

DEEP-WATER EVAPORITE MINERAL FORMATION IN LAKES OF WESTERN CANADA*

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ABSTRACT: Despite more than a century of multidisciplinary study, our understanding of the genesis of evaporite minerals in deep-water sedimentary environments remains poor. This is most likely due to a paucity of modern settings in which deep-water evaporites are forming. Several of the present-day deep, saline to hypersaline lakes in the northern Great Plains of western Canada provide excellent opportunities to examine subaqueous salt mineral formation, and to document the processes by which these salts are deposited, preserved, and altered.

Deadmoose, Little Manitou, and Freefight lakes are lacustrine basins in which soluble and sparingly soluble evaporite minerals are accumulating today in the relatively deep offshore areas of the lakes. Both Deadmoose and Freefight lakes are hypersaline and meromictic, with strongly anoxic bottom waters. Little Manitou is also hypersaline but seasonal density and chemical stratification usually breaks down by early to midsummer. The salts in these basins, which are comprised of a complex assemblage of hydrated sodium and magnesium sulfates and carbonates, reflect, in general terms, the high alkalinity of the brines and the overall dominance of Na^+ , Mg^{2+} , and SO_4^{2-} ions. Modern sediment-trap data show that salt precipitation and sedimentation are extremely rapid, with the precipitates being derived from a variety of positions in the water columns. Salt accumulation is most rapid in the deepest parts of the lakes. The evaporites are generally coarsely crystalline, massive to thickly bedded, and interfinger laterally with laminated organic-rich clays and poorly sorted carbonate-clastic debris derived from nearshore areas. Even in the shallowest basin, the salts show no indication of dissolution or recycling. Indeed, preliminary augering and coring of the late Holocene sediment reveals that relatively thick sections of evaporites have accumulated and are being preserved in the basins.

INTRODUCTION

It has long been recognized that there are very few examples of modern sedimentary environments in which true deep-water evaporite mineral formation is occurring. Even the basinal sediments of the Dead Sea, cited by Warren (1989) as one of the best approximations to a modern deep-water evaporite forming environment, contain very little soluble evaporite mineral material. In contrast, many ancient evaporite deposits are interpreted to have been deposited in deep, subaqueous settings (see summaries in Warren, 1989; Dronkert, 1985; Till, 1978). The strong emphasis on theoretical considerations of deep-water evaporites without a rigorous understanding of modern deep-water analogues has led to considerable discussion and controversy in the literature over the interpretation of these ancient suspected deep subaqueous deposits. The northern Great Plains region of western Canada contains lacustrine basins in which deep-water, soluble and sparingly soluble endogenic precipitates are forming and being preserved in the Holocene stratigraphic record. The objective of this paper is to describe these deep-water lacustrine settings and discuss the formation of the soluble salts.

Terminology

As discussed by Sonnenfeld (1984), the terms "deep" and "shallow" are very poorly defined in most evaporite mineral depositional settings. Absolute values of the usual morphological measures of water depth of a basin, such as mean depth, maximum depth, and relative depth, have little meaning in saline/evaporitic basins because the water column is often chemically stratified. This brine stratification, which can develop even in relatively shallow basins (less than 3 m), effectively isolates the sediment-water interface from wave action, physical sorting, and immediate dissolution of the very soluble precipitates. "Deep-water" conditions are present in each of the lacustrine basins discussed

in this paper by virtue of the presence of a relative stable chemical and/or density gradient within the water columns.

An evaporite mineral is generally taken to be a salt deposited by chemical precipitation from a natural brine due to the process of evaporation. Although a wide variety of sparingly soluble carbonate minerals occur in the deep basinal sediments of the salt lakes of the Great Plains (Last, 1990; Ghebre-Egziabhier and St. Arnaud, 1983a, b), this paper will concentrate only on the most soluble salts precipitated.

SETTING AND LOCATION

The northern Great Plains of western Canada stretch from the Precambrian Shield near Winnipeg, Manitoba, westward for nearly 1600 km to the foothills of the Rocky Mountains (Fig. 1). This is a vast region of flat to gently rolling terrain interrupted only by occasional steeply sided, deeply entrenched river valleys. Within this region there are millions of salt lakes, with estimates ranging as high as 5.5 million individual saline basins and wetlands. Indeed, nearly all of the surface water present in the Great Plains of western Canada is saline. Based on a morphological survey of over 500 of these lakes (Fig. 2), the vast majority of the basins are small (less than 100 km²) and shallow (maximum depth less than 3 m). Although few in number, the permanent, deep-water lakes are important because their sediment records are usually undisturbed by either bioturbation, desiccation, or erosion and, therefore, often contain finely laminated sequences which form the basis of high resolution paleoenvironmental reconstructions (Last, 1992).

The climate of the northern Great Plains ranges from a cold, sub-humid continental regime in the eastern and northern parts of the region to semi-arid and arid conditions in the west. The high salinity of most of the surface water in the region is controlled by the high evaporation/precipitation ratios and the presence of large areas of closed drainage. Over 100,000 km² of southern Saskatchewan and eastern Alberta are characterized by internal drainage (Fig. 1). Although the origin and ultimate source of ions in the salt

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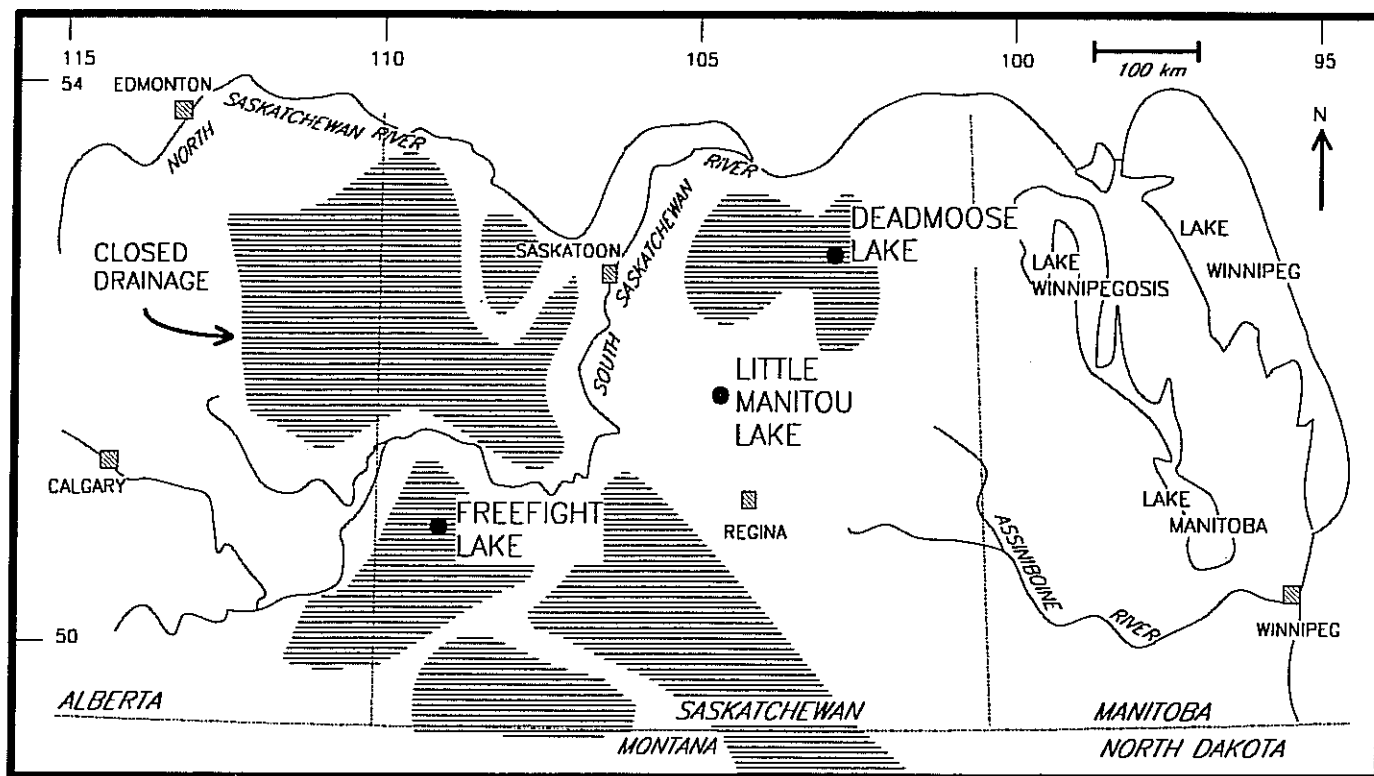


FIG. 1.—Map showing the location of Freefight, Deadmoose, and Little Manitou lakes in the northern Great Plains region. The shaded areas are areas of internal drainage.

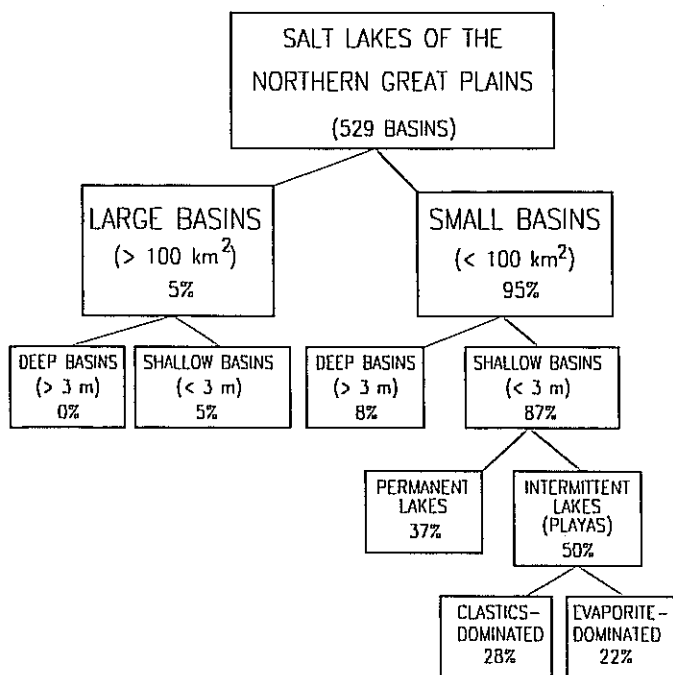


FIG. 2.—Morphological summary of salt lakes in the northern Great Plains.

lakes have been topics of considerable discussion in the scientific literature, most investigators suggest that weathering, leaching, and cation exchange reactions taking place in the thick, unconsolidated glacial drift of the region can provide an adequate source of dissolved components to the closed drainage basins.

The locations of the lakes discussed in this paper are shown in Figure 1. Freefight Lake is located in the Great Sand Hills region of southwestern Saskatchewan, the most arid portion of the northern Great Plains. Deadmoose Lake, situated about 100 km east of Saskatoon, is located in aspen parkland at the northern margin of the Great Plains. Little Manitou Lake is located about 100 km north of Regina.

PREVIOUS WORK

Of the millions of salt lakes in this region, the hydrochemical characteristics (total salinity, major ion concentrations) and morphology (area, depth) of about 500 basins are known (Last, 1988; Hammer, 1978; Hammer and Haynes, 1978; Rutherford, 1970). Because salt lakes are the only surface water present in large areas of the Great Plains, the lakes have been examined in some detail by biological limnologists and water resources managers (e.g., Hammer and others, 1983; Haynes and Hammer, 1978). Much of this work, including previously published information on Deadmoose Lake and Little Manitou Lake, is summarized by Hammer (1986). Data on the nature of the

modern offshore sediments (mineralogy, texture, organic content) and the modern facies relationships within the basins are available for about 100 of the lakes (Last, 1989). Details of the Quaternary stratigraphy and post-glacial history of twenty of the basins in this large region have been published (see summaries in Last, 1992; Schweger and Hickman, 1989; Last and Slezak, 1988). Slezak (1989) and Boden (1985) provide details of the modern facies relationships and geochemistry in Freefight Lake and stable isotope stratigraphy of the endogenic carbonates in Deadmoose Lake, respectively.

METHODS

This report is based on information and data collected from the three modern saline lacustrine basins over a period of eight years. Bathymetry of the basins was determined during the summers of 1983–1989 using an echo sounder and weighted line. Modern facies mapping and grab samples of surficial sediment and shallow subsurface sediment were collected from the basins during the period 1983–1990. Water levels, brine chemistries, and various environmental parameters of the basins have been monitored since 1984. Water samples were collected using a 2-l Kemmerer sampling bottle. Bottom dredge samples were collected during various times of the year using a modified Ponar grab sampler. Cores were acquired during the winter seasons using various methods: a modified Livingstone piston corer, an Acker 5 cm split tube sampler, and a mechanized rotary drill.

Sediment traps have been installed in two of the basins: Freefight Lake and Deadmoose Lake. In each case, the trap configuration consisted of an array of solitary cylindrical PVC vessels of 9 cm diameter suspended at various depths by a surface buoy–subsurface anchor system. Following suggestions by Håkanson and Jansson (1983), the aspect ratio of the vessels (i.e., height/diameter) was approximately 10. A compensating fin and rotating swivels assured vertical orientation of each collection vessel. The traps were positioned such that accumulation data were acquired from: (a) immediately above the chemocline, (b) immediately below the chemocline, and (c) just above the sediment–water interface.

Sediment samples were analysed for bulk mineralogy and detailed evaporite mineralogy by X-ray diffraction. Estimates of the percentages of the various minerals were obtained from the diffractograms using a method modified after Schultz (1964). Standard analytical techniques were used to determine the chemistry of the water samples. Temperature, pH, Eh, O₂, H₂S, and conductivity were measured in the field; cation and anion concentrations were determined in the laboratory by atomic absorption, gravimetric, and turbidimetric methods.

RESULTS

Basin Morphology

Figure 3 and Table 1 summarize the bathymetry and various morphological parameters of the three lakes discussed in this paper. All of the lakes are deep and contain per-

manent water bodies. Freefight Lake is the deepest of the three and, with a mean depth of over 19 m, is the deepest saline lake in the Great Plains. It has very steeply sloping sides and a flat, featureless bottom. Little Manitou Lake is shallower and occupies a long, steep-walled, riverine channel-shaped basin. It similarly has steeply sloping sides and a flat bottom. In contrast to Freefight and Little Manitou basins, Deadmoose Lake has a very irregular basin morphology and bottom topography with numerous deep (greater than 35 m) troughs and holes.

Water Chemistry

All three lakes contain hypersaline brines. The water columns in both Freefight Lake and Deadmoose Lake were chemically stratified during the entire observation period. Little Manitou Lake was chemically stratified for much of the period between 1987–1989, but was isochemical during 1984–1986 and again in 1990. In general, the lakes' waters are highly alkaline, with pH values between 8 and 11. The ionic composition of the water in the three basins, as well as that of many of the other saline lakes of the region, is dominated by sodium, magnesium, and sulfate ions (Fig. 4).

The chemocline in Freefight Lake is located at approximately 6-m depth. The average salinity of the mixolimnion is 112 ppt TDS (total dissolved solids), whereas the monimolimnion has a salinity of about 180 ppt. Both water masses are dominated by Na⁺, Mg²⁺, and SO₄²⁻. The water below the chemocline has a considerably higher proportion of HCO₃⁻ than that of the surface water (Fig. 4). The lower water mass is also very strongly anoxic and has H₂S contents as high as 1200 mg l⁻¹.

Little Manitou Lake water is likewise usually in excess of 100 ppt TDS but has different ionic ratios than Freefight Lake water; Little Manitou shows a strong dominance of Mg²⁺ and a higher proportion of Cl⁻. During the episode of temporary meromixis (1987–1989), the ionic ratios of waters in both layers were similar. Because it is the shallowest of the three lakes, the salinity of Little Manitou Lake showed the greatest temporal variation, ranging from a low of 67 ppt (surface water during spring of 1984) to 192 ppt (bottom water in winter, 1989). The water composition of this lake is also quite variable on a spatial basis, presumably due to subaqueous spring discharge. The water below about 3 m depth in Little Manitou Lake was reducing even during isochemical periods.

Deadmoose Lake is the least saline of the lakes discussed here, with an average salinity of the mixolimnion of 34 ppt and a monimolimnion salinity of 85 ppt. The chemocline is located at approximately 8 m depth. The brines in both water masses have nearly identical ionic ratios: Na > Mg >> K = Ca and SO₄ > Cl >> HCO₃. Deadmoose Lake has the highest Na⁺ and Cl⁻ proportions of the three basins. Like Freefight Lake, the monimolimnion of Deadmoose Lake is permanently strongly reducing (Eh values to -400 mv) and has high levels of H₂S (to 200 mg l⁻¹).

Modern Basinal Sediments

The modern, offshore (deep-water) sediment of each of the basins is dominated by very soluble salts. In general,

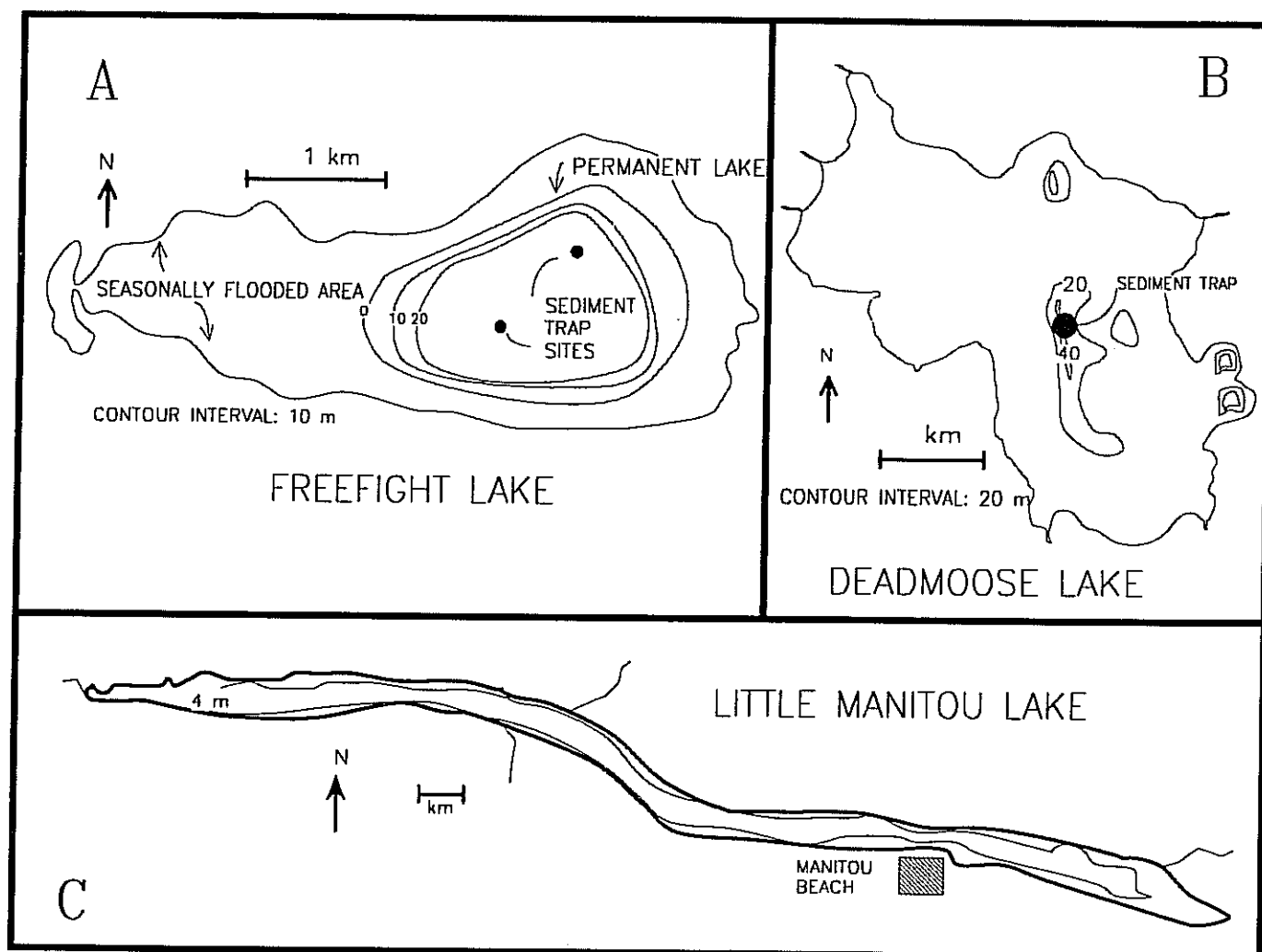


FIG. 3.—Bathymetry and basin morphology of (A) Freefight Lake, (B) Deadmoose Lake and (C) Little Manitou Lake.

TABLE 1.—SUMMARY OF MORPHOMETRIC DATA FOR FREEFIGHT, DEADMOOSE, AND LITTLE MANITOU LAKES.

	Freefight	Deadmoose	Little Manitou
Area (km ²)	2.59	10.50	13.9
Volume (10 ⁶ m ³)	30	109	53
Drainage basin area (km ²)	55.20	70.19	169
Maximum length (km)	2.95	5.69	20.1
Maximum width (km)	1.25	3.23	1.1
Maximum depth (m)	24.92	48.10	5.9
Mean depth (m)	19.52	9.90	4.0

these salts are coarsely crystalline, massive to very poorly bedded, with only minor amounts of sparingly soluble and insoluble inorganic components. At the sediment-water interface, the salts range from loose, porous accumulations of single, euhedral crystals (Fig. 5A) to well-lithified crystalline rock (Fig. 5B). Organic matter content of these modern sediments is variable but often quite high (up to 38 percent). Over twenty non-detrital minerals have been identified, however most of the minerals making up the non-carbon-

ate, soluble salts in the deposits are composed of variable proportions of the sodium and sodium + magnesium sulfates: bloedite [$\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 4\text{H}_2\text{O}$], epsomite ($\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$), or mirabilite ($\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$). Lesser amounts of gypsum and halite are also commonly present. The major endogenic/authigenic carbonate minerals identified include: aragonite, both Ca-rich and Mg-rich dolomite, natron, and huntite. Pyrite is also found in relatively high proportions in the deep-water sediment of the lakes.

Deadmoose Lake contains the simplest salt mineral assemblage: mainly mirabilite with minor gypsum (Fig. 6A). The soluble basinal salts in Little Manitou Lake are composed of a mixture of epsomite and bloedite with secondary abundances of mirabilite, gypsum, and halite (Fig. 6B). Freefight Lake sediments contain the most complex assemblage of evaporite minerals: bloedite and mirabilite are usually dominant but significant proportions of epsomite and gypsum also occur (Fig. 6C). Glauberite [$\text{Na}_2\text{Ca}(\text{SO}_4)_2$], halite, hexahydrite [$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$], kieserite [$\text{MgSO}_4 \cdot \text{H}_2\text{O}$], konyaite [$\text{Na}_2\text{Mg}(\text{SO}_4)_2 \cdot 5\text{H}_2\text{O}$], loewite [$\text{Na}_{12}\text{Mg}_7(\text{SO}_4)_{13} \cdot 5\text{H}_2\text{O}$], and tychite

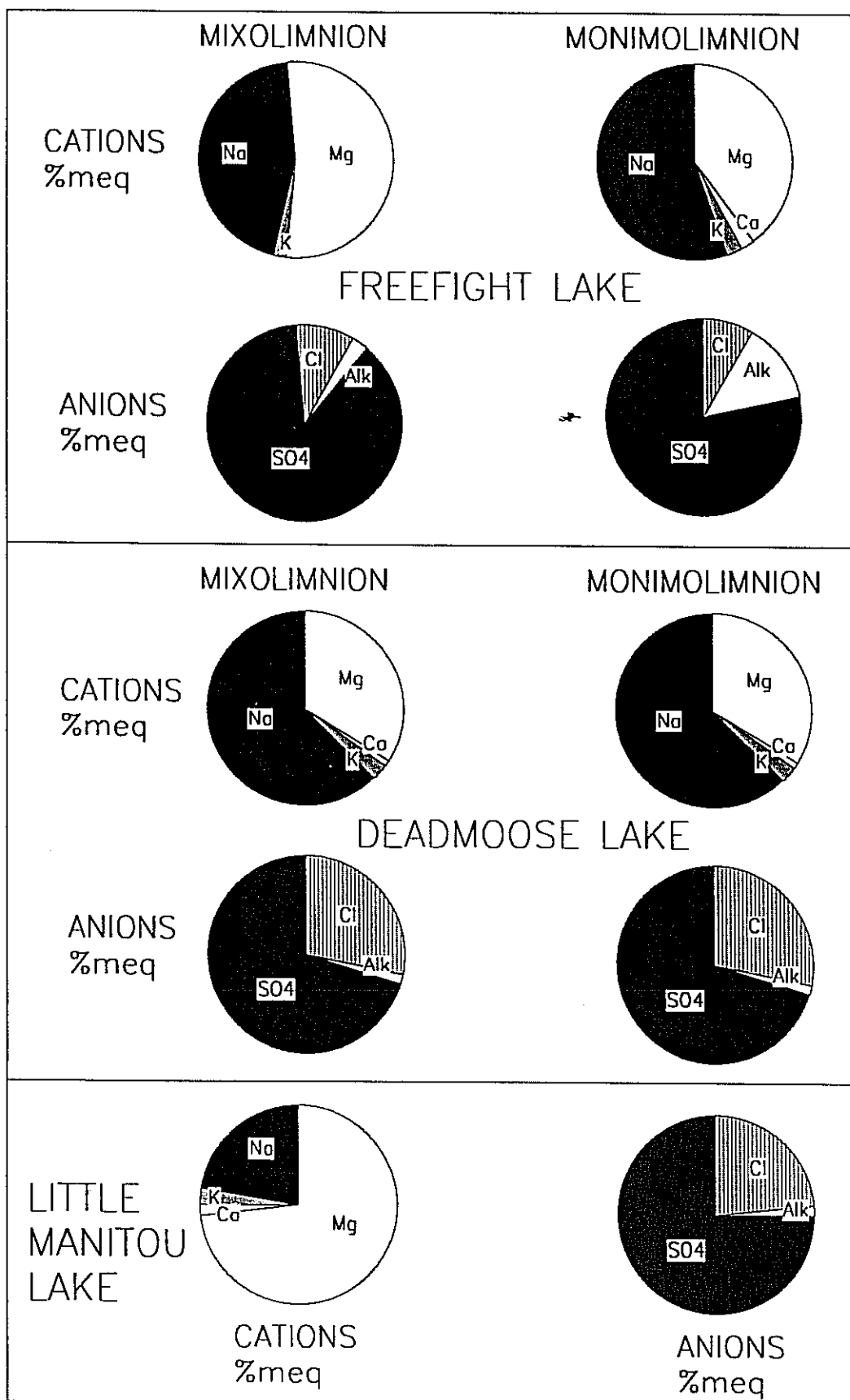


FIG. 4.—Pie charts showing the cation and anion ratios (in percent milliequivalents) of water in Freefight, Deadmoose, and Little Manitou lakes.

TABLE 2.—AVERAGE VALUES OF WATER COMPOSITION OF FREEFIGHT, DEADMOOSE, AND LITTLE MANITOU LAKES.

	Na	K	Ca	Mg (mmol l ⁻¹)	Cl	HCO ₃	SO ₄
Freefight Lake mixolimnion	708	59	4	450	197	51	665
monimolimnion	1313	64	11	504	201	263	956
Deadmoose Lake mixolimnion	208	7	4	56	144	7	174
monimolimnion	389	14	11	104	270	16	285
Little Manitou Lake	480	20	22	703	455	18	741

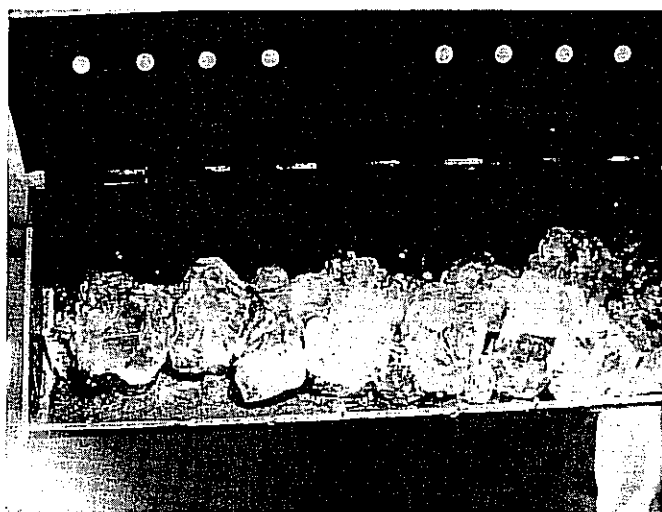


FIG. 5.—(A) Example of loose, unconsolidated sediment composed of a mixture of mirabilite and bloedite crystals from the modern, deep-water surficial sediment of Freefight Lake. Long dimension of sediment dredge is 35 cm. (B) Example of lithified aggregates of euhedral mirabilite crystals from the modern, deep-water surficial sediment of Deadmoose Lake. Diameter of coin is 2 cm.

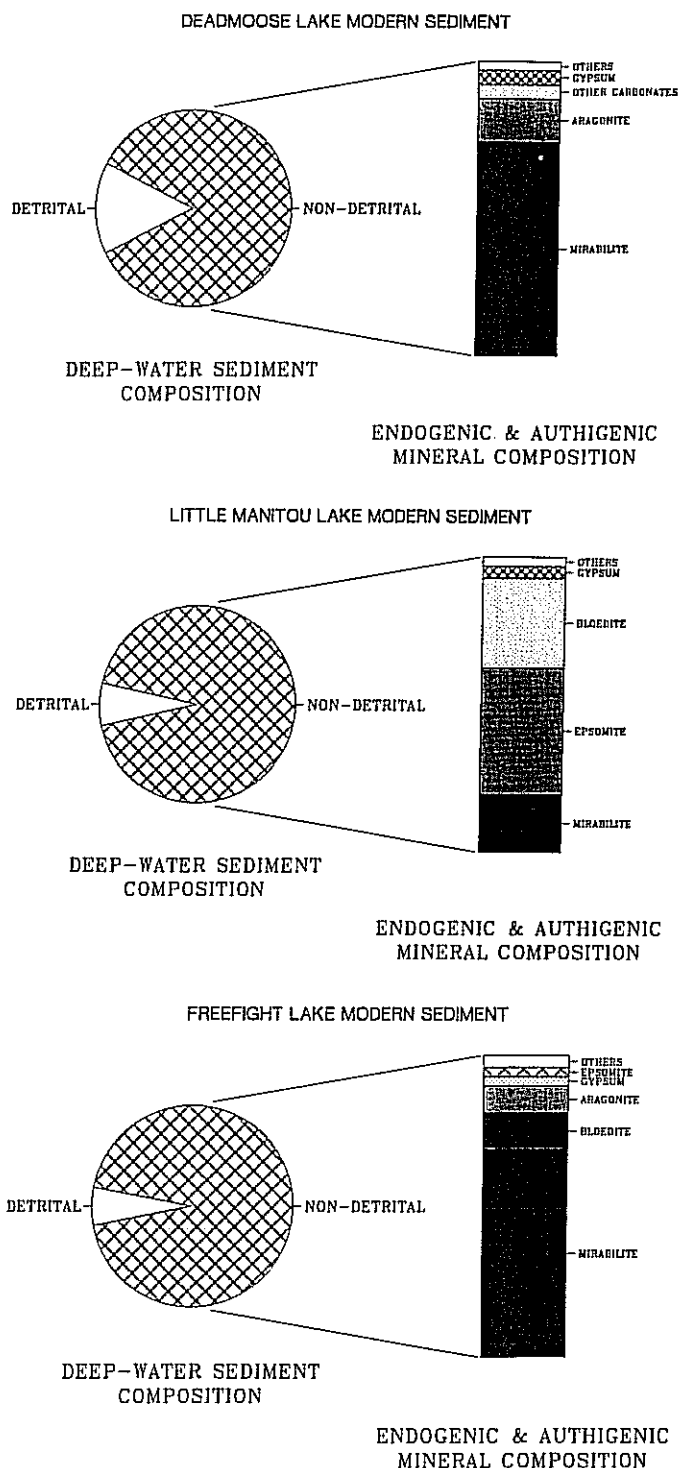


FIG. 6.—Modern basinal sediment composition in (A) Deadmoose Lake, (B) Little Manitou Lake, and (C) Freefight Lake.

[Na₆Mg₂(CO₃)₄SO₄] have all been identified in small quantities.

The spatial distribution of these salts within the basins varies. In Freefight Lake, the entire lake bottom below water depths about 7.5 m is uniformly covered with salt. Total

maximum thickness of the salt in this lake is still unknown because coring has not yet penetrated a complete section in the basin center. In water depths greater than 23 m, the salt is at least 1 m thick, whereas near the edges of the lake the precipitates thin to several centimeters and interfinger shoreward with nearshore shallow-water, evaporitic and organic carbonates. Little Manitou Lake shows a similar widespread spatial distribution of the basinal salts in water depths greater than about 4 m. Maximum thickness of salt penetrated by augering and coring in this basin is 1.25 m. Shoreward in Little Manitou Lake the salts interfinger with finely laminated aragonite-clay couplets and nonbedded shoreline clastics. In contrast to the even, uniform spatial distribution of salts in Freefight and Little Manitou lakes, the distribution of deep-water evaporites in Deadmoose Lake is much less regular and is confined just to the deep troughs and holes (greater than 25 m) where at least 1 m of salt is present.

Sediment Trap Data

Annual and seasonal sediment trap data have been collected from two sites in the Freefight basin for a total of four years between 1984 and 1990. Deadmoose trap data span only two years during this same period and is limited to one site near the center of the basin. Figure 7 summarizes the composition and quantities of material caught in the sediment-water interface traps.

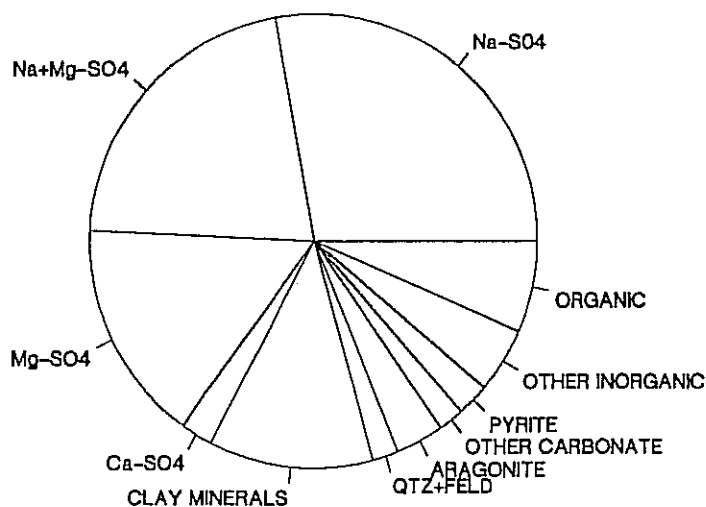
Freefight Lake is currently experiencing very high sedimentation rates. The average accumulation rate at the sediment-water interface in depths greater than 22 m is approximately $12 \text{ kg m}^{-2} \text{ yr}^{-1}$, with rates reaching as high as $55 \text{ kg m}^{-2} \text{ yr}^{-1}$. Nearly all of this material is soluble salt

and is composed mainly of sodium and sodium + magnesium sulfate minerals. About a quarter of the sediment trap material is composed of sparingly soluble endogenic precipitates (mainly finely crystalline aragonite and pyrite), clastic and biogenic carbonates derived from nearshore and mudflat areas, and detrital silicates. Less than 10 percent of the sediment trap material is organic matter. Striking differences in the amount of material in traps positioned above versus below the chemocline indicate that most of the sediment is originating from within the monimolimnion.

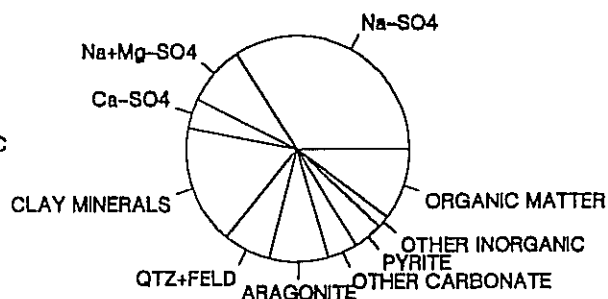
The two years of trap data from Deadmoose Lake suggest that this basin is undergoing more moderate sedimentation rates in the deep basinal areas. The average accumulation rate is about half that of Freefight Lake. In addition, the trap sediment in Deadmoose Lake has a higher proportion of sparingly soluble carbonates, gypsum, and detrital silicates and a correspondingly lower proportion of soluble salts relative to Freefight Lake. Finally, the above versus below chemocline traps show that a much larger amount of material is originating from the mixolimnion in Deadmoose than is the case in Freefight.

CONCLUSIONS AND FUTURE WORK

The genesis of deep-water evaporites is one of the most problematic topics in all of sedimentology. There is abundant evidence from ancient rocks that deep-water evaporite mineral formation did occur in a variety of marine and non-marine settings (Schreiber, 1986; Schmalz, 1969), however there are very few modern environments where such sedimentation has been identified. The primary focus of this paper is to document the occurrence of deep-water evaporite mineral formation in several modern saline lakes of the



FREEFIGHT LAKE BOTTOM TRAP
4-YEAR AVERAGE: $12 \text{ kg/m}^2/\text{yr}$



DEADMOOSE LAKE BOTTOM TRAP
2-YEAR AVERAGE: $690 \text{ g/m}^2/\text{yr}$

FIG. 7.—Pie charts summarizing the average composition and amount of material retrieved from sediment-water interface sediment traps in Freefight and Deadmoose lakes.

northern Great Plains. The results show that the surficial sediments in the deep basinal areas of three lakes in this region are dominated by soluble salts. The composition of these salts varies as dictated by the major ion content of the brines: mirabilite is dominant in the lake with the highest proportions of Na^+ and SO_4^{2-} ions; epsomite and bloedite dominate the salts in the lake with a high Mg^{2+} content.

Although winter freeze-out precipitation of soluble salts has been reported from numerous lakes in this region (e.g., Last and Schweyen, 1983; Hammer, 1978; Rawson and Moore, 1944), until now it has been tacitly assumed that these freeze-out salts redissolved during the ice-free season. Preliminary coring and augering of the deep basin sediments in Freefight, Deadmoose, and Little Manitou lakes reveals that relatively thick (greater than 1 m) sections of salt have accumulated. Although it is clearly misleading to generalize about long-term sedimentation and precipitation rates on the basis of the relatively short temporal observational results reported here, the data do show several interesting features. Modern sedimentation rates in Freefight Lake are exceptionally high. If the observed accumulation rates are maintained, this 25 m deep basin would be filled with salt in less than 2500 years. While sedimentation rates of this magnitude have not been reported from saline lakes elsewhere, the post-glacial stratigraphic records of other lacustrine basins in western Canada suggest that such high rates of evaporite mineral formation did occur, at least periodically, during the Holocene. For example, Ingebright Lake in western Saskatchewan contains in excess of 45 m of salt which was deposited in approximately 6000 years.

There is considerable scope for future work on the deep-water evaporites of the saline lakes of the Great Plains region. While significant advances have been made in our ability to recognize shallow-water/salt pan evaporites (e.g., Lowenstein and Hardie, 1985; Hardie and others, 1985; Rosen, 1991), it is essential that the deep-water deposits of modern evaporitic settings be examined from a petrographic and sedimentary structure perspective. It is commonly accepted that closed basin saline lakes provide the best record of changing hydrological and geochemical conditions in a continental region. However, if the salts of these basins are to be effectively used in paleoenvironmental reconstruction, it is particularly important to identify and evaluate criteria that can be used to differentiate shallow-water and salt pan sediments from true deep-water evaporites.

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