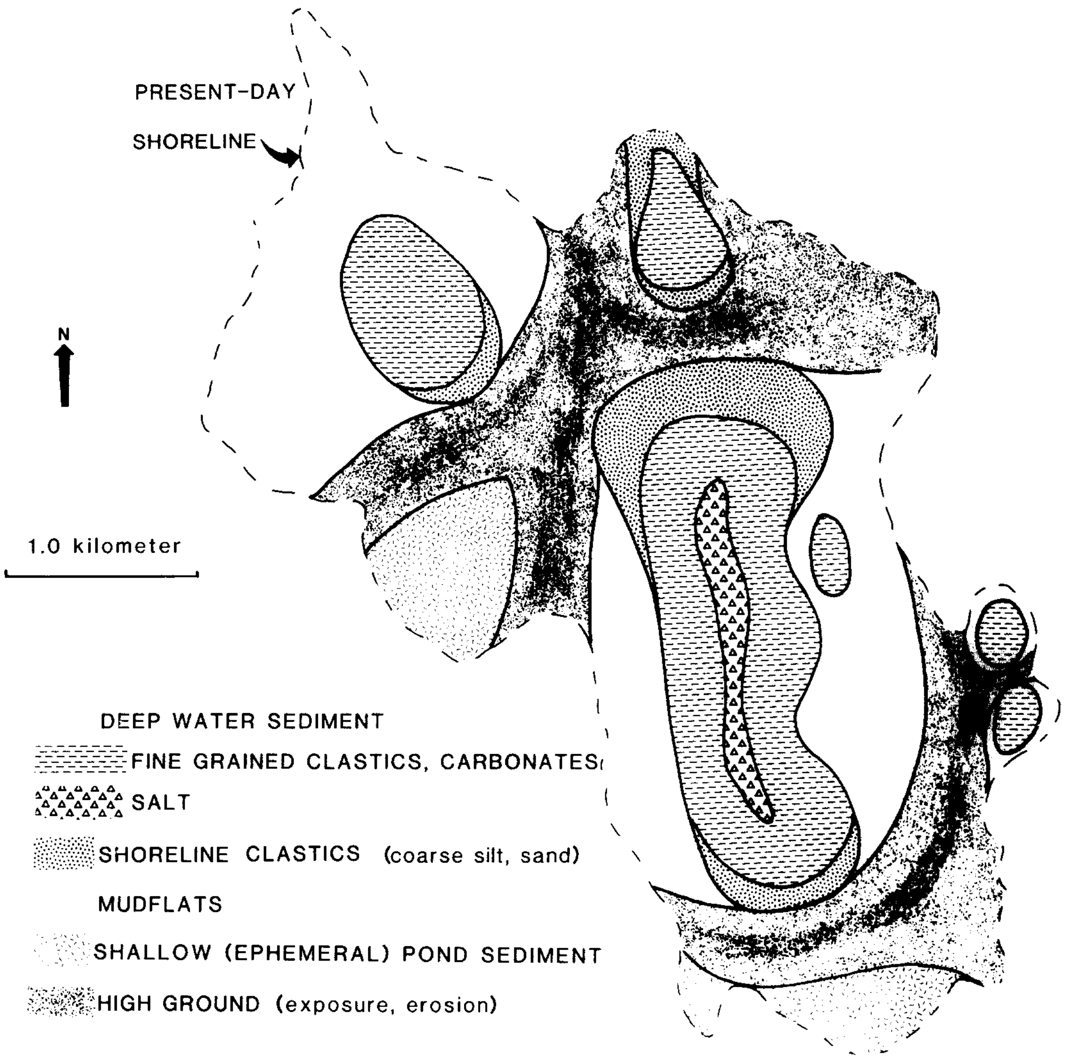

Fig. 5. Interpreted facies distribution in Deadmoose Lake about 1000 years ago.

cised about 60 m below the surrounding hills of the Missouri Coteau (Fig. 2). At present the lake is a salt-dominated playa. During spring and early summer the basin can be flooded with as much as 1 m of brine. Throughout most of the year water depths of less than 5 cm are common, with the basin drying completely for long periods. When water does occupy the basin, it is usually of the Mg-Na-SO_4 type, although enormous seasonal and spatial changes in salinity and ionic ratios do occur (see Fig. 6 of Last, 1984b). Last & Slezak (1984) and Last (1984b; 1987) review the modern sedimentology and geochemistry of Ceylon Lake.

The stratigraphic sequence in the basin (Fig. 6) is known from 12 auger test holes reported by Cole (1926) and two 7 m cores obtained in 1983. The lowermost sediment penetrated in the basin is a brown pebbly clay (till) which immediately underlies up to several meters of coarse-grained sand and gravel. Overlying this is: (a) stiff, greenish-grey, homogeneous, calcareous clay interbedded with thin beds of silty sand, (b) soft, black, anoxic, nonlaminated, organic-rich mud with abundant intrasedimentary gypsum and mirabilite crystals, and finally at the top of the section (c) salt with thin beds of black silty clay. The salt consists mainly of mirabi-

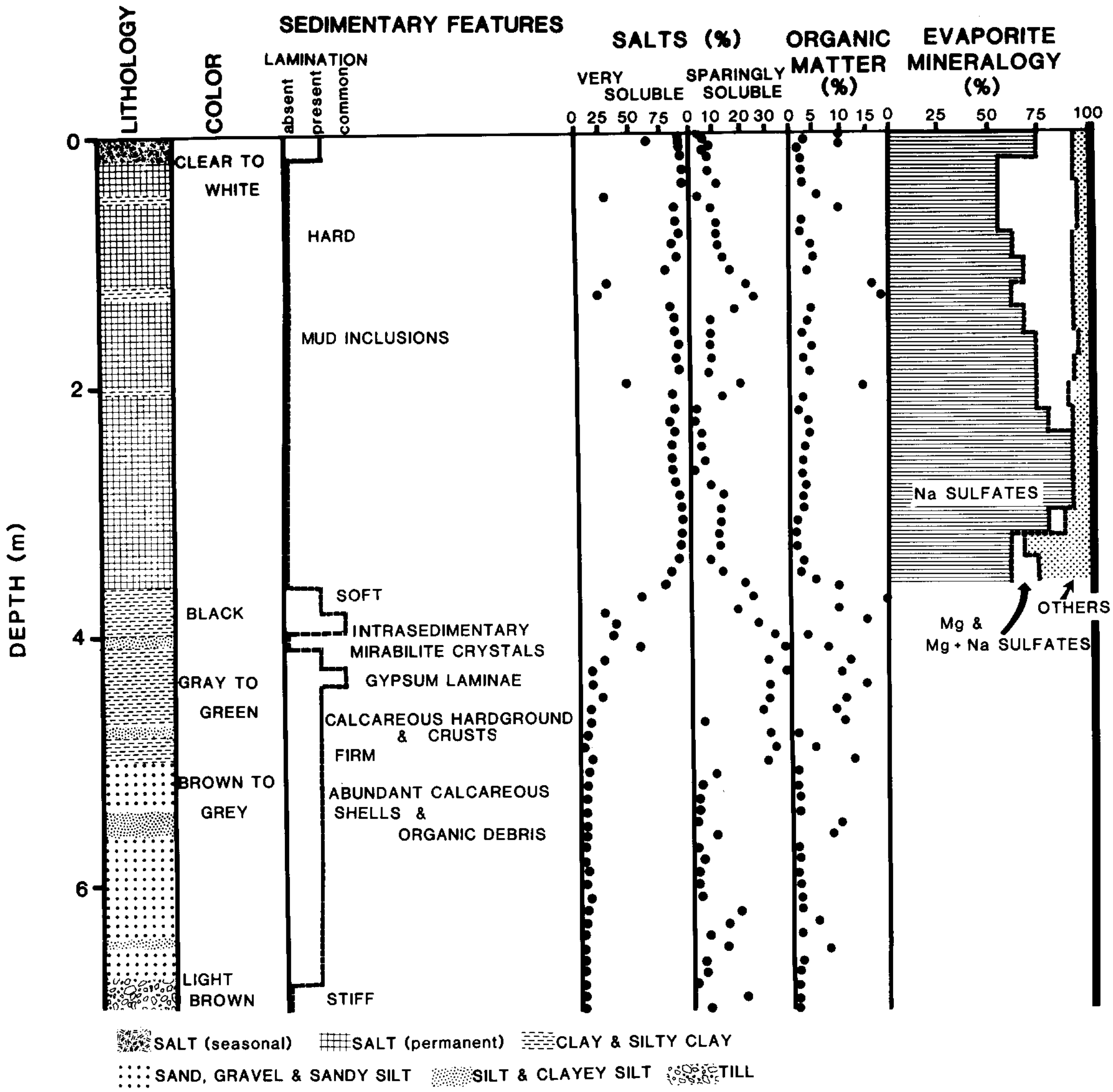

Fig. 6. Ceylon Lake stratigraphy. Very soluble salts are those that can be dissolved in water; sparingly soluble salts are those that are not soluble in water but can be dissolved in dilute HCl acid. The percentage of these salts are expressed relative to the total sediment and do not necessarily sum to 100. Organic matter is the percentage loss after heating to 500 °C. The evaporite mineralogy was determined by a combination of X-ray diffraction and wet chemical methods and is expressed as a percentage of the total very soluble plus sparingly soluble salts.

lite but also contains appreciable amounts of gypsum, bloedite and epsomite. Natron and halite occur in trace amounts. Several discontinuous strandline features (beaches or wave cut terraces) occur on the steep walls of the valley above the present level of the lake. Much of the lower slope of the valley is mantled with a residual boulder pavement.

The clastic and chemical sediment in lakes such as Ceylon cannot be easily used to reconstruct individual climatic parameters because the sediments reflect the combined influences of varying evaporation/precipitation ratios, quantity and chemistry of groundwater inflow, and runoff characteristics (Slezak & Last, 1985b). However, the stratigraphy does record, in a general way, considerably differing depositional conditions, hydrologic budgets, and water chemistries.

The Ceylon Lake basin, as well as several other large riverine valleys in the area, originated as a glacial meltwater spillway about 15 000 years ago. The well sorted, coarse clastics immediately overlying ice laid deposits in the basin were probably deposited in this fluvial environment. Due to slumping of the valley walls, differential isostatic rebound, and decreased meltwater flow, water gradually became ponded in the basin and lacustrine sedimentation began. Assuming the various strandline features were implaced soon after the lake formed, the basin was initially about 6 to 10 m deep. The presence of calcite and the absence of Mg-bearing carbonates and other salts in the compact clay at the base of the section suggests a relatively dilute, low Mg/Ca ratio brine. The homogeneous nature of this sediment further implies a lack of stratification in the water body or an abundance of bottom dwelling organisms. Interpretation of the thin beds of coarse clastics in this lower clay is somewhat problematic. These sands could have originated by slumping and turbidity flowage from the shoreline of the steep sided basin. Alternatively, they may have been deposited during periods of substantially lower water levels, and thus could actually represent major gaps in the early stratigraphic record.

The increase in soluble salts versus clastics upward in the core and the abundance of intrasedimentary precipitates in the upper units strongly point toward increasing salinity, decreasing water levels and possibly increased aridity with time. The change from black silty clay upward into the evaporite facies marks the transition from a mud dominated playa to a salt playa. Because chronological control has not yet been established, little can be said of the temporal duration of these changes. Periods of a more positive hydrologic budget are recorded by thin silty clay interbeds within the salt column. However, these changes do not necessarily reflect dramatic fluctuations in water levels. Today, for example, an influx of freshwater from seasonal storms and snowmelt in the drainage basin is capable of redissolving up to 50 cm of previously precipitated salts within days. Conversely, during periods of extreme aridity when the basin was completely dry, transport of fine-grained clastics and removal of salts by wind likely played an important role. The upward increase in Mg-bearing epsomite and bloedite at the expense of mirabilite suggests a shift in overall brine chemistry from a Na-dominated system to one of mixed Mg and Na. The source of the added Mg is not known.

Lake Manitoba

Sediments deposited in the Lake Manitoba basin from about 9000 B.P. to the present contain variable amounts of endogenic Mg-calcite. This carbonate was deposited in response to supersaturated conditions brought about by photosynthetic utilization of CO_2 in the lake. The $^{18}O/^{16}O$ analyses of these carbonates indicate relatively higher but gradually decreasing temperatures between 9000 and 5000 B.P. (Fig. 7). Between 4000 and 2000 years ago the isotope ratios suggest relatively stable temperatures followed by a strong decrease during the most recent 2000 year record. These isotope temperature trends fit well with palynological analyses of the basin (see for example Fig. 9 in Teller & Last, 1981). The period of maximum warmth coincides with a pollen zone dominated by Gramineae, *Chenopodiineae, Cyperaceae,* and *Ambrosia,* which suggests open prairie conditions. The uppermost pollen zone in Lake Manitoba is characterized by high percentages of arboreal and shrub pollen, supporting the shift toward cooler temperatures indicated by the oxygen isotopes.

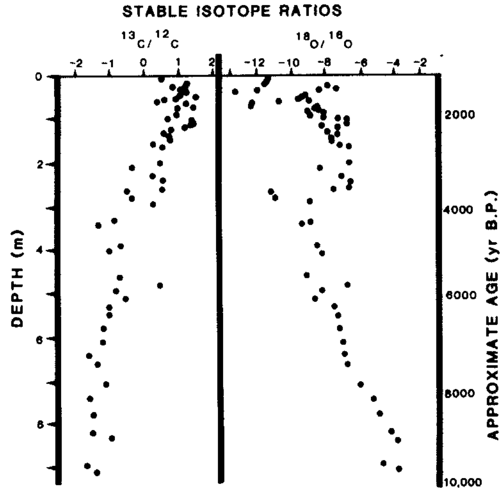

Fig. 7. Results of stable oxygen and carbon isotope analyses (in δppt PDB) on endogenic carbonates from Lake Manitoba.

The stable carbon isotope data on this high-Mg calcite of Lake Manitoba (Fig. 7) record a gradually increasing level of organic productivity. This corresponds to the lithostratigraphic record presented by Teller & Last (1981) in which the abundance of organic matter shows a gradual increase upward in the cores.

The paleolimnological studies discussed in this paper clearly demonstrate the usefulness of saline lake deposits in helping to gain an understanding of the postglacial environmental changes in the northern Great Plains. The salt lakes of western Canada are particularly attractive for such studies because there are a large number of basins located in a wide variety of modern hydrologic, climatic, and vegetational settings, and there is a great diversity of lacustrine chemical and sedimentological systems within this large geographic area. The salt lakes of western Canada offer a rare opportunity to evaluate regional environmental changes and climatic perturbations versus more local events.

Acknowledgements

Our on-going stratigraphic investigations of salt lakes in the northern Great Plains is supported by grants from American Association of Petroleum Geologists, Canadian Plains Research Center, Energy, Mines and Resources Canada, Environment Canada, and Natural Sciences and Engineering Research Council of Canada. Pollen analyses from Waldsea and Deadmoose lakes were done by S. Kroker (Quaternary Consultants, Winnipeg). Dr. C. Hillaire-Marcel (Universite du Quebec a Montreal) kindly provided much of the Lake Manitoba stable isotope data. Earlier versions of this paper were improved by the comments of Robert W. Holmes and John M. Melack.

References

Broughton, P. L., 1984. Sodium sulphate deposits of western Canada. In G. R. Guillet & W. Martin (eds.) The Geology of Industrial Minerals in Canada. Can. Inst. Mining and Met., Spec. 29: 195–200.

Carlson, E. Y., 1956. Sturgeon Lake marl deposit. Sask. Dept. Min. Resour. Rep. Invest. No. 8, 55 pp.

Carlson, E. Y. & W. J. Babey, 1955. Core drilling for industrial minerals in Saskatchewan. Sask. Dept. Min. Resour. Rep. Invest. No. 6, 53 pp.

Christiansen, E. A., 1967. Collapse structures near Saskatoon, Saskatchewan, Canada. Can. J. Earth Sci. 4: 757–767.

Christiansen, E. A., 1971. Geology of Crater Lake collapse structure in southeastern Saskatchewan. Can. J. Earth Sci. 8: 1505–1513.

Christiansen, E. A., D. J. Gendzwill & W. A. Meneley, 1982. Howe lake: a hydrodynamic blowout structure. Can. J. Earth Sci. 19: 1122–1139.

Cole, L. H., 1926. Sodium sulfate of western Canada. Occurrence uses and technology. Can. Dept. Mines Pub. 646, 155 pp.

Delorme, L. D., 1965. Pleistocene and post-Pleistocene ostracoda of Saskatchewan. Ph.D. thesis, Univ. Saskatchewan, 282 pp.

Delorme, L. D., 1969. Ostracodes as Quaternary paleoecological indicators. Can. J. Earth Sci. 6: 1471–1476.

Delorme, L. D., 1970a. Freshwater ostracodes of Canada, part 1. Subfamily Cypridinae. Can. J. Zool. 48: 153–168.

Delorme, L. D., 1970b. Freshwater ostracodes of Canada, part 2. Subfamily Cypridopsinae and Herpetocypridinae, and family Cyclocyprididae. Can. J. Zool. 48: 253–266.

Delorme, L. D., 1970c. Freshwater ostracodes of Canada, part 3. Family Candonidae. Can. J. Zool. 48: 1099–1127.

Delorme, L. D., 1970d. Freshwater ostracodes of Canada, part 4. Families Ilyocxyprididae, Notodromadidae, Darwinulidae, Cytherideidae, Entocytheridae. Can. J. Zool. 48: 1251–1259.

Delorme, L. D., 1971a. Freshwater ostracodes of Canada, part 5. Families Limnocytheridae, Loxoconchidae. Can. J. Zool. 49: 43–64.

Delorme, L. D., 1971b. Paleoecology of Holocene sediments from Manitoba using freshwater ostracodes. In A. C. Turnock (ed.), Geoscience Studies in Manitoba. Geol. Assoc. Can. Spec. Paper No. 9: 301–304.

Delorme, L. D., S. C. Zoltai & L. L. Kalas, 1977. Freshwater shelled invertebrate indicators of paleoclimate in northwestern Canada during late glacial times. Can. J. Earth Sci. 14: 2029–2046.

Forbes, J. R. & M. Hickman, 1978. The environmental history of LacSte. anneanditsbasin. Alta. Environ. Rpt., Water Qual. Sect., 30 pp.

Forbes, J. R. & M. Hickman, 1981. Paleolimnology of two shallow lakes in central Alberta, Canada. Int. Revue ges. Hydrobiol. 66: 863–888.

Fritz, P. & H. R. Krouse, 1973. Wabamun Lake past and present, an isotopic study of the water budget. In E. R. Reinelt, A. H. Laycock & W. M. Schultz (eds.), Proc. Symposium on the Lakes of Western Canada. Univ. Alberta Water Res. Cen. Pub. No. 2: 244–259.

Gendzwill, D. J. & Z. Hajnal, 1971. Seismic investigation of the Crater Lake structure in southeastern Saskatchewan. Can. J. Earth Sci. 8: 1514–1524.

Govett, G. J. S., 1958. Sodium sulfate deposits in Alberta. Res. Coun. Alberta, Rep. 58–5, 34 pp.

Grossman, I. G., 1949. The sodium sulfate deposits of western North Dakota: a progress report. N. Dakota Geol. Surv. Rep. Invest. 1, 65 pp.

Grossman, I. G., 1968. Origin of sodium sulfate deposits of the northern Great Plains of Canada and the United States. U.S. Geol. Surv. Prof. Pap. 600-B: B104–B109.

Guliov, P., 1963. Paleoecology of invertebrate fauna from postglacial sediments near Earl Grey, Saskatchewan. M.Sc. thesis, Univ. Saskatchewan, 104 pp.

Hammer, U. T., 1978a. The saline lakes of Saskatchewan. I. Background and rationale for saline lakes research. Int. Revue ges. Hydrobiol. 63: 173–177.

Hammer, U. T., 1978b. The saline lakes of Saskatchewan. 3. Chemical characterization. Int. Rev. ges. Hydrobiol. 63: 311–335.

Hammer, U. T. & R. C. Haynes, 1978. The saline lakes of Saskatchewan. 2. Locale, hydrology and other physical aspects. Int. Revue ges. Hydrobiol. 63: 168–203.

Hammer, U. T., R. C. Haynes, J. R. Lawrence & M. C. Swift, 1978. Meromixis in Waldsea lake, Saskatchewan. Verh. int. Ver. Limnol. 20: 192–200.

Hammer, U. T., J. Shamess & R. C. Haynes, 1983. The distribution and abundance of algae in saline lakes of Saskatchewan, Canada. Hydrobiologia 105: 1–26.

Haynes, R. C. & U. T. Hammer, 1978. The saline lakes of Saskatchewan. 4. Primary production of phytoplankton in selected saline ecosystems. Int. Revue ges. Hydrobiol. 63: 337–351.

Hendy, C. H. & A. T. Wilson, 1968. Paleoclimatic data from speleothems. Nature 216: 48.

Hickman, M. & D. M. Klarer, 1981. Paleolimnology of Lake Isle, Alberta, Canada. Arch. Hydrobiol. 91: 490–508.

Hickman, M., C. E. Schweger & T. Habgood, 1984. Lake Wabamun, Alta.: a paleoenvironmental study. Can. J. Bot. 62: 1438–1465.

Holloway, R. G., V. M. Bryant & S. Valastro, 1981. A 16000 year pollen record from Lake Wabamun, Alberta, Canada. Palynology 5: 195–208.

Last, W. M., 1982. Holocene carbonate sedimentation in Lake Manitoba, Canada. Sedimentology 29: 691–704.

Last, W. M., 1984a. Modern sedimentology and hydrology of Lake Manitoba, Canada. Envir. Geol. 5: 177–190.

Last, W. M., 1984b. Sedimentology of playa lakes of the northern Great Plains. Can. J. Earth Sci. 21: 107–125.

Last, W. M., 1987. Sedimentology, geochemistry, and evolution of a saline playa from the northern great plains, Canada. Estud. geol. in press.

Last, W. M. & T. H. Schweyen, 1983. Sedimentology and geochemistry of saline lakes of the Great Plains. Hydrobiologia 105: 245–263.

Last, W. M. & T. H. Schweyen, 1985. Late Holocene history of Waldsea Lake, Saskatchewan, Canada. Quat. Res. 24: 219–234.

Last, W. M. & L. A. Slezak, 1984. A sedimentological overview of Ceylon Lake, Saskatchewan. Geol. Assoc. Can. Prog. Abst. 9: p. 82.

Last, W. M. & Slezak, L. A., 1986. Paleohydrology, sedimentology, and geochemistry of two meromictic saline lakes in southern Saskatchewan. Geog. et Quat. XL: 5–16.

Last, W. M. & J. T. Teller, 1983. Holocene climate and hydrology of the Lake Manitoba basin. In J. T. Teller & L. Clayton (eds.), Glacial Lake Agassiz. Geol. Assoc. Can. Spec. Paper 26: 333–353.

Lawrence, J. R., R. C. Haynes & U. T. Hammer, 1978. Contribution of photosynthetic green sulfur bacteria to total primary production in a meromictic saline lake. Verh. int. Ver. Limnol. 20: 201–207.

Lieffers, V. J. & J. M. Shay, 1983. Ephemeral saline lakes on the Canadian prairies: their classification and management for emergent macrophyte growth. Hydrobiologia 105: 85–94.

McKenzie, J. A., 1982. Carbon-13 cycle in Lake Greifen: a model for restricted ocean basins. In S. O. Schlanger & M. B. Cita (eds.), Nature and Origin of Cretaceous Carbon-rich Facies. Academic Press, N.Y.: 197–207.

Nambudiri, E. M. V. & C. T. Shay, 1986. Late pleistocene and holocene pollen stratigraphy of the Lake Manitoba basin, Canada. Palaeontographica 202: 155–177.

Nambudiri, E. M. V., J. T. Teller & W. M. Last, 1980. Pre-Quaternary microfossils – a guide to errors in radiocarbon dating. Geology 8: 123–126.

Parker, R. D., J. R. Lawrence & U. T. Hammer, 1983. A comparison of phototropic bacteria in two adjacent saline meromictic lakes. Hydrobiologia 105: 53–62.

Rawson, D. S. & G. E. Moore, 1944. The saline lakes of Saskatchewan, Can. J. Res. D22: 141–201.

Rueffel, P. G., 1968. Development of the largest sodium sulphate deposit in Canada. C.I.M. Bull. 61(678): 1217–1228.

Rutherford, A. A., 1970. Water quality survey of Saskatchewan surface waters. Sask. Res. Council Rep. C 70-1, 133 pp.

Savin, S. M., 1977. The history of the Earth's surface temperature during the past 100 million years. Ann. Rev. Earth Planet. Sci. 5: 319–355.

Schweyen, T. H., 1984. The sedimentology and paleohydrology of Waldsea Lake, Saskatchewan. M.Sc. Thesis, University of Manitoba, 151 pp.

Slezak, L. A. & W. M. Last, 1985a. Geology of sodium sulphate deposits of the northern Great Plains. Proc. 20th Forum on the Geology of Industrial Minerals, Maryland Geol. Surv., Spec. Pub. No. 2, p. 105–115.

Slezak, L. A. & W. M. Last, 1985b. Holocene climatic implications of the stratigraphic records of saline playas of the northern Great Plains. Proceedings of Symposium on Paleoenvironmental Reconstruction of Late Wisconsin Deglaciation and Holocene, CANQUA Meeting Program with Abstracts: p. 56.

Sproule, T. A., 1972. A paleoecological investigation into the postglacial history of Delta Marsh. M.Sc. Thesis, University of Manitoba, 49 pp.

Stuiver, M., 1970. Oxygen and carbon isotope ratios of fresh water carbonates as climatic indicators. J. Geoph. Res. 5: 251–262.

Swanson, S. M. & U. T. Hammer, 1983. Production of *Cricotopus ornatus* (Meigen) (Diptera: Chironomidae) in Waldsea Lake, Saskatchewan. Hydrobiologia 105: 155–164.

Teller, J. T. & W. M. Last, 1979. Post-glacial sedimentation and history in Lake Manitoba. Man. Dept. Mines, Nat. Resour., Envir. Rep. 79–41, 184 pp.

Teller, J. T. & W. M. Last, 1981. Late Quaternary history of Lake Manitoba, Canada. Quat. Res. 16: 97–116.

Teller, J. T. & W. M. Last, 1982. Pedogenic zones in postglacial sediment of Lake Manitoba, Canada. Earth Sur. Proc. Land. 7: 367–397.

Tomkins, R. V., 1953. Magnesium in Saskatchewan. Sask. Dept. Min. Resour., Rep. 11, 23 pp.

Tomkins, R. V., 1954. Natural sodium sulfate in Saskatchewan (2nd ed.). Sask. Dept. Min. Resour., Rep. 6, 71 pp.

Vance, R. E., D. Emerson & T. Habgood, 1983. A mid-Holocene record of vegetative change in central Alberta. Can. J. Earth Sci. 20: 364–376.

Wallick, E. I., 1981. Chemical evolution of groundwater in a drainage basin of Holocene age, east-central Alberta, Canada. J. Hydrology 54: 245–283.

Wallick, E. I. & H. R. Krouse, 1977. Sulfur isotope geochemistry of a groundwater-generated Na_2SO_4/Na_2CO_3 deposit and the associated drainage basin of Horseshoe Lake, Metiskow, east central Alberta, Canada. 2nd Intern. Symp. Water-rock Interaction, Strasbourg, France: II56–II64.

Warwick, W. F., 1979. Palaeolimnology of Pasqua Lake: preliminary report on benthic fauna responses to the sediment-water environment and long core collection during February–March, 1979. Can. Dep. Envir., Inl. Waters Direct., Nat. Water Res. Inst. Tech. Rep. W.N.R.-PR-79-4: 1–113.

Warwick, W. F., 1982. The palaeolimnology of Pasqua Lake, southeastern Saskatchewan. Can. Dep. Envir., Inl. Waters Direct., Nat. Water Res. Inst. Tech. Rep. W.N.R.-82-1, 70 pp.

Whiting, J. M., 1977. The hydrological and chemical balance of the Big Quill Lake basin. Sask. Res. Coun., Pub. E 77-12, 98 pp.