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Paleohydrology of playas in the northern Great Plains: Perspectives from Palliser's Triangle

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ABSTRACT

Palliser's Triangle, the most arid portion of the Great Plains of western Canada, contains many playa lake basins. Because of the great diversity in basin types, brine chemistries, and depositional processes, the sediments in these lakes offer a tremendous opportunity to examine past hydrological and environmental conditions and changes in the region. Despite the sensitivity of these deposits to environmental change, interpreting the records in terms of paleohydrology, chemistry, and climate 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 proper 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 playas has obliterated, and will likely continue to adversely affect, the stratigraphic records of some of the basins with the greatest research potential. Notwithstanding these problems, the sediments of the playa lakes provide the best and, in some cases, only record of past environmental conditions in this semiarid region. Paleohydrology in this area of the northern Great Plains is poised for a rapid expansion, fueled by the combination of significant technological breakthroughs, improvements in methodology, and a more positive view of the importance of paleohydrological research in environmental management.

INTRODUCTION

The northern Great Plains of western Canada form a unique setting for millions of lakes. Because of the relatively high evaporation to precipitation ratios in this region, and the presence of extensive areas of closed drainage, saline and hypersaline waters dominate these lakes. Most of the lakes that occur in Palliser's Triangle (Fig. 1), the most arid portion of this large geographic region, are shallow and exhibit playa characteristics: filling with water during the spring and early summer and drying completely by late summer/autumn.

The past decade has witnessed considerable growth in interest and research on both the modern sedimentary processes and the Holocene stratigraphic records in these saline playa basins. Indeed, it is now recognized that the playas of Palliser's Triangle provide nearly the only source of detailed, high resolution, physical and chemical paleoenvironmental information for the Holocene of the region. Unfortunately, the very aspects that make these salt-lake sediments so potentially attractive for paleohydrological, paleolimnological, and paleoclimatic analyses also give rise to significant interpretative problems.

The objectives of this paper are threefold: (1) introduce the features of the northern Great Plains, and specifically Palliser's Triangle, that are important to the occurrence of the salt lakes, briefly summarizing the main sedimentological and geochemical characteristics of the playas; (2) discuss the more serious difficulties that must be faced in attempting to interpret the Holocene stratigraphic records of these basins; and (3) highlight future paleohydrological research directions and opportunities in this region. This is not intended to be either a review or synthesis of specific playa basins in the Great Plains; several other recent publications have already done this (Last and Slezak,

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Palliser Triangle Global Change Contribution Number 4

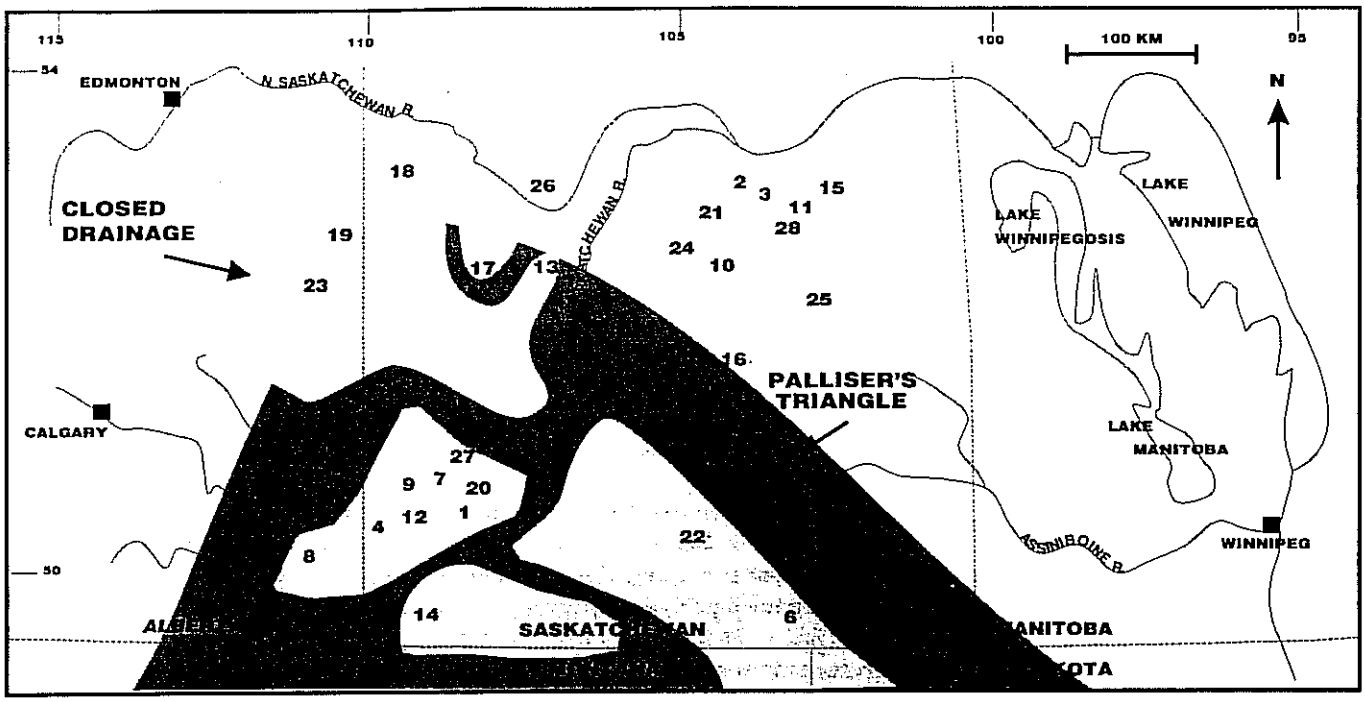

Figure 1. Location map of the northern Great Plains showing Palliser's Triangle. Also shown are the areas of internal (endoreic) drainage and the approximate locations of the lakes mentioned and discussed in the text: 1, Antelope; 2, Arthur; 3, Basin; 4, Bitter; 5, Blackstrap; 6, Ceylon; 7, Chain; 8, Chappice; 9, Corral; 10, Dana; 11, Deadmoose; 12, Freefight; 13, Grandora; 14, Harris; 15, Lenore; 16, Little Manitou; 17, Lydden; 18, Manitou; 19, Metiskow; 20, Mud; 21, Muskiki; 22, Old Wives; 23, Oliver; 24, Porter; 25, Quill; 26, Redberry; 27, Vincent; 28, Waldsea.

1988; Teller and Last, 1990). Finally, the emphasis of this paper is nonbiological. Smol's (1989) discussion on recent advances and future developments of biological paleolimnology are directly applicable to the study of the paleohydrology of playas in Palliser's Triangle. In general, however, the wealth of paleobiological information contained in the sediments of these lakes has not been as extensively exploited as elsewhere in the world (e.g., Löffler, 1987; Meriläinen et al., 1983).

WHAT DO WE KNOW ABOUT THE PLAYAS OF THE REGION?

Location and setting

. . . . in the central part of the continent there is a region, desert, or semi-desert in character, which can never be expected to become occupied by settlers . . . . Although there are fertile spots throughout its extent, it can never be of much advantage to us as a possession. (Palliser, 1862)

The northern Great Plains of Canada stretch from the Precambrian Shield near Winnipeg, Manitoba, westward for nearly 1,600 km to the Foothills of the Rocky Mountains. This is a vast region of flat to gently rolling terrain, interrupted only by occasional steep-sided and deeply entrenched river valleys. Palliser's Triangle, named after Captain John Palliser, the leader of one of the first scientific expeditions into the western interior of Canada, is informally defined as the area between longitude 100° and 114°, extending north from the 49th parallel to an apex at about 52° (Fig. 1). Although it is misleading to generalize about such a large area, Palliser's Triangle does experience a cold, semiarid steppe climate, with a mean annual temperature of about 3°C and average precipitation of 325 mm per year (CNC/IHD, 1978). The area of Palliser's Triangle is somewhat warmer and drier than the rest of the northern Great Plains. Warm summer temperatures combine with low humidity and strong winds to give the area an annual moisture deficit of generally greater than about 1 m.

Another important regional characteristic is the occurrence of large areas of internal drainage. In total, the drainage in well over half of the entire Palliser's Triangle is closed; southern Saskatchewan alone has more than 90,000 km^2 of internal drainage, representing about 10% of North America's total (Fig. 1). Although not all playas of the region occur in these endoreic areas, and not all lakes in these large areas of internal drainage are saline, the great expanse of closed drainage does play 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. Pleistocene continental glaciation has resulted in a thick sequence of unconsolidated glacial, glaciofluvial, and glaciolacustrine sediment mantling the generally flat-lying Phanerozoic sedimentary bedrock. The origin of nearly all of the natural lake basins in the Great Plains is a direct result of this Pleistocene glaciation or of fluvial activity associated with meltwater from these glaciers.

Similarly, the dissolved ions that make the lake waters so salty are, to a major degree, ultimately derived from the thick section of Phanerozoic sedimentary bedrock and glacial deposits. The bedrock of the region consists of a sequence of Mesozoic and Cenozoic siliciclastic rocks overlying a series of Paleozoic carbonates and evaporites. Many authors have noted a striking correlation between the presence of salt lakes at the surface and the occurrence of subsurface preglacial and englacial valleys in the region (e.g., Witkind, 1952; Rueffel, 1968; Freeze, 1969), and have surmised that these buried valleys act as conduits for water and ions to the salt lakes. Although details of the groundwater hydrodynamics and the interaction of groundwater with individual salt lake basins in the northern Great Plains are poorly studied and understood, variation in subsurface water composition is reasonably well documented on a regional basis (e.g., Brown, 1967; Lennox et al., 1988). Most of the groundwater in unconsolidated surficial deposits is of low to moderate salinity (<3 ppt TDS) and dominated by calcium, magnesium, and bicarbonate ions. In western Saskatchewan and eastern Alberta, this shallow-drift groundwater is usually characterized by sulfate rather than bicarbonate ions. The shallow bedrock aquifers (Upper Cretaceous and younger rocks) are mainly sodium-bicarbonate in southern Alberta, calcium-magnesium-sodium-sulfate in Saskatchewan, and calcium-magnesium-sodium-bicarbonate in western Manitoba. The deeper Paleozoic and Cenozoic bedrock contains much higher salinity water (up to 300 ppt TDS) that is usually dominated by sodium and chloride.

The lakes

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. (Bell, 1875)

In most of the northern Great Plains and Palliser's Triangle, 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 concentration and diversity of saline lake environments exhibited in the western interior region of Canada and northern United States. The immense number of individual salt lakes and saline wetlands in this region of North America is staggering. Estimates vary from about 1.5 million to greater than 10 million, with densities in some areas being as high as 120 lakes/km^2 (Last, 1989a). As shown in Figure 2, the vast majority of these lakes in Palliser's Triangle are small, shallow, and ephemeral (i.e., playas).

Despite nearly a century of scientific investigation of these salt lakes, we have, in the last two decades only, advanced far enough to appreciate the wide spectrum of basin types, water chemistries, and geolimnological processes that are operating in the modern settings. Hydrochemical data are available for about 500 lake brines in the region. Mineralogical, textural, and geochemical information on the modern bottom sediments has been collected for just over 100 of these lakes. The stratigraphic records of only twenty of the basins in the entire northern Great Plains of both Canada and United States have been examined, with just eight of these from Palliser's Triangle per se. Complete sequences of the entire Holocene have been reported from only three of these lakes.

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 (Cole, 1926; Sahinen, 1948; Govett, 1958). It is now realized, however, that not only is there a complete spectrum of salinities from less than 1 ppt TDS to over 400 ppt, but also virtually every water chemistry type is represented in lakes of the region (Fig. 3). Rawson and Moore (1944), Rutherford (1970), Hammer (1978), and Lambert (1989) have compiled lake-water chemistries in the region. Details of spatial trends and regional variations in the lake-water composition in adjacent areas 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 (1989a, 1988). Lake brines with the highest propor-

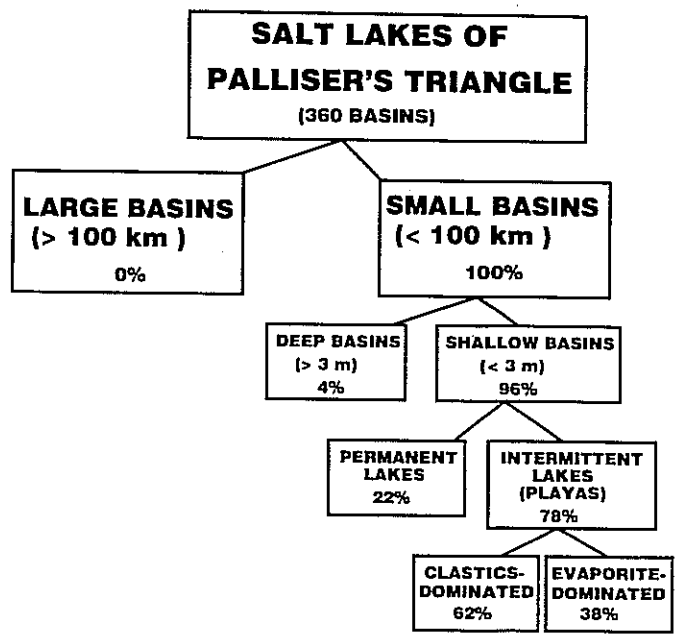

Figure 2. Summary of the morphology and modern sediment type of 360 surveyed lakes in Palliser's Triangle.

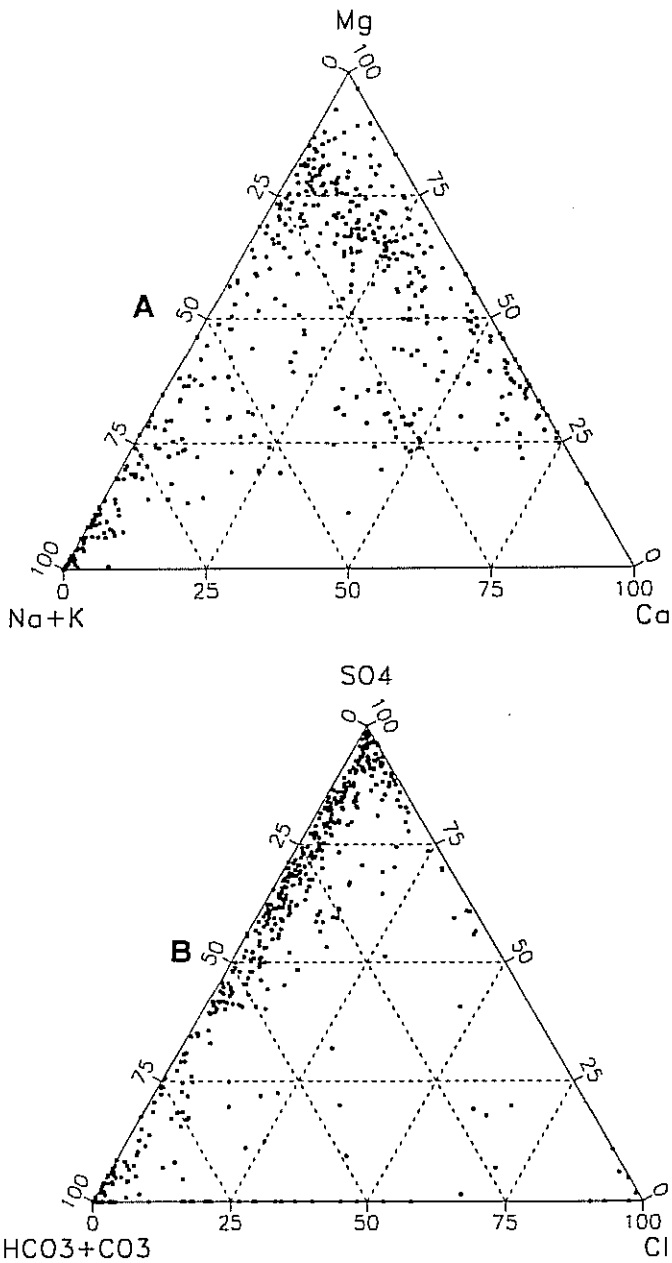

Figure 3. Trilinear diagrams showing (A) cation and (B) anion ratios in 360 surveyed lakes in Palliser's Triangle.

tions of sodium and sulfate ions generally occur in east-central Alberta and west-central Saskatchewan, whereas calcium and carbonate-rich brines dominate in the north and east part of the region. Brines with relatively high chloride and magnesium contents occur in western and central Manitoba.

With such a vast array of compositions, it is difficult to generalize. Nonetheless, the paucity of Cl-rich lakes makes the basins of Palliser's Triangle somewhat unusual compared with salt lakes in many other areas of the world (e.g., Australia, western United States). Significant short-term temporal variations in the brine composition, which can have important effects on the composition of the modern sediments, have been well documented in several individual playa basins (Hammer, 1990, 1986, 1978; Last, 1989b, 1984; Lieffers and Shay, 1983; Rozkowska and Roskowski, 1969). For example, the water in Ceylon Lake, a salt playa located about 100 km south of Regina, is dominated by sodium, sulfate, and bicarbonate ions during early spring but becomes a magnesium-chloride-sulfate brine by late summer.

From a sedimentological/mineralogical perspective, the wide range of water chemistries exhibited by the lakes results in an unusually large diversity of modern sediment compositions. Over 40 species of endogenic precipitates (i.e., originating directly from the lake water) and authigenic minerals (i.e., derived by diagenetic alteration of previously deposited sediment, or by direct precipitation from pore-water solutions) have been identified in the lacustrine sediments (Last, 1989a; Last and Slezak, 1987). The most common nondetrital 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 precipitates in lake sediments of the Great Plains.

Sediment accumulation in these salt lakes is controlled and modified by a wide variety of physical, chemical, and biological processes. Smoot and Lowenstein (1991), Warren (1989), Allen and Collinson (1986), Kendall (1984), Eugster and Kelts (1983), Eugster and Hardie (1978), and Hardie et al. (1978) provide discussions and comprehensive overviews of the general suite of processes operating in salt lakes. The details of the many modern sedimentary processes can be exceedingly complex and difficult to discuss in isolation. In broad terms the processes operating in the salt lakes of the Great Plains are ultimately controlled by three basic factors or conditions of the basin: (a) basin morphology, (b) basin hydrology, and (c) water salinity and composition. Combinations of these parameters interact to control nearly all aspects of modern sedimentation in these lakes and give rise to four "end member" types of modern saline lacustrine settings in the region: (1) shallow lakes (playas) dominated by clastic sediment, (2) shallow lakes (playas) dominated by chemically precipitated sediment, (3) deep water (perennial) lakes dominated by clastic sediment, and (4) deep water (perennial) lakes dominated by chemically precipitated sediment (Fig. 4).

Table 1 summarizes the dominant nonbiological processes operating in the four types of basins. Two fundamental processes common to all of the lakes in the region are (1) the acquisition of water, sediment, and solutes by direct precipitation, river and stream inflow, and groundwater influx; and (2) the concentration of solutes by evaporation. The playa basins are further affected by a distinct suite of physical and chemical

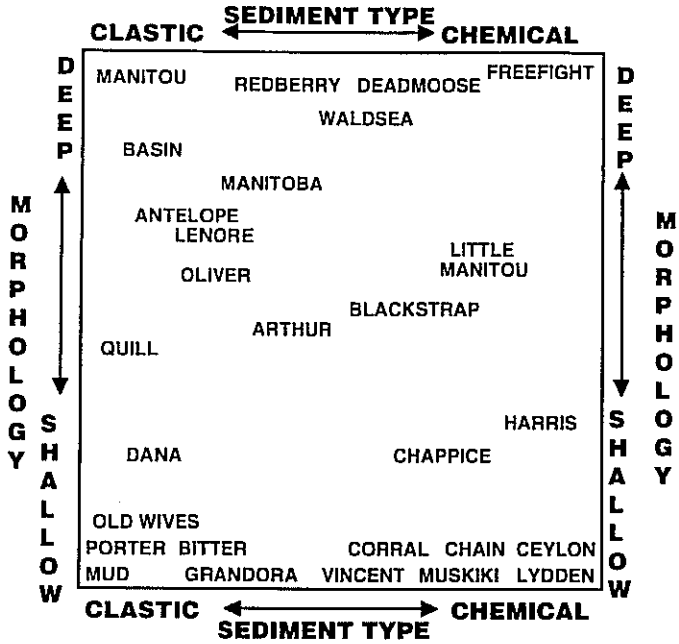

Figure 4. Schematic diagram showing the range of lacustrine settings in the northern Great Plains on the basis of basin morphology and modern sediment type. See Figure 1 for locations of representative lakes identified.

processes dominated by seasonal (or periodic) flooding and desiccation, influx of clastic debris by sheetflood and wind, precipitation of soluble and sparingly soluble salts, formation of detrital vegetation mats and microbialites, deflation, and sediment disruption by various cryogenic, biogenic, and chemical processes. In contrast, the deep-water basins are characterized by a suite of processes dominated by seasonal (or rhythmic) carbonate mineral precipitation and detrital sedimentation, formation of subaqueous salt cumulates by evaporative concentration and freeze-out precipitation, sulfate reduction and sulfide mineral precipitation, shoreline deposition and erosion, turbidity flow, and pelagic fallout.

Although overlap does occur, the sedimentological controls, the biological influences, and the diagenetic susceptibility of these four basic lake types differ dramatically. Therefore, the resulting sedimentary facies are (or should be) readily distinguished from one another in a stratigraphic succession as shown in Figure 5. How well this distinction can be made in the paleorecord of a given basin is a direct reflection of our level of understanding about each modern end-member type. Even though today the number of salt-dominated playas is small relative to the clastics-dominated basins, the former have received much more attention because they constitute the basis of a $\$40 \times 10^6$ yr^{-1} salt minerals industry in the Great Plains (Broughton, 1984). Thus, our knowledge about the processes and our ability to recognize and interpret the stratigraphic signals within the salt-dominated playa basins is high relative to other saline lake types in the region.

TABLE 1. DOMINANT PHYSICAL AND CHEMICAL PROCESSES AFFECTING SEDIMENTATION IN LAKES OF THE NORTHERN GREAT PLAINS*

Processes important in all the lakes
Influx of water, sediment, solutes from streams, groundwater, direct precipitation, sheetwash.
Evaporative concentration of water.

Processes important in deep-water, clastics-dominated lakes
Development of thermal stratification of water column.
Turbidity flow, interflow.
Flocculation of fine-grained material.
Cyclic and rhythmic sedimentation.
Shoreline erosion, deposition.
Delta sedimentation.
Aeolian sediment influx.

Processes important in deep-water, salt-dominated lakes
Development of meromixis.
Bio-mediated carbonate precipitation.
Evaporative carbonate precipitation.
Formation of subaqueous salt cumulates.
Solute concentration by formation of ice cover.
Freeze-out precipitation of salts.
Sulfate reductation, sulfide mineral precipitation.
Cyclic and rhythmic sedimentation.
Clay mineral authigenesis.

Processes important in shallow-water, clastics-dominated lakes
Cyclic flooding, desiccation.
Deposition, erosion by sheetflood flow.
Aeolian influx, deflation.
Intrasedimentary salt precipitation.
Formation of efflorescent crusts.
Formation of vegetation mats.
Formation of subsurface salt cements.
Pedogenesis.
Sediment disruption by freeze-thaw, bioturbation.

Processes important in shallow-water, salt-dominated lakes
Cyclic flooding, desiccation.
Wind set-up, wind-controlled localization of salt precipitation.
Precipitation of salts at air-water interface.
Formation of crystal rafts and aggregates.
Evaporative pumping. Formation of efflorescent crusts.
Formation of carbonate hardgrounds, crusts.
Formation of microbialites.
Development of meromixis.
Subaqueous cumulate and bottom salt precipitation.
Formation of salt spring deposits.
Formation of rounded accretionary salt grains.
Reworking and distribution of clastic salts.
Temperature-induced mineral transformations, phase changes.
Formation of salt cements.
Salt karsting.
Mud diapirism, reworking of fine-grained clastic material.

*Modified from Last and Schweyen, 1983.

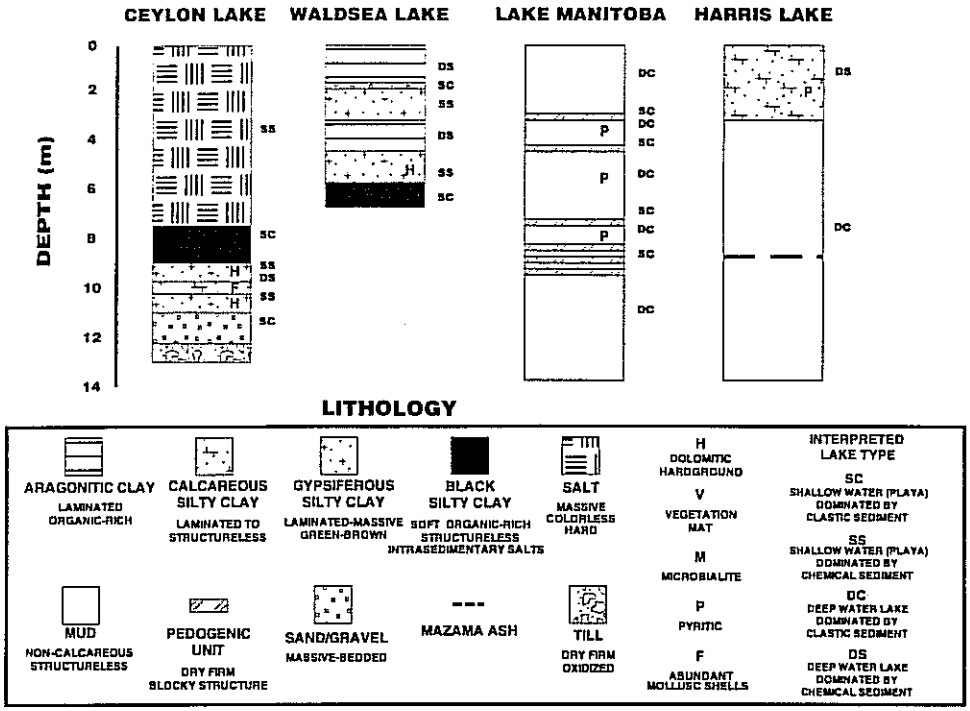

Figure 5. Generalized, composite vertical sequences from representative well-studied lakes in the northern Great Plains. Ceylon Lake from Last (1990); Waldsea Lake from Last and Schweyen (1985); Lake Manitoba from Teller and Last (1981); Harris Lake from Last and Sauchyn (1993).

Finally, despite the fact that playas and shallow salt lakes have been the most extensively studied saline terrestrial environments, not only in the Plains region of North America but also on a worldwide basis (Eugster and Kelts, 1983), it is commonly held that these types of basins provide a less-than-desirable record of paleoenvironmental conditions (e.g., Street-Perrott and Harrison, 1985; Hammer, 1986). Because playas in arid and semiarid regions undergo periodic and frequent subaerial exposure, the likelihood of significant post-depositional alteration of the sediment is great and the loss of record through erosion, non-deposition, and deflation is to be expected. Clearly the level of resolution that can be achieved in some deep-water, permanently stratified basins cannot usually be matched in the ephemeral playa environment. However, such is the nature of paleohydrological investigations in the Great Plains that: (a) most of the lakes are, indeed, shallow playa basins; and more importantly, (b) nearly all of the lakes in the region, both deep and shallow, for which we do have stratigraphic information have experienced shallow-water, playa phases at some point in their Quaternary history (Schweger and Hickman, 1989; Last and Slezak, 1988).

PROBLEMS AND PITFALLS

Mining industry activity

The playas and saline wetlands of the northern Great Plains serve a great variety of uses. Many studies have documented the importance of these saline terrestrial environments to surface runoff and flow stabilization, erosion control, waste assimilation, agriculture, and wildlife habitat (e.g., Waite, 1980, 1986; Adams, 1988; Richardson and Arndt, 1989). The economic significance of some playa 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 70 years. In the last two decades the dollar value of this industrial mineral produced from the lakes in western Canada has increased fivefold. 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 mines. Historically, production has occurred from 28 separate basins in the region, with 9 playas being mined today. There are more than 60 basins in Palliser's Triangle with proved commercial reserves of Na_2SO_4 greater than 100,000 tonnes (Slezak and Last, 1985). Magnesium salts are also a potential commercial 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, 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 and water level fluctuations through time, the mining of nearly 40 of the salt lakes, and the likelihood of expanded mining efforts in the near future, becomes a major concern for paleohydrological work in Palliser's Triangle.

Metiskow Lake example. An example of irretrievable loss of valuable paleoenvironmental data due to mining activities is that of Metiskow Lake, Alberta. The economic potential of this playa lake in eastern Alberta was first recognized by Cole (1926) who calculated a sodium sulfate reserve in the lake of about 5×10^6 tonnes. Metiskow is unusual in that its brine is dominated by bicarbonate ions, rather than sulfate. Subsequent drilling and bulk chemical analyses of the sediments in the lake by various companies during the 1960s confirmed that the 17-m-thick lacustrine salt sequence contained some 250,000 tonnes of sodium carbonate in addition to the large sodium sulfate reserve.

Before mining operations obliterated the stratigraphic record in the basin, Wallick and Krouse (1977) and Wallick (1981) were able to decipher the groundwater flow and likely water-rock chemical reactions that gave rise to this unusual deposit. These two studies, as important as they are in providing quantitative information on the source of the salts, merely serve to accentuate the tremendous potential of the paleoenvironmental record in Metiskow. The basin contained a thick sequence of alternating sodium carbonate salts, sodium and calcium sulfates, and detrital material; similar mineral assemblages have been used very effectively in other salt-lake sequences to reconstruct the details of paleohydrochemical conditions and changes (e.g., Eugster and Smith, 1965). The magnitude of this lost opportunity is further emphasized by the report of a single ^{14}C date of 10,250 yr B.P. (Wallick, 1981) from the base of the salt section, which indicates that Metiskow was one of the few lakes cored in the region to date that may have provided a complete record of Holocene and late Pleistocene environmental change.

Postdepositional changes

Numerous summary and overview papers have already stressed the susceptibility of salt-lake sediments, particularly evaporites, to post-depositional changes. As a generalization, the playa basins are more prone to post-depositional changes than perennial lakes because of their periodic desiccation and subaerial exposure. In the playa lakes of the northern Great Plains, three major types of diagenetic alteration have been documented: (1) saline mineral diagenesis, (2) salt dissolution and karsting, and (3) diapirism.

Mineral diagenesis. 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 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, dense, hypersaline surface brines percolate downward into porous and permeable 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).

Salt dissolution and karsting. 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 playa lake. The formation of deep karst chimneys and large dissolution pits is occurring today in numerous saline playa basins in Palliser's Triangle. 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, 1989b). In Lydden Lake, another salt playa located west of Saskatoon, Saskatchewan, solution pits up to 30 m wide and 3 m deep are present. In still other basins, the occurrence of buried mud "mounds", highly irregular salt thicknesses (Fig. 6), and abrupt compositional changes over short distances (Fig. 7) 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 playas because large vertical sections of the lacustrine sediment can be affected.

Mud diapirism. Diapirism, or the process of piercing an overlying geological unit by an underlying mobile core material, is a phenomenon commonly described in several modern and recent sedimentary environments. Mud diapirs, or mudlumps, are particularly abundant in birdfoot-type 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 playas 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 an instability brought about by the loading of relatively low density, water saturated lacustrine muds by a thick section of dense and nonpermeable salt. This instability causes the muds to flow upward through the salt to the lake surface. 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.

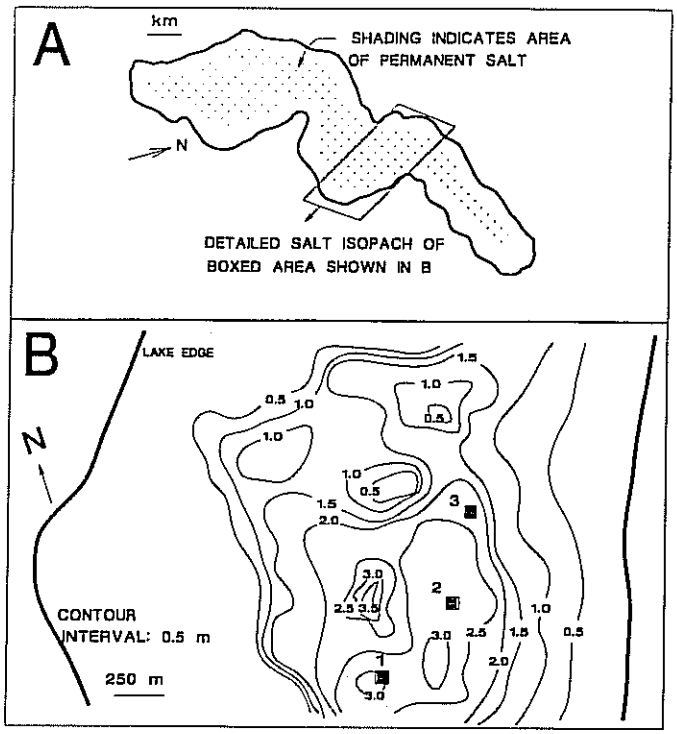

Figure 6. Isopach map of the salt in an unnamed playa basin near Verlo, Saskatchewan, in Palliser's Triangle showing dramatic fluctuations in thickness due to active and paleo-salt karst development. The isopach map in B was constructed on the basis of a grid of auger hole data at approximately 250 m spacing. The rectangles numbered 1, 2, and 3 in B are the locations of cores shown in Figure 7.

Incomplete understanding of sedimentary and geochemical processes

As discussed in the previous section, a complete understanding of the sedimentary processes operating in the entire spectrum of salt lakes of the Great Plains is still far off. Because virtually all geological interpretations of the stratigraphic records in these basins depend on a knowledge of the modern environments and modern sedimentary processes, it is important that these deductions be made with great care. Following are several of the more important, but still unresolved "conceptual" problems that continue to obscure the paleohydrological interpretation of the sediment record in these playas.

Significance of fine-grained clastic units. In a sedimentary basin strongly influenced by physical factors such as wind-generated waves, currents, and river inflow, the distribution and character of the accumulating sedimentary material is controlled to a major degree by the level of energy at the depositional site. Thus, coarse-grained sediments (sands, gravels) are generally interpreted to have been deposited under relatively shallow water, high energy conditions (e.g., a beach or delta), whereas very fine grained sediment (clay-sized material) requires settling through a deep, essentially motionless water mass. As stressed by Sly (1978), Håkanson and Jansson (1983), Rust and Nanson (1989), and Teller and Last (1990), many other factors can interfere with this simple grain size–water depth–energy relationship, including flocculation of fine-grained material, formation of pedogenic aggregates within the watershed, basin morphology, weathering and erosion characteristics of the watershed, and vegetation cover.

Thin beds and laminae of fine-grained siliciclastic material commonly occur interbedded with evaporites in the stratigraphic records of the salt-dominated playas of the Great Plains. Their paleohydrological significance and sedimentological interpretation are particularly problematic. They may represent periods of relatively deep and fresh water conditions in which increased runoff from the surrounding watershed (the result of 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 induced by a more arid climate. The fine clastics may also have been deposited during periods of increased aeolian activity associated with increased aridity, or carried into the basin as sand-sized pedogenic aggregates by sheet floods. Obviously, each of these possible interpretations represents significantly different hydrological conditions in the basin.

Significance of carbonate mineralogy. Carbonate minerals are among the most common and also the most useful inorganic constituents of lakes 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; Dean and Fouch, 1983; Behbehani et al., 1986). The application of other carbonate mineral species, such as dolomite, magnesite, and siderite, which commonly occur in salt lake sediments, has been less widespread but does offer considerable potential (e.g., Rosen et al., 1988).

Based mainly on observational data provided by Müller et al. (1972), conventional wisdom holds that the mineral sequence of: low-Mg calcite → high-Mg calcite → aragonite → dolomite → magnesite/huntite reflects increasing Mg/Ca ionic ratios in the precipitating solution (Fig. 8) and, most 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 (e.g., Müller and Wagner, 1978; Last, 1982; Last and Schweyen, 1985; Allen and Collinson, 1986; Vance et al., 1993). Unfortunately, there are many possible sources of error associated with this cookbook approach. In order to be used the carbonates must be of primary origin and must be in situ precipitates. However, it is commonly difficult to distinguish primary endogenic carbonates from either primary or secondary diagenetic precipitates. Talbot and Kelts (1986, 1990) and Talbot (1990) discuss the complexity of the interpretations if any of the carbonate components are of diagenetic origin. Furthermore, other factors besides, or in addition to, Mg/Ca and salinity have a

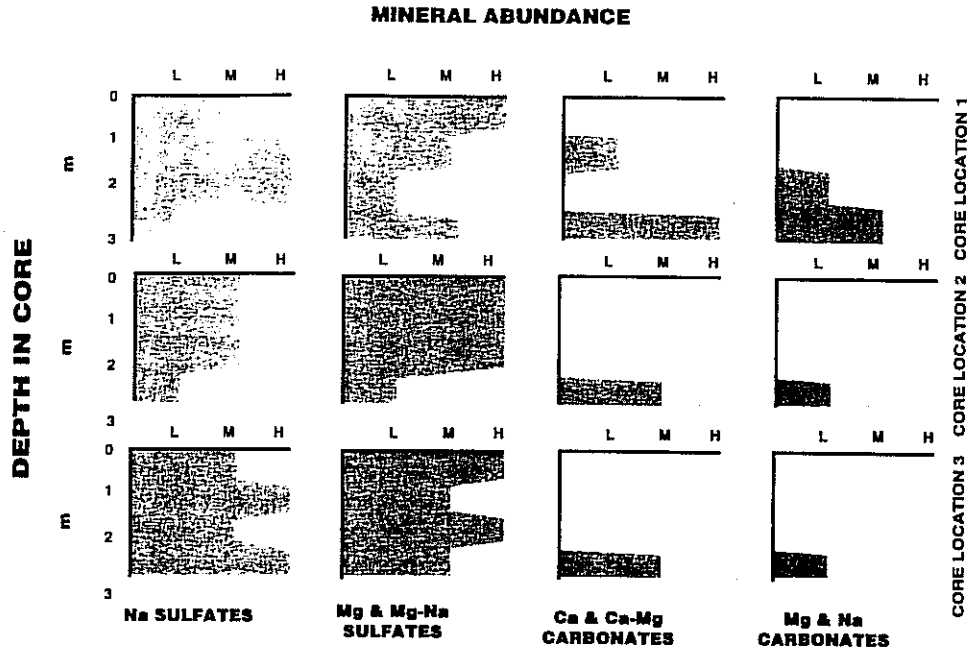

Figure 7. Summary of fluctuations in relative abundance of the major evaporite and endogenic/authigenic carbonate mineralogy in cores from the un-named lake shown in Figure 6. L, M, and H stand for low, medium, and high relative abundance. Diagram is generalized from semiquantitative X-ray diffraction analysis data of samples taken at appproximately 20 cm spacing in the cores. The core locations are about 500 m apart.

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 factors controlling the formation of dolomite (Morrow, 1982; Baker and Kastner, 1981; Kastner, 1986). 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 (Müller and Wagner, 1978).

Importance of saline mineral metastability. The two fundamental assumptions that allow sedimentologists to deduce the composition of a brine from the mineral record preserved in the lake 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 already been mentioned. If the saline playa 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, indeed, a reasonable reflection of the brine composition at the point of precipitation. Unfortunately, this view of a playa or any 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 thermally or chemically stratified water column greatly increases the likelihood of mineral alteration even before being incorporated into the sediment record. Secondly, this simple view does not take into account metastability of the salts. The

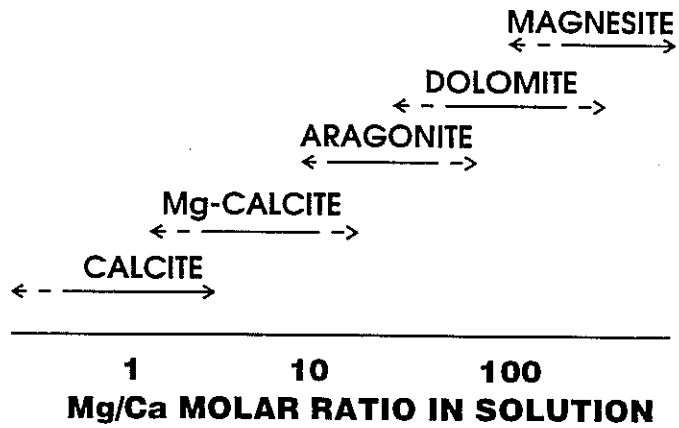

Figure 8. Summary of commonly cited ranges of Mg/Ca ratios in carbonate-precipitating solutions relative to the stable Ca-Mg carbonate mineral.

formation of metastable phases is a common phenomenon in low-temperature geochemistry, particularly in late-stage evaporation of brines (Krauskopf, 1979; Holser, 1979; 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.

FUTURE PALEOHYDROLOGICAL RESEARCH DIRECTIONS

Where does playa lake paleohydrology in the northern Great Plains go from here? The multidisciplinary nature of paleoenvironmental work being undertaken on lakes today makes it difficult to predict future development of the science. However, within the geographic and topical constraints of this paper, the axiom "more, better, faster" does apply. I do not think that we should be too cynical about attempting to "do" paleohydrology without first knowing everything about the modern lakes. Sedimentologists have long accepted the fact that much of what is known about some depositional settings is based not on the modern environments but rather on the preserved ancient record. A high priority must, however, be placed on overcoming the most crucial deficiencies in present sedimentological and geochemical concepts/knowledge as summarized in the previous section: quite simply, *more* modern sedimentological data must be collected from the lakes, especially from the clastics-dominated playas. At the same time, however, many *more* salt lake basins have to be cored, with particular emphasis in areas where there is little data today (i.e., most of western and southwestern Saskatchewan and eastern/southern Alberta) and in strategically significant areas, such as near present-day climatic/vegetational boundaries.

The quality of sedimentological/geochemical data has to be improved. This is particularly important in the collection of mineralogical data; for example, it is much more useful from a paleochemical perspective to know that the stratigraphic unit contains bloedite than merely that it contains traces of magnesium. Our understanding of the evolution of salt lakes in the western interior of Canada may be quite different today had the large amount of data collected in conjunction with industrial development of the Metiskow Lake sodium carbonate-sulfate deposit been placed in a mineralogical framework, rather than a bulk chemistry context.

Finally, there has been no better time than now to begin this new wave of paleohydrological/paleoenvironmental investigation. Regional climatic changes, drought, salinization, and sustainable development have all become "buzz words" of the 1990s. Local, provincial, and federal governments as well as international scientific bodies have rapidly become aware of the need for documentation of past environmental changes in order to properly evaluate present-day trends and fluctuations.

In many ways the study of lake sediments in most of western Canada has remained relatively simple and traditional, more or less unchanged from the 1960s and 70s. The next decade will likely bring a great increase in sophistication of methodology as well as technology. Although the general evolutionary histories of several playa basins in the region are reasonably well known, because of recent technological advances, the potential for deducing much more explicit paleohydrological information from the sediment records is still high. Today it is possible to analyze, rapidly and with high confidence, the crystal size distribution and crystal-shape characteristics of the endogenic and authigenic material in a single submillimeter lamina of sediment core. It is also now possible to determine the bulk chemical composition, the trace-element content, the stable-isotopic composition, and even the zoning characteristics of single micron-sized crystals from one of these laminae. Such detailed investigations, unthinkable just a decade ago, would almost certainly significantly advance the understanding of playa sedimentology, evolution of mineral-brine systems through time, and paleoclimatic/hydrologic fluctuations in this region. The recent advances in geochronology and sample acquisition discussed by Smol (1989) have yet to be applied to playa lakes of the region; these also will help to revolutionize the paleohydrological efforts in Palliser's Triangle.

SUMMARY AND CONCLUSIONS

Palliser's Triangle encompasses a large portion of the northern Great Plains of Canada. It is a 200,000-km^2, semiarid to arid region in which geology, climate, and hydrology have interacted to form many saline lakes. Although there is a wide spectrum of basin morphologies, sedimentary characteristics, and water compositions and concentrations, the modern lakes can generally be pigeon-holed into one of several basic types: (1) clastics-dominated playa; (2) salt-dominated playa; (3) deep-water, perennial lake dominated by clastic sediment; and (4) deep-water, perennial lake dominated by chemically precipitated sediment. The playa basins vastly outnumber the perennial lakes in the region. The level of understanding of the physical, chemical, and biological processes operating in these lakes, and the resulting sedimentary facies in the basins, is incomplete and uneven. Salt-dominated playas have received most of the past sedimentological and paleohydrological study.

Three major problems and pitfalls can be identified in using the stratigraphic records of playas to help interpret the paleohydrology of the basins and hydrological changes that occurred in Palliser's Triangle. (1) The playas of the region support an active and growing salt minerals industry. Unfortunately, often the lakes that are most attractive for mining are also the ones that contain the best potential for paleohydrological research. (2) A variety of post-depositional changes can significantly alter the composition and nature of the preserved stratigraphic records in these playa lakes, thereby obscuring the paleorecord. (3) Our incomplete understanding of several basic sedimentary processes and genesis of some commonly occur-

ring stratigraphic units in these basins is limiting the precision of our interpretations.

There are no conclusions to this paper, only several words of encouragement and caution. The scientific study of playa lakes in the northern Great Plains is ripe for an explosive expansion. The paleoenvironmental problems are difficult but not intractable. The tools are available. The potential payoffs are big. However, we must guard against resorting to excessive use of comparison and analogue study. The sedimentary realm of the playa environments of the Great Plains is, in many ways, unique. What is fashionable in Australia or what "works" in southwestern United States, for example, may not necessarily be applicable in the Great Plains.

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REFERENCES CITED

Adams, G. D., 1988, Wetlands of the Prairies of Canada, *in* National Wetlands Working Group, Canada Committee on Ecological Land Classification. Wetland of Canada: Ecological Land Classification Series, no. 24, p. 155–198.

Allen, P. A., and Collinson, J. D., 1986, Lakes, *in* Reading, H. G., ed., Sedimentary environments and facies (second edition): Oxford, Blackwell Scientific Publications, p. 63–94.

Baker, P. A., and Kastner, M., 1981, Constraints on the formation of sedimentary dolomite: Science, v. 213, p. 214–216.

Behbehani, A., and 6 others, 1986, Sediments and sedimentary history of Lake Attersee (Salzkammergut, Austria): Hydrobiologia, v. 143, p. 233–246.

Bell, J. S., 1875, Report on the country between Red River and the South Saskatchewan: Geological Survey of Canada Report of Progress 1873–74, p. 66–93.

Broughton, P. L., 1984, Sodium sulphate deposits of western Canada, in Guillet, G. R., and Martin, W., eds., The geology of industrial minerals in Canada: Canadian Institute of Mining and Metallurgy Special Volume 29, p. 195–20.

Brown, I. C., ed., 1967, Groundwater in Canada: Geological Survey of Canada Economic Geology Report 24, 228 p.

Cole, L. H., 1926, Sodium sulfate of western Canada. Occurrence, uses and technology: Canadian Department of Mines Publication 646, 155 p.

Coleman, J. M., and Prior, D. B., 1980, Deltaic sand bodies: American Association of Petroleum Geologists Continuing Education Course Note Series, no. 15, 171 p.

CNC/IHD (Canadian National Committee for the International Hydrologic Decade), 1978, Hydrologic atlas of Canada: Ottawa, Fisheries and Environment Canada, 75 p.

Dean, W. E., 1981, Carbonate minerals and organic matter in sediments of modern north temperate hard-water lakes, *in* Ethridge, F. G., and Flores, R. M., eds., Recent and ancient nonmarine depositional environments: Models for exploration: Society of Economic Paleontologists and Mineralogists Special Publication 31, p. 213–231.

Dean, W. E., and Fouch, T. D., 1983, Chapter 2: Lacustrine, *in* Scholle, P. A., Bebout, D. G., and Moore, C. H., eds., Carbonate depositional environments: American Association Petroleum Geologists Memoir 33, p. 98–130.

Drever, J. I., 1988, The geochemistry of natural waters (second edition): Englewood Cliffs, New Jersey, Prentice Hall, 437 p.

Eugster, H. P., and Hardie, L. A., 1978, Saline lakes, *in* Lerman, A., ed., Lakes: Chemistry, geology, physics: New York, Springer-Verlag, p. 237–293.

Eugster, H. P., and Kelts, K., 1983, Lacustrine chemical sediments, *in* Goudie, A. S., and Pye, K., eds., Chemical sediments and geomorphology: London, Academic Press, p. 321–368.

Eugster, H. P., and Smith, G. I., 1965, Mineral equilibria in the Searles Lake evaporites, California: Journal of Petrology, v. 6, p. 473–522.

Freeze, R. A., 1969, Regional groundwater flow—Old Wives Lake drainage basin, Saskatchewan: Department of Energy Mines and Resources Inland Waters Branch Scientific Series 5, 245 p.

Frey, D. G., 1988, What is paleolimnology?: Journal of Paleolimnology, v. 1, p. 5–8.

Gorham, E., Dean, W. E., and Sanger, J. E., 1983, The chemical composition of lakes in the north-central United States: Limnology and Oceanography, v. 28, p. 287–301.

Govett, G.J.S., 1958, Sodium sulfate deposits in Alberta: Alberta Research Council Preliminary Report 58-5, 34 p.

Håkanson, L., and Jansson, M., 1983, Principles of lake sedimentology: New York, Springer-Verlag, 316 p.

Hammer, U. T., 1990, The effects of climate change on the salinity, water levels and biota of Canadian prairie saline lakes: Verhandlung des Internationalen Vereins der Limnologie, v. 24, p. 321–326.

Hammer, U. T., 1986, Saline lake ecosystems of the World: Dordrecht, The Netherlands, Dr. W. Junk Publications, 616 p.

Hammer, U. T., 1978, The saline lakes of Saskatchewan, III. Chemical characterization: International Revue der Gesamten Hydrobiologie, v. 63, p. 311–335.

Hardie, L. A., Smoot, J. P., and Eugster, H. P., 1978, Saline lakes and their deposits: A sedimentological approach, *in* Matter, A., and Tucker, M. E., eds., Modern and ancient lake sediments: International Association of Sedimentologists Special Publication Number 2, p. 7–42.

Holser, W. T., 1979, Mineralogy of evaporites, *in* Burns, R. G., ed., Marine minerals: Mineralogical Society of America Short Course Notes, v. 6, p. 211–294.

Kastner, M., 1986, New insights into origin of dolomite: 12th International Sedimentologists Congress, Abstracts Volume, p. 158.

Kelts, K., and Hsü, K. J., 1978, Freshwater carbonate sedimentation, in Lerman, A., ed., Lakes: Chemistry, geology, physics: New York, Springer-Verlag, p. 295–324.

Kendall, A. C., 1984, Evaporites, *in* Walker, R. G., ed., Facies models: Geoscience Canada Reprint Series 1, p. 259–296.

Krauskopf, K. B., 1979, Introduction to Geochemistry (second edition): New York, McGraw-Hill Book Company, 615 p.

Lambert, S., 1989, Hydrogeochemistry of saline lakes in the northern Interior Plains of western Canada and northern United States [B.Sc. thesis]: Winnipeg, University of Manitoba, 162 p.

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

Last, W. M., 1984, Sedimentology of playa lakes of the northern Great Plains: Canadian Journal of Earth Science, v. 21, p. 107–125.

Last, W. M., 1988, Salt lakes of western Canada: A spatial and temporal geochemical perspective, *in* Nicholaichuk, W., and Steppuhn, H., eds., Proceedings, Symposium on Water Management Affecting the Wet-to-Dry Transition: Saskatoon, Saskatchewan, Water Studies Institute, p. 99–113.

Last, W. M., 1989a, Continental brines and evaporites of the northern Great Plains of Canada: Sedimentary Geology, v. 64, p. 207–221.

Last, W. M., 1989b, Sedimentology of a saline playa in the northern Great Plains, Canada: Sedimentology, v. 36, p. 109–123.

Last, W. M., 1990, Paleochemistry and paleohydrology of Ceylon Lake, a salt-dominated playa basin in the northern Great Plains, Canada: Journal of Paleolimnology, v. 4, p. 219–238.

Last, W. M., and Sauchyn, D. J., 1993, Mineralogy and lithostratigraphy of Harris Lake, southwestern Saskatchewan, Canada: Journal of Paleolimnology, v. 9, p. 23–39.

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

Last, W. M., and Schweyen, T. H., 1985, Late Holocene history of Waldsea Lake, Saskatchewan, Canada: Quaternary Research, v. 24, p. 219–234.

Last, W. M., and Slezak, L. A., 1987, Sodium sulfate deposits of western Canada, *in* Gilboy, C. F., and Vigrass, L. W., eds., Economic minerals of Saskatchewan: Saskatchewan Geological Society Special Publication 8, p. 197–205.

Lennox, D. H., Maathuis, H., and Pederson, D., 1988, Region 1, Western glaciated plains, *in* Back, W., Rosenshein, J. S., and Seaber, P. R., eds., Hydrogeology: The Geology of North America, v. O-2, p. 115–128.

Lieffers, V. J., and Shay, J. M., 1983, Ephemeral saline lakes in the Canadian prairies—Their classification and management for emergent macrophyte growth: Hydrobiologia, v. 105, p. 85–94.

Löffler, H., ed., 1987, Paleolimnology IV: Hydrobiologia, v. 143, p. 1–431.

Meriläinen, J., Huttunen, P., and Battarbee, R. W., eds., 1983, Paleolimnology: Hydrobiologia, v. 103, p. 1–318.

Morrow, D. W., 1982, Diagenesis, 1. Dolomite—Part 1: The chemistry of dolomitization and dolomite precipitation: Geoscience Canada, v. 9, p. 95–107.

Müller, G., and Wagner, F., 1978, Holocene carbonate evolution in Lake Balaton (Hungary), a response to climate and impact of man, in Matter, A., and Tucker, M. E., eds., Modern and ancient lake sediments: International Association of Sedimentologists Special Publication 2, p. 55–80.

Müller, G., Irion, G., and Förstner, U., 1972, Formation and diagenesis of inorganic Ca-Mg-carbonates in the lacustrine environment: Naturwissenschaften, v. 59, p. 158–164.

Palliser, J., 1862, Journals, detailed reports and observations relative to the exploration by Captain Palliser of a portion of British North America; Exploration of British North America: Report presented to both houses of Parliament, London, 325 p.

Richardson, J. L., and Arndt, J. L., 1989, What use prairie potholes?: Journal of Soil and Water Conservation, v. 44, p. 196–198.

Rawson, D. S., and Moore, G. E., 1944, The saline lakes of Saskatchewan: Canadian Journal of Research (Series D), v. 22, p. 141–201.

Rosen, M. R., Miser, D. E., and Warren, J. K., 1988, Sedimentology, mineralogy and isotopic analysis of Pellet Lake, Coorong Region, South Australia: Sedimentology, v. 35, p. 105–122.

Rozkowska, A. D., and Roskowski, A., 1969, Seasonal changes of slough and lake water chemistry in southern Saskatchewan, Canada: Journal of Hydrology, v. 7, p. 1–13.

Rueffel, P. G., 1968, Development of the largest sodium sulfate deposit in Canada: Canadian Mining and Metallurgical Bulletin, v. 61, p. 1217–1228.

Rust, B. R., and Nanson, G. C., 1989, Bedload transport of mud as pedogenic aggregates in modern and ancient rivers: Sedimentology, v. 36, p. 291–306.

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

Sahinen, U. M., 1948, Preliminary report on sodium sulfate in Montana: Montana School of Mines Bureau of Mines and Geology Report, 9 p.

Schweger, C. E., and Hickman, M., 1989, Holocene paleohydrology of central Alberta: Testing the general-circulation-model climate simulations: Canadian Journal of Earth Science, v. 26, p. 1826–1833.

Slezak, L. A., and Last, W. M., 1985, Geology of sodium sulfate deposits of the northern Great Plains, *in* Glaser, J. D., and Edwards, J., eds., Twentieth Forum on the Geology of Industrial Minerals: Maryland Geological Survey Special Publication 2, p. 105–115.

Sly, P. G., 1978, Sedimentary processes in lakes, *in* Lerman, A., ed., Lakes: Chemistry, geology, physics: New York, Springer-Verlag, p. 65–90.

Smol, J. P., 1989, Paleolimnology—Recent advances and future challenges, *in* de Bernardi, R., Giussani, G., and Barbanti, L., eds., Scientific perspectives in theoretical and applied limnology: Memorie dell'Instituto Italiano di Idrobiologia, v. 47, p. 247–272.

Smoot, J. P., and Lowenstein, T. K., 1991, Depositional environments of nonmarine evaporites, *in* Melvin, J. L., ed., Evaporites, petroleum and mineral resources: New York, Elsevier, Developments in Sedimentology 50, p. 189–347.

Sonnenfeld, P., 1984, Brines and evaporites: New York, Academic Press, 613 p.

Street-Perrott, F. A., and Harrison, S. P., 1985, Lake levels and climate reconstruction, *in* Hecht, A. D., ed., Paleoclimate analysis and modeling: New York, John Wiley and Sons, p. 291–340.

Talbot, M. R., 1990, A review of the palaeohydrological interpretation of carbon and oxygen ratios in primary lacustrine carbonates: Chemical Geology (Isotope Geoscience Section), v. 80, p. 261–279.

Talbot, M. R., and Kelts, K., 1986, Primary and diagenetic carbonates in the anoxic sediments of Lake Bosumtwi, Ghana: Geology, v. 14, p. 912–916.

Talbot, M. R., and Kelts, K., 1990, Paleolimnological signatures from carbon and oxygen isotopic ratios in carbonates from organic carbon-rich lacustrine sediments, *in* Katz, B. J., ed., Lacustrine basin exploration—Case studies and modern analogs: American Association of Petroleum Geologists Memoir 50, p. 99–109.

Teller, J. T., and Last, W. M., 1981, Late Quaternary history of Lake Manitoba, Canada: Quaternary Research, v. 16, p. 97–116.

Teller, J. T., and Last, W. M., 1990, Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 76, p. 215–240.

Tomkins, R. V., 1954, Magnesium in Saskatchewan: Saskatchewan Department of Mineral Resources Report 11, 23 p.

Vance, R. E., Clague, J. J., Mathewes, R. W., 1993, Holocene paleohydrology of a hypersaline lake in southeastern Alberta: Journal of Paleolimnology, v. 8, p. 103–120.

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

Wallick, E. I., and Krouse, H. R., 1977, Sulfur isotope geochemistry of a groundwater-generated Na_2SO_4/Na_2CO_3 deposit and the associated drainage basin of Horseshoe Lake, Metiskow, east-central Alberta, Canada: 2nd International Symposium on Water-rock Interaction, Strasbourg, France, p. 1156–1164.

Waite, D. T., ed., 1980, Prairie surface waters: Problems and solutions: Canadian Plains Proceedings, v. 7, 102 p.

Waite, D. T., ed., 1986, Evaluating saline waters in a plains environment: Canadian Plains Proceedings, v. 17, 107 p.

Warren, J. K., 1989, Evaporite sedimentology: Importance in hydrocarbon accumulation: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 285 p.

Winter, T. C., 1977, Classification of the hydrologic settings of lakes in the north central United States: Water Resources Research, v. 13, p. 753–767.

Witkind, I. J., 1952, The localization of sodium sulfate deposits in northeastern Montana and northwestern North Dakota: American Journal of Science, v. 250, p. 667–676.

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