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SALT LAKES OF WESTERN CANADA: A SPATIAL AND TEMPORAL GEOCHEMICAL PERSPECTIVE

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ABSTRACT

The Great Plains of Canada stretch from Winnipeg westward to the Foothils of the Rocky Mountains. 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 thousands of salt lakes. Indeed, nearly all of the surface water present in the Great Plains of Canada is saline. In this regard, the Northern Great Plains of Canada is unique: there is no other area in the world that can match the concentration and diversity of saline lake environments exhibited in the prairie region of Manitoba, Saskatchewan, and Alberta. These salt lakes and sloughs are a very important component of the prairie landscape and ecosystem. They provide a major staging ground for over 80% of North America's ducks; their brines and salt deposits are a source of valuable industrial minerals, contributing over $50,000,000 annually to the prairie economy; their sediment records contain clues about past climates and environmental changes that have occurred in the region.

Geochemical, sedimentological, and environmental data have been collected from nearly 400 of the lakes in this region. The brines show a great range in concentrations on both a spatial as well as a temporal basis. Although many of the lakes are dominated by Na and SO_4, there is considerable diversity in ionic composition, with nearly every major water chemistry type represented. Statistical analyses suggest that the most important factors controlling the brine chemistry in this region are basin morphology, climate, and groundwater.

The chemical diversity of the lakes gives rise to a surprisingly complex suite of endogenic and authigenic minerals. A wide variety of Na and Mg sulfates, chlorides, carbonates, and silicates are present in the modern sediments of the lakes. The stratigraphic sequences in selected basins suggest that significant changes have occurred in brine composition during the last 12,000 years.

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INTRODUCTION

"In this region, there are numerous ponds and small lakes in the hollows among the hills, most of them being more or less brackish or nauseous to the taste from the presence of sulphates of magnesia and soda and other salts. During the dry season of autumn, the water evaporates completely from many of these ponds leaving their beds covered by the dry white salts, which look like snow and are blown about in the wind. Around all the ponds, except those which become completely dry, there is a rank growth of reeds, sedges and grasses, the deep green colour of which forms a strong contrast to the dull grey appearance of the stunted and scanty grass of the hills, which indeed, in many places are almost bare." J. S. Bell, 1875.

The Northern Great Plains of western Canada contain thousands of lakes. These lakes show a tremendous diversity in size, basin morphology, hydrology, hydrochemistry, and sedimentary and biological characteristics. As pointed out in the above quote from one of the first scientific efforts in this region, in much of the area ponded saline and hypersaline brines are the only surface waters present. In this water stressed region of western Canada any changes in lake salinity or chemistry are of major concern to the environmental manager.

Salinity has a significant impact on the emergent vegetation of the lake's littoral zone and thus influences the value of the area as a waterfowl nesting and staging ground. In addition to the importance of this surface water within the realm of wildlife conservation, future industrial and agricultural development in the Great Plains will likely lead to conflicts and potential environmental problems associated with the lakes in the region. For example, western Canada is presently the world's leading producer of natural Na_2SO_4. This valuable industrial mineral is extracted by solution and open pit mining of deposits in the more saline lakes of the region. If the demand for Na_2SO_4 continues to increase as it has in the last decade, more lakes will be leased and more mining operations initiated. Increased industrial development of this type will have a profound impact on the wetlands resource.

If the future industrial and agricultural development that is projected for this region is to take place with a minimum of damage to the natural environment, high priority must be given to the study and understanding of the salinity and chemistry of the lakes and the factors that control their chemical variability. The purpose of this paper is to examine, on a regional scale, the hydrochemistry of lakes in the Northern Great Plains.

PREVIOUS WATER CHEMISTRY WORK

The Northern Great Plains lie between the Canadian Shield to the east and north and the Rocky Mountains to the west. Northcote and Larkin (1963) summarized the early limnological efforts in this 350,000 km^2 area of western Canada. In one of the first systematic lacustrine surveys in the region, Rawson and Moore (1944) reported the water chemistry of 53 lakes from southern Saskatchewan. Although still not as advanced as in some parts of North America, our knowledge and chemical characterization of the surface waters of the Great Plains has progressed considerably in the last 15 years. Rutherford (1970) showed that Mg, Na, and SO_4 components are the most common in Saskatchewan and recognized five main water types on the basis of ionic ratios. He also related spatial variation in water types to the climatic gradients and groundwater composition in the province. More recently, Hammer (1978) reported the water chemistry for 60 saline lakes in southern Saskatchewan and also stressed the importance of Mg, Na, and SO_4 in these basins. Other important discussions covering smaller geographic areas of the Plains include: Govett (1958) and Bierhuizen and Prepas (1985) in central and eastern Alberta; Driver (1965) and Barica (1975) in the Riding Mountain area of western Manitoba; Rozkowski (1965) in the Moose Mountain area of southern Saskatchewan; Hartland-Rowe (1966) in southeastern Alberta; and Lieffers and Shay (1983) in central Saskatchewan.

REGIONAL SETTING

The Northern Great Plains, a vast region of over 350,000 km^2, is the agricultural heartland of Canada and also contains most of the population of western Canada. The region is characterized by flat to gently rolling topography and experiences a cold, semi-arid climate. Pleistocene continental glaciation has resulted in a thick mantle of unconsolidated glacial, glaciofluvial, and glaciolacustrine sediment overlying the generally flat lying Cretaceous and Tertiary bedrock.

From the standpoint of salt lake development the two most important physical features of the region are high evaporation/precipitation ratios and the presence of large areas of endoreic drainage. Although the mean annual temperature of about 3°C would imply relatively low evaporation rates, the high winds, low humidity, and warm summer temperatures create evaporation/precipitation ratios of generally between 3 and 10. The average annual moisture deficit over the region is about 300 mm. These climatic features, combined with the poorly integrated drainage, in which nearly a third of southern Saskatchewan and eastern Alberta is topographically closed, result in a large number of saline lakes of diverse morphologies and sedimentary characteristics. In contrast to many other areas of the world in which there is an abundance of salt lakes, the Northern Great Plains region is tectonically stable, does not exhibit striking topographic relief, nor is there dramatic lithologic diversity on either a local or regional scale.

Groundwaters in the region are of several main types. Most of the groundwater in unconsolidated surficial deposits is of low to moderate salinity (< 3000 ppm TDS) and dominated by Ca, Mg, and HCO_3 ions. In the areas of lowest precipitation, shallow drift groundwater is usually dominated by the SO_4 ion rather than HCO_3. The shallow bedrock aquifers (Upper Cretaceous and younger rocks) are mainly Na-HCO_3 in southern Alberta, Ca-Mg-Na-SO_4 in Saskatchewan, and Ca-Mg-Na-HCO_3 in western Manitoba. The deeper Paleozoic and Cenozoic bedrock contains higher salinity water (up to 300 ppt TDS) that is usually dominated by Na and Cl.

SOURCES OF DATA

Much of the data used in this paper is derived from previously published sources. Most of the Saskatchewan information is from Last (1984), Hammer (1978), Rutherford (1970), and Rozkowska and Roskowski (1969). The data on Alberta lakes is mainly from Bierhuizen and Prepas (1985) and Govett (1958). Information on Manitoba lakes is from Barica (1978), Driver (1965), and Thomas (1959). In addition to the 268 published lake water analyses, 111 previously unpublished analyses are also included to bring the total number of lakes discussed in this report to 379. Most of these analyses represent single samples, however, some of the data are averages of numerous samples collected over a period of months or years. Of the 379 lakes used in this study, 11% are located in Manitoba, 73% in Saskatchewan, and 16% in Alberta (Fig. 1).

CHEMICAL CHARACTER OF THE LAKE WATERS

General

The lake waters of the Northern Great Plains show a considerable range in ionic composition and concentration. The lakes range in salinity from relatively dilute water (0.1 ppt TDS) to brines more than an order of magnitude greater than normal sea water (Table 1). While the "average" lake water has about 31 ppt TDS, nearly 85% of the lakes surveyed have salinities less than 20 ppt.

Although the lakes are dominated by only a few major ions, these major solutes exhibit a considerable range in concentrations and relative proportions. The frequency distributions of Mg, Na+K, Cl, and SO_4 concentrations in the

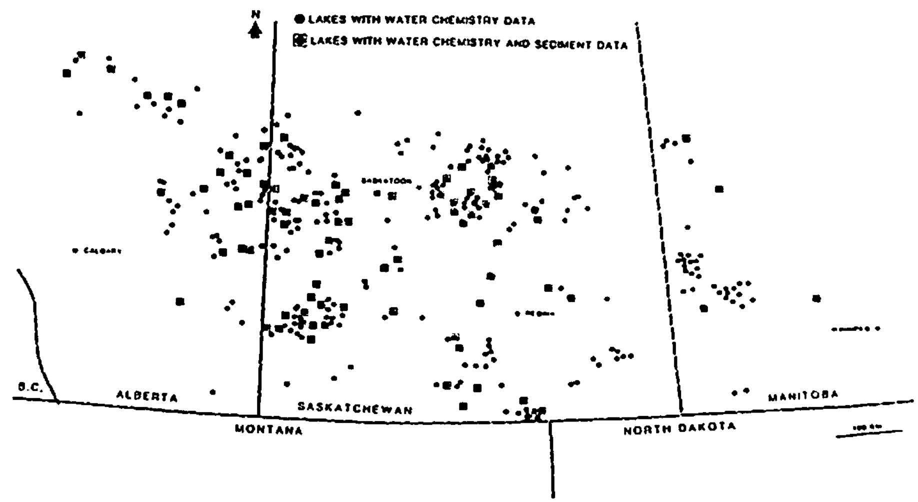

Figure 1. Location of salt lakes of the Northern Great Plains used in this paper.

Table 1. **Mean Chemical Composition of Saline Lakes of the Northern Great Plains. Values in brackets indicate range. Concentration units are mmol/l except for Total Dissolved Solids, which are parts per thousand. Total number of lakes used in analysis is 379.**

Total Dissolved Solids	31.9	(0.02-408)
Calcium	7.8	(0.0-1150.0)
Magnesium	68.4	(0.0-2814.1)
Sodium	345.2	(0.0-4832.7)
Potassium	5.1	(0.0-644.5)
Bicarbonate	12.4	(0.0-312.0)
Carbonate	17.9	(0.0-1008.0)
Chloride	54.8	(0.0-2961.6)
Sulfate	402.1	(0.0-2467.0)

lake waters of the region are multimodal (on a log10 basis) as opposed to the Ca and HCO_3 ions which show a more normal distribution pattern.

Ionic Ratios

Nearly every major water composition type is represented in lakes of the Northern Great Plains (Fig. 2). SO_4 and carbonate rich lakes clearly dominate the anion field comprising over 95% of the total lakes. The cation ratios are much more diverse with the abundance of all three major types showing approximately subequal proportions. The "average" lake is the region shows: Na>>Mg>Ca>K and SO_4>>Cl>HCO_3>CO_3.

Trends and Interrelationships Among Major Ions

Most of the solutes in the lake waters of the Northern Great Plains increase in concentration with increasing total salinity (Fig. 6). Na, K, and SO_4 ions show the best correlation with TDS, while Ca and carbonate concentrations are less directly related to salinity.

The proportions of some of the solutes also show a systematic change with salinity (Fig. 3). Na and SO_4 increase in relative ionic proportion from less than 30% equivalents in dilute lakes to generally more than 90% in lakes with more than 10 ppt TDS. Ca and HCO_3 proportions show an inverse relationship with salinity, decreasing from over 70% equivalents in the dilute waters to nearly 0% in lakes with more than 25 ppt TDS.

Spatial Variation

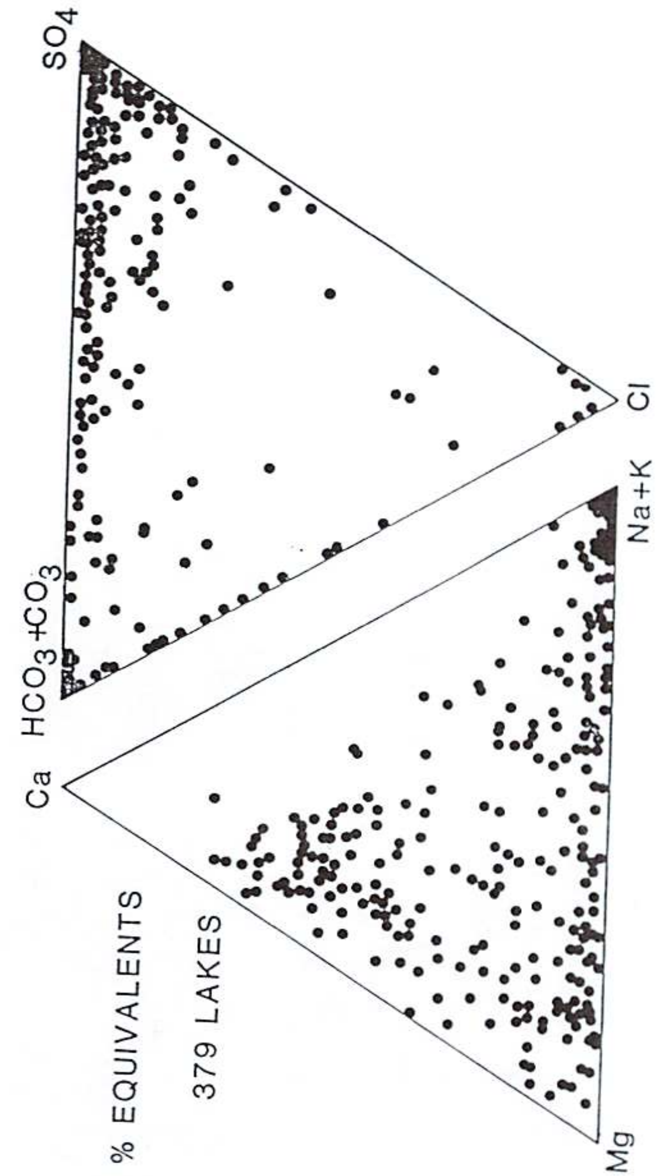

Figure 2. Ionic composition of saline lake brines of the Northern Great Plains.

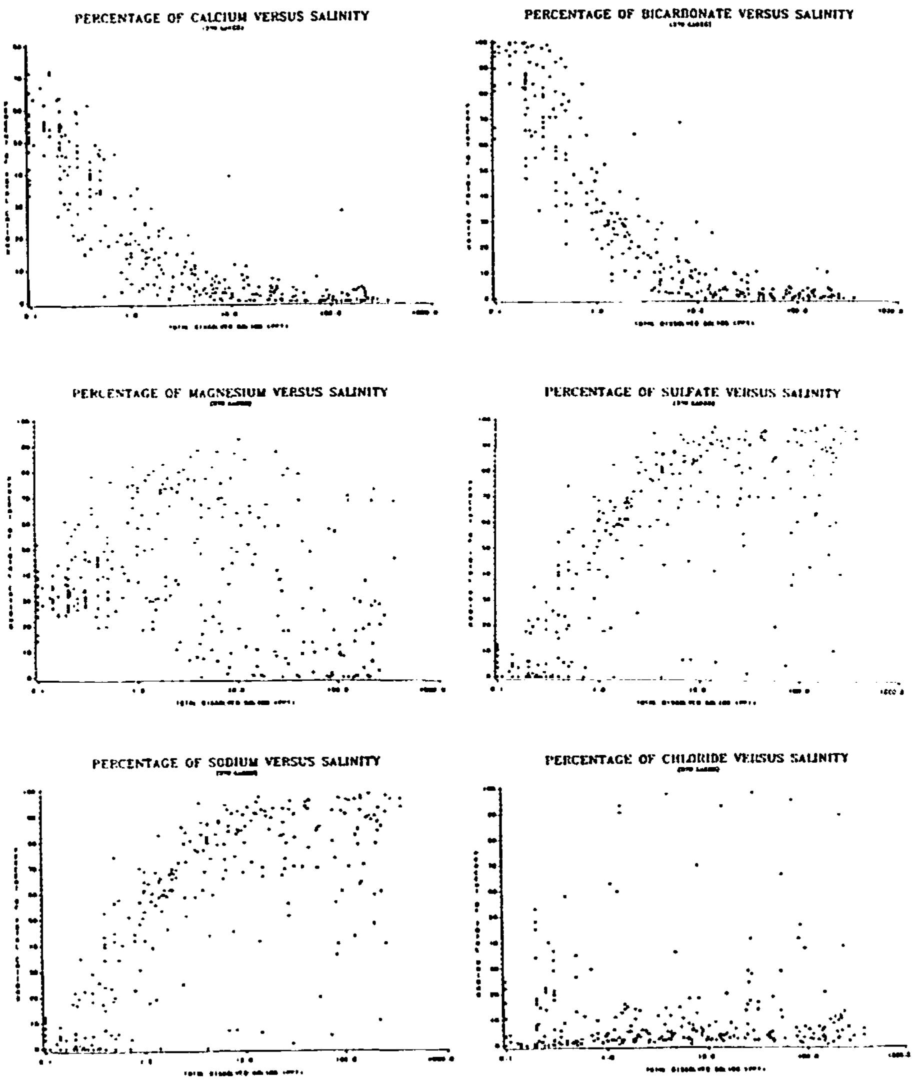

Figure 3. Variation in proportion of Ca, Mg, Na, HCO_3, SO_4, Cl with increasing salinity.

The relatively uniform distribution of lakes in the Northern Great Plains for which water chemistry data exists permits examination of the ionic contents on a spatial basis. Last and Schweyen (1983) discuss these regional trends and present isohaline maps for the saline lakes of Saskatchewan, Alberta, North Dakota, and Montana. Figure 4 shows the total salinity, SO_4, HCO_3, Cl, Na, and Ca isohaline maps for the region. Lakes with highest TDS, Na, SO_4, and Cl contents generally occur in the southeastern Alberta-western and central Saskatchewan area, whereas lakes with high Ca and HCO_3 contents are found in central Alberta and west-central Saskatchewan. The spatial distribution of Mg (not shown) generally follows that of Na, whereas K shows no systematic spatial trends.

Statistical Analysis

Various statistical techniques have been successfully used in previous water chemistry studies in other areas to help group or classify lake basins and variables, and to assist in deciphering the relative importance of environmental factors (Reeder et al., 1972; Dean and Gorham, 1976; Winter, 1977). The lake chemistry data for the Northern Great Plains salt lakes was subjected to both cluster analysis and factor analysis. Details of the analyses are published elsewhere (Last, 1988b).

Cluster Analysis. A Q-mode analysis (clustering the 379 lakes) was unsuccessful. The results failed to subdivide the basins into statistically significant groups in relation to major ion composition. R-mode analysis (clustering the nine variables), however, indicated the following groups of variables: (i) TDS, Na, and SO_4; (ii) K and Cl; (iii) Ca and Mg; and (iv) HCO_3 and CO_3.

Factor Analysis. A variety of morphological (basin area, maximum depth), geological (bedrock type, depth to bedrock, till type), hydrological (drainage basin area, number of streams entering lake, elevation, groundwater composition), and climatic (moisture deficit) variables were added to the original water chemistry data set and analyzed by R-mode factor analysis. The results indicate that nearly 85% of the variance in the data can be explained by factors related to basin morphology (38%), climate (29%), and groundwater composition (17%).

TEMPORAL VARIATION IN WATER CHEMISTRY

Short-Term Temporal Variation

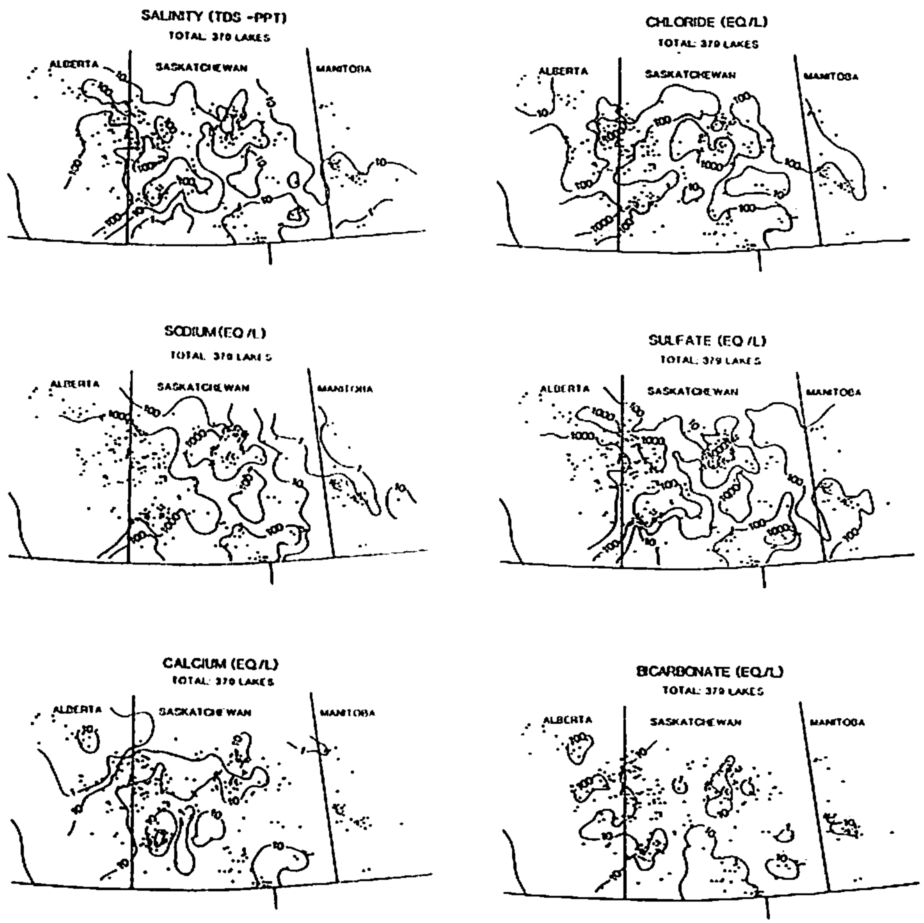

Figure 4. Spatial variation in Total Salinity, Na, Ca, Cl, SO_4, and HCO_3 in saline lakes of the Northern Great Plains.

A major complicating factor in characterizing the chemistry of the salt lakes of the Northern Great Plains is that many of the lakes exhibit playa characteristics: filling with water during the spring and early summer and drying during the late summer or fall. Last and Schweyen (1983) estimate that 85% of the salt lakes in this region are influenced by this type of seasonal hydrologic cycle. This strong seasonality of water levels gives rise to dramatic changes in both ion concentrations and ratios, as demonstrated by numerous studies. For example, Last (1987, 1984) shows that Ceylon Lake, a salt-dominated playa in southern Saskatchewan, annually undergoes changes in concentration from about 30 ppt TDS to greater than 300 ppt. This lake also exhibits dramatic fluctuations in ionic ratios on a seasonal basis from a Na-(Mg)-SO_4-HCO_3 type in early spring to a Mg-(Na)-Cl-SO_4 composition by fall. Unfortunately, only a few lakes in the Northern Great Plains have undergone periodic detailed sampling over a period of years.

Long-Term Temporal Variation

Because lake basins are sinks for sediment they provide a very important source of information about past chemical, hydrological, and climatic conditions in the drainage basin and surrounding area. The sediment records of topographically closed basins, in particular, offer excellent opportunities to evaluate changes in the chemical nature of the brine and the inflowing waters, and to relate these changes to climatic fluctuations or evolutionary changes in the watershed of the lake. Although the literature on the paleochemistry of saline lakes is small relative to that of freshwater lacustrine environments, numerous examples exist which demonstrate the large potential of salt lake sediment records in terms of deducing past geochemical conditions (e.g., Smith, 1979; Bowler, 1981; Smith et al., 1983; Wasson et al., 1984; Spencer et al., 1985). However, paleoenvironmental interpretations of salt lake sediments are not without pitfalls. Saline and hypersaline lacustrine environments are amongst the least understood depositional regimes in sedimentary geology. Thus, interpretations of the preserved stratigraphic records are hampered by this incomplete understanding of the modern depositional and diagenetic processes.

Few of the many thousands of saline lake basins in the Northern Great Plains have been examined from a sedimentological/stratigraphic perspective. Of the approximately 400 lakes for which water chemistry has been documented, we have knowledge of the sediments in only about a third of these. Similar to the early brine composition work, initial sedimentological efforts on these lakes stressed the dominance of sodium sulfate salts, and were directed mainly toward basins with large reserves of economically important industrial minerals. We now realize that the lakes exhibit a complete spectrum of sediment types, from basins dominated by allogenic or clastic material to those in which relatively pure, clastic-free evaporite minerals are forming. The sedimentology and sediment geochemistry of these lakes have been reviewed elsewhere (e.g., Last, 1984; 1988a). The endogenic and authigenic components of the sediment record in the salt lakes of the Northern Great Plains exhibit a wide range of mineralogies. Sulfates and evaporite-related carbonates dominate the modern endogenic fraction of most of the basins, although more rarely silicates and chlorides are present. Our limited knowledge of the postglacial sequences in these evaporitic basins reveals an equally diverse mineral assemblege.

Of the approximately 100 salt lakes for which sedimentological information is available, the stratigraphic records of fewer than 15 have been investigated in any type of detail (Last and Slezak, 1988). Two deep, meromictic basins east of Saskatoon (Waldsea and Deadmoose Lakes) have received considerable paleolimnological attention. The mid to late Holocene records in these two basins suggest dramatic fluctuations in water levels, organic productivity, and chemical composition (Last and Schweyen, 1985; Last and Slezak, 1986). Similar changes in brine chemistry and hydrology were interpreted from the stratigraphy of Ceylon Lake in southern Saskatchewan. The salts deposited in this playa lake suggest 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 (Last, 1988c). Lake Manitoba, a large, hyposaline lake located in the eastern Great Plains has also undergone intensive paleoenvironmental study (e.g., Teller and Last, 1979, 1981; Last and Teller, 1983; Last, 1982; Nambudiri and Shay, 1986). Significant changes in water levels during the 12,000 year long history of this lake are associated with brine chemistry changes (particularly with respect to the Mg/Ca ratio of the lake water) and organic productivity fluctuations.

Although the few lacustrine sedimentary records that have been examined clearly indicate dramatic changes in water levels and related brine chemistry, the causal mechanism(s) of these temporal changes are still largely unknown. Climate has certainly controlled the sedimentation and geochemistry of nearly all of the basins. However, the precise roles of other factors, such as fluctuating groundwater hydrology and hydrochemistry, or postdepositional alteration of the sediments, still remain to be evaluated (Teller and Last, 1988).

The few paleolimnological studies discussed above demonstrate the usefulness of saline lake deposits in helping to gain an understanding of postglacial changes in brine chemistry in the Northern Great Plains. The salt lakes of this region 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.

REFERENCES CITED

Barica, J. 1975. Geochemistry and nutrient regime of saline eutrophic lakes in the Erickson-Elphinstone district of southwestern Manitoba. Can. Fish. Mar. Serv. Res. Dev. Tech. Rept. Invest. 4880. 41 p.

Bell, J. S. 1875. Report on the country between the Red River and the South Saskatchewan, with notes on the geology of the region. Geol. Surv. Canada, Report of Progress, 1873-74.

Bierhuizen, J. F. H., and E. E. Prepas. 1985. Relationships between nutrients, dominant ions, and phytoplankton standing crop in prairie saline lakes. Can. J. Fish. Aquatic Sci. 42: 1588-1594.

Bowler, J. M. 1981. Australian salt lakes. A palaeohydrological approach. Hydrobiol. 82: 431-444.

Dean, W. E., and Gorham, E. 1976. Major chemical and mineral components of profundal surface sediments in Minnesota lakes. Limnol. Oceanogr. 21: 259-284.

Driver, E. A. 1965. Limnological aspects of some saline lakes in west-central Manitoba. J. Fish. Res. Bd. Canada. 22: 1165-1173.

Gorham, E., W. E. Dean, and J. E. Sanger. 1983. The chemical composition of lakes in the north-central United States. Limnol. Oceanogr. 28: 287-301.

Govett, G. J. S. 1958. Sodium sulfate deposits of the western in Alberta. Alta. Res. Coun. Prelim. Rept. 58-5. 34 p.

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

Hartland-Rowe, R. 1966. The fauna and ecology of temporary pools in western Canada. Verh. Internat. Verein. Limnol. 16: 577-584.

Last, W. M. 1988a. Continental brines and evaporites of the Northern Great Plains - An overview. in press, Sed. Geol.

Last, W. M. 1988b. Hydrogeochemistry of saline lakes of the Northern Great Plains. Submitted Environ. Geol.

Last, W. M. 1988c. Sedimentology of a saline playa in the Northern Great Plains. In press, Sedimentology.

Last, W. M. 1987. Sedimentology, geochemistry, and evolution of a saline playa in the Northern Great Plains. Geochemistry and Mineral Formation in the Earth Surface. (Eds. Rodriguez-Clemente, R. and Y. Tardy), Mardrid, p. 319-337.

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

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

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

Last, W. M., and T. H. Schweyen. 1983. Sedimentology and geochemistry of saline lakes of the northern Great Plains. Hydrobiol. 105: 245-263.

Last, W. M., and L. A. Slezak. 1988. The salt lakes of western Canada: A paleolimnological overview. Hydrobiol. 153: 301-316.

Last, W. M. and L. A. Slezak. 1986. Paleohydrology, sedimentology, and geochemistry of two deep saline lakes from southern Saskatchewan. Geog. phys. Quat. XI:5-15.

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

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

Nambudiri, E. M. V. and C. T. Shay. 1986. Late Pleistocene and Holocene pollen stratigraphy of the Lake Manitoba basin, Canada. Palaeontographica 202: 155-177.

Northcote, T. G. and P. A. Larkin. 1963. Western Canada. Limnology in North America (Ed. D. G. Frey). Madison. p. 451-469.

Rawson, D. S., and G. E. Moore. 1944. The saline lakes of Saskatchewan. Can. J. Res. (Ser. D). 22: 141-201.

Reeder, S. W., B. Hitchon, and A. A. Levinson. 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada - I. Factors controlling inorganic composition. Geochem. et. Cosmochim. Acta. 36: 825-865.

Rozkowska, A. D., and A. Roskowski. 1969. Seasonal changes of slough and lake water chemistry in southern Saskatchewan, Canada. J. Hydrol. 7: 1-13.

Rozkowski, A. 1965. The origin of hydrochemical patterns in hummocky morain. Can. J. Earth Sci. 4: 1065-1092.

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

Smith, G. I. 1979. Subsurface stratigraphy and geochemistry of late Quaternary evaporites, Searles Lake, California. U.S. Geol. Surv. Prof. Paper 1043, 130 p.

Smith, G. I., V. J. Barczak, G. F. Moulton, and J. C. Liddicoat. C., 1983. Core KM-3, a surface to bedrock record of late Cenozoic sedimentation in Searles Valley, California. U. S. Geol. Surv. Prof. Paper 1256, 129 p.

Spencer, R. J., H. P. Eugster, B. F. Jones, and S. L. Rettig. 1985. Geochemistry of Great Salt Lake, Utah I: Hydrochemistry since 1850. Geochim. et Cosmochim. Acta 49: 727-738.

Teller, J. T., and W. M. Last. 1988. Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa. in press, Palaeogeogr., Palaeoclimat., Palaeoecol.

Teller, J. T. and W. M. Last. 1979. Post-glacial sedimentation and history in Lake Manitoba. Manitoba Dept. Mines, Res. and Environ. Rept. 79-41, 182 p.

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

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

Teller, J. T., Bowler, J. M., and Macumber, P. G., 1982. Modern sedimentation in Lake Tyrrell, Victoria, Australia. Geol. Soc. Aust., 29:159-175.

Thomas, J. F. J. 1959. Industrial water resources of Canada. Nelson River drainage basin in Canada, 1953-56. Can. Water Surv. Rept. No. 10. 147 p.

Wasson, R. J., G. I. Smith, and D. P. Agrawal. 1984. Late Quaternary sediments, minerals, and inferred geochemical history of Didwana Lake, Thar Desert, India. Palaeogeogr., Palaeoclimatol., Palaeoecol. 46: 345-372.

Winter, T. C. 1977. Classification of the hydrologic settings of lakes in the North Central United States. Water Resources Res. 13: 753-767.