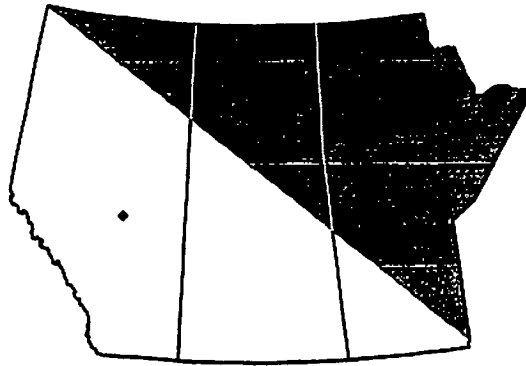


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EVOLUTION OF SALINE LAKES IN WESTERN CANADA¹

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The Great Plains of western Canada contain many salt lakes. Because of the great diversity in lake types, brine chemistries, and depositional processes, the sediments in these salt lake basins offer a tremendous opportunity to examine past environmental conditions and changes in the region. Despite the sensitivity of these deposits to environmental change, interpreting the records in terms of paleoclimate, hydrology, and chemistry is fraught with difficulty. Factors that complicate these interpretations include: diagenesis of the evaporites, post-depositional physical disruption of the sediments, and a lack of sufficient understanding of the depositional processes operating in lakes of this type. Furthermore, an active and growing industrial minerals industry based on the deposits of the salt lakes has, and will likely continue to obliterate the stratigraphic records of some of the basins with the greatest research potential. Notwithstanding these problems, the endogenic (i.e., originating directly from the lake water) and authigenic minerals (i.e., derived by diagenetic alteration of previously deposited sediment or by precipitation from pore water solutions) of these salt lakes provide abundant evidence of long-term systematic change and evolutionary trends in brine composition during the Holocene.

INTRODUCTION

The northern Great Plains of western Canada contain many saline and hypersaline lakes. Estimates of the number of lakes in this vast 350,000 km² region of North America range from about one million to greater than 10 million, with spatial densities of individual saline lake basins reaching as high as 120 lakes/km² in some areas (Last, 1989). Although the general limnological characteristics and hydrochemistry of representative examples of these lakes have been known for some time (e.g., Cole, 1926; Rawson & Moore, 1944), it is only within the past decade that sufficient data has been acquired to allow an appreciation of the tremendous range of sedimentological and geochemical processes operating in these lakes.

Basin morphology, hydrology, and chemical characteristics of the lakes interact to create four distinct types of saline lacustrine settings in the region (Last, 1994a): (i) playas dominated by clastic (allogenic) sediment; (ii) playas dominated by chemically precipitated (endogenic and authigenic) sediment; (iii) deep-water (perennial) lakes dominated by clastic sediment; and (iv) perennial lakes dominated by chemically precipitated sediment. Most of the lakes of the northern Great Plains today occupy shallow playa basins. Only a small proportion (less than 5%) are deep, perennial bodies of water. The focus of this presentation is on those salt lakes, both deep and shallow, whose sediment records are dominated in whole or in part by endogenic and authigenic chemical precipitates. These chemical-sediment-dominated salt lakes of the Great Plains offer an unparalleled opportunity to test and evaluate basic

¹Portions of this paper were originally presented at the 6th International Palaeolimnology Symposium, Australian National University, Canberra, Australia, 1993, and in Last (1994a).

principles of the evolution of nonmarine brines. By achieving a better understanding of natural, long-term brine evolution, we will ultimately be more adequately prepared to decipher the stratigraphic records contained in these basins in terms of past regional climatic changes and local hydrologic fluctuations.

SETTING

The climate, geology, and geomorphology of the Canadian portion of the northern Great Plains region, as these features pertain to the salt lakes, have been described by Rutherford (1970), Hammer & Haynes (1978), Last & Schweyen (1983), and Last (1992a, 1989). The northern Great Plains of Canada stretch from the Precambrian Shield near Winnipeg, Manitoba, westward for nearly 1600 km to the Foothills 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. In general, the region experiences a cold, semi-arid steppe climate, with a mean annual temperature of about 3°C and average precipitation of 320 mm per year (CNC/IHD, 1978). Warm summer temperatures combine with low humidity and strong winds to give the area an annual moisture deficit of about 1.3 m.

In addition to a semi-arid climate, another important regional characteristic is the occurrence of large areas of internal drainage. In total, the drainage in nearly a quarter of the entire northern Great Plains is closed; southern Saskatchewan alone has more than 90,000 km² of internal drainage, representing about 10% of North America's total. While it must be noted that not all of the saline lakes of the Great Plains occur in these endoreic areas, and conversely, not all of the lakes in these large areas of internal drainage are saline, the great expanse of closed drainage plays a pivotal role in development of the tremendous number of saline water bodies that occur.

Finally, the many salt lakes of the region are inextricably linked to the geological history of the northern Great Plains. For instance, the origin of nearly all of the lake basins in the Great Plains is a direct result of Pleistocene glaciation or of fluvial activity associated with meltwater from these glaciers. Similarly, the dissolved ions which make the lake waters so salty are, to a major degree, ultimately derived from the sedimentary bedrock and glacial deposits of the region.

OVERVIEW OF THE SALT LAKES

In much of the northern Great Plains, ponded saline and hypersaline brines are the only surface waters present. As a group, the lakes of this region are unique: there is no other area in the world that can match the abundance and diversity of saline lake environments exhibited in the prairie region of Canada and northern United States. From a practical standpoint, the immense number of individual salt lakes and saline wetlands in this region of North America implies that most geolimnological and paleolimnological research conducted on the prairies involves *saline* lacustrine sediments and environments rather than freshwater deposits. Although the science of paleolimnology in the northern Great Plains is still in its infancy, virtually all of the lakes in the prairie region for which we do have stratigraphic information have experienced phases of elevated salinity at some point in their Quaternary history. More

principles of the evolution of nonmarine brines. By achieving a better understanding of natural, long-term brine evolution, we will ultimately be more adequately prepared to decipher the stratigraphic records contained in these basins in terms of past regional climatic changes and local hydrologic fluctuations.

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importantly, however, from a paleoenvironmental perspective, the large number of salt lake basins suggests that attempts to reconstruct past climate, hydrology, or vegetation characteristics can draw upon the data from multiple sites throughout the entire prairie region.

Despite nearly a century of scientific investigation of these salt lakes, we have only in the past two decades advanced far enough to appreciate the wide spectrum of lake types, water chemistries, and limnological/sedimentological processes that are operating in the modern settings. Hydrochemical data are available for about 600 of the lake brines in the region. Mineralogical, textural, and geochemical information on the modern bottom sediments has been collected for just over 150 of the lakes. The stratigraphic records of only 56 of the basins have been examined to date.

The lake waters show a considerable range in ionic composition and concentration. Early investigators, concentrating on the most saline brines, emphasized a strong predominance of Na^+ and SO_4^{2-} in the lakes. It is now realized, however, that not only is there a complete spectrum of salinities from less than 1 ppt TDS to nearly 400 ppt, but also virtually every water chemistry type is represented in lakes of the region. Compilations of the lake water chemistries in the region can be found in Rawson and Moore (1944), Rutherford (1970), Hammer (1978), Lambert (1989), and Last (1991). Spatial trends and regional variations in the lake water composition in the prairie region of northern United States have been discussed by Gorham et al. (1983) and Winter (1977), and in western Canada by Last and Schweyen (1983), and Last (1992b, 1989). Short-term temporal variations in the brine composition, which can have significant effects on the composition of the modern sediments, have been well documented in several individual basins (see, for example, Last 1989, 1984; Hammer 1986, 1978; Lieffers and Shay 1983; Rozkowska and Roskowski 1969). Using multivariate R-mode and Q-mode factor analysis, Last (1992b) concluded that the most important controls of brine composition in the modern salt lakes of the northern Great Plains are: (i) composition of the inflowing groundwater, (ii) elevation of the lake within the drainage system, and (iii) precipitation to evaporation ratio. Factors related to bedrock type, glacial drift composition, and lake basin morphology appear to have a less important influence on lake brine chemistry.

From a sedimentological and mineralogical perspective, the wide range of water chemistries exhibited by the salt lakes leads to an unusually large diversity of modern sediment composition. Over 70 species of endogenic precipitates and authigenic minerals have been identified in the lacustrine sediments (Last 1989; Last and Slezak 1987). The most common non-detrital components of the modern sediments include: calcium and calcium-magnesium carbonates (magnesian calcite, aragonite, dolomite), and sodium, magnesium, and sodium-magnesium sulfates (mirabilite, thenardite, bloedite, epsomite). Many of the basins whose brines have very high Mg/Ca ratios also have hydromagnesite, magnesite, and nesquehonite. Unlike salt lakes in many other areas of the world, halite, gypsum, and calcite are relatively rare endogenic/authigenic precipitates in the Great Plains lakes.

This geochemical and mineralogical diversity exhibited by the salt lakes of the prairies provides a powerful tool for deciphering past chemical processes and brine ionic

compositions of the lakes, and for interpreting hydrological conditions in the drainage basins. Indeed, compositional reconstructions of lake water can be particularly explicit when based on a detailed knowledge of the endogenic/authigenic mineralogy of the sediments as demonstrated by Last, et al. (1995), Van Stempvoort, et al. (1994), Sack (1993), Sack and Last (1994), and Last (1990). The exceptionally high sedimentation rates which characterize salt deposition in many of these lakes (Last, 1994b, 1993a) further enhances the precision with which their stratigraphic records can be interpreted.

PROBLEMS

Industry Activity

The salt lakes and wetlands of the northern Great Plains serve a great variety of uses. Many studies have documented the importance of these saline terrestrial environments on surface runoff and flow stabilization, erosion control, waste assimilation, agriculture, and wildlife habitat. The economic significance of the salt lakes is further enhanced by the presence of large quantities of economically valuable industrial minerals. A form of sodium sulfate known as Glauber's salt has been mined and commercially extracted from these lakes for over seventy years. In the last twenty-five years the dollar value of this industrial mineral produced from the lakes in western Canada has increased by about 500%. Associated with this increase in market value is an increase in tonnage produced and, to meet the demand, an increase in the number of lakes being mined. Historically, production has occurred from 28 separate basins in the region, with nine lakes being mined today. There are more than 60 basins in the region with commercial reserves of Na_2SO_4 greater than 100,000 tonnes (Slezak and Last 1985). Magnesium salts are also a potential product from a number of the saline lakes (Tomkins 1954).

Although mining of these industrial minerals from the lakes occurs in various ways (e.g., solution mining, excavation, precipitation from brine), the end result of the extraction process(es) on the basin is, from the standpoint of paleoenvironmental research, overall undesirable. Because the lakes that are the most economically attractive for mineral exploitation are often also those whose sediments provide some of the best evidence for geochemical and brine compositional changes through time, the mining of nearly forty of the salt lakes, and the likelihood of expanded mining efforts in the near future, becomes a major concern for paleolimnological work in the Great Plains. At present, the lakes affected by mining are all playa basins. This will not likely be the case in the future; several perennial, deep water lakes in the region have salt reserves which rival that of the playas.

Post-depositional Changes

Numerous summary and overview papers have already stressed the susceptibility of salt lake sediments, particularly evaporites, to post-depositional changes. In the salt lakes of the northern Great Plains, three major types of diagenetic alteration have been documented: (i) saline mineral diagenesis; (ii) salt dissolution and karsting; and (iii) diapirism.

Evaporites of salt lakes of the Great Plains have a distinct and characteristic mineralogy. It is

this mineralogy that can be so useful in helping to decipher paleochemistry of the brines and paleohydrology of the basins (Teller and Last 1990). Regardless of precisely *how* a certain evaporite formed (e.g., by "simple" concentration of lake water via isothermal evaporation, by a temperature increase or decrease of the brine, by mixing of brines of different compositions, by biologically-induced precipitation, etc.), the mere presence of that particular salt mineral in a stratigraphic sequence implies the formative brine was saturated (or supersaturated) with respect to that precipitate. Thus, a given suite of evaporite minerals can be used to calculate, in considerable detail, the thermodynamic conditions of the evaporating solution. Problems arise, however, if it cannot be assumed that the minerals are either endogenic or at least very early diagenetic (formed essentially at the sediment-water interface). In many salt lakes, very dense, hypersaline surface brines can percolate downward into subsurface sediments. Because these dense brines are late stage residual products, they often have dramatically different chemical compositions than the normal lake or groundwater. The ability of these descending brines to radically alter the original mineral composition of large sections of the subsurface sediments has been well documented (Sonnenfeld 1984; Warren 1989).

In addition to conversion of one evaporite mineral to another, undersaturated groundwater or surface water can completely dissolve the most soluble components of the stratigraphic record of a salt lake. The formation of deep karst chimneys and large dissolution pits is occurring today in numerous saline lakes in the Great Plains. For example, in Ceylon Lake, a salt-dominated playa located in south-central Saskatchewan, saline karst chimneys up to 9 m deep have been identified (Last 1993b). In Lydden Lake, another salt playa located west of Saskatoon, Saskatchewan, solution pits up to 30 m wide are present. A single salt karst feature in Ingebright Lake in southwestern Saskatchewan comprises a volume over 25,000 m³. The occurrence of buried mud "mounds", highly irregular salt thicknesses, and abrupt compositional changes over short distances in some basins indicate that the process of salt removal has also taken place in the past. It is especially important to recognize this when attempting to interpret the stratigraphic record of the lakes because large vertical sections of the lacustrine sediment can be affected.

Diapirism, or the process of piercing of an overlying geological unit by an underlying mobil core material, is a commonly described phenomenon in several modern and recent sedimentary environments. Mud diapirs, or mudlumps, are particularly abundant in birdfoot type of deltas, where, for example in the Mississippi River delta, they can penetrate 100 m of delta front sands (Coleman and Prior 1980). Features of similar origin also occur in saline lakes of the northern Great Plains (Last, 1984). Although the precise mechanisms of the diapirism are not yet known, these features in the salt lakes are likely the result of instability brought about by the loading of a thick section of dense and nonpermeable salt on top of relatively low density, water saturated lacustrine muds. This instability causes the muds to flow upward through the salt to the surface of the lake. At the surface, this clastic sediment is redistributed by wave action and incorporated into the modern deposits of the lake thereby leading to potential contamination.

Sedimentary and Geochemical Processes/Concepts

Virtually all geological interpretations of the stratigraphic records in these lacustrine basins depend on a knowledge of the modern environments and modern sedimentary processes. However, our understanding of some of these modern processes is still incomplete. Thus, it is important that the stratigraphic interpretations and conclusions drawn from examination of the sedimentary record be viewed with caution.

Foremost among these still unresolved "conceptual" problems which continue to obscure the interpretation of the paleoenvironmental record in these salt lakes is that of the significance of fine grained clastic units. Thin beds and laminae of fine grained siliciclastic material commonly occur interbedded with evaporites in the stratigraphic records of the salt-dominated lakes of the Great Plains. Their paleoenvironmental significance and sedimentological interpretation are problematic. They may represent periods of relatively deep and fresh water conditions in which increased runoff from the surrounding watershed, due to a more humid climate, brought an increased influx of clastic material to the lake. Conversely, the fine silt and clay units could be residual products, the end result of dissolution and downward leaching of the salts due to prolonged desiccation of the playa and a lowered groundwater table brought about by a more arid climate. Finally, the fine clastics may have been deposited during periods of increased aeolian activity, also possibly associated with increased aridity.

Carbonate minerals are among the most common and also most useful inorganic constituents of lake sediments. Many studies have documented the suitability of calcite and aragonite in paleolimnology (e.g., Kelts and Hsü 1978; Dean 1981; Eugster and Kelts 1983). The application of other carbonate mineral species, such as dolomite, magnesite, and siderite, which commonly occur in salt lake sediments, has been less widespread. Based to a major degree on observational data provided by Müller et al. (1972), conventional wisdom holds that the mineral sequence of: low-Mg calcite \Rightarrow high-Mg calcite \Rightarrow aragonite \Rightarrow dolomite \Rightarrow magnesite/huntite reflects increasing Mg/Ca ionic ratios in the precipitating solution and, very likely, increasing salinities. Thus, it has become commonplace to use the stratigraphic variation of these species in a lacustrine basin to deduce past ionic ratios and salinity of the lake water. Unfortunately, there are many pitfalls associated with this cookbook approach. The application of the sequence to paleochemical interpretations implies that the minerals being used are endogenic precipitates. Talbot and Kelts (1986) provide an example of the complexity of the interpretations if any of the carbonate components are diagenetic in origin. It is often very difficult to distinguish primary endogenic carbonates from either primary or secondary diagenetic precipitates. Furthermore, it is likely that other factors besides, or in addition to, Mg/Ca and salinity have a major influence on the specific carbonate species being precipitated. For example, both the alkalinity and the sulfate concentration of the water are thought to be key controlling factors in the formation of dolomite. Temperature of the solution, in addition to the Mg/Ca ratio, plays a major role in dictating how much Mg^{+2} is incorporated into the calcite lattice in the formation of high-Mg calcite.

The two fundamental assumptions that allow investigators to deduce the composition of a brine from the mineral record preserved in the sediment are that: (a) the composition of the

mineral suite has not been significantly altered by post-depositional changes, and (b) the mineral suite that is ultimately preserved is a true reflection of the water composition that existed in the basin at the time of deposition. Problems associated with (a) have been discussed above. If the salt lake is viewed simply as a container of water in which relatively dilute inflow is concentrated by evaporation to the point of saturation with respect to the minerals present, assumption (b) is valid: the mineralogy is a reasonable reflection of the brine composition at the point of precipitation. Unfortunately, this view of a salt lake as a container of water undergoing evaporation is an oversimplification of the real world. Apart from ignoring the role of biological processes in mineral formation, this approach is inadequate for at least two major geochemical reasons: Firstly, the newly formed minerals are not necessarily isolated from the brine immediately upon precipitation. This ability of the salts to react with a changing brine composition on a seasonal basis (as is the case in many playa basins) or as the precipitate settles through a deep, chemically stratified water column greatly increases the likelihood of mineral alteration even before being incorporated into the sediment record. Secondly, the simple view does not take into account metastability of the salts. The formation of metastable phases is a common phenomenon in low temperature geochemistry, particularly in late-stage evaporation of brines (Drever, 1988). Although with time, the metastable phases should transform to thermodynamically stable phases, this transformation can be slow enough to allow the metastable material to persist in the geological record, thereby muddling the interpretation of the mineral suite.

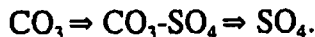
BRINE EVOLUTIONARY SEQUENCES

The basic principles of nonmarine brine evolution have been known and discussed for over thirty years and there have been many studies dealing with the theoretical aspects of these evolutionary sequences. Probably the best known conceptual model of brine evolution is still that of Hardie and Eugster (1970), which interprets the composition of closed-basin waters in terms of a series of chemical divides. Although the principles of chemical divides and evolutionary paths as presented by these early researchers are valid, clearly the model(s) is an oversimplification of a complex series of sedimentary and geochemical processes. Only relatively recently have we begun to understand this complexity (Drever, 1988; Bryant, et al., 1994).

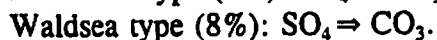
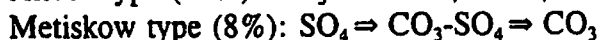
Although the stratigraphic records of over 50 salt lakes in the prairie region of western Canada are known and/or currently being investigated, most of the observational data relative to brine compositional changes and evolution comes from just 24 of these basins. The endogenic and authigenic mineral suite preserved in the sedimentary fill in these lakes have been interpreted in terms of major ion composition (ionic ratios) following procedures outlined by Smith, et al. (1983) and Last (1990). These detailed brine composition records were then subjected to Markov chain analysis in order to decipher any overall cyclicity or underlying repetitive sequences. Finally, each stratigraphic sequence was summarized in terms of a single evolutionary sequence using only the most statistically significant Markov chains.

Four generalized anion sequences and five generalized cation sequences were identified in these 24 lakes. The most commonly occurring anion sequence, present in 46% of the basins

studied, is that of:

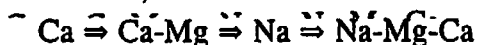


This anion evolutionary sequence is best represented in Ceylon Lake in south-central Saskatchewan and is thus termed the Ceylon type. The three other anion sequences which occur less frequently are:

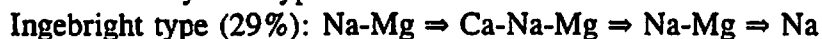


Approximately 20% of the lakes examined exhibited no statistically significant temporal anion composition trends.

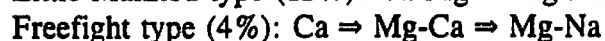
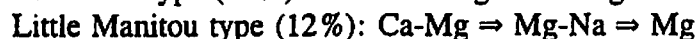
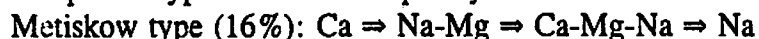
The cation evolutionary sequences present in these 24 lakes were considerably more complex than the anion sequences. The most common type (Lydden type), which occurs in about a third of the lakes studied, is:



Nearly as common as the Lydden type is the



The three other sequence types of lower frequency occurrence are:



Because of the complexity of the interplay between intrinsic processes (sedimentary, geochemical, hydrologic, and biological processes operating within the lake basin itself) and extrinsic processes ("external" factors such as climate change, drainage basin modification), identification of the causal mechanisms for these various evolutionary sequences is not straightforward. Clearly, much more quantitative data from these and other saline lakes in the region needs to be collected in order to explain and properly model the observed compositional trends. In particular, the relatively poor chronological control, which has hampered paleolimnological investigations throughout the Great Plains, must be better resolved in these basins before attempting to discriminate between the various possible intrinsic versus extrinsic factors that likely influence the chemical composition these saline lakes.

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