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PALEOHYDROLOGY, SEDIMENTOLOGY, AND GEOCHEMISTRY OF TWO MEROMICTIC SALINE LAKES IN SOUTHERN SASKATCHEWAN

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ABSTRACT The Northern Great Plains of western Canada contain numerous saline and hypersaline lakes. Most of these lakes are shallow (< 3 m) and exhibit playa characteristics. Some, however, are relatively deep, permanent water bodies. The sediment records of these deep perennial saline lakes offer an excellent opportunity to evaluate key paleohydrologic and hydrochemical parameters. Variations in these parameters may, in turn, be interpreted with respect to climatic fluctuations in the region. Waldsea and Deadmoose lakes, located in south-central Saskatchewan, are both presently meromictic, with saline Mg-Na-SO_4-Cl waters overlying denser hypersaline brines of similar composition. The modern sediments of the lakes consist of a mixture of organic matter, fine-grained detrital clastics (mainly clay minerals, carbonate minerals, quartz, and feldspars), and finely crystalline endogenic/authigenic precipitates (aragonite, gypsum, calcite, pyrite, and mirabilite). Variations in mineralogy and chemistry of sediment cores from the morphologically simple Waldsea basin show that the lake was much shallower and more saline about 4000 years ago. Although water levels have since generally increased in the basin giving rise to higher organic productivity and greater inorganic carbonate precipitation, there is also evidence of several hydrologic reversals during the last 2000 years. The stratigraphy preserved in nearby Deadmoose Lake is much more complex because of the irregular basin morphology. Lower water levels about 1000 years ago created several isolated but still relatively deep lakes in the Deadmoose basin.

RÉSUMÉ *Paléohydrologie, sédimentologie et géochimie de deux lacs méromictiques du sud de la Saskatchewan.* Les grandes plaines du nord de l'ouest du Canada contiennent de nombreux lacs salés et hypersalés. La plupart de ces lacs sont peu profonds (< 3 m) et offrent les caractéristiques des playas. D'autres, par contre, sont des plans d'eau permanents relativement profonds. Les données sédimentologiques de ces derniers permettent d'évaluer certains paramètres clés de paléohydrologie et d'hydrochimie. Les variations qu'offrent ces paramètres peuvent à leur tour être interprétées en fonction des fluctuations climatiques qu'a connues la région. Les lacs Waldsea et Deadmoose, dans le centre-sud de la Saskatchewan, sont méromictiques et leurs eaux composées de Mg-Na-So_4-Cl recouvrent une saumure hypersaline plus dense, mais de composition semblable. Les sédiments actuels de ces lacs consistent en un mélange de matière organique, de roches détritiques à grains fins (surtout des minéraux argileux et carbonatés ainsi que des quartz et des feldspaths) et de calcaires de précipitation cristallins à grains fins endogènes et authigènes (aragonite, gypse, calcite, pyrite et mirabilite). La minéralogie et la chimie des sédiments contenus dans les carottes recueillies dans le bassin du lac Waldsea, de morphologie simple, montrent des variations qui indiquent que le lac était beaucoup moins profond et plus salé il y a 4000 ans. Bien que, de façon générale, les niveaux lacustres se soient haussés depuis, ce qui a donné lieu à une production accrue de matière organique et à une plus forte précipitation des carbonates inorganiques, on trouve les témoins de plusieurs inversions de nature hydrologique depuis les 2000 dernières années. Non loin, au lac Deadmoose, la stratigraphie est beaucoup plus complexe en raison de la morphologie irrégulière du bassin. Il y a 1000 ans environ, les bas niveaux lacustres ont été à l'origine de la formation de plusieurs lacs isolés et relativement profonds dans le bassin Deadmoose.

ZUSAMMENFASSUNG *Paleohydrologie, Sedimentologie und Geochemie von zwei meromiktischen salinen Seen in Süd-Saskatchewan.* In den nördlichen großen Ebenen von West-Kanada gibt es zahlreiche salzhaltige und hypersalzhaltige Seen. Die meisten dieser Seen sind seicht (< 3 m) und zeigen Pfannen Charakteristika. Einige hingegen sind relativ tiefe permanente Wasserspiegel. Die Sediment-Belege dieser tiefen, beständigen Salz-Seen bieten eine ausgezeichnete Gelegenheit, die paleohydrologischen und hydrochemischen Schlüssel-Parameter zu bewerten. Variationen dieser Parameter können ihrerseits interpretiert werden in Bezug auf die klimatischen Fluktuationen in dieser Region. Die Seen Waldsea und Deadmoose, die im südlichen Zentrum von Saskatchewan liegen, sind gegenwärtig beide meromiktisch, mit salinen Mg-Na-SO_4-Cl Wassern, welche dichtere, hypersaline Salzlaken ähnlicher Zusammensetzung überlagern. Die gegenwärtigen Sedimente dieser Seen bestehen aus einer Mischung von organischem Material, fein-körnigen Trümmergesteinen (hauptsächlich Lehm-Minerale, Karbonat-Minerale, Quartz und Feldspate), und fein kristallinen endogenen/authigenen Niederschlägen (Aragonit, Gipsstein, Kalkspat, Pyrit und Mirabilit). Variationen in der Mineralogie und Chemie der Sediment-Kerne von dem morphologisch einfachen Waldsea-Becken zeigen, daß der See vor etwa 4000 Jahren viel seichter und saliner war. Obwohl die Wasserspiegel seitdem im Allgemeinen in dem Becken angestiegen sind, was zu höherer organischer Produktivität und vestärktem inorganischem Karbonat-Niederschlag führte, findet man auch Belege für einige hydrologische Umschwünge während der letzten 2000 Jahre. Die im nahegelegenen Deadmoose-See erhaltene Stratigraphie ist viel komplexer auf Grund der unregelmäßigen Morphologie des Beckens. Niedrigere Wasserspiegel vor ungefähr 1000 Jahren führten zu einigen isolierten, aber immer noch relativ tiefen Seen im Deadmoose-Becken.

INTRODUCTION

The Prairie region of western Canada contains hundreds of brackish, saline, and hypersaline lakes ranging in size from small sloughs and potholes to several of the largest bodies of salt water in North America. Within the past decade significant advances have taken place in our understanding of the modern physical, chemical, and biological processes operating in these saline environments. In addition to serving as large-scale natural 'laboratories' for the investigation of sedimentological and geochemical processes, the lakes of the Prairie region offer an excellent opportunity to examine the recent climatic history of western Canada.

Among the various lake basin types present in the Great Plains, topographically closed basins respond most dramatically to environmental fluctuations, and, therefore, potentially yield the most sensitive record of changes in environmental conditions. The purpose of this paper is to summarize the results of on-going investigations of the paleohydrology, sedimentology, and chemistry of two of these salt lakes: Waldsea Lake and Deadmoose Lake.

METHODS

This report is based on analyses of approximately 115 meters of sediment core taken from two adjacent saline lakes in south-central Saskatchewan. Cores were acquired during the winter seasons of 1981-84 using a modified Livingstone piston corer (CUSHING and WRIGHT, 1965). Recovery of the fine-grained lacustrine sediment typically ranged from 2 to 4 m per core, with maximum penetration depth usually limited by salt beds or coarse clastic horizons. In addition to cores, surface sediment grab samples were collected using an Eckman dredge, and water samples were taken with a 2-liter Kemmerer sampling bottle. *In situ* pH, Eh, and water temperature measurements were taken at the time of sample collection. The bathymetry of the basins was determined during the summer of 1985 using a Raytheon echo sounder (model DE719B).

After extrusion, visual logging and subsampling, the sediment cores were analyzed for a variety of physical and chemical parameters including: bulk mineralogy, detailed carbonate, evaporite and clay mineralogy, organic matter content, total carbonate content, grain size, pore water salinity, and stable oxygen and carbon isotope ratios. The pollen content of the core from one site in each basin has been examined by S. Kroker (Quaternary Consultants, Winnipeg). The chronologies discussed in this report are based on radiocarbon dates listed in LAST and SCHWEYEN (1985) and LAST and SLEZAK (1986). Details of the standard laboratory procedures can be found in APHA (1981), TELLER and LAST (1979), and SCHWEYEN (1984).

THE MODERN LAKES

SETTING

Waldsea and Deadmoose lakes are located approximately 100 km northeast of Saskatoon, Saskatchewan (NTS 73A) in the Great Plains physiographic province of North America (Fig. 1). The lakes are part of a chain of basins that occur in a large area (14,000 km^2) of internal drainage. Nearly all of the larger ($>$ 1 km^2) lakes in the area are brackish to hypersaline, with concentrations ranging from about 3 g/1 to over 300 g/1 (HAMMER, 1978).

Mean daily temperature during January over the area is about -18°C; during July it is 17°C. One of the more important characteristics of the region is the extreme variability of temperature. There are wide temperature variations between seasons, between years, and between day and night. This temperature variability has a significant impact on many of the modern processes in the salt lakes of the region (LAST and SCHWEYEN, 1983).

Another important climatic factor influencing the modern saline lakes is the high evaporation/precipitation ratio. The basins at present receive about 35 cm of precipitation per year, whereas more than twice this amount can be lost per year through evaporation from open water bodies (CNC/IHD, 1978; McKAY and STICKLING, 1961).

The natural vegetation of the area is aspen parkland — transitional between the prairie grasslands a short distance to the south and west and the pine-spruce forests to the north. However, much of the natural vegetation cover has been cleared for agricultural purposes, and most of the area immediately surrounding the two lakes is cultivated.

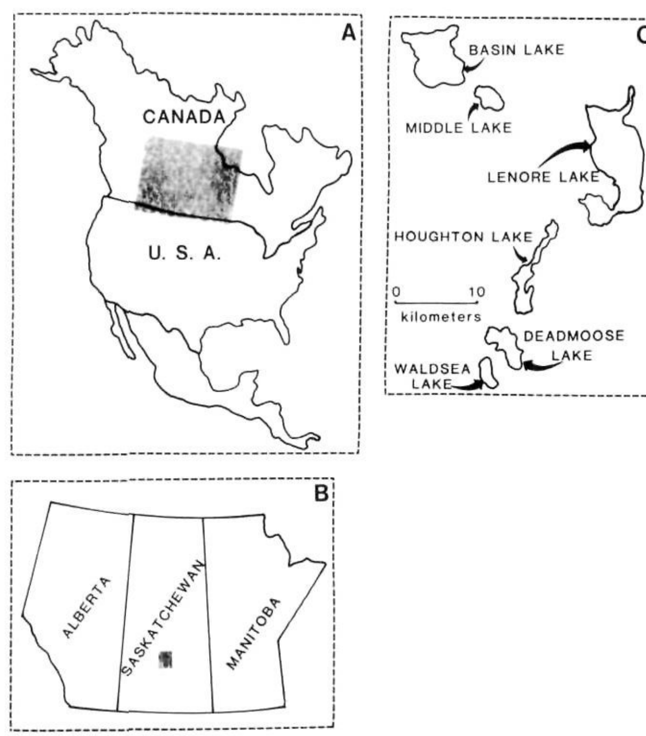

FIGURE 1. Maps showing the location of Waldsea and Deadmoose lakes in the Northern Great Plains of North America. North is toward the top on all the figures.

Cartes de localisation des lacs Waldsea et Deadmoose dans les grandes plaines du nord de l'Amérique du Nord.

The Northern Great Plains region is underlain by about 1500 m of nearly horizontal Phanerozoic sedimentary rocks. The Paleozoic section consists mainly of a series of carbonate-evaporite cycles; the overlying Mesozoic and Cenozoic bedrock is dominantly a sand-shale sequence. The relatively simple stratigraphic and structural bedrock relationships in the Waldsea-Deadmoose area have been somewhat complicated by: (a) dissolution of Paleozoic evaporites creating collapse structures (CHRISTIANSEN, 1967, 1971); and (b) preglacial erosion of the bedrock surface creating buried bedrock valleys (see WHITAKER and PEARSON, 1972). One such buried valley, the Hatfield Valley, a major 150 m deep incision, lies about 50 km to the west of Waldsea Lake, with a branch valley passing directly beneath Deadmose Lake (MENELEY, 1967).

Unconsolidated ice-laid, fluvial, and lacustrine Quaternary sediments now blanket the area, reaching over 300 m thickness in places. The many salt lakes of the area fill local depressions or kettles in the Pleistocene sediment, or occupy dammed glacial meltwater channels.

LIMNOLOGY AND HYDROGEOLOGY

The limnologic and biological characteristics of the two lakes have been discussed in HAMMER and HAYNES (1978), HAMMER (1978), and HAYNES and HAMMER (1978). To provide some background information a brief synopsis of the main morphometric and chemical parameters of these lakes is given in Tables I and II. Waldsea Lake has relatively steeply sloping sides and a flat bottom. Deadmoose Lake has a much more irregular basin morphology with several deep (> 35 m) troughs and holes (Fig. 2).

The groundwater hydrology and resources of the area have been reviewed by MENELEY (1967) and RUTHERFORD (1967). Sands and gravels within the unconsolidated Pleistocene section and sandstones at the top of the Cretaceous bedrock form the most continuous and abundant aquifers in the area. The groundwater nearest the surface (shallow glacial drift) is relatively dilute (< 1000 mg/l TDS) and dominated by calcium and bicarbonate ions (Fig. 3). The lower glacial drift contains higher salinity water (1000 to 3000 mg/l) of the Ca-Mg-HCO_3 type, whereas the shallow bedrock groundwater is generally of similar salinity but sodium and sulfate rich. The formation waters of older sediments (pre-Cretaceous) rapidly increase in salinity with depth to greater than 300 g/l, and are usually of the Na-Cl type. Detailed groundwater hydraulic and flow analyses have not been published for the area.

Both Waldsea and Deadmoose lakes are saline with average surface water salinities of about 30 g/l. Both are also meromictic, having monimolimnions with approximately twice the salinity of their mixolimnions. The lakes contain phototrophic bacterial plates located at their chemoclines (LAWRENCE *et al.*, 1978; PARKER *et al.*, 1983). In Waldsea the dominant species in the plate is *Chlorobium*; in Deadmoose *Thiocapsa roseopersicina* dominate. The lower layers of these two lakes are typically strongly reducing (Eh values of −300 to −400 mv.), high in H_2S (150-200 mg/l), and slightly less alkaline than the surface waters. The mixolimnions also exhibit seasonal temperature stratification.

TABLE I

Summary of morphometric data for Waldsea and Deadmoose lakes (compiled from LAST and SCHWEYEN, 1985; LAST and SLEZAK, 1986; HAMMER, 1978)

	Waldsea Lake	Deadmoose Lake
Surface area (km^2)	4.7	10.5
Maximum depth (m)	14.5	48.0
Mean depth (m)	8.2	9.7
Maximum width (km)	1.4	3.1
Maximum length (km)	3.7	5.5
Volume ($10^6 m^3$)	38	101

TABLE II

Summary of water chemistry data for Waldsea and Deadmoose lakes

	K^+	Na^+	Ca^{+2}	Mg^{+2} (mmol l^{-1})	HCO_3^-	Cl^-	SO_4^{-2}
Waldsea Lake							
Mixolimnion	4	192	8	162	5	111	130
Monimolimnion	7	304	11	231	7	250	313
Deadmoose Lake							
Mixolimnion	7	208	4	56	7	144	174
Monimolimnion	14	389	11	104	16	270	285

The ionic composition of the water in Waldsea and Deadmoose lakes, as well as that of many of the other salt lakes in the immediate area, is dominated by Na^{1+}, Mg^{2+}, and SO_4^{2-} (Fig. 3). Although higher in total dissolved solids, the bottom waters of the study lakes have major ion ratios similar to their surface waters (Table II). These lakes are saturated or supersaturated with respect to various carbonate minerals at all times of the year and at all depths in the water columns (Fig. 4), although the degree of supersaturation decreases considerably beneath the chemoclines and during winter. The monimolimnions of Waldsea and Deadmoose lakes are at or near saturation with respect to gypsum, while in winter their surface waters come close to saturation with respect to mirabilite.

MODERN SEDIMENTOLOGY

The modern (upper 2 cm) sediments of the two lakes consist mainly of organic-rich, silty clay and clayey silt in the offshore portions of the basins grading to coarser clastics (sands and gravels) in the nearshore areas (Fig. 5). In Waldsea Lake the shoreline and nearshore sands are restricted to a very narrow, 50-100 m wide perimeter of the basin, whereas in Deadmoose Lake sands and coarse silts extend farther out into the basin. Away from the relatively nearshore areas, however, there is little variation in grain size in either of the basins.

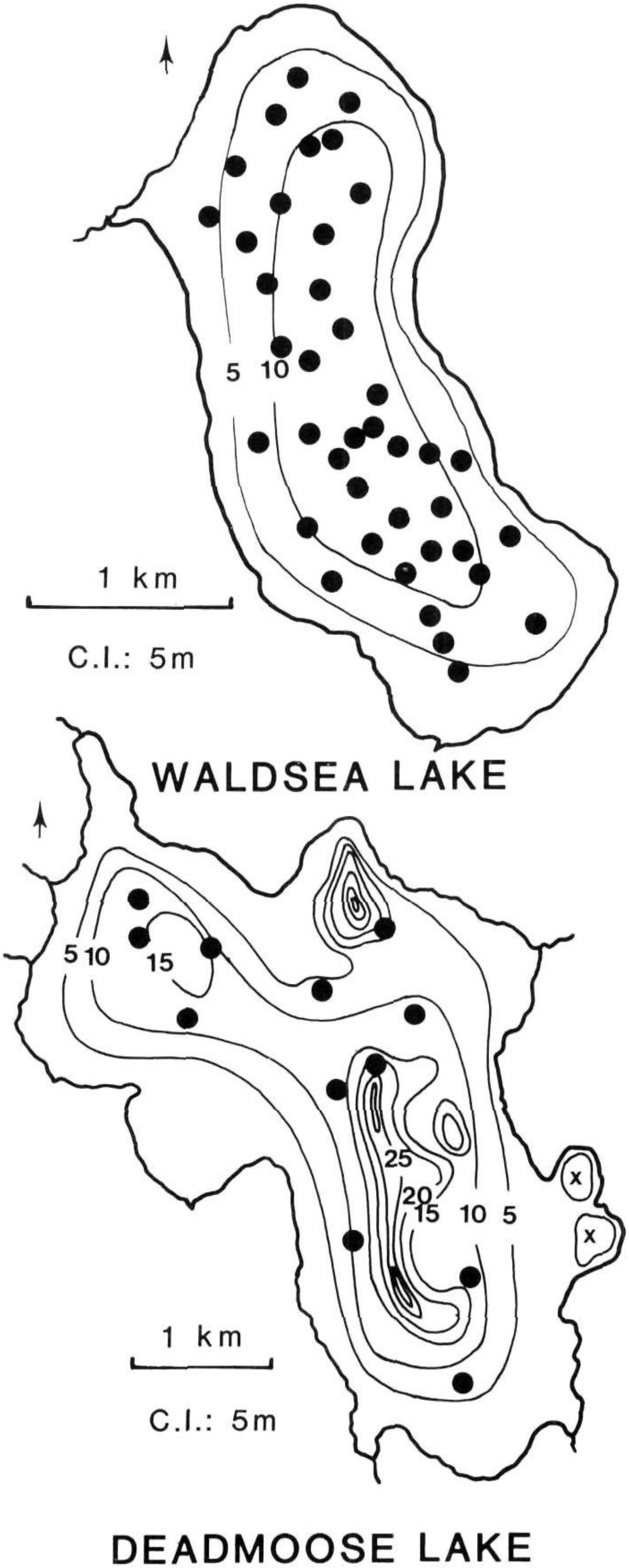

FIGURE 2. Bathymetric contour maps of Waldsea and Deadmoose lakes. Black dots indicate core locations. The X's in Deadmoose Lake indicate holes greater than 45 m in depth.

Cartes bathymétriques des lacs Waldsea et Deadmoose. Les points noirs montrent l'emplacement des sites de sondage. Les X dans le lac Deadmoose identifient les trous de plus de 45 m de profondeur.

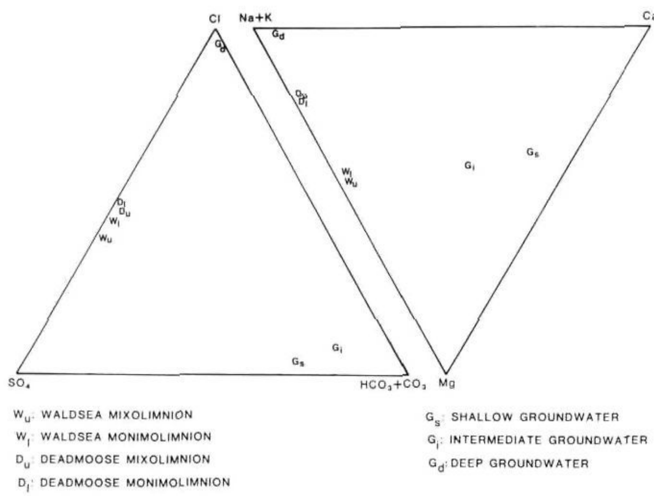

FIGURE 3. Ternary diagram showing average ionic composition (in percent equivalents) of water from Waldsea and Deadmoose lakes and groundwater of the area.

Diagramme triangulaire de la composition ionique (en pourcentages équivalents) des eaux des lacs Waldsea et Deadmoose et des eaux souterraines de la région.

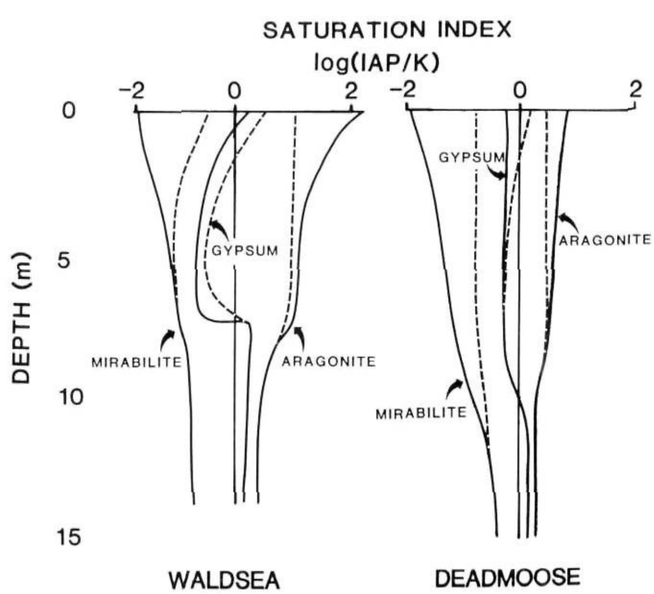

FIGURE 4. Degree of saturation with respect to aragonite, gypsum, and mirabilite of Waldsea and Deadmoose lakes. Solid lines are for summer; dashed lines are for winter. Saturation indices calculated using WATSPEC (WIGLEY, 1977).

Degrés de saturation en ce qui a trait à l'aragonite, au gypse et à la mirabilite contenus dans les lacs Waldsea et Deadmoose. Pour l'été, la courbe est continue, pour l'hiver, la courbe est brisée. Les indices de saturation sont calculés à l'aide du logiciel WATSPEC (WIGLEY, 1977).

The bulk mineralogical composition of the modern offshore sediments of the lakes is summarized in Table III. The modern mineral suite in each lake is roughly similar: mainly clay minerals, carbonate minerals, and pyrite. Waldsea sediment has up to about 15% gypsum, whereas this sulfate mineral is less abundant in Deadmoose surface sediment. The clay-sized fractions of the sediment in each basin are likewise similar, consisting of a complex mixture of clay minerals, non-clay mineral silicates, carbonates, pyrite, and inorganic amorphous material. The proportions of major clay mineral constituents (illite, kaolinite + chlorite, and expandable lattice clays) do not vary significantly from basin to basin. In Deadmoose Lake mirabilite ($Na_2SO_4 \cdot 10H_2O$) is found in the surface sediments in water depths greater than 25 m.

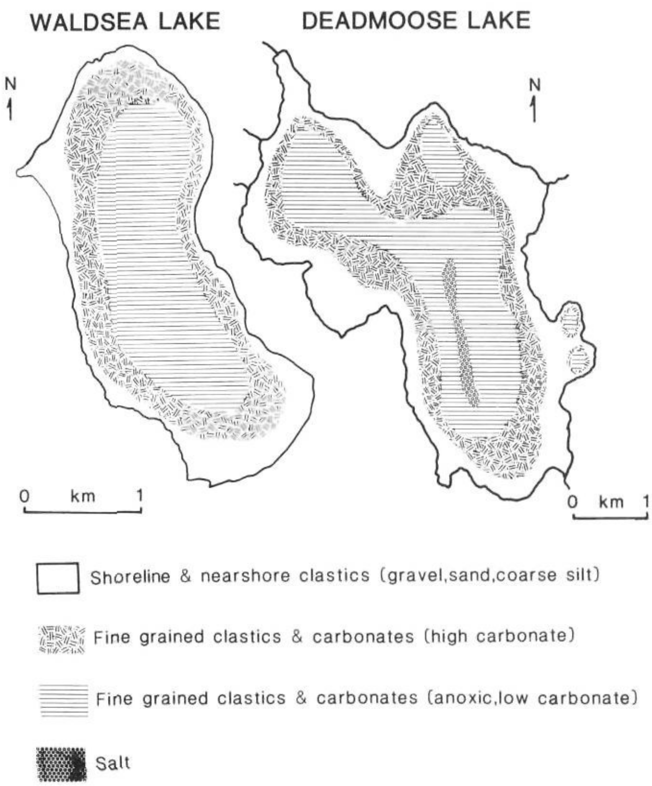

FIGURE 5. Modern sediment distribution in Waldsea and Deadmoose lakes.

Répartition actuelle des sédiments dans les lacs Waldsea et Deadmoose.

Three genetic types of sediment can be recognized in the modern offshore deposits of these lakes: (a) detrital, (b) endogenic, and (c) authigenic. The detrital component, consisting of clay minerals, quartz, dolomite, feldspars, and low-Mg calcite, is derived from shoreline and stream erosion of the surrounding glacial sediments. The endogenic component, or that portion of the sediment originating from within the water column, consists of aragonite, high-Mg calcite, gypsum, mirabilite, and organic matter. Both the aragonite and high-Mg calcite are precipitated inorganically in response to supersaturated conditions brought about by uptake of CO_2 by primary organic productivity. As shown in studies of numerous other saline lakes, (*e.g.*, MULLER *et al.* 1972, CALLENDER, 1968; LAST, 1982), the high Mg/Ca ratio of the lake water (5 to 50), is the reason that aragonite and magnesian calcite are generated rather than low-Mg calcite. The two sulfate minerals (gypsum and mirabilite) likely originated by inorganic precipitation from the hypersaline monimolimnion. The only authigenic component recognized in the modern sediments is pyrite, which is likely derived as a very early diagenetic product of H_2S, organic matter, and dissolved iron in the near surface sediment.

STRATIGRAPHY AND HOLOCENE SEDIMENTOLOGY

GENERAL

The upper 3 to 4 m of offshore sediment in each of the basins consists mainly of organic-rich silty clays and clayey silts with occasional thin (< 1 cm) beds of coarser clastics. Sediment colors are generally dark grey (2.5 Y 2.5/1, Munsell) to dark greenish grey (5 Y 2.5/2). Lighter laminae (10 YR 8/1, white) are common in Deadmoose and Waldsea cores. Moisture contents generally decrease from 80% in the youngest sediment to about 40% at the base of the cores. Organic

TABLE III

Summary of modern (0-2 cm) offshore sediment characteristics of Waldsea and Deadmoose lakes. Data represent averages of sixty surficial sediment samples from Waldsea Lake and thirty-one samples from Deadmoose Lake. Percentages of sand + silt + clay sum to 100; Percentages of the various mineral components sum to 100.

	% Moisture	% Organic	% Sand	% Silt	% Clay	% Quartz	% Feldspars	% Gypsum	% Aragonite	% Calcite[1]	% Dolomite	% Pyrite	% Illite	% Smectite	% Chlorite	% Kaolinite
Waldsea Lake	82.1	24.0	0.8	29.4	69.8	6.2	4.7	9.5	12.8	8.3	7.4	19.4	15.8	6.3	4.1	4.7
Deadmoose Lake[2]	79.5	20.1	1.0	31.0	68.0	7.6	13.5	2.9	6.9	3.9	6.1	14.4	18.6	12.8	7.0	5.7

[1] includes magnesian calcite

[2] Mirabilite ($Na_2SO_4 \cdot 10H_2O$) is found in the modern sediment at depths >35 m.

matter contents range from less than 5% to over 60%, but do not exhibit any specific trend. Sediment from both basins is generally well laminated throughout. Lamination is of several types: (a) irregularly-spaced alternating laminae (couplets) of aragonite and organic-rich clay; (b) laminae of subhedral to euhedral gypsum crystals and grains; (c) laminae and thin beds composed of calcareous intraclasts and calcite-coated plant fragments; (d) dolomite cemented crusts; and (e) laminae and thin beds composed primarily of organic material and debris such as plant fibers, fiber mats, ostracods, and fecal pellets. Overall, the mineral suite of the older sediments in the basins is similar to that of the modern sediments described above, except that protodolomite (disordered calcium-magnesium carbonate) and magnesite are also present.

WALDSEA LAKE

With over 90 m of sediment core from 40 sites, Waldsea Lake is one of the most intensively cored saline basins in western Canada. LAST and SCHWEYEN (1985), LAST and SLEZAK (1986), and SCHWEYEN (1984) discuss in detail the mineralogy and genesis of the sedimentary components of this meromictic lake. Based primarily on texture, mineralogy, and sedimentary structures, six lithostratigraphic units have been recognized in the upper 4 m of lacustrine fill (Fig. 6). Unit 1, the oldest unit, is a black, faintly laminated, organic-rich silty clay that is characterized by an abundance of disseminated plant fibers and fiber mats, and the presence of large (1-3 cm), subhedral to euhedral crystals of mirabilite. Unit 2 is a finely laminated, greenish grey (5 Y 2/2), gypsiferous clayey and sandy silt. This unit also contains dolomitic hardgrounds (dolomite and protodolomite cemented laminae) and beds of calcareous intraclasts as well as finely disseminated magnesian calcite and magnesite. Unit 3 is a finely laminated, dark grey (2.5 Y 2.5/1) silty clay. It is characterized by the presence of aragonite-clay couplets, a relatively low gypsum content, and much organic matter. Unit 4, similar to Unit 2, consists of a laminated, gypsum-rich clayey silt with occasional dolomite crusts and beds of sand-sized calcareous intraclasts. Unit 5, the thickest unit in most areas of the basin, is a well laminated, clastic-rich carbonate mud containing an abundance of finely disseminated organic matter. Unit 5 is marked by intercalated mm-thick aragonite laminae similar to those of Unit 3. These aragonite laminae often show a distinct pink to red color (5 R 7/4 to 5 R 4/6), presumably from staining by organic pigments. Unit 6 occurs only in the nearshore areas of the basin, and consists of silty sand and sandy gravel.

Stable carbon isotope ratios of the endogenic carbonates in these sediments show a general increase in $\delta^{13}C$ upward in the cores. Pore water salinities are highest in the lower parts of the section and decrease to about 50 g/l in the upper meter of sediment (Fig. 6).

Preliminary palynological analysis has been done on one core from the center of Waldsea basin. Three pollen zones are identified in this core (see Figure 7 in LAST and SCHWEYEN, 1985):

Pollen Zone 1 (*ca.* 4000-2800 yr BP). The basal zone is dominated by Gramineae pollen at the base and *Pinus* at the top, with *Picea* and *Betula* also conspicuous. Except for *Alnus*, other arboreal pollen types are minor components. In addition to Gramineae, herbs are represented by *Artemisia* (5-12%), Chenopodiineae (3-5%), and Ambrosieae (1-3%).

Pollen Zone II (*ca.* 2800-2400 yr BP). Zone II is characterized by a sharp increase in Gramineae to double the frequency recorded in the lower zone, with a corresponding decrease in both pine and spruce. The deciduous arboreal species all register increased values, as do some of the herbs. Pollen frequencies of aquatic plants (*Typha, Equisetum*) also increase in Zone II.

Zone III (*ca.* 2400 yr BP to present). The pollen assemblage in the uppermost 2 m of sediment of Waldsea Lake shows a decrease in Cyperaceae and Gramineae and, at the very top of the section, sharp increases in *Artemisia*, and Cruciferae.

DEADMOOSE LAKE

A total of 25 m of core from 12 sites in the Deadmoose basin have been recovered and studied. Although less intensively cored than Waldsea Lake, our sampling of Deadmoose indicates that the basin's irregular morphology has given rise to a considerably more complex stratigraphic sequence. Six sediment types are identified on the basis of mineralogy, sedimentary structures, color, moisture and organic contents, and grain size characteristics. These are described in Table IV.

TABLE IV

Summary of main sediment types in Deadmoose Lake

Aragonite Laminated Muds: alternating light (7.5 YR 8/8 to 10 YR 4/1) and dark (5 Y 2/1) couplets; irregular spacing and thickness; microlaminae common; sharp contacts between light and dark laminae; light laminae composed of very fine (1-5 μm) aragonite crystals, dark laminae are mixtures of organic matter, clay minerals, carbonates and quartz.

Gypsum-Carbonate Laminated Muds: variable color from greenish grey (5 Y 2.5/2) to dark grey (2.5 Y 2.5/1) to light grey (N7); clayey silt with occasional sand laminae; carbonate intraclasts, hardgrounds and cemented laminae; fibrous organic matter laminae; high gypsum content; some protodolomite, magnesian calcite.

Homogeneous sands and silts: grey (5 Y 4/1) to brown (5 YR 3/4); silty sand to sandy silt; rare faint lamination; sharp contacts; low moisture, organic matter and carbonate contents; occasional wood fragments.

Homogeneous Carbonate Muds: dark grey (N3) to greenish black (5 GY 2/1); silty clay; nonlaminated; high organic matter and carbonate contents.

Salt: clear to cloudy; mirabilite; variable inclusions and mud content; massive and bedded.

Till: light grey (N7); massive; very clayey, with abundant granules and pebbles; coarser material mainly igneous rock fragments; low carbonate and organic matter contents; compact; sticky.

Cores from the relatively shallow portions of the basin (<15 m water depth) exhibit a rather intricate facies assemblage (Fig. 7). In the southern part of the lake in water depths less than about 7 m, a light grey (N6), poorly sorted, pebbly sandy clay (till) underlies a thin veneer (2-5 cm) of brownish black (5 YR 2/1), homogeneous organic-rich, calcareous clay. The sequences recovered from the northern and western sides of the basin are much more diverse. In the north, the cores consist of a very stiff, nonlaminated basal clay which is overlain by 50-100 cm of well sorted, fine grained sand. This is overlain by up to 75 cm of faintly laminated, gypsiferous, greyish green (5 GY 4/2) mud containing abundant vegetative debris and carbonate-cemented crusts. The upper meter of section consists of 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 been dated at 1080 ± 110 BP (Beta 9888). In the western part of the basin the stiff basal clay is capped by a thin carbonate-

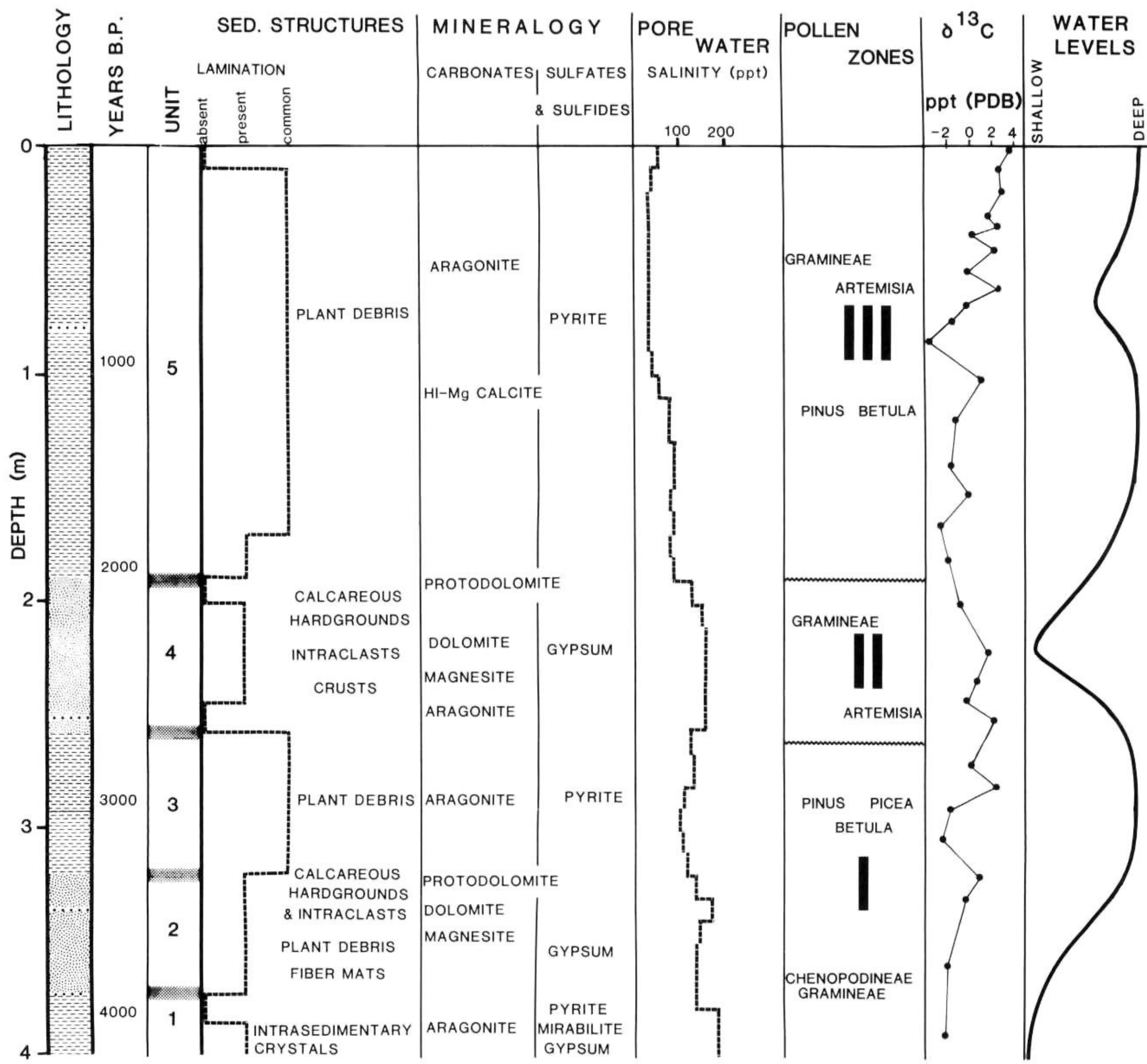

FIGURE 6. Summary of Waldsea Lake stratigraphy. Pore water salinity is reported in parts per thousand (ppt). The lithologic sequence, radiocarbon chronology, sedimentary structures, and mineralogy represent syntheses of information from all the cores in the basin. The pore water salinity, pollen stratigraphy, and stable isotope values are derived from single cores. The water level curve is an interpretation based mainly on the lithostratigraphy.

Stratigraphie sommaire du lac Waldsea. La salinité est donnée en parties par mille. La séquence lithologique, la chronologie radiométrique, les structures sédimentaires et la minéralogie sont les résultats synthétisés des données recueillies dans l'ensemble des trous de forage du bassin. La salinité, la stratigraphie pollinique et les valeurs des isotopes stables proviennent de carottes individuelles. La courbe du niveau lacustre représente une interprétation fondée sur la lithostratigraphie des lieux.

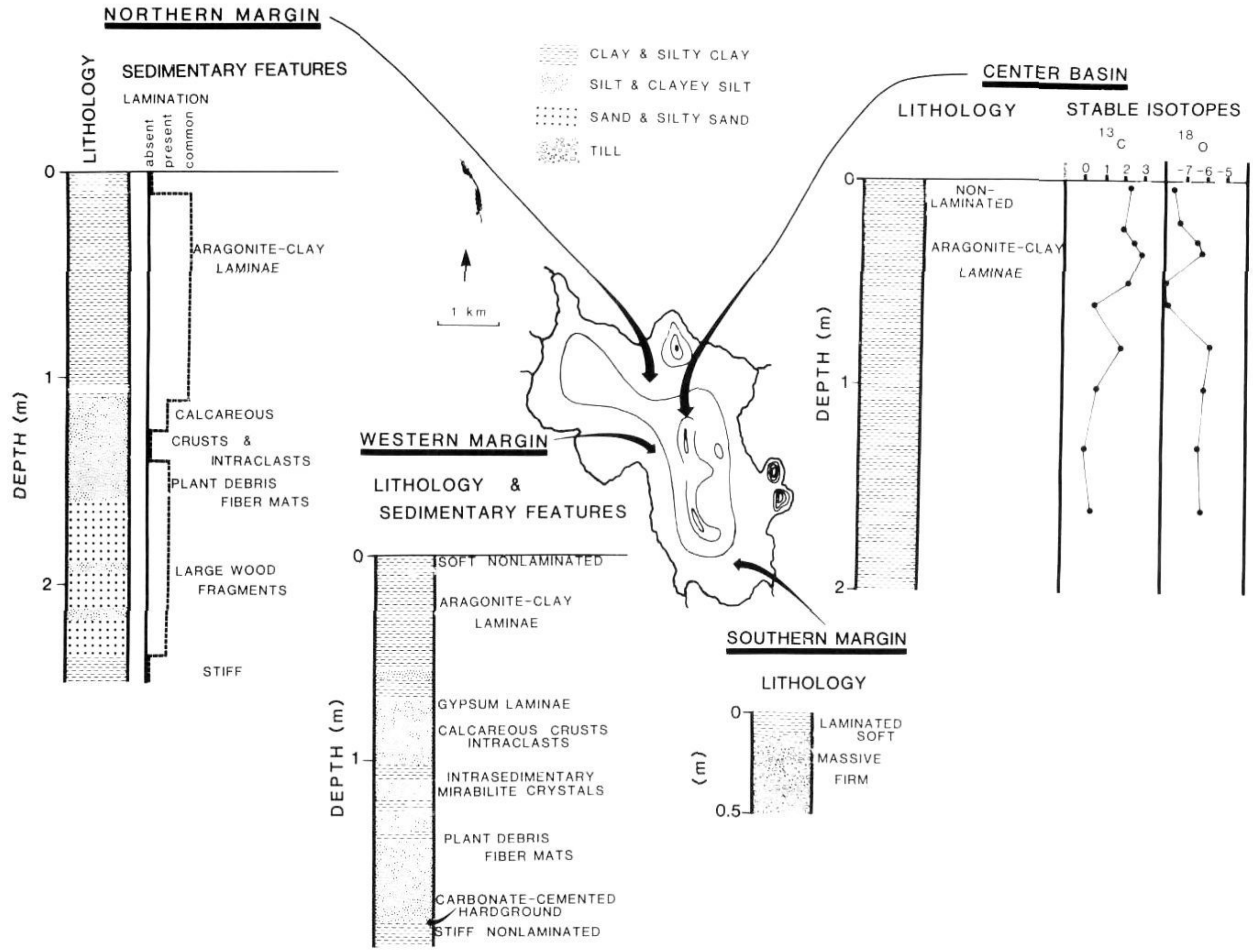

FIGURE 7. Representative stratigraphic sequences from Deadmoose Lake. Contour interval on the bathymetric map is 10 m. Stable isotope values are reported in δ% PDB for carbon and δ% SMOW for oxygen.

Séquences stratigraphiques représentatives des différents milieux du lac Deadmoose. Les courbes bathymétriques sont à intervalle de 10 m. Les valeurs des isotopes stables sont exprimées en δ% PDB pour le carbone et en δ% SMOW pour l'oxygène.

cemented hardground. Overlying this sharp contact is a dark greenish gray (5 G 4/1), organic-rich, gypsiferous mud which contains fragments of carbonate crust, vegetative 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.

From Figure 7 it can be seen that the stratigraphic sequences recovered from relatively deep portions of Deadmoose Lake (> 15 m water depth) are quite different. Cores taken in water of 15 to about 30 m depth consist entirely of well laminated, black, organic-rich clay with abundant, irregularly spaced aragonite laminae. In the deepest parts of the basin (> 30 m depth), coring could not penetrate the hard bottom substrate. Echo sounding and sediment grab samples confirm the presence of massive salt (mirabilite) in this area.

Stable carbon isotope ratios of the endogenic aragonite from the relatively deep water cores show a general increase upward in the section while the $\delta^{18}O$ values decrease toward the top of the cores (Fig. 7). The preliminary pollen sequence identified from a 2 m-long core on the northern edge of the basin shows little systematic variation. The lower several centimeters of sediment contain relatively high levels of *Artemisia* and low *Pinus* values. This grades upward into a complacent pollen assemblage dominated by *Pinus* and Gramineae. The upper 15-20 cm of the core register slightly increased levels of *Chenopodiineae, Cruciferae, Ambrosia, Artemisia*, and *Selaginella*.

INTERPRETATION AND DISCUSSION

LITHOSTRATIGRAPHY

The late Holocene sediments recovered from Waldsea and Deadmoose lakes indicate that both basins have experienced fluctuations in hydrology and water chemistry during this period. The nature of these fluctuations can be determined by comparing the sedimentary facies preserved in the stratigraphic records of the basins with sedimentary and mineralogical features of modern lacustrine environments in the Northern Great Plains and elsewhere. Table V summarizes this modern analog approach to interpreting the stratigraphic records of Waldsea and Deadmoose lakes.

Waldsea Lake cores show two basic facies assemblages: (a) a shallow water, mudflat/hypersaline playa association and (b) a deep water, stratified lake association. The distinctive mineral suite (gypsum, protodolomite, magnesite, mirabilite), and the morphologies and textures of these components in the lowermost sediment (Units 1 and 2) indicate that deposition occurred in a saline, clastic-dominated playa. Water levels fluctuated significantly, probably on a seasonal basis, but likely were never much greater than about 1 m in depth. When there was ponded water in the basin, it was dominated by Na and SO_4 ions. Total dissolved solid concentrations in the lake probably exceeded 200 g/l and seasonal precipitation of mirabilite and other salts occurred. Despite the high salinity, sedimentation in the basin was dominated by clastic (detrital) influx from sheetwash, wind and possibly ephemeral streams.

The mudflats surrounding this shallow lake were sites of abundant gypsum and organic/inorganic carbonate precipitation. Organic debris mats and algal stromatolites formed on the sporadically wetted reaches of the basin margin. Dramatic fluctuations in salinity on these mudflats gave rise to alternating vegetation debris mats (low salinity), algal carbonates (moderate salinity), and gypsum laminae (high salinity). In addition, carbonate-coated twigs and other plant fragments suggest tufa deposition associated with spring discharges and groundwater seeps.

The intense evaporation on these mudflats created a dynamic diagenetic environment. Evaporative pumping of subsurface brines caused intrasedimentary gypsum precipitation and the formation of carbonate crusts and hardgrounds at the surface of the playa. High Mg/Ca ratios in the pore waters altered much of the original calcium carbonate to protodolomite, dolomite, or magnesite. Periodic flooding of the mudflats led to fragmentation of the crusts and rounding of the gypsum grains. When water levels were lower, algal carbonate and gypsum-laminated mudflats, and vegetation mats covered most of the basin.

LAST and SCHWEYEN (1985) suggest that these shallow water phases were in existence in the Waldsea basin about 4000 years ago (Units 1 and 2) and again between 2800 and 2200 yr BP (Unit 4). A minor lake level drop also occurred about 1000 years ago as evidenced by coarse clastics (Unit 6) interbedded with fine grained aragonite-laminated sediment in cores collected near the basin margins.

More moderate climatic conditions or an increasingly more positive hydrologic budget would cause water levels to rise in a closed basin. The fine, undisturbed carbonate laminae alternating with organic-rich muds of Units 3 and 5 are evidence of deposition in a relatively deep, stratified lake. Although high pore water salinities indicate that the lake was saline during these high water phases, it cannot be unequivocally established that the basin was also meromictic. Deposition

TABLE V

Summary of modern analog approach to interpretation of Waldsea and Deadmoose cores. The features listed in the lefthand column were identified in various cores from Waldsea and Deadmoosse lakes. These features have also been found in the modern sediments from the lakes listed in the right column.

Stratigraphic feature	Modern lake(s) in which feature is present
Cemented hardground	Freefight Lake, Sask.
Carbonate crusts and intraclasts	Freefight Lake, Sask. Muskiki Lake, Sask.
Tufa	Muskiki Lake, Sask.
Vegetation mats	Dana Lake, Sask.
Algae lamination	Freefight Lake, Sask.
Intrasedimentary gypsum	Patience Lake, Sask. Lydden Lake, Sask.
Clastic (rounded) gypsum	Patience Lake, Sask.
Intrasedimentary mirabilite	Corral Lake, Sask. Boot Lake, Sask. Vincent Lake, Sask.
Laminated/massive mirabilite	Freefight Lake, Sask. Little Manitou Lake, Sask.

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. Although whitings have not been documented in any of the deep saline lakes of the Northern Great Plains, they have been described in a variety of other lacustrine and marine environments (*e.g.* STRONG and EADIE, 1978; BATHURST, 1971).

The lithostratigraphy of the Deadmoose basin also suggests an earlier low water phase. Although much more work needs to be done on deciphering the chronology and correlating the units on a basin-wide scale, the presence of coarse clastics, carbonate-cemented hardgrounds and crusts, vegetation mats, and gypsum laminae in cores from the relatively shallow margins of Deadmoose indicate considerably lower lake levels. A drop in water level of 6-8 m would create a series of "satellite" basins surrounding the deep, but much smaller, main basin of Deadmoose Lake. The sandy facies in the northern end of the basin was part of a shoreline/delta complex that was active about 1100 years ago. Mudflats covered with vegetation debris and carbonate-cemented hardgrounds and crusts, similar to those in Waldsea Lake, 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 desposited lacustrine sediment occurred during this lower water phase.

Despite substantially lowered lake levels, there is no evidence to date that Deadmoose basin dried completely. Conditions within the main (deep) part of the lake 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 throughout the cores points toward elevated (> 10) but probably stable Mg/Ca ratios. The occurrence of mirabilite in the deepest part of the basin indicates hypersaline bottom water conditions.

With higher water levels and a transgressing shoreline, the nearshore coarse clastics and mudflat deposits were inundated and deeper water (aragonite laminated) sediment was desposited. The nonlaminated uppermost 5-15 cm of sediment in the basin was probably deposited during the last 100 years, and relates to changes in the nature of sedimentation in the basin caused by human disturbances of the lake and its watershed.

STABLE ISOTOPES

Isotope ratio differences in substances containing oxygen and carbon have been used with considerable success in paleolimnology (*e.g.*, STUIVER, 1970, 1975; COVICH and STUIVER, 1974; FRITZ *et al.*, 1975). McKENZIE (1982) has shown that stable carbon isotope data collected from endogenic precipitates in a lacustrine basin reflect 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 record the fluctuations of organic productivity. The $\delta^{13}C$ values for aragonite from Waldsea Lake sediment (Fig. 6) suggests initially low productivity (low $\delta^{13}C$) grading upsection to higher productivity levels. There is a reversal in this trend, indicating decreased productivity, about 2200 years ago. Finally, the upper 1.5 m of sediment shows a trend toward increasing productivity. Likewise, $\delta^{13}C$ data on the endogenic carbonates from a relatively deep water (14 m depth) core of Deadmoose Lake show generally increasingly levels of organic productivity upward in the section (Fig. 7).

Stable oxygen isotope information collected from calcareous sediment has been widely used as a paleothermometer (*e.g.*, HENDY and WILSON, 1968; STUIVER, 1970; SAVIN, 1977). The $\delta^{18}O$ data on the endogenic carbonates from Deadmoose Lake (Fig. 7) confirm a warmer, more evaporitic regime at the base of the core grading upward to cooler conditions at the top of the section.

BIOSTRATIGRAPHY AND PALEOCLIMATE

The vegetation history of the region, based on the pollen stratigraphy of Waldsea Lake presented by LAST and SCHWEYEN (1985), indicates a transition from a period of warmth and aridity about 4000 years ago to cooler and moister conditions by 3000 yr BP (Zone I). Following a brief return to more open prairie vegetation and warmer, drier conditions at about 2500 yr BP (Zone II), the modern assemblage of pine, birch, grass, and sage pollen (Zone III) was established in the region by 2000 years ago.

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