Sedimentology of playa lakes of the northern Great Plains

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The semi-arid plains of western Canada and northern United States contain a large number of saline and hypersaline lakes, with many of the shallow lakes exhibiting playa characteristics. For over 60 years a number of these playas have provided a source of valuable industrial minerals. The present study deals with the modern sediments and sedimentary processes operating in selected playa basins located throughout the northern Great Plains region.

The playas generally occupy small, closed basins commonly having an elongate, riverine shape. Most of the brines are dominated by sodium, magnesium, and sulfate ions; however, examples of lakes rich in chloride and bicarbonate ions are also present. Significant variation in the brine chemistry can exist on a seasonal as well as a diurnal basis. The modern sediments of the playas consist of: (1) very soluble salts of mainly sodium and magnesium sulfates and carbonates; (2) sparingly soluble precipitates, including calcite, protodolomite, gypsum, and mixed layer clays; (3) detrital minerals consisting dominantly of quartz, carbonates, feldspars, and clays; and (4) organic matter.

Much of the physical and mineralogical character of the playas is due to processes that are largely of a chemical nature and are associated with either evaporative concentration of the brines or groundwater discharge. The most significant processes include: cyclic flooding and desiccation of the playa surface, formation of salt crusts, efflorescent crusts, spring deposits, and intrasedimentary salts, formation of solution pits and chimneys, wind displacement of brines, and periodic detrital sedimentation by sheet flow and wind. These processes combine to create a very dynamic modern depositional environment. The establishment and prolonged maintenance of delicate physical and chemical equilibria have allowed the deposition of over 40 m of salt in some basins.

Les plaines semi-arides de l'ouest du Canada et du nord des États-Unis renferment un grand nombre de lacs salés et hypersalés, et plusieurs lacs peu profonds exhibent les caractéristiques des playas. Il y a plus de 60 années que certaines de ces playas constituent une source d'approvisionnement de minéraux industriels. Notre étude porte sur les sédiments récents et sur les processus sédimentaires qui agissent dans les bassins de playas représentatifs de toute la région des Grandes Plaines du nord.

Les playas occupent généralement des bassins fermés d'étendue restreinte présentant un contour riverain allongé. Les ions sodium, magnésium et sulfate prédominent dans les saumures, cependant, on observe que certains lacs sont riches en ions chlorure et bicarbonate. Des variations significatives de la composition chimique des lacs se manifestent selon les saisons et le cycle diurne. Les sédiments récents des playas sont composés: (1) de sels très solubles principalement de sulfates et carbonates de magnésium, (2) de précipités sporadiques de sels solubles comme la calcite, la protodolomite, le gypse et les minéraux argileux interstratifiés, (3) de minéraux détritiques dont les principaux sont le quartz, les carbonates, les feldspaths et les argiles et (4) de matière organique.

Les caractéristiques physiques et minéralogiques des playas sont largement influencées par les processus chimiques et sont reliées soit avec la concentration en évaporites des saumures ou avec le débit des eaux souterraines. Les processus les plus importants sont: les inondations et les périodes de dessiccation cycliques des surfaces des playas, les incrustations de sels, les incrustations efflorescentes, les dépôts de source et de sels intrasédimentaires, la formation de cupules et de cheminées de dissolution, le mouvement des saumures dû au vent et la sédimentation périodique de matériaux détritiques par écoulement laminaire ou d'origine éolienne. Ces processus se combinent pour créer un environnement très dynamique d'accumulation de sédiments récents. L'instauration et le maintien prolongé des conditions d'équilibre physique et chimique ont favorisé l'accumulation de plus de 40 m de sel dans certains bassins.

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Introduction

The Great Plains region of western Canada and northern United States contains thousands of saline lakes ranging in size from small prairie "potholes" (less than 1 km^2) to some of the largest bodies of inland salt water in North America (greater than 300 km^2). Many of the shallow lakes exhibit playa[1] characteristics, filling with brine during the spring and early summer and usually drying completely by late summer. The purposes of this paper are to present the results of reconnaissance geological field and laboratory work on these playas and to describe the contemporary sedimentologic environment. The paper is divided into three main sections. First, the regional climatic, hydrologic, and geologic setting is reviewed. Next, the character of the playas and the near-surface sediment is described. Finally, the important physical and chemical processes affecting the sediments in these basins are summarized.

[1]The term "playa," as used in this report, refers to the intermittently flooded low area of a basin (Reeves 1978) and does not have any more precise geomorphic, hydrologic, or climatic implications. The terms "salt lake" and "saline lake" refer to any standing body of water with salinity greater than 5000 mg/L.

Regional setting

Area and climate

The playa lakes discussed in this paper are found in the Great Plains physiographic province of North America. This region is characterized by hummocky to gently rolling topography interspersed with numerous deep, often terraced, valleys that have been cut by glacial meltwater. The Missouri Coteau, a major topographic feature of the region, is a distinct 50–100 km wide band of knob and kettle topography that extends for over 1200 km through this area from central South Dakota northwestward into central Saskatchewan. In general,

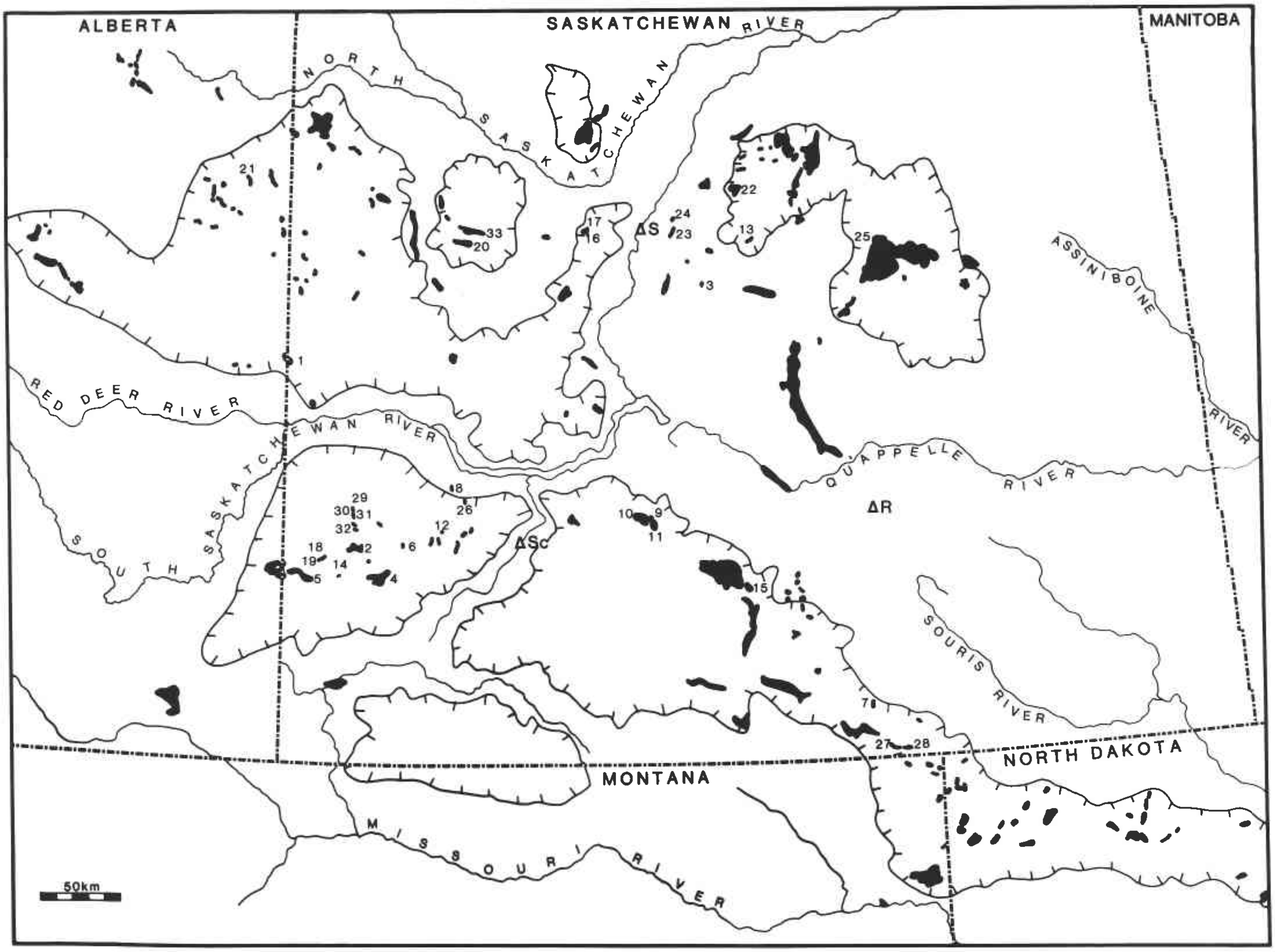

FIG. 1. Map of the northern Great Plains showing saline and hypersaline lakes (shaded) and areas of internal drainage (hash marks). The numbers refer to approximate locations of the playas listed in Table 1. R = Regina; SC = Swift Current; S = Saskatoon. Compiled, in part, from Grossman (1949), Tomkins (1953), Cole (1926), and Hammer (1978).

the playa basins studied are surrounded by agricultural land with ranching and grazing dominant in the west and grain farming most common in the south and central parts of the region.

The northern Great Plains experience a cold continental, semi-arid climate. Mean daily temperature during January over most of the region is about −17°C; during July it is 18°C. One of the most important climatic factors influencing the playa lakes of this region is the high evaporation/precipitation ratio. Annual precipitation averages about 30 cm, whereas more than 125 cm of water can be lost per year through evaporation from open water bodies (CNC/IHD 1978; McKay and Stichling 1961).

Hydrology and geology

Large areas of the northern Great Plains are characterized by internal drainage (Fig. 1). Because of its lack of integrated drainage, the Missouri Coteau contains many closed basins. Large areas of internal drainage also exist east of Saskatoon and west of Swift Current. In total, an area of over 160 000 km^2 or nearly 45% of southern Saskatchewan and 30% of North Dakota is characterized by interior drainage.

The rest of the northern Great Plains is drained in two directions by two large river systems. The Saskatchewan system originates in western Alberta and, together with the Qu'Appelle−Assiniboine basin, drains southern Saskatchewan to the east and, ultimately, flows north into Hudson Bay. Runoff in the Dakotas, Montana, and parts of southern Saskatchewan and Alberta is directed south into the Missouri River system and the Gulf of Mexico.

The region is underlain by nearly horizontal Phanerozoic sedimentary rocks of thicknesses up to 5000 m. The Paleozoic section consists mainly of a series of stacked carbonate−evaporite cycles, whereas the overlying Mesozoic and Cenozoic bedrock is dominantly a sand−shale sequence. Dissolution of the highly soluble Paleozoic evaporites by groundwater has modified the relatively simple structural relationships of the flat-lying formations and has created collapse structures over much of the area (Christiansen 1967*a*, 1971). Grossman (1968) maintains that this evaporite dissolution has provided a source of ions for the many salt lakes of the region.

The bedrock surface has also been strongly modified by preglacial erosion (Whitaker and Pearson 1972). By the start of the Quaternary Period a mature, dendritic drainage pattern had been established over much of the northern Great Plains (Stalker 1961; Christiansen 1967*b*). In general, this ancestral

TABLE 1. General description of selected playas of the northern Great Plains

Lake	Map No.[b]	Maximum area (km^2)	Maximum water depth[c] (cm)	Dominant sediment type	Dominant ions
Alsask[a]	1	2.2	50	Mixed clastic–chemical	$Na-SO_4-Cl$
Bad	2	12.5	75	Clastic	$Na-SO_4$
Berry	3	3.7	20	Mixed clastic–chemical	$Na, Mg-SO_4$
Bigstick	4	11.1	80	Clastic	$Na, Mg-SO_4$
Bitter	5	16.9	40	Mixed clastic–chemical	$Mg-SO_4, Cl$
Boot	6	0.6	20	Chemical	$Na-SO_4$
Ceylon	7	2.9	40	Chemical	$Na, Mg-SO_4$
Chain	8	2.1	50	Chemical	$Na-SO_4$
Chaplin complex[a]					
Chaplin east	9	12.1	25	Mixed clastic–chemical	$Na-SO_4$
Chaplin west	10	19.2	100	Clastic	$Na-SO_4$
Chaplin south	11	28.8	125	Clastic	$Na-SO_4$
Corral	12	0.6	20	Chemical	$Na-SO_4$
Dana	13	2.2	30	Mixed clastic–chemical	$Na, Mg-SO_4$
Freefight	14	2.8	80	Mixed clastic–chemical	$Na-SO_4, Cl$
Frederick[a]	15	3.3	30	Mixed clastic–chemical	$Na-SO_4$
Grandora complex					
Grandora south	16	0.6	10	Mixed clastic–chemical	$Na-SO_4$
Grandora north	17	0.5	20	Clastic	$Na-SO_4$
Ingebright complex[a]					
Ingebright north	18	0.6	10	Mixed clastic–chemical	$Na-SO_4$
Ingebright south	19	2.8	100	Mixed clastic–chemical	$Na-SO_4$
Lydden	20	1.6	40	Chemical	$Na, Mg-SO_4$
Metiskow[a]	21	10.6	100	Mixed clastic–chemical	$Na-SO_4, HCO_3$
Muskiki	22	16.7	60	Mixed clastic–chemical	$Mg, Na-SO_4$
Patience[a]	23	5.6	160	Clastic	$Na-Cl$
Porter	24	1.8	80	Clastic	$Na-SO_4$
Quill (Big Quill)	25	307	195	Clastic	$Mg, Na-SO_4$
Snakehole[a]	26	12.8	100	Mixed clastic–chemical	$Na-SO_4$
Sybouts complex[a]					
Sybouts west	27	6.41	150	Clastic	$Na-SO_4$
Sybouts east	28	4.36	20	Mixed clastic–chemical	$Na-SO_4$
Verlo complex					
Verlo No. 1	29	0.8	20	Mixed clastic–chemical	$Na-SO_4$
Verlo No. 2	30	1.8	60	Mixed clastic–chemical	$Na-SO_4$
Verlo No. 3[a]	31	1.5	40	Mixed clastic–chemical	$Na-SO_4$
Vincent	32	2.8	50	Chemical	$Na-SO_4$
Whiteshore[a]	33	22.9	100	Mixed clastic–chemical	$Na-SO_4$

NOTE: Lakes in italics received the most detailed sediment sampling and analyses.
[a]Indicates that the lake has undergone significant modification because of commercial salt extraction.
[b]Numbers refer to lakes shown in Fig. 1.
[c]Maximum values measured in the field and rounded to nearest 5 cm.

pattern is reflected by today's streams, except that much of the upper Missouri River actually flowed northeast into Hudson Bay rather than into the Mississippi River basin (Meneley *et al.* 1957).

The bedrock of the region is mantled by unconsolidated Quaternary sediment, which is over 300 m thick in places. These deposits consist of till, fluvial sands and gravels, and lacustrine silts and clays (Prest 1970). During deglaciation, meltwater from the retreating ice sheet carved numerous ice-marginal channels and spillways in this sediment (Christiansen 1979). Although now abandoned or buried under more recent sediment, these valleys are often sites of playa lakes. The hydrodynamic properties of the Quaternary sediments influence, to a major degree, the location and development of the playas by controlling the direction of flow and quantity of groundwater discharge.

Selection of study lakes

Forty-six playa lake basins in the northern Great Plains were examined on a reconnaissance basis during 1981–1982. Thirty-three of these were selected for more detailed sampling and study (Table 1). Lakes that were selected were representative in terms of basin morphology, location, hydrologic regime, brine chemistry, and expected sediment type. Accessibility, amount and type of information available from previous studies, and the degree of man-induced modification were also considered in selecting the playas.

Field sampling

Four hundred and sixty-two surface and near-surface sediment samples were collected from the 33 playa lake basins.

Although samples were collected from all the basins, the 19 lakes shown in italics in Table 1 received the most detailed

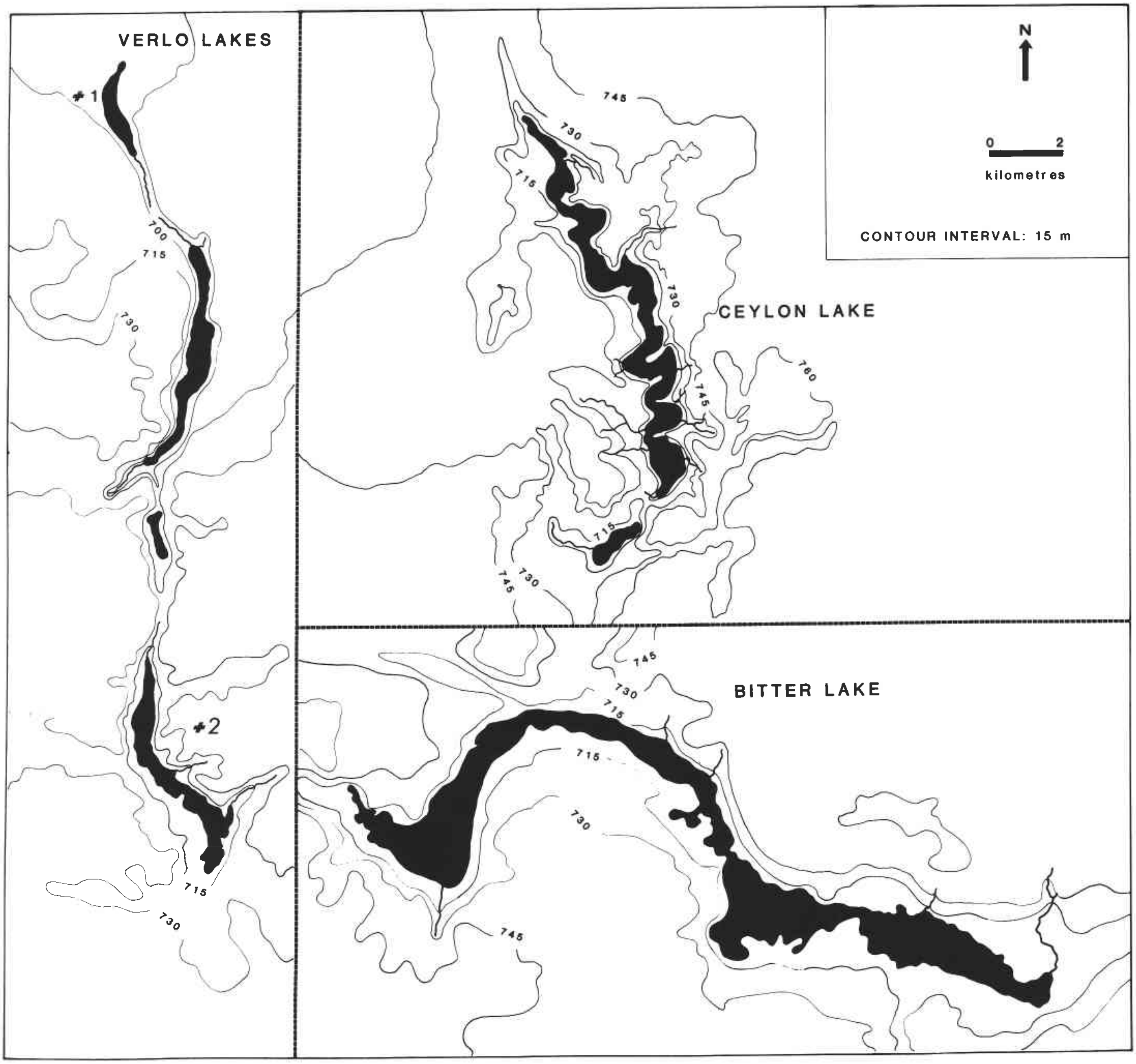

FIG. 2. Outline and topography of several representative playas illustrating the riverine nature of the basins.

sample coverage. This detailed sediment sampling was done at intervals of about 50–200 m along profiles extending across the basin. In addition, the location of sample points was controlled by changes in surface characteristics (texture, color, morphology) of the playa. Shallow pits were manually dug and auger holes drilled in order to assess the near-surface (upper 2–4 m) stratigraphic variation. Limited coring was done using a modified Livingstone piston corer for soft, clay-rich sediment and a motorized rotary drill for dense, coarsely crystalline precipitates. Evaporite mineralogy was estimated in the field using solubility, taste, and crystal morphology characteristics. In playas where water was present at the time of sediment sampling, brine density, temperature, conductivity, and pH were recorded in the field and representative water samples were taken. Several of the basins have been visited and sampled repeatedly during the 1981–1983 period in order to assess seasonal and short-term temporal changes.

Laboratory study

Detailed mineralogy was determined in the laboratory by X-ray diffraction, using both air-dried samples and samples in their original wet state. Quantitative estimates of the bulk mineralogy were obtained using the method of Schultz (1964). Moisture and organic matter contents of non-crystalline sediment were approximated by weight loss on ignition to 105 and 500°C, respectively. The "water-insoluble residue" of evaporite-rich sediment was determined according to the method of Cole (1926). This technique was used in order to compare the results of the present study with data of earlier published work (e.g., Cole 1926; Grossman 1949; Tomkins

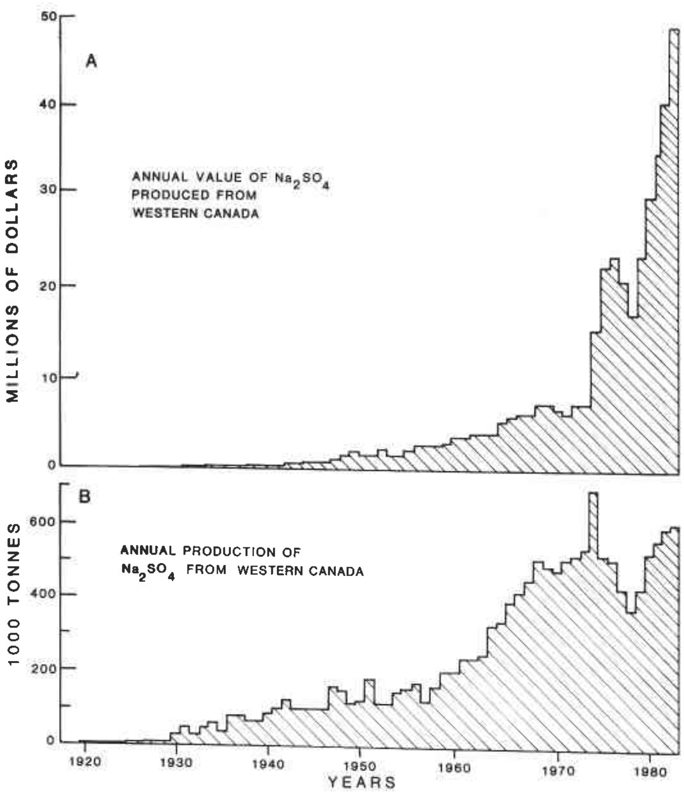

FIG. 3. Amount and value of sodium sulfate produced from saline playas in southern Saskatchewan, 1918–1982.

1953, 1954). Analysis of particle size distribution and fractionation of selected clastic-rich samples was done by standard sieve and pipette methods and microscope examination. Major ion concentrations of water samples were determined by standard atomic absorption, gravimetric, and turbidimetric methods.

Description of playas

General

There is a considerable range in playa lake types in the northern Great Plains as would be expected considering the large number of individual basins involved and the variable topography, climate, and geology over this large region. In general, the playas are small (less than 100 km^2) and frequently occupy elongate, riverine basins (Fig. 2). No regular long-term records of brine depth have been kept for any of these lakes, but maximum water depths during the past 60 years probably have not greatly exceeded 2 m (Cole 1926; Tomkins 1954; Grossman 1949; Table 1). Based on the reports of Cole (1926) and Tomkins (1954) and observations during the course of this study, most of the playas have a "flooding ratio" (the time playa contains water divided by the total time; Motts 1972) of less than 0.5.

Economic exploitation of the playas

Nearly all of the published geological work on these playas and the salt lakes in the Great Plains has been of an economic nature. Anhydrous sodium sulfate has been produced commercially from playas in Saskatchewan since 1918 (Fig. 3). Total composite reserves for the region (Saskatchewan, Alberta, North Dakota, and Montana) are among the largest in the world (Weisman and Tandy 1975). Presently, about 540 000 t/year of sodium sulfate is produced from 10 deposits in Saskatchewan and Alberta. In 1982 the total value of this product exceeded \$47 000 000, making Canada the world's leading producer.

Sodium sulfate is used in a wide variety of industries, including the manufacture of kraft paper, glass, ceramics, detergents, and paints. It is normally extracted from the lake brine by allowing mirabilite ("Glauber's salt") to precipitate upon brine cooling. By controlling the density and composition of the brine, a relatively pure $Na_2SO_4 \cdot 10H_2O$ product can be formed and harvested. In addition, the actual crystalline sodium sulfate within the lake's bed is extracted by dredge

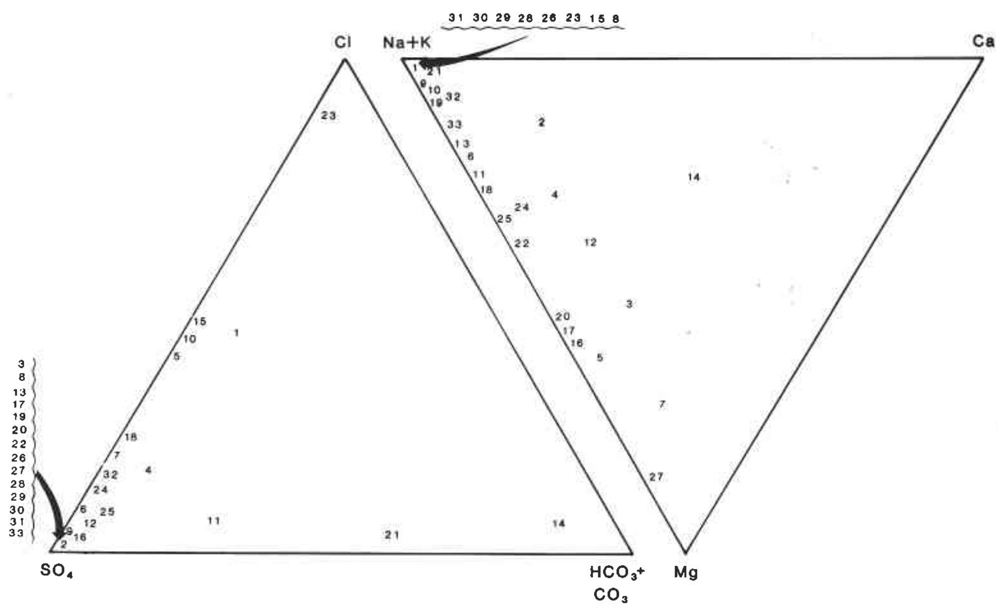

FIG. 4. Triangular diagram showing the average water composition (mol%) of selected playa lakes. Numbers refer to the lakes listed in Table 1. In the anion field lakes 3, 8, 13, 17, 19, 20, 22, 26, 27, 28, 29, 30, 31, and 33 all plot at the same point as lake 2. In the cation field lakes 8, 15, 23, 26, 28, 29, 30, and 31 all plot at the same point as lake 1. Compiled, in part, from Cole (1926), Tomkins (1953, 1954), Hammer (1978), and Last and Schweyen (1983).

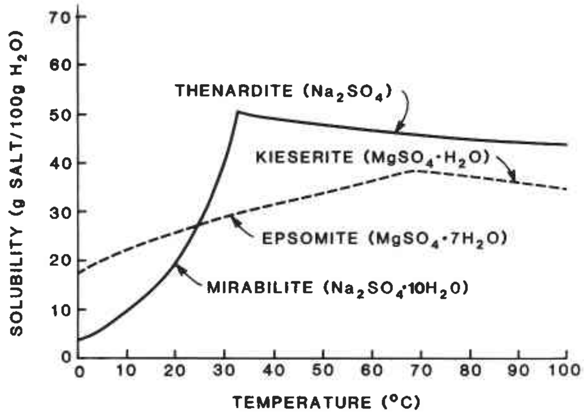

FIG. 5. Temperature–solubility curves for sodium sulfates and magnesium sulfates in pure water (after Cooke 1981).

mining and solution mining.

The harvested sodium sulfate must then be dehydrated before marketing. The methods for this processing vary considerably (see Rueffel 1968). Most producers simply raise the temperature of the salt to above its fusion point (about 32°C), and then either continue heating to evaporate the water of crystallization or remove the solid anhydrous precipitate from the $Na_2SO_4-H_2O$ slurry (Tomkins 1954).

In addition to sodium sulfate, several playa lakes in Saskatchewan and Alberta contain sufficient amounts of magnesium to be considered marginally economic. Magnesium salts were commercially extracted from Muskiki Lake (Fig. 1) for a short time during the early part of the century (Cole 1926). Tomkins (1953) listed the total lacustrine magnesium reserves of the Canadian Plains at about 5 000 000 t.

Finally, selected zooplankton (specifically *Artemia salina* or brine shrimp, *Diaptomus*, and *Daphnia*) that grow in large

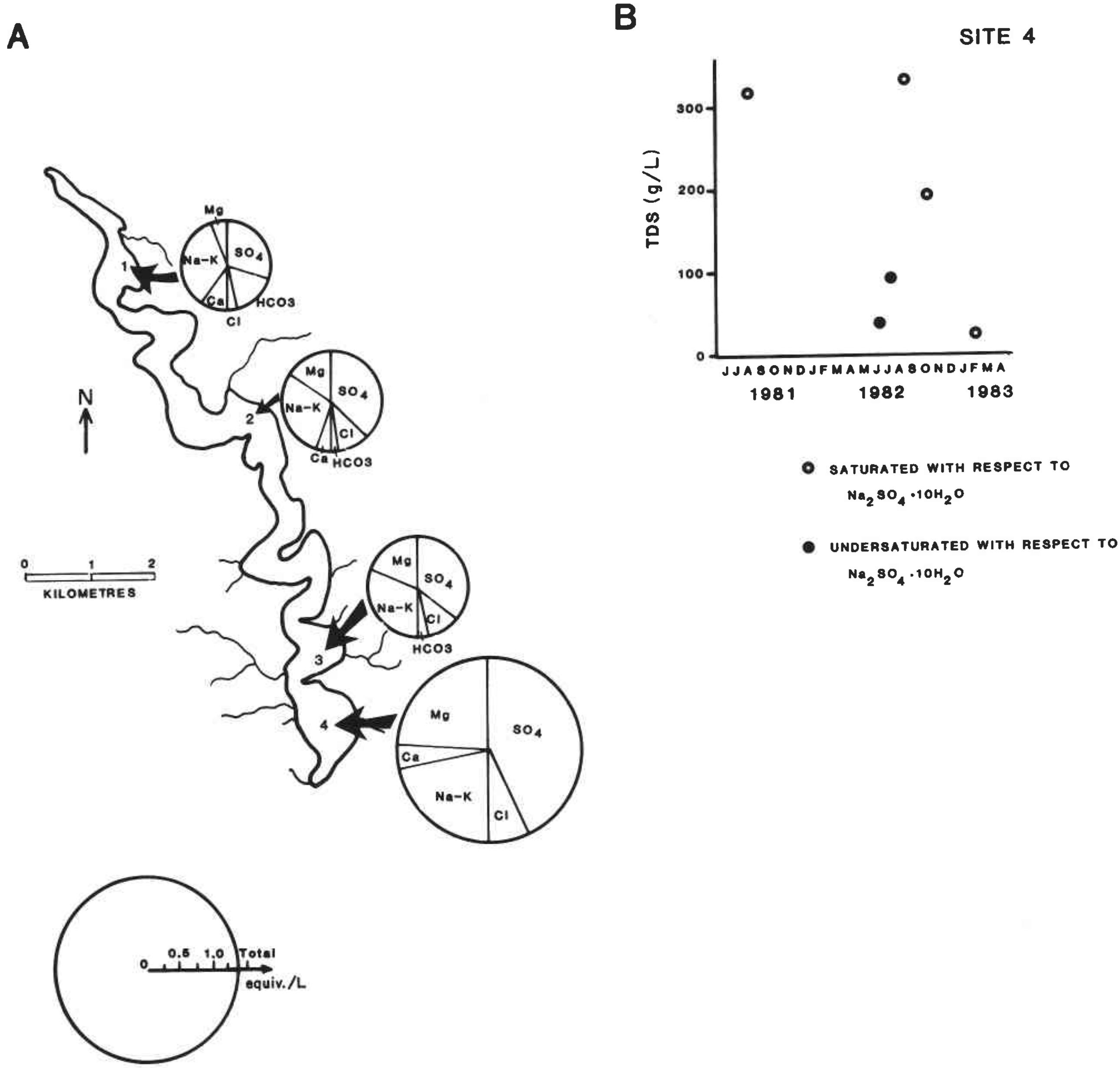

FIG. 6. (*A*) Spatial variation in brine chemistry in Ceylon Lake on June 24, 1982 (in equiv./L and % equiv./L). (*B*) Temporal variation in salinity (TDS) at site 4 in Ceylon Lake, 1981–1983.

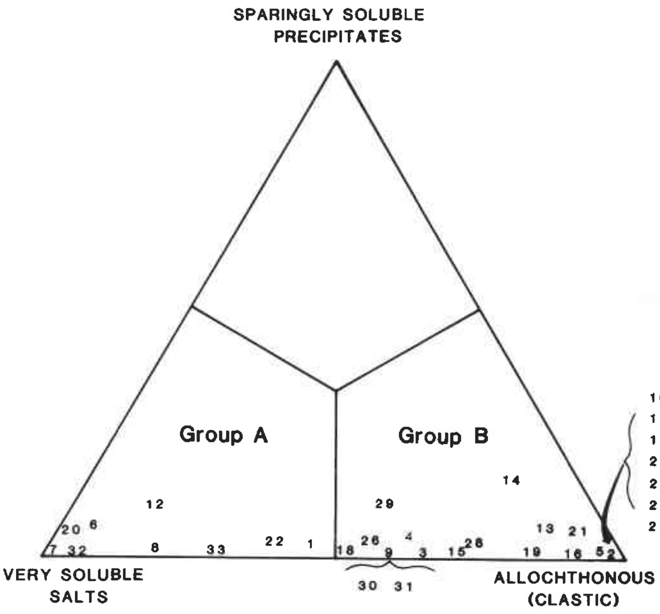

FIG. 7. Triangular diagram showing modern sediment type of selected playas. Numbers refer to lakes listed in Table 1. Lakes 10, 11, 17, 23, 24, 25, and 27 all plot at the same point as lake 2.

numbers in many of the playas have been harvested as food for fish farms and the tropical fish industry.

Hydrochemistry

Hammer (1978) and Rawson and Moore (1944) pointed out that overall the salt lakes of the Canadian Plains are dominated by sodium and sulfate ions, although significant variations in hydrochemistry do exist on a regional scale as well as on an individual drainage basin scale (Last and Schweyen 1983). Figure 4 shows that the playa lakes included in this report are mainly of the Na–Mg–SO_4 type. However, beyond the gross compositional characteristics, it is difficult to generalize about the ionic content of the playa lake water because any individual brine system can exhibit significant variation on both a temporal and spatial basis.

Enormous seasonal changes in salinity and ion ratios are common in these playas. Much of this variation is a consequence of the influence of a climate with large seasonal temperature variations combined with the unique physical and chemical properties of a sodium sulfate-rich aqueous system. The solubility of sodium sulfate is strongly temperature dependent, decreasing from a maximum of about 50 g/100 mL at 32°C to less than 5 g/100 mL at 0°C (Fig. 5). Thus the lake brines exhibit an annual cycle of high sodium and sulfate levels during late spring and summer, grading to lower relative pro-

TABLE 2. Minerals of the playa lakes of the northern Great Plains. Compiled, in part, from Egan (1984) and Cole (1926)

Carbonates	
Aragonite (a)	$CaCO_3$
Calcite (e)	$CaCO_3$
High-magnesian calcite (a)	$CaCO_3$
Dolomite (e)	$CaMg(CO_3)_2$
Protodolomite (a)	$CaMg(CO_3)_2$
Nesquehonite (a)	$Mg(HCO_3)(CO_3)_4$
Huntite (a)	$CaMg_3(CO_3)_4$
Natron (a)	$Na_2CO_3 \cdot 10H_2O$
Trona (a)	$NaHCO_3 \cdot Na_2CO_3 \cdot 2H_2O$
Scarbroite (a)	$Al_2(CO_3)_3 \cdot 13Al(OH)_3$
Dawsonite (a)	$NaAl(CO_3)(OH)_2$
Sulfates and chlorides	
Gypsum (e)	$CaSO_4 \cdot 2H_2O$
Mirabilite (a)	$Na_2SO_4 \cdot 10H_2O$
Thenardite (a)	Na_2SO_4
Bloedite (a)	$Na_2Mg(SO_4)_2 \cdot 4H_2O$
Loeweite (a)	$Na_{12}Mg_7(SO_4)_{13} \cdot 15H_2O$
Kieserite (a)	$MgSO_4 \cdot H_2O$
Epsomite (a)	$MgSO_4 \cdot 7H_2O$
Burkeite (a)	$Na_2CO_3 \cdot 2Na_2SO_4$
Hexahydrite (a)	$MgSO_4 \cdot 6H_2O$
Halite (a)	NaCl
Hydrohalite (a)	$NaCl \cdot 2H_2O$
Jarosite (a)	$KFe_3(SO_4)_2(OH)_6$
Silicates	
Quartz (d)	SiO_2
Feldspars (d)	K–Na–Ca aluminosilicate
Kaolinite (d)	$Al_2Si_2O_5(OH)_4$
Chlorite (d)	$(Fe, Mg)_2Al_4Si_2O_{10}(OH)_4$
Illite (d)	Hydrous K–Mg–Fe aluminosilicate
Smectite (d)	Hydrous Mg–Fe aluminosilicate
Mixed-layer clay (e)	Variable
Muscovite (d)	$K_2Al_4Si_6Al_2O_{20}(OH, F)_4$

NOTES: Italics indicate common occurrence. Letters indicate likely origin: a = authigenic; d = detrital; e = either authigenic or detrital.

portions of these ions upon cooling during autumn and, finally, to nearly complete loss of the Na^+ and SO_4^{2-} over winter due to salt precipitation. Reflooding of the basin with meltwater runoff and shallow (local) groundwater discharge during early spring can generate temporarily high relative abundances of calcium and bicarbonate ions.

In addition to these seasonal fluctuations, the lakes sometimes show considerable spatial variation in water chemistry. Lakes occupying elongate basins are particularly susceptible to hydrochemical inhomogeneity as shown, for example, in Ceylon Lake (Fig. 6). The mechanisms responsible for such a variation are not straightforward and are possibly different for each basin. In Ceylon Lake, spatial differences in bottom sediment types, amount of stream inflow, and nature of subaqueous spring discharge apparently account for the differences in brine chemistry.

Modern sediments and sedimentary environments

As emphasized by Hardie *et al.* (1978), a saline lake basin must be viewed as simply one part of a complex system of subenvironments. For example, playas of the Great Basin of western United States typically include a central salt pan–ephermeral lake subenvironment ringed by mud flats and sand flats, which grade into alluvial fans. Wadi, or less frequently, dune systems also occur at the playa margin between the toe of the alluvial fan and the mud flat. Within the playa lake itself, chemical differentiation of the brine during evaporative concentration leads to the well known "bull's-eye" pattern of mineral and sediment distribution.

The playas of the northern Great Plains, in general, show a distribution of modern subenvironments similar to that found in playa – ephemeral lake complexes elsewhere. The salt pan – playa lake subenvironment occupies the lowest central portion of the playa complex. It is flooded during spring and early summer by runoff from melting snow and discharge due to high groundwater levels. However, by late summer to fall the surface water of most of the playas has completely evaporated. During wet years (such as 1982), or if fall precipitation is unusually high, brine can persist in the basins throughout the winter. High solute contents, particularly in the low-sulfate brines such as those of Patience and Bitter lakes, suppress the freezing point and ice may not form.

The modern sediments of the playa lakes are composed of: (1) very soluble evaporites; (2) sparingly soluble precipitates; (3) allochthonous or clastic inorganic material; and (4) organic detritus. Figure 7 shows the variation in inorganic sediment type of the playa lakes examined. Although some of the lakes may be composed of nearly pure "end-member" components, most are mixtures of the three basic sediment types.

The sediments in playas of group A consist mainly of very soluble salts. Most commonly these salts are sodium and magnesium sulfates (mirabilite, thenardite, bloedite, and epsomite), although halite has also been identified (Table 2). The salts are rarely pure and are usually mixed with at least small amounts of mud and less soluble precipitates.

The sediments in group B playas are composed mainly of clastic material brought into the lake by surface runoff, shoreline erosion, and wind. This sediment is dominantly silt- and clay-sized quartz, feldspars, carbonates, and detrital clay minerals. Smectite is the main clay mineral present, typically constituting over 75% of the clay fraction. Minor amounts of coarser grained components (sand, gravel) are also found in some basins.

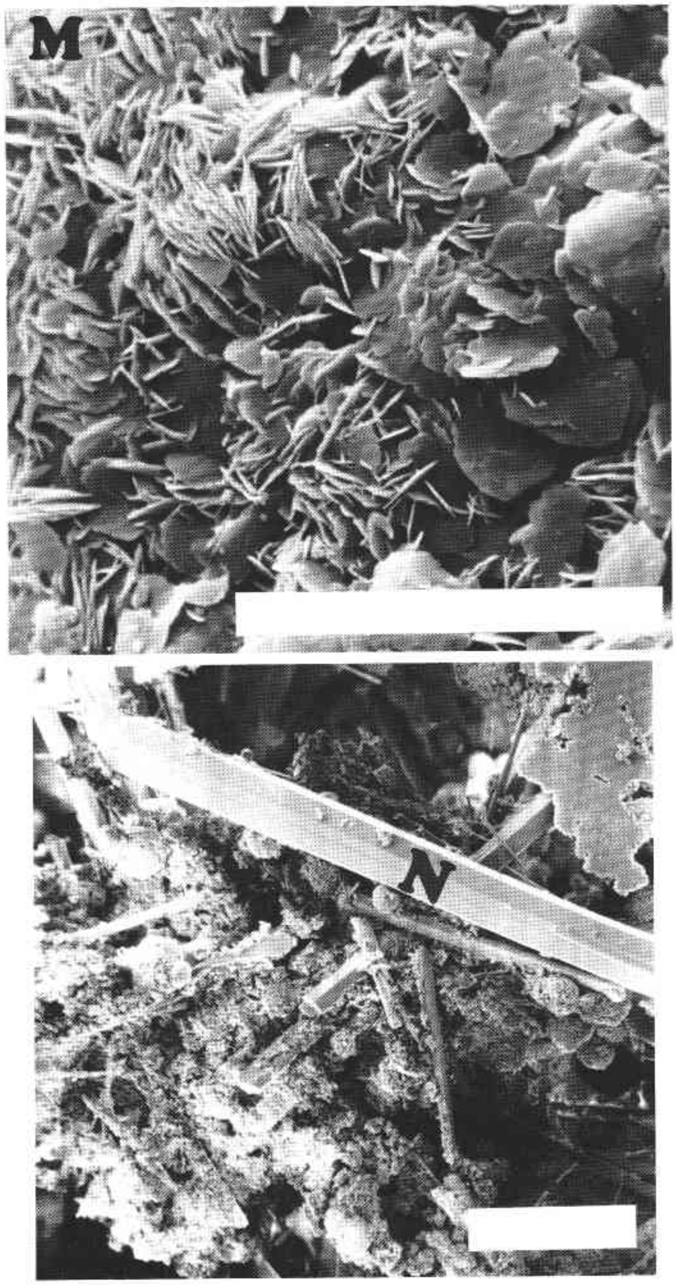

FIG. 8. Examples of mixed-layer clays (M) and nesquehonite (N) from Freefight Lake. Scale bars = 5 μm.

Sparingly soluble minerals, including gypsum, calcite, aragonite, protodolomite, huntite, and mixed layer clays (Table 2, Fig. 8), occur in varying amounts in most of the playas either as primary precipitates or very early diagenetic products.

The organic component of the sediment (not shown in Fig. 7) is variable, ranging from less than 1% to nearly 60% (dry weight basis). The identifiable material in the sediment usually consists of a mixture of brine shrimp egg capsules, ostracodes, fibers, rootlets, and other vegetation debris. *Artemia* can also be so plentiful in the brine that the water takes on a distinct reddish hue and, if mirabilite precipitation is occurring, the salt can also be pink to pale red in color (5YR 8/3 to 10R 6/3 Munsell). In some lakes (e.g., Berry, Dana, Grandora, Verlo) the sediment–water interface can be covered with a laminated, carpetlike vegetation mat up to several centi-

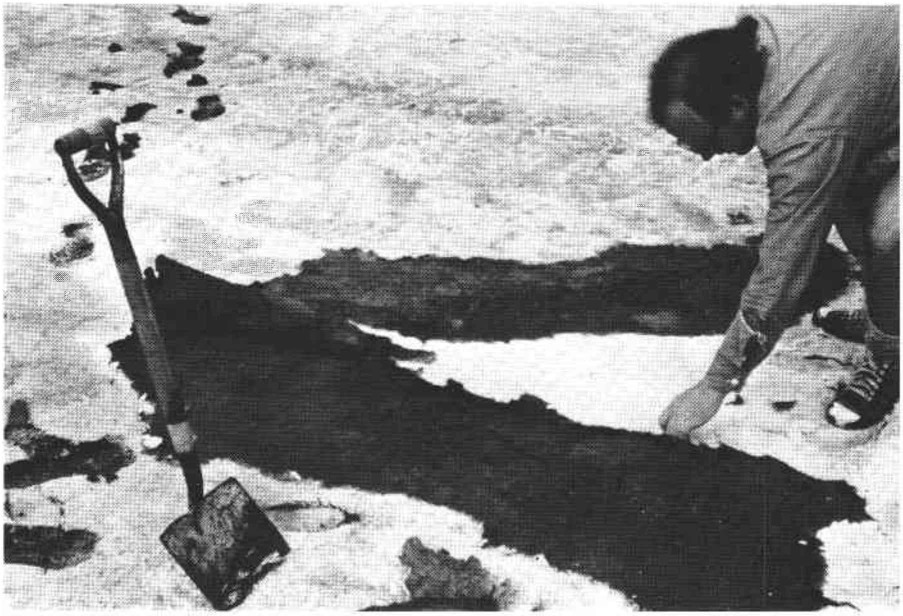

FIG. 9. Example of a vegetation mat from Dana Lake.

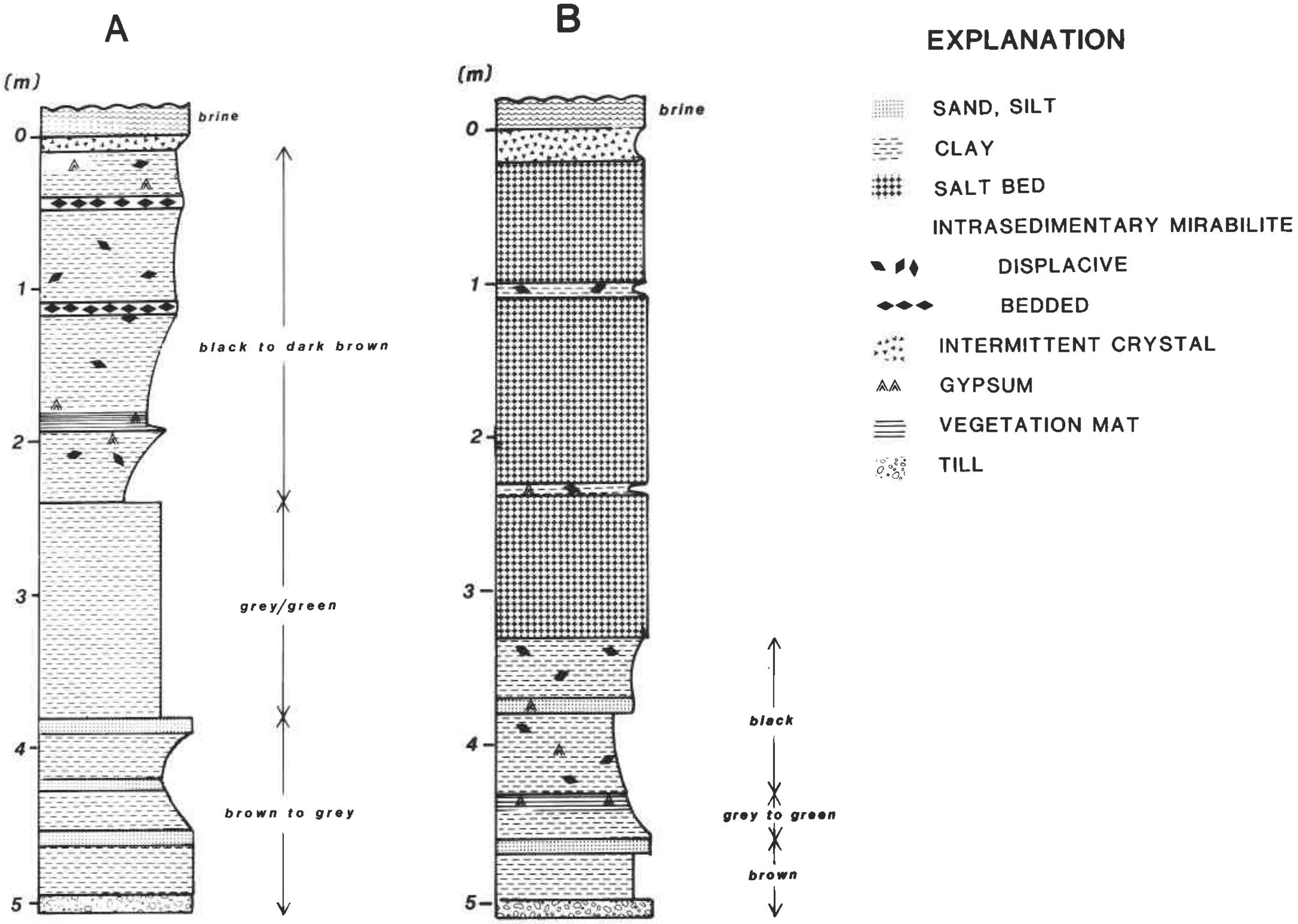

FIG. 10. Representative stratigraphic sequences in (*A*) mud-dominated playas and (*B*) salt-dominated playas.

metres thick (Fig. 9). Occasionally these mats can be composed of nearly 100% organic matter, but more often they are mixed with clastic and authigenic minerals and ostracode shell material.

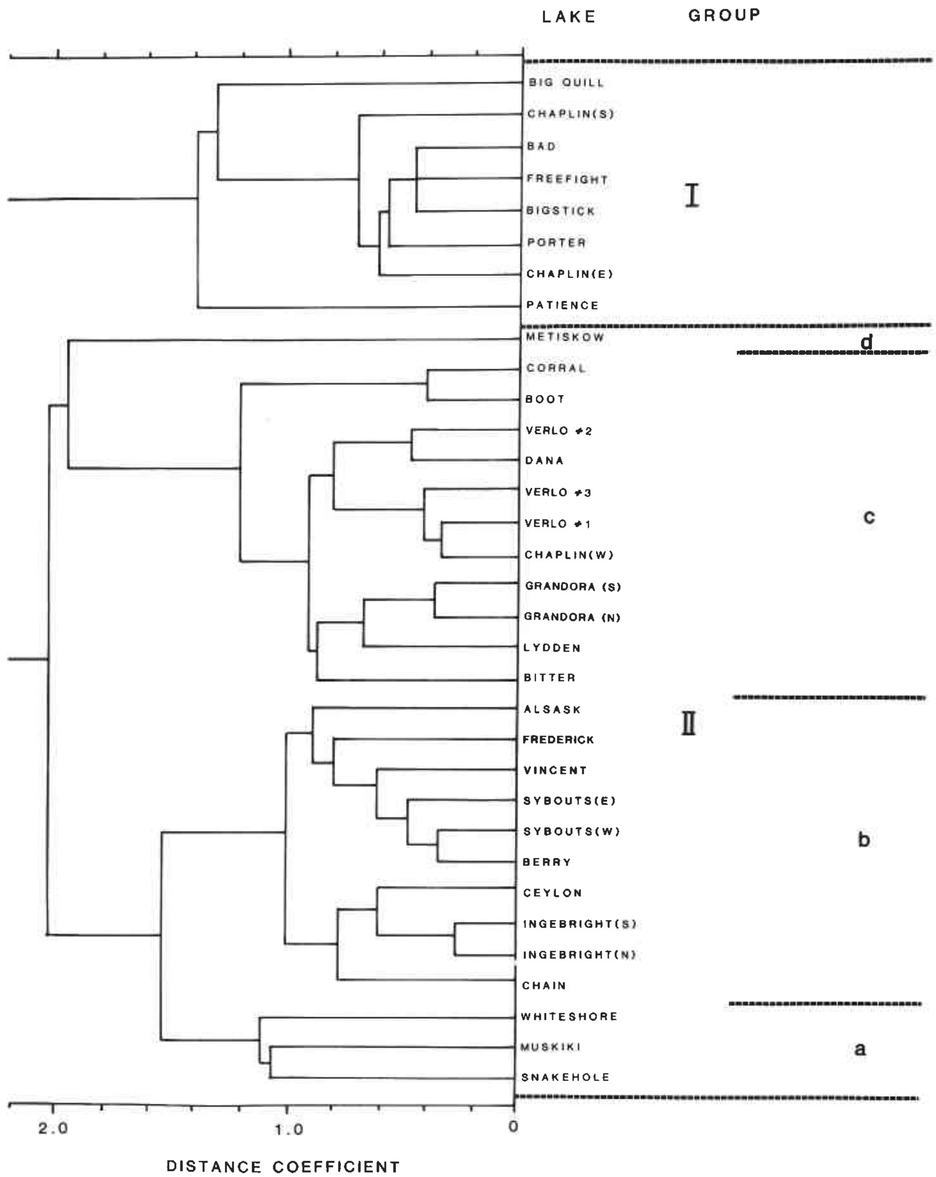

FIG. 11. A *Q*-mode cluster dendogram showing classification of playas.

As the lake waters recede during the year, large areas of saline and clastic mud flats are exposed. The distinction between these two types of mud flats and the processes operating in each are discussed in the following section. The mud-flat sediments are generally fine grained and organic rich and show only very indistinct lamination. Colonization and stabilization of the newly exposed mud flats by emergent macrophytes such as *Scirpus* sp. can be very rapid (Lieffers 1981). Desiccation and exposure features such as mud cracks, efflorescent salt crusts, and adhesion ripples and warts are common features on the mud-flat surface.

The mud flats usually grade laterally into a hillslope subenvironment. The sediments of the hillslope are generally poorly sorted, non-bedded colluvium. In many basins the colluvium clearly predates an earlier high-water stage of the lake as evidenced by beach deposits and wave-cut scarps present up to several metres above the present playa surface. The colluvium is quite variable in thickness, ranging from only a thin (less than 0.3 m) veneer to greater than 3 m.

Stratigraphic characteristics

There is considerable variation in the nature of basin fill in the playas examined as well as significant differences within any individual playa. In general, the playas dominated by clastic material (group B in Fig. 7) are underlain by up to several metres of soft, black silty and clayey sediment. Overall, the sequence is very poorly bedded with occasional laminae composed of fiber mats, authigenic precipitates, concentrations of ostracodes and brine shrimp eggs, or, rarely, coarse clastics. Euhedral mirabilite crystals up to several centimetres long are commonly found dispersed throughout the mud, as are smaller gypsum crystals. This upper mud unit usually grades downward into a light grey to greyish green, compact, calcareous clay-rich sediment. Finally, the lower several metres of section often consists of sandy silt to silty sand and gravel interbedded with poorly sorted, very compact pebbly clay. Figure 10*A* summarizes the typical near-surface stratigraphy in the center of one of the playas dominated by clastic sediment.

The playas whose modern sediment is dominated by very

TABLE 3. Variable means for five lake groups

Variable	Group I	IIa	IIb	IIc	IId
pH	8.9	8.1	8.0	8.5	8.8
Conductivity (mmhos/cm at 25°C)	43.9	92.3	55.9	96.1	101.0
Salinity (TDS; ppt)	53.0	240.2	105.4	205.6	257
Ca^{2+} (mmol/L)	11.0	34.6	4.2	13.8	2.5
Mg^{2+} (mmol/L)	58.3	555.0	147.9	743.7	67.3
Na^{+} (mmol/L)	554.3	2303.8	1084.5	1993.5	4832.9
K^{+} (mmol/L)	86.4	21.7	0	15.7	5.0
$HCO_3^{-} + CO_3^{2-}$ (mg/L)	15.9	20.9	24.9	30.3	1060.8
Cl^{-} (mg/L)	409.7	243.1	224.4	349.3	262.4
SO_4^{2-} (mg/L)	385.2	3421.7	1408.4	2613.7	1700.9
Maximum area of lake (km^2)	47.7	17.5	3.2	5.5	5.1
Shoreline length (km)	27.2	32.8	13.3	18.1	9.8
Shoreline development index	1.7	2.2	1.9	1.7	2.9
Maximum depth (m)	1.0	0.6	0.4	0.2	0.1
Maximum thickness of permanent salt (m)	0	1.6	3.0	1.6	6.5
Insoluble material in permanent salt (%)	100	9.8	9.5	41.8	12.0
Mirabilite + thenardite in permanent salt (%)	0	75.8	84.6	61.2	80.1
Halite in permanent salt (%)	0	0.8	0.4	0.2	0.1
Natron in permanent salt (%)	0	0.5	0.5	0.1	3.5
Gypsum in permanent salt (%)	0	5.0	1.6	0.7	1.5
Epsomite in permanent salt (%)	0	7.1	1.8	1.4	0.2
Total tonnage of permanent salt (Mt)	0	9.7	4.0	0.6	5.1
Soluble + sparingly soluble minerals in modern sediment (%)	13.8	97.2	85.6	58.4	55.0

soluble salts usually exhibit a stratigraphic sequence as shown in Fig. 10*B*. The upper several centimetres of salt crust is underlain by hard, coarse crystalline material. Except for thin interbeds of dark, reducing mud, this salt is massive and has sharp upper and lower contacts. The salt is mainly mirabilite and thenardite with small amounts of trona, halite, epsomite, gypsum, natron, bloedite, calcite, and kieserite. The purity of this unit is also variable, ranging from nearly 100% soluble and sparingly soluble precipitates to as much as 40% insoluble mud. The salt is generally thickest near the center of the basin and thins toward the basin margins. The thickest section of salt penetrated in this study is 4.5 m in Ceylon and Boot lakes. However, Cole (1926) and Rueffel (1968) reported up to 45 m of massive, continuous crystal in some basins. Although radiocarbon dating is not yet complete, and a chronology has not yet been established for these basins, such thicknesses of this unit suggest a prolonged maintenance of delicate physical and chemical equilibria.

Underlying this upper massive salt unit is usually several metres of soft, black, reducing mud with abundant euhedral salt crystals. Occasional thin beds of salt are also common. Reconnaissance geochemistry has indicated that this mud unit is sometimes enriched in trace metals, particularly Pb, Zn, and Cu. This mud grades downward into firm, grey to greyish green, calcareous clay and finally into either sand, gravel or pebbly clay at the base of the section.

Classification of playa lakes

Hammer (1978) classified 60 saline lakes of Saskatchewan on the basis of dominant ion equivalence proportions. In this study of mainly perennial saline lakes, he found that the most common brine type was the magnesium–sodium–sulfate type, followed by sodium–magnesium–sulfate and sodium–chloride types.

TABLE 4. Major physical and chemical processes influencing sedimentation in the playa lakes of the northern Great Plains

Physical processes
- Surface flooding–desiccation
- Evaporative pumping
- Wind transport, deflation, setup
- Stream transport
- Freezing–thawing

Chemical processes
- Evaporative concentration and subaqueous precipitation of soluble salts
- Formation of salt crusts, crystal rafts
- Formation of salt spring deposits
- Formation of pipes, karst
- Intrasedimentary growth of salts
- Cyclic precipitation–dissolution
- Freeze-out precipitation

Last and Schweyen (1983) expanded this classification effort to include playa as well as perennial lakes and used various morphological criteria (area, depth, shape) as parameters for classification. They pointed out that most of the saline lakes in the northern Great Plains are small and shallow (less than 5 m in depth) and about half of these exhibit playa characteristics.

The morphological, geochemical, and mineralogical data available on the 33 playa lakes listed in Table 1 were subjected to cluster analysis in an effort to identify groupings of playas with similar characteristics and to quantitatively compare the various classes of playas of the northern Great Plains. Initially, 30 variables were used in the analyses. However, several of these variables were found to be highly correlated with one another and, therefore, were likely biasing the grouping pro-

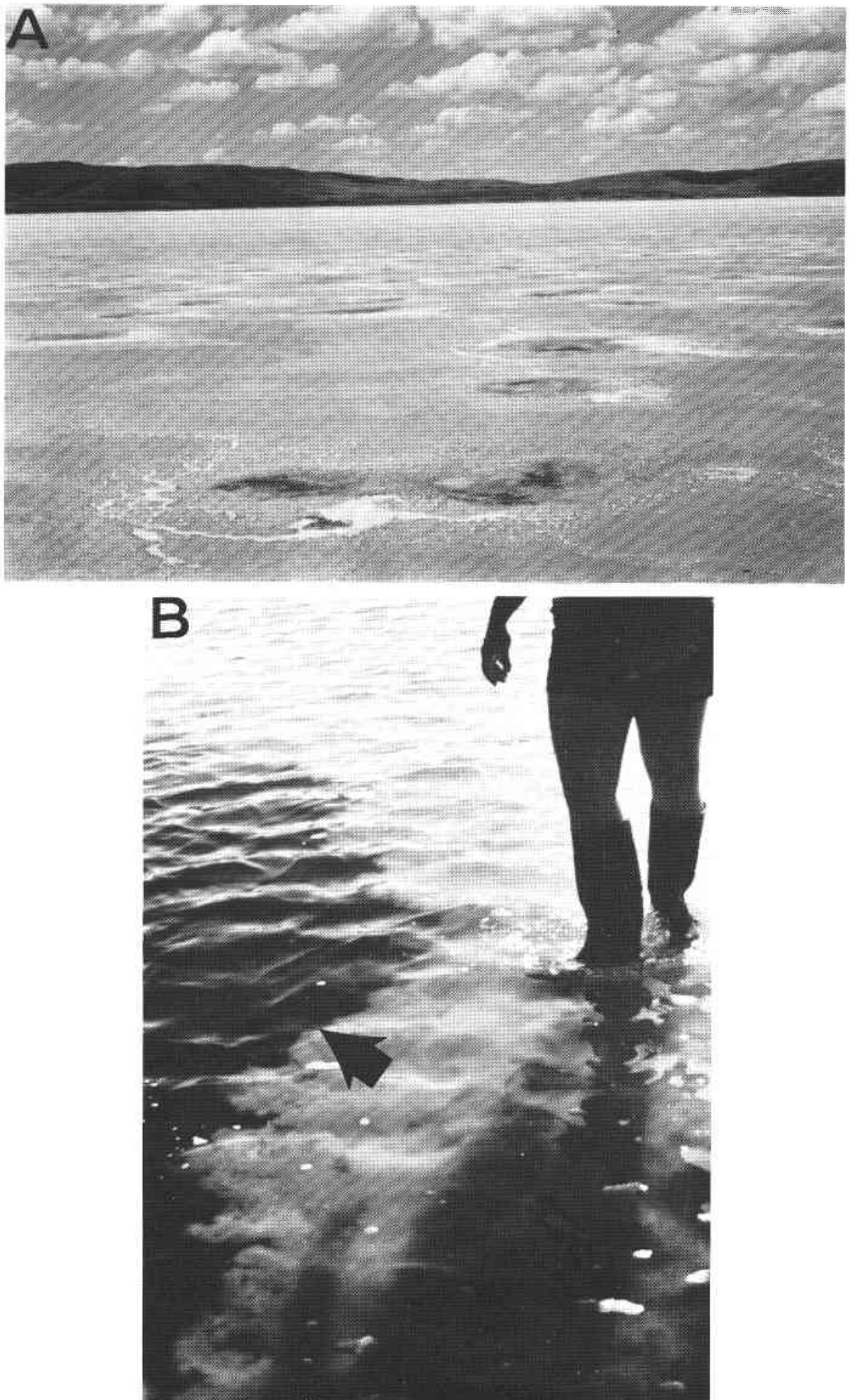

FIG. 12. (*A*) Numerous small, saline springs in Boot Lake. (B) Edge of solution chimney (arrow) in Ceylon Lake. At time of photograph (September 1982) the pit was 2.5 m wide and 9.1 m deep with vertical to overhanging sides. By February 1983, the depth of water in the pit was 2.8 m and the rest of the chimney was filled in with salt.

cedure. Nine redundant variables were deleted from the analyses. The resulting cluster dendrogram (Fig. 11) is based on analysis of data for the following parameters: total dissolved solids, pH, Ca^{2+}, Mg^{2+}, Na^{+}, $HCO_3^{-} + CO_3^{2-}$, Cl^{-}, SO_4^{2-}, maximum lake area, shoreline development index, maximum depth of brine, amount of soluble and sparingly soluble salts in the recent sediment, thickness of "permanent" salt bed, amounts of insoluble material, mirabilite or thenardite, halite, gypsum, and epsomite in the permanent salt, and the estimated total tonnage of salt in the playa basin. These raw variable data were standardized (mean = 0, standard deviation = 1) and clustered using both average linkage and Ward's method (Ray 1982). The two techniques gave similar groupings.

The *Q*-mode cluster dendogram of the 33 playa lake basins

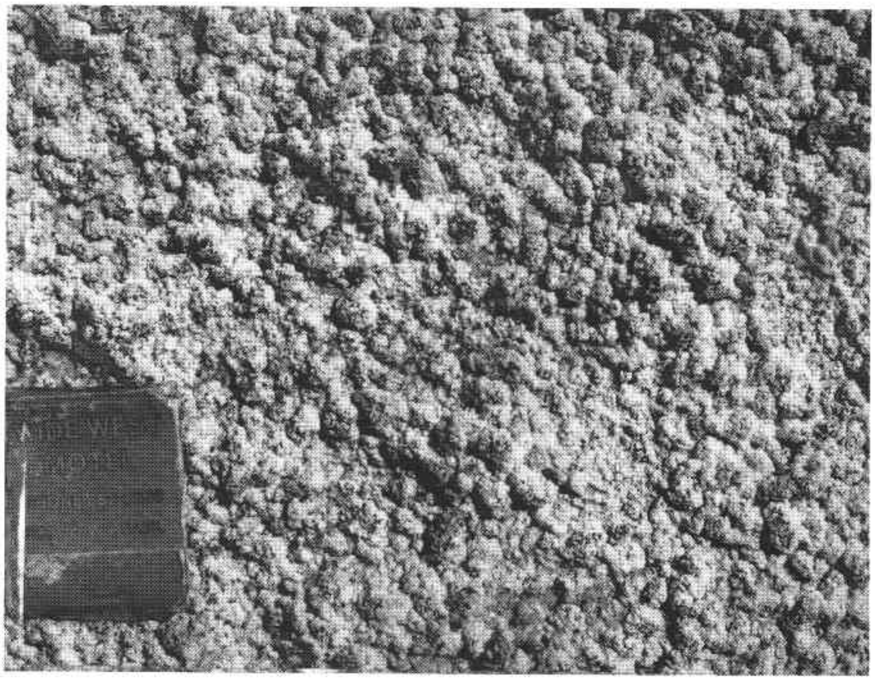

FIG. 13. Example of efflorescent crust from saline mud flat at Corral Lake. Crust is 12 cm thick and composed entirely of thenardite. Matchbook is 3.5 cm wide.

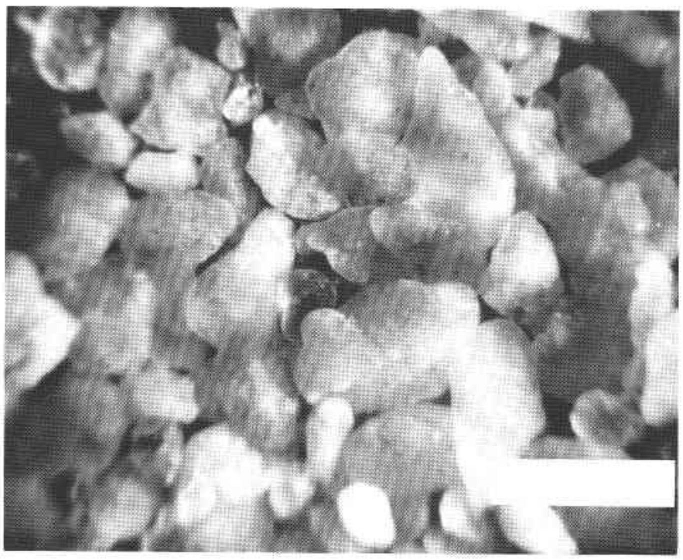

FIG. 14. Abraded gypsum crystals collected from the shoreline of Patience Lake. Scale bar = 1 mm.

(Fig. 11) defines two major groups at a distance coefficient of greater than 2.0. Basically, this very broad subdivision classifies the basins into: a group (I) having relatively low salinities, high clastic content, and no permanent salt bed, and a group (II) having high salinities, high soluble and sparingly soluble mineral content, and a permanent salt bed.

Although a useful summary, this two-fold subdivision of playas is much too broad to be meaningful. Instead, five lake classes (I, IIa, IIb, IIc, and IId) were selected from the dendrogram using a distance coefficient of greater than 1.5. The variable means for each of these five classes are shown in Table 3.

Group I lakes have high pH, relatively low total salinities but comparatively high Cl^- (and K^+) contents, large areal extent, high clastic (insoluble) content in the modern sediment, and no permanent salt bed. Group IIa playas are characterized by very high salinity that is dominantly Na^+ and SO_4^{2-}, and a large deposit (tonnage) of permanent salt. These lakes tend to occupy long, riverlike basins as indicted by the high shoreline length and development indices. Their modern sediments are dominated by soluble and sparingly soluble salts. Group IIb lakes occupy the smallest basins and have the purest (i.e., low insoluble and high mirabilite or thenardite contents) and thickest permanent salt beds. Group IIc lakes are, in many ways, similar to those of group IIa except they have relatively high Ca^{2+}, Mg^{2+}, and HCO_3^- contents and small quantities of permanent salt. Finally, group IId, represented in this study by only one lake (Metiskow Lake), is characterized by very high salinity with a large amount of HCO_3^- and a corresponding relatively high proportion of natron in the permanent salt.

Modern sedimentary processes

Many individual physical, chemical, and biological processes that influence the formation and sedimentary character of playa basins have been described and discussed in the literature (e.g., Reeves 1968, 1972; Neal 1975; Kendall 1979; Nissenbaum 1980; Williams 1981; Handford 1981). Eugster and Hardie (1978) and Hardie *et al.* (1978) reviewed the dominant processes influencing saline lakes in general, but gave particular attention to basins occurring in arid, high-relief environments such as the Basin and Range province of western United States. Overall, the playas of the northern Great Plains share many processes in common with these latter, well studied continental sabkhas and playas. The details of the processes and the resultant sedimentary facies, however, can be quite different. The processes that are of major importance in influencing the modern sediment record of playa lakes in the Great Plains region are summarized in Table 4.

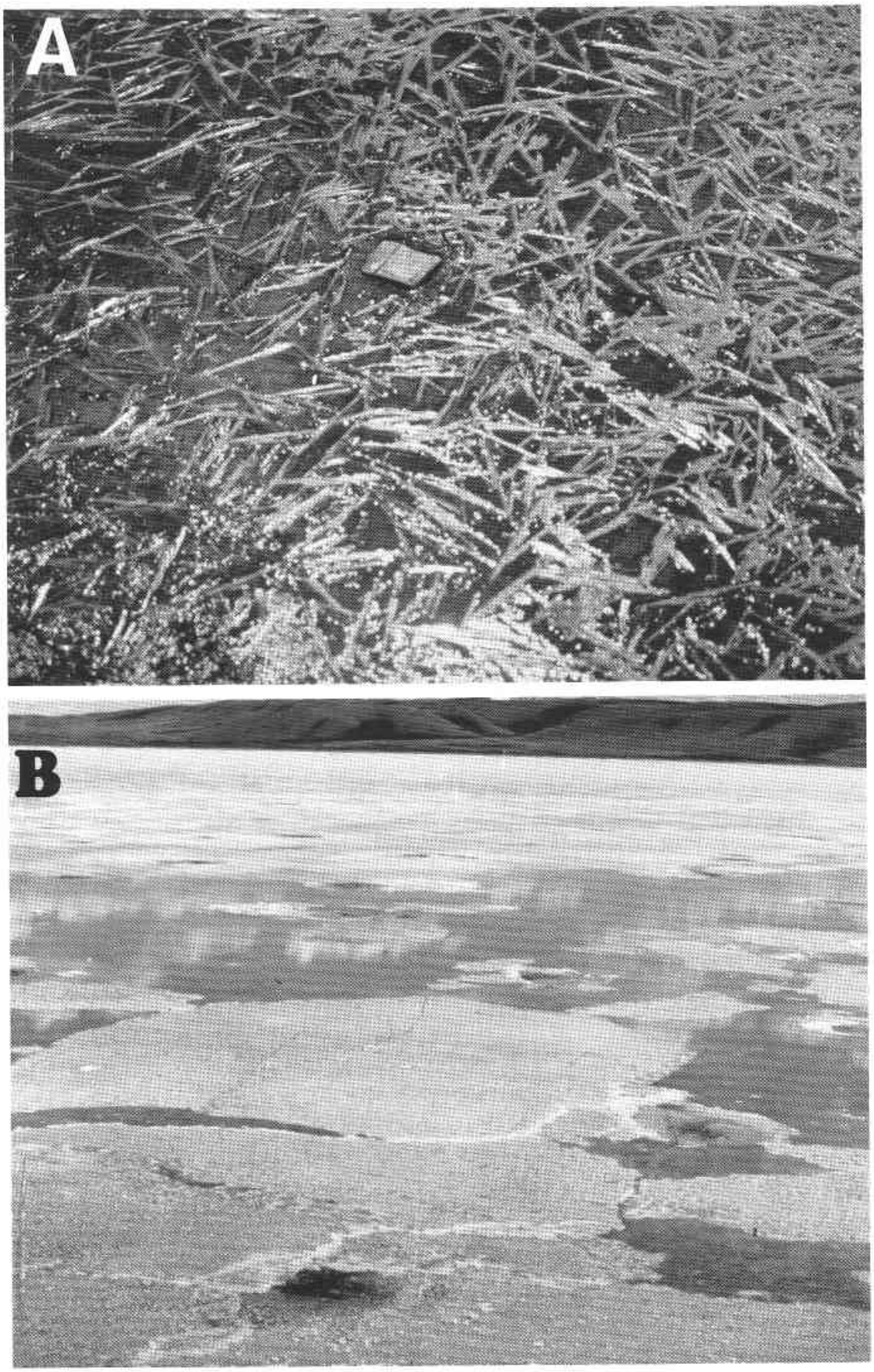

FIG. 15. (*A*) Delicate acicular thenardite crystals formed at the surface of the brine in Ceylon Lake. Crystals are being supported by surface tension. The depth of brine beneath the crystals is 15 cm. Temperature of brine is 34°C. Matchbook is 3.5 cm wide. (*B*) Coalesced crystal rafts being driven by wind across the brine surface at Ceylon Lake.

Evaporation assumes a pivotal role in controlling nearly all aspects of playa sedimentation. By definition, playas have a negative hydrologic budget. The high rates of evaporation in the Great Plains region greatly exceed the inflow of water to the playas, and ponded brine occupying the basins during spring and early summer is usually lost by mid to late summer. During the latter stages of playa desiccation the rate of water loss by evaporation can be greatly reduced because of the effect of increased brine salinity (Harbeck 1955) and the formation of crystal crusts and floating crystal rafts.

Groundwater discharge also plays an important role in the maintenance of the playa lakes, in the acquisition of salts, and in the modification of the sedimentary record within the basin. Both brine and brackish water springs and seeps are common features on the surface of the playas (Fig. 12*A*). Although both the discharge and the salinity of the upper groundwater in this region are generally low (less than 0.03 m^3/min and 1000 ppm total dissolved solids (TDS); Brown 1967), individual lake bottom springs having measured discharges of up to 7 m^3/min (Cole 1926) and salinities in excess of 200 ppt (Grossman 1949) confirm the importance of groundwater contribution to these salt pans. In some of the playas, such as Muskiki and

Metiskow, the presence of "chemical deltas," tufas, and carbonate hardgrounds is further indication of substantial spring discharge. Ceylon, Ingebright, Berry, and Muskiki lakes have a sufficient flow of brine to build up cones of soluble salts (mainly mirabilite and epsomite) on the surface of the playas. These salt spring orifice deposits range in size from cones less than 1 m high to mounds approximately 3 m high and 30 m in diameter.

In addition to saline groundwater discharge, freshwater springs are also a very common occurrence in and adjacent to the playas. Approximately half of the springs listed and sampled by Cole (1926) had salinities of less than 1000 ppm. Dissolution of the solid crystal bed by this freshwater discharge has created deep pipes or chimneys in several of the playas. These pipes can be filled with either fresh water, brine, crystal, or mud depending on the time of year and the sedimentological/hydrological regime of the specific playa. For example, at least two large solution pits have formed in the salt bed of Ceylon Lake during the past several decades. These pits are narrow and deep and during much of the summer season are filled with dense, saturated sodium sulfate solution (Fig. 12*B*). Upon cooling during winter, mirabilite precipitation occurs, filling the pipes to within 3 m of the surface. Because of this freeze-out precipitation and removal of Na_2SO_4, the remaining water in the solution pipe is relatively fresh (less than 5000 ppm TDS). During spring and early summer increased flow of fresh groundwater redissolves the soluble salts. Cole (1926) described chimneys and pipes of similar morphology in the salt beds of Snakehole, Ingebright, Berry, and Boot lakes that are filled with soft mud.

In addition to groundwater, the playa basins seasonally receive water from direct precipitation, diffuse overland runoff, and, in some cases, small streams. This seasonal basin flooding affects the sediment in several ways. Most importantly, the dilute brine occupying the basin during wet periods is capable of redissolving previously precipitated soluble salts. The amount of dissolution is controlled by the nature of the inflowing water (temperature, suspended load, salinity, composition, etc.) and the kinetics of dissolution of the precipitated phases. A partial or total re-solution of the previous year's precipitate, or even of older salt beds, can occur. For example, in Lydden Lake complete dissolution of the salt crust and partial dissolution of the underlying "permanent" salt bed during the spring of 1981 created an irregular, hummocky surface on the playa floor with solution depressions up to 20 cm deep. By September these irregularities were refilled with newly precipitated salt.

The seasonal influx of water also transports clastic sediment to the basin and allows this material to be distributed and sorted within the lake. In most of the playas examined diffuse sheet flow is a more important clastic-sediment transportation agent than stream flow. Once in the lacustrine environment, the coarser fraction of the sediment is often reworked into small beaches and bars by normal shoreline processes, whereas the finer components are transported basinward and eventually deposited as thin mud laminae on the playa floor. It is likely that this deposition is aided by flocculation of the fines upon exposure to the saline waters.

Evaporation of the ponded water during summer lowers the level of the brine, subaerially exposing the margins of the basin and creating a mud-flat perimeter. The newly exposed mud flats often become encrusted with white, finely crystalline salts that are formed by the evaporation of brine films brought to the surface by capillary action and evaporative pumping. These efflorescent crusts, which can be up to 14 cm thick, have a distinctive bulbous appearance (Fig. 13) and are usually monomineralic. The crusts are dry and porous, and are easily eroded by wind or dissolved by runoff from a summer shower.

Two types of mud flats have been recognized in the playas studied: (1) saline mud flats and (2) clastic mud flats. The saline mud flat consists of fine-grained clastic sediment with crystals of sodium and (or) calcium sulfate minerals. These salts occur as displacive and (or) poikilitic crystal growths that have nucleated within the brine-saturated sediment after evaporation of the overlying lake water.

In several basins, such as Boot, Freefight, and Corral, this intrasedimentary precipitation of salts has resulted in a hard, cemented unit up to several metres thick at the perimeter of the mud flat. In other lakes, sand- and granule-sized, euhedral gypsum crystals are concentrated as lag deposits following drying and deflation of the playa surface. These grains then accumulate as small beach and dune deposits (Fig. 14).

The clastic mud flat is also dominated by fine-grained detrital material, but, in contrast to the saline mud flat, has no intrasedimentary salt crystals and usually only a very thin efflorescent crust. Desiccation cracks are common on the surface. These clastic mud flats are zones of shallow diffuse groundwater discharge; they remain water saturated and soft throughout the season, unlike the "dry mud flats" described by Hardie *et al.* (1978). Because this shallow groundwater seepage is relatively fresh compared with the lake brine, authigenic salt crystals and thick efflorescent crusts do not form.

Continued evaporation concentrates the remaining lake brine, which occupies the lower portions of the playa basin. As supersaturation is reached, nucleation and growth of crystals occur at the brine surface. Under calm conditions these crystals can be temporarily supported by surface tension (Fig. 15*A*) and sometimes coalesce into floating rafts (Fig. 15*B*). Wind may then drive large fragments of the rafts across the brine surface, eventually grounding the salt on the shore or on irregularities within the lake itself.

Wind also influences the distribution of brine in the playas. Several hours of moderately strong wind from one direction can displace the entire water body toward the downwind end of the basin. For example, on July 13 and 14, 1982, after several successive days of strong westerly winds, the upwind end of Vincent Lake was completely dry, whereas the downwind portion of the basin had up to 25 cm of brine. Six days later equilibrium had been re-established and the basin contained 6 cm of brine throughout. Whiting (1977) described the same phenomenon occurring regularly on Big Quill Lake and, likewise, Teller *et al.* (1982) described similar wind "setup" on a saline playa in Australia. Although further studies are needed, the importance of this process in the playas of the Great Plains appears to be at least twofold. (1) Wind-controlled placement of the brine can result in differences in thickness of salt from one end of a basin to the other. (2) If setup occurs in the latter stages of brine concentration, it is possible that the mineralogy of the evaporite deposits will be different from one end of the basin to the other, resulting in the less soluble salts occurring in the upwind direction and the more soluble precipitates concentrated in the downwind areas.

As the brine approaches saturation with respect to sodium sulfate, temperature variation assumes a significant role in conrolling salt precipitation and water chemistry. Between 10 and 30°C, the solubility of mirabilite increases rapidly with in-

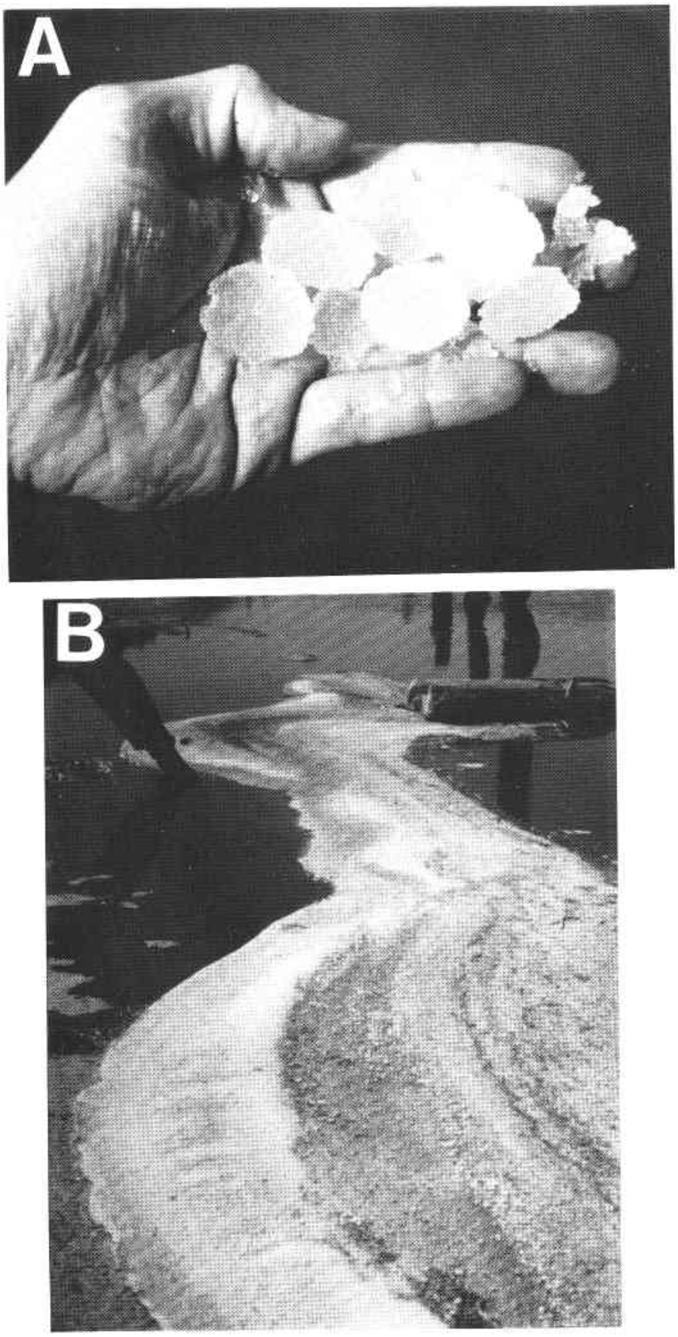

FIG. 16. (*A*) Mirabolites from Lydden Lake. (*B*) Beach of mirabolites from Lydden Lake.

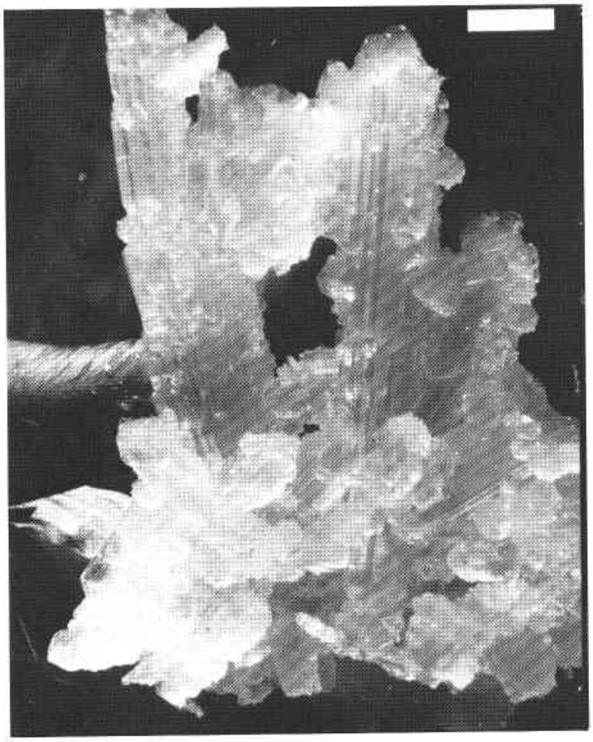

FIG. 17. Example of a large mirabilite crystal aggregate from Ceylon Lake. Scale bar = 5 cm.

creasing temperature (Fig. 5). Above this temperature the anhydrous phase of sodium sulfate (thenardite) is the stable precipitate. Thus, a shallow brine concentrated sufficiently to be near saturation during a warm summer day will likely form thenardite crusts during midday but will exhibit massive crystallization of mirabilite overnight as the temperature drops. An extended period of repeated diurnal alteration from brine to crystal may ensue depending on the rate of evaporation versus groundwater and surface water recharge to the playa. These processes are greatly enhanced by the presence of a common ion salt in the brine, such as sodium chloride or magnesium sulfate, which further lowers the mirabilite solubility and also decreases the transition temperature between the two metastable sulfate salts, mirabilite and thenardite.

The subaquatic playa floor during this period of near saturation with respect to sodium sulfate is quite dynamic. Spherical to ellipsoidal accretionary grains commonly form in the shallow, wave-agitated brine. These grains are similar to the halolites of the Dead Sea (Weiler *et al.* 1974) except they are considerably larger (4–20 mm in diameter, Fig. 16*A*) and are composed of mirabilite rather than halite. While some of these mirabilite ooids (termed "mirabolites") show an indistinct concentric or radial internal lamination, many are composed of a single, rounded mirabilite crystal. Angular overgrowths on the grains are common. During periods of high wind and wave conditions the mirabolites can form ripples, small dunes, and narrow beach ridges (Fig. 16*B*).

Equally noticeable during the latter stages of brine concentration is the rapid subaqueous growth of very large individual mirabilite crystals (Fig. 17). Single crystals up to 1.5 m in length have been observed to grow within a 48 h period in Boot, Vincent, Corral, and Ceylon lakes. In some cases the entire playa floor can be covered with a dendritic mosaic of giant interlocking mirabilite crystals.

The salt bed deposited by complete evaporation of the ponded water is variable in thickness but averages between 10 and 30 cm in most of the playas of the region. Cole (1926) reported "intermittent" crystal (= annual salt bed) thicknesses of up to 60 cm. These large thicknesses imply significant sedimentation rates but, in fact, much of this annual salt bed is redissolved each spring and early summer and overall net annual sedimentation rates may be much lower. Important exceptions occur when irregularities or depressions such as the previously mentioned solution pits are created in the playa surface. For example, observation pits up to 1.5 m deep in Boot, Corral, and Muskiki lakes were nearly completely filled with salt within a 2 month period and have remained salt filled throughout successive wet seasons.

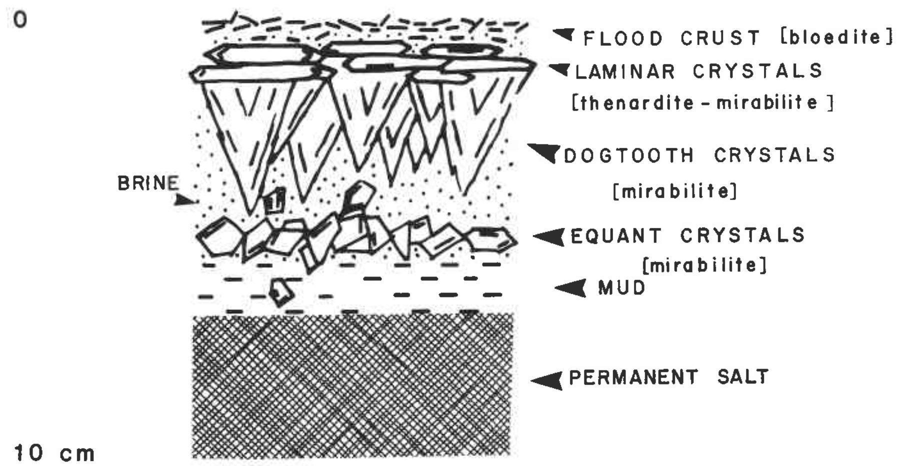

FIG. 18. Schematic profile of typical salt crust stratigraphy.

The annual salt beds are often crudely laminated. When viewed in cross section, this layering is enhanced by differences in crystal morphology, mineralogy, and, in some cases, the presence of thin, discontinuous mud interbeds. The salts of the uppermost crust are composed mainly of mirabilite except near the crust's surface where thenardite and bloedite predominate. Figure 18 shows a typical vertical section through the upper several centimetres of the salt-pan sediment. Simple removal of water by evaporation causes precipitation of a mirabilite crust consisting of either large, thin interlocking hopper crystals or fine, radiating, acicular crystals, depending on nucleus availability. The formation of this crust slows the rate of evaporation by isolating the underlying brine. Further slow precipitation within the saturated brine results in the formation of mirabilite in two modes: as large, pointed "dogtooth" crystals attached to the lower surface of the crust and as interlocking clusters of equant crystals growing at the base of the brine.

Thenardite is formed at the surface of the crust by either of two mechanisms: dehydration of the exposed surface to convert hydrous sodium sulfate to thenardite, or precipitation of the anhydrous form at elevated temperatures. The formation of mirabilite and (or) thenardite enriches the remaining brine in magnesium through preferential extraction of sodium. Leaking of this brine from beneath onto the surface of the crust inundates the crust with Mg-rich water, which then evaporates to precipitate a lamina of bloedite. The stratigraphy of this surface crust can be further complicated by temporary reflooding of the salt pan by summer rainfall or modification by wind.

If the evaporation/inflow ratio of the playa is sufficiently high, nucleation and displacive growth of crystals can occur within the mud underlying the crust. Handford (1982) discussed similar intrasedimentary precipitation in Bristol Lake, California, and outlined the complexity of the precipitation–dissolution events as the level of the brine fluctuates through the season.

Finally, a process unique to playas in cold climates is freeze-out precipitation of very soluble minerals. If summer evaporation of the brine is incomplete, mirabilite will precipitate when the brine cools during autumn and winter. The formation of an ice cover on the brine further concentrates the remaining Mg-rich solution, resulting in precipitation of epsomite. Muskiki and Lydden lakes have up to 30 cm of magnesium sulfate crystal overlying about 25 cm of mirabilite or thenardite during winter. In lakes that are characterized by relatively high concentrations of ions other than SO_4^{-2} (i.e., group I lakes in Fig. 11) this freeze-out concentration can result in the precipitation of various non-sulfate salts. For example, hydrohalite ($NaCl \cdot 2H_2O$), which, like mirabilite, shows a strong decrease in solubility with decreasing temperature, will precipitate from the chloride-rich brine of Patience Lake upon cooling during winter.

Summary and conclusions

The sedimentology of playa lakes in the Great Plains of western Canada and northern United States is poorly understood. Despite their abundance and their importance as a source of economic minerals, until now relatively little modern work has been done detailing the genesis and diagenesis of these deposits.

The playas of the northern Great Plains are generally small and of a non-tectonic origin in contrast to the well studied playa basins of western United States, Australia, or northern Africa. Although significant spatial and temporal variations exist, the brines are dominated by sodium, magnesium, and sulfate ions. The modern sediments are composed of variable proportions of very soluble and sparingly soluble precipitates, allochthonous material, and organic debris. Mirabilite typically constitutes over 90% of the soluble plus sparingly soluble precipitate fraction, whereas the mineralogy of the allochthonous component reflects that of the surrounding till: mainly quartz and smectite with minor amounts of feldspars and detrital carbonates. Many of the playa lakes sustain high levels of organic productivity, resulting in a high proportion of organic matter in the surface sediment.

Shallow auger holes and observation pits dug into the desiccated playas and limited coring show a stratigraphic sequence in which the upper "intermittent" evaporite crust overlies a massive salt unit, a black, reducing mud unit with abundant intrasedimentary salts, and finally a coarse clastic and (or) till unit. In some basins the massive salt unit can be very thick (45 m); in others it may be completely absent.

In terms of process sedimentology, the most important phenomena affecting the sediments of the playa lakes include: cyclic flooding (salt dissolution) and desiccation (salt precipitation); formation of efflorescent crusts and intrasedimentary salts by evaporative pumping; and periodic detrital sedimentation by sheet flow, stream flow, and wind. These processes combine to create a dynamic setting that fluctuates on a diurnal as well as seasonal basis.

It is evident from the discussion of these various modern processes that the sedimentology of the northern Great Plains playas is dynamic and relatively complicated. At present the most significant processes affecting the basins are mainly of a chemical nature and are associated with either evaporation or groundwater discharge. While many of the processes discussed above produce sediments and sedimentary features that likely have little chance of preservation, some are capable of having a significant impact on the sedimentary record of the basins. In particular, the creation of large dissolution pits or chimneys and the extremely high sedimentation rates over short periods of time are processes that must be considered in any interpretation of the evolution and postglacial history of these lakes based on their stratigraphic record.

Acknowledgments

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