*Sedimentology* (1989) **36**, 109–123

# Sedimentology of a saline playa in the northern Great Plains, Canada

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## ABSTRACT

Ceylon Lake, a small salt playa located in southern Saskatchewan, is typical of many shallow ephemeral lacustrine basins found in the northern Great Plains of western Canada. The present-day brine, dominated by magnesium, sodium, and sulphate ions, shows wide variation in composition and concentration on both a temporal and a spatial basis. The modern sediments overall exhibit relatively simple facies relationships. An outer ring of coarse grained shoreline and colluvial clastics surrounds mixed fine grained clastics and salts and, in the centre of the basin, salt pan evaporites composed mainly of mirabilite, thenardite, and bloedite.

Coring of the late Pleistocene and Holocene sedimentary fill shows that the lake has evolved from a relatively dilute, deep water, clastic dominated basin through a shallower, brackish water, carbonate–clastic phase, and finally into the present salt dominated playa. The thick sequence of evaporites preserved in the basin suggests evolution of the brine from a Na-rich solution to a mixed Mg–Na system. The most important post-depositional processes affecting Ceylon Lake sediments are mud diapirism and salt karsting.

## INTRODUCTION

The plains of western Canada contain hundreds of saline, hypersaline, and brackish-water lakes. These lakes range in size from small ($<1$ km$^2$) prairie 'potholes' to relatively large ($>300$ km$^2$) bodies of water. The shallowest lakes exhibit playa characteristics; they fill with water during the wet season, but dry up during the summer and fall. Glauber's salt (sodium sulphate) has been produced commercially from many of these playas since 1918. Total composite reserves for the region are among the largest in the world. Presently, about 400 000 tonnes of sodium sulphate are produced per year from the playas in western Canada, with the total value of this product exceeding $40 000 000 annually (Last & Slezak, 1987a).

Despite their economic importance, there is little modern sedimentological or geochemical data and essentially no stratigraphic information published about these playas. A knowledge of the sedimentary processes, mineralogy, and post-depositional alterations of the sediment is essential, not only to assess the present and future potential of the sulphate resource, but also to evaluate both the short-term changes and long-term evolution of the depositional system.

In addition to developing the required knowledge base for exploitation of the salts, investigation of these saline lakes is important for several other reasons. Although our knowledge of modern playa sedimentology and geochemistry has advanced considerably over the past decade (e.g., Eugster & Hardie, 1978; Hardie, Smoot & Eugster, 1978; Handford, 1981; Kendall, 1984), continental saline and hypersaline environments still represent one of the least understood depositional regimes in sedimentary geology. A study of the evaporite mineralogy and its relation to basin morphology, hydrochemistry, and brine evolution in the northern Great Plains will do much to advance our knowledge of terrestrial evaporite sequences. Because of the closed nature of the basins, the sediments in these playas may be a sensitive indicator of any changes in the hydrologic budget within each drainage basin. Thus, the stratigraphic record in the lakes should be a good reflection of past climatic fluctuations. Saline lacustrine deposits have played a pivotal role in helping deduce Quaternary palaeoclimates elsewhere in North America, Africa, Europe, Asia, and Australia (e.g. Stoffers & Hecky, 1978; Livingstone & van der Hammen, 1978; Smith, 1979; De Deckker, Geurts & Julia, 1979; Bowler, 1981). Finally, elevated levels of heavy metals such as copper, zinc, and lead have been reported from several of these deposits. Mining and extraction of the salts can release these elements, thereby creating a potential environmental problem.

The purpose of this paper is to discuss the modern sedimentology of one of these playa lakes, Ceylon Lake, and to interpret the postglacial evolution of this basin on the basis of the preserved stratigraphic sequence.

## METHODS

Water levels and brine chemistry of Ceylon Lake have been monitored since 1981. The modern sedimentary facies were mapped during the summer field seasons of 1982–1985. Grab samples of the surficial sediment were collected, along with water samples and various environmental data such as temperature, sediment colour, texture, crystal morphology and brine density. Shallow subsurface sediment samples (10–100 mm depth) were also collected. Cores were taken using a modified Livingstone piston sampler and a motorized rotary drill. Hand augering was used to further supplement the stratigraphic information and samples collected by coring. Soil samples were collected from the margins of the basin.

Sediment samples were analysed for bulk mineralogy, clay mineralogy, detailed carbonate mineralogy and detailed evaporite mineralogy by X-ray diffraction. Standard laboratory techniques were used to determine grain size, organic content and water chemistry. Grain size analysis was done using an automated X-ray particle size analyser (SEDIGRAPH); organic matter content was measured by loss on ignition, and elemental analyses were carried out by atomic absorption, gravimetric, and turbidimetric methods. The molalities and activities of chemical species in the brines and the saturation state of the waters with respect to a variety of mineral components was calculated using WATEQF (Rollins, 1987). Samples were also studied using scanning electron microscopy (SEM) and energy dispersive analysis (EDAX).

## SETTING

Ceylon Lake is located in the semi-arid Great Plains of western Canada (Fig. 1). The lake occupies a long, narrow closed basin that is incised some 60 m below the level of the surrounding hummocky terrain. Pleistocene glacial and fluvial deposits up to 30 m thick mantle the Tertiary and Cretaceous bedrock (Whitaker, 1974). The bedrock surface has been considerably modified by preglacial and glacial erosion. The Ceylon Lake basin occupies part of a north–south oriented preglacial drainage bedrock valley.

A summary of the morphological and hydrologic features of Ceylon Lake is presented in Table 1. Last & Schweyen (1983) and Last (1984, 1988) describe the regional geological, climatic, and hydrological setting of the saline lakes (including Ceylon Lake) of the Northern Great Plains. Cole (1926), Tompkins (1954), and Slezak & Last (1985a) review the mineral extraction potential of Ceylon Lake.

## HYDROLOGY AND HYDROCHEMISTRY

As with most of the playas and ephemeral lakes of the region, the water levels in Ceylon Lake vary considerably, usually on an annual basis. Water depths of up to 2 m can occur immediately after snowmelt in April or after heavy spring rainfalls. In most years the lake approaches dryness by August or September. Any water remaining in the basin after October is frozen until the next spring thaw. The typical annual cycle is

**Table 1.** Morphological, hydrological and chemical characteristics of Ceylon Lake.

Surface Area: 3·82 km$^2$
Drainage Basin Area: 125 km$^2$
Maximum recorded Water Depth (excluding karst features): 2·1 m
Average Annual Precipitation: 350 mm
Average Annual Evaporation: 920 mm

Brine Chemistry (mol/l):

| | May average (13 samples) | August average (21 samples) |
|---|---|---|
| Ca | 0·086 | 0·132 |
| Mg | 0·127 | 2·301 |
| Na | 1·117 | 1·150 |
| K | 0·020 | 0·480 |
| $SO_4$ | 0·237 | 0·398 |
| Cl | 0·107 | 2·541 |
| $HCO_3$ | 0·280 | 0·060 |
| TDS(ppt) | 68 | 241 |

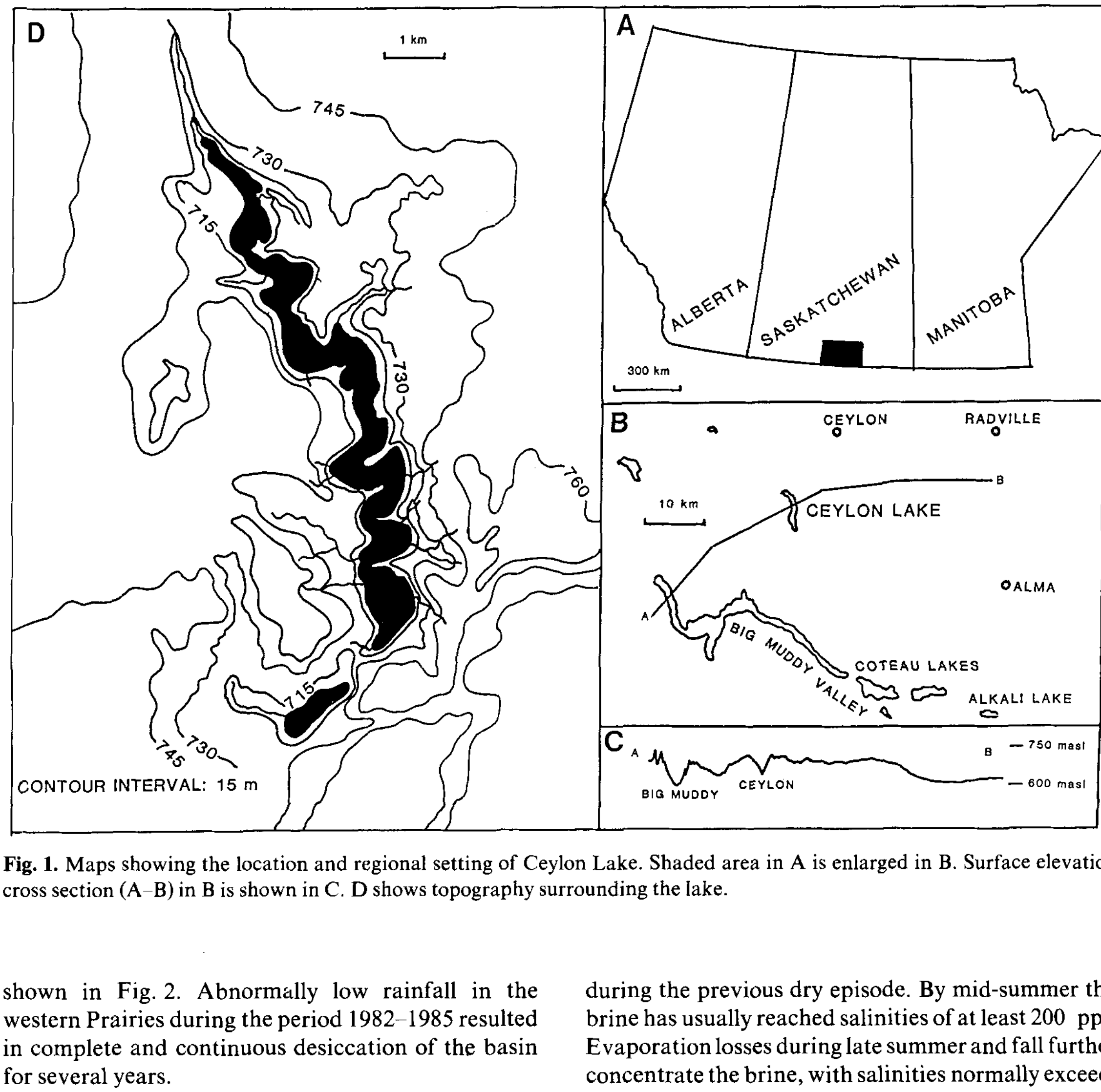


**Fig. 1.** Maps showing the location and regional setting of Ceylon Lake. Shaded area in A is enlarged in B. Surface elevation cross section (A–B) in B is shown in C. D shows topography surrounding the lake.

shown in Fig. 2. Abnormally low rainfall in the western Prairies during the period 1982–1985 resulted in complete and continuous desiccation of the basin for several years.

Water is delivered to the basin via numerous small, ephemeral streams, diffuse runoff, direct precipitation on the lake's surface and groundwater discharge. In normal years the groundwater contribution and evaporation are the largest components of the hydrologic budget.

Ceylon Lake brine is hypersaline and usually dominated by magnesium and sulphate ions (Fig. 3 and Table 1), although ion ratios and salinities vary greatly on a seasonal and spatial basis. Seasonal variation in salinity is brought about by the annual hydrologic cycle. Relatively dilute inflow from melting snow and rainfall quickly dissolves the very soluble sodium and magnesium salts that were precipitated during the previous dry episode. By mid-summer the brine has usually reached salinities of at least 200 ppt. Evaporation losses during late summer and fall further concentrate the brine, with salinities normally exceeding 300 ppt.

Because the dilute inflow waters are relatively rich in calcium and bicarbonate ions, during the early spring the lake can contain up to 20% equivalent $Ca^{2+}$ and 35% equivalent $HCO_3^-$. With increasing concentration, calcium and bicarbonate are lost through mineral precipitation, and the remaining brine becomes enriched in Na–Mg–$SO_4$–Cl. During the latter stages of desiccation massive quantities of sodium salts are precipitated, thereby leaving a Mg–$SO_4$–Cl rich brine.

Spatial variation in water chemistry occurs due to the distinct morphology of the playa basin. Even during very windy periods water circulation is re-

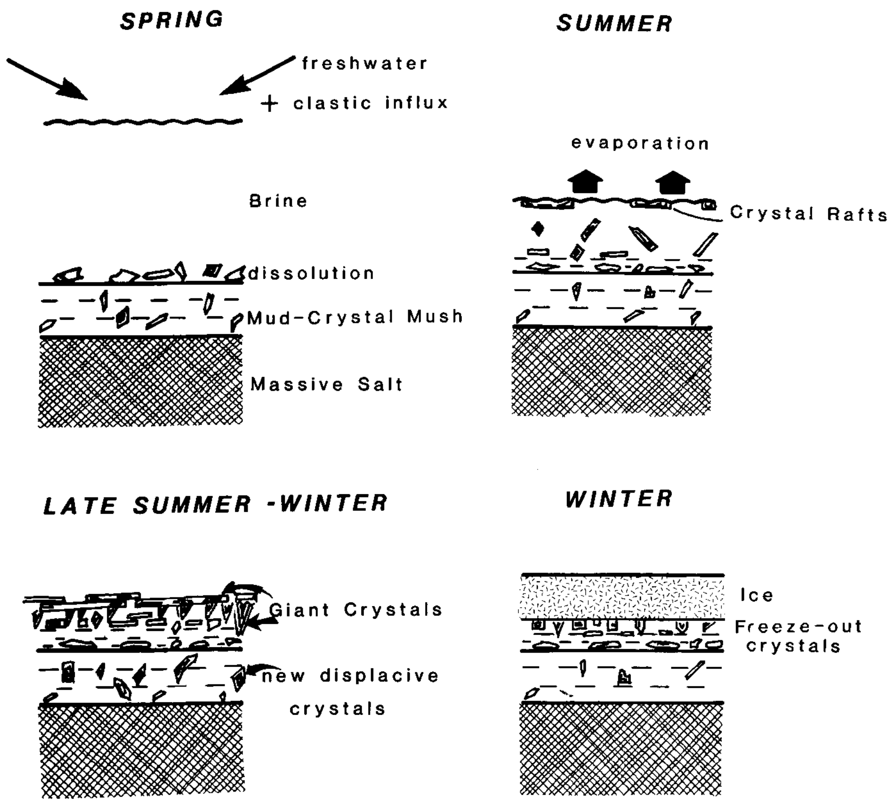


**Fig. 2.** Typical annual cycle in Ceylon Lake (see text for discussion).

stricted, resulting in slightly less saline brine at the northern end of the basin relative to that of the south (see Fig. 6 in Last, 1984).

During the final stages of lake drying the basin can still contain relatively large volumes of brine in a very porous salt crust. This crust dissolves and reprecipitates many times during the year in response to

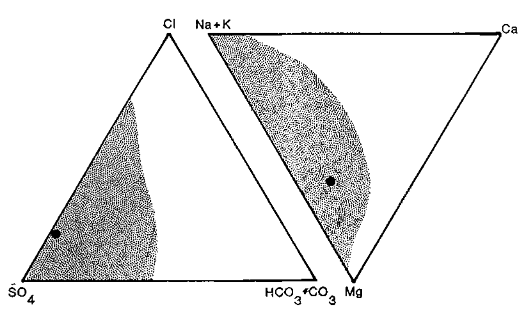


**Fig. 3.** Average water composition (mol %) of Ceylon Lake (black dots) and the range of compositions (shaded) of the brine.

temperature and humidity conditions. At the end of a warm summer day during which the water temperature may reach 45°C, the brine concentration is at a maximum. Because of the striking decrease in solubility of the hydrous sodium and magnesium sulphates with decreasing temperatures (see, for example, Cooke, 1981; Last, 1984), overnight cooling of the brine can result in large amounts of hydrous sodium and magnesium salts being precipitated. Crusts and crystalline aggregates up to 0·35 m thick can form over much of the basin floor in 6–8 hours. The hydrated salts making up these crusts (mainly mirabilite and bloedite) incorporate large quantities of water into their crystal structures and can temporarily 'solidify' the brine. With solar heating of the crusts the next day, some of the salts redissolve releasing the crystal water, and brine again covers the lake floor. Minor rainfall or groundwater inflow can prolong this daily cycle for several weeks to several months. Eventually, however, evaporation losses decrease the level of the brine to well below the salt crust surface and diurnal heating of the playa results only in dehydration of the salts. Further evaporation cements the upper 0·1–0·2 m of this crust, effectively sealing the underlying sediment and salt from desiccation. This seal also prevents surface water from infiltrating into the substrate.

## MODERN SEDIMENTS

Ceylon Lake is a salt dominated playa. The modern sediments consist mainly of highly soluble sodium and magnesium evaporitic salts, with secondary abundances of sparingly soluble carbonates and sulphates, clastic material and organic detritus. Several major environmental zones can be easily recognized in the basin, giving rise to six distinct sedimentary microfacies. These facies can be defined on the basis of texture, mineralogy, organic content, evaporite to clastic ratio, and crystal morphology. Although the facies are visually distinct and can be mapped (Fig. 4), facies boundaries are usually gradational.

### Shoreline/nearshore complex

#### *Colluvium facies (Fig. 5A)*

This facies occurs at the base of the steep slopes of the basin and usually grades laterally into the sand flat and mud flat facies. It consists of a chaotic mixture of coarse and fine clastic material that has been derived from the adjacent till banks by creep and mass wasting. Although usually thin (< 0·25 m), in places the colluvium can reach several metres in thickness. The upper several centimetres of the sediment is commonly coarse grained and well sorted and forms a thin cobble pavement at the surface. The colluvium has a low content of organic matter and moisture. Efflorescent crusts are rare. The mineral composition of the colluvium closely resembles that of the till. It is mainly composed of detrital clay minerals, carbonates, quartz, and feldspars. Minor amounts of diagenetic gypsum and calcite also occur.

#### *Mud flat/sand flat facies (Figs 5b, 6)*

This facies normally only occurs in a narrow band at the shoreline or edge of the lake. Ceylon Lake is somewhat unusual compared with other playas of the region in that large areas of mud flats are not present. True mud flats, characterized by fine grained clastics, abundant organic matter and indistinct lamination are rare in Ceylon Lake. Mud flat facies dominate at the northern end of the basin. Coarser grained sand flats are more common along the southern and western sides of the basin.

During high water levels in the lake the mud flats and sand flats are sites of clastic sedimentation from sheetwash and stream transport. The flats are exposed during lower water levels and quickly develop efflorescent crusts. These crusts, which can be up to 0·25 m thick, are mineralogically complex. Mirabilite, thenardite, epsomite, bloedite, halite, burkeite, and hexahydrite have been identified. Once formed, these crusts greatly hinder further evaporation from the underlying sediment, resulting in the mud flats and sand flats maintaining a high moisture content during the entire dry season. If the efflorescent crusts are removed by rainfall or wind, vegetation can quickly colonize the flats. However, extensive areas of vegetation and cyanobacterial mats such as reported in other playas of the region (Lieffers, 1981; Last, 1984; Last & Slezak, 1987b) do not occur at Ceylon Lake.

#### *Beach facies (Fig. 7)*

Although distinct wave-cut scarps and beach ridges occur on the steep walls of the valley several metres above the present level of the lake, the present-day strandline of the lake is poorly developed. Numerous low (< 1 m), indistinct and non-continuous beaches composed of rounded accretionary sulphate salt grains and crystals, organic debris and clastics can be present in a concentric pattern around the lake. These beaches are ephemeral and are usually best developed on the downwind (south and east) edges of the basin.

### Salt Pan Complex

Nearly 80% of the total area of Ceylon Lake is classified as salt pan facies. The salt pan is usually covered by brine for much of the year and is completely exposed only during the final stages of basin desiccation. Overall, this facies is characterized by high evaporite to clastic component ratios and low organic matter content. The salt pan sediments grade laterally into and interfinger with the mud flat and sand flat facies. Beach sediments can be found deposited directly on top of the salt pan evaporites.

The evaporite minerals making up this facies consist mainly of mirabilite, thenardite and bloedite. Epsomite, trona, and halite occur in lesser amounts. If brine remains in the basin after the onset of freezing conditions considerable thicknesses (10–50 mm) of

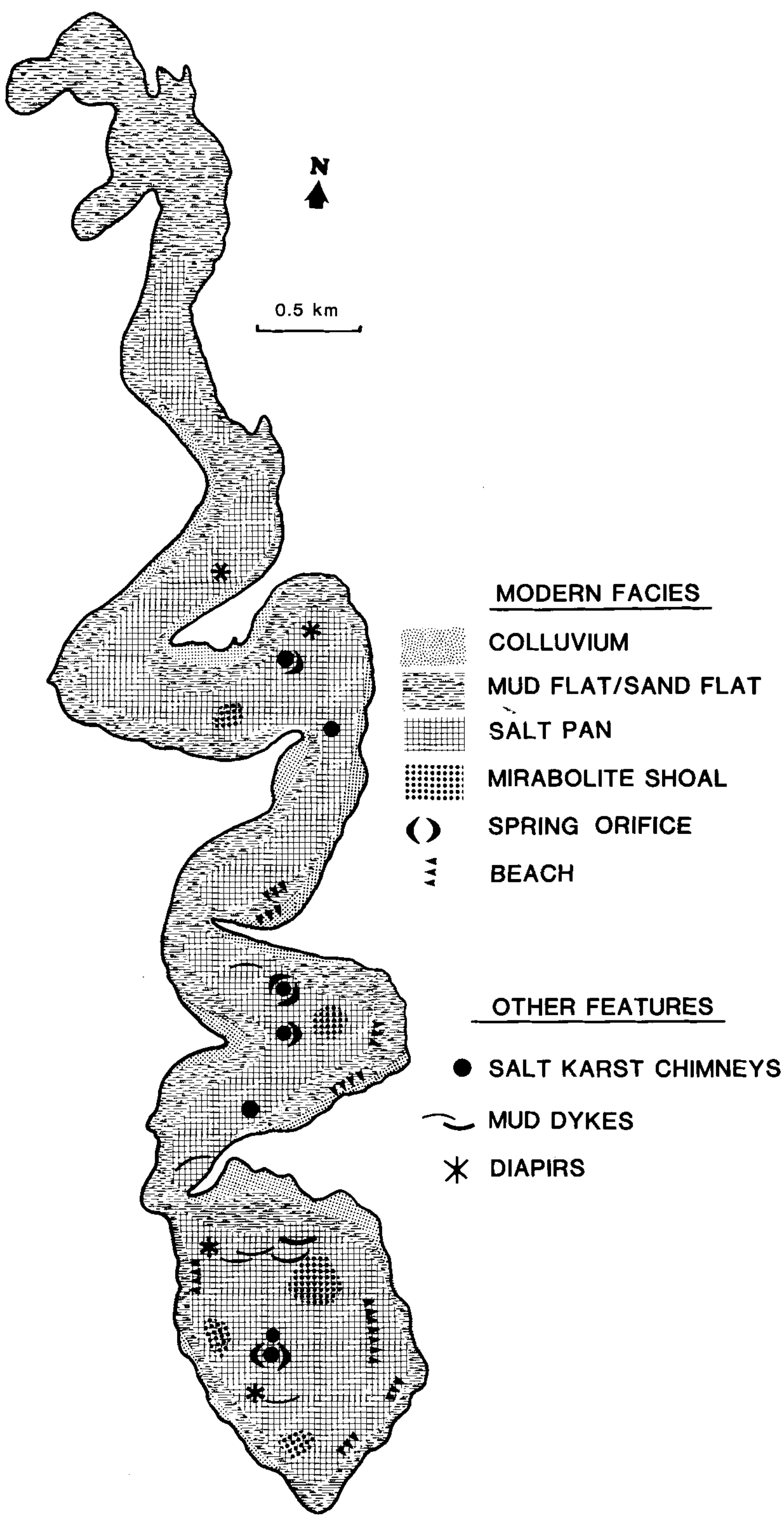


**Fig. 4.** Modern sediment facies of Ceylon Lake. Also shown are occurrences of salt karst chimneys and mud dykes/diapirs.

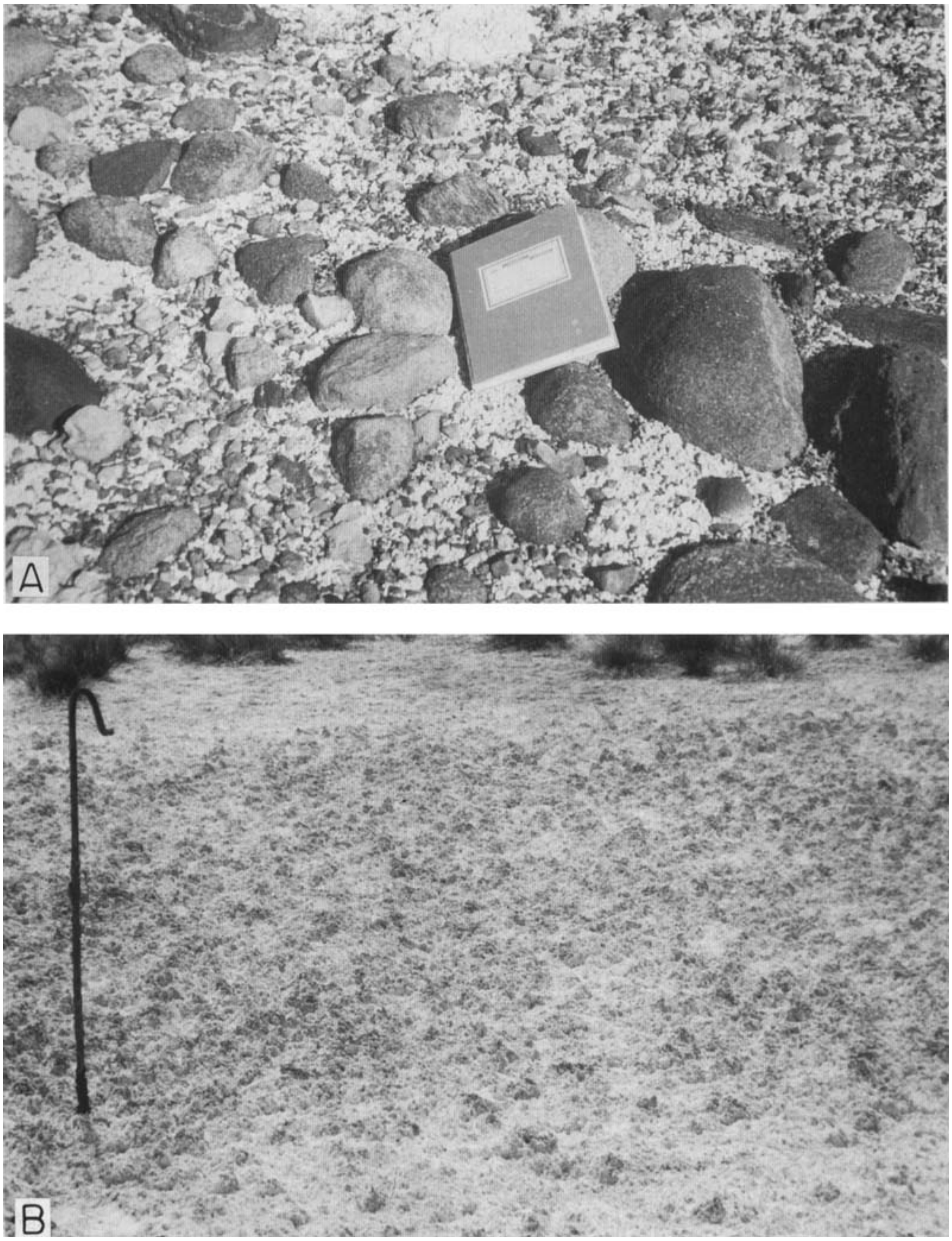


**Fig. 5.** (A) Poorly sorted colluvium near the edge of the basin. Notebook is 0·25 m long. (B) Efflorescent crust developed on top of the mud flat facies. Crust is 0·12 m thick. Pole is 0·70 m long.

**Fig. 6.** Mud flat facies at the north end of Ceylon Lake showing abundant mud cracks.

epsomite and hydrohalite can occur as winter freeze-out precipitates.

Several subfacies can be identified within the salt pan complex on the basis of mineralogy, crystal morphology and texture. Near the margins of the salt pan where the evaporites interfinger with clastics of the mud flat/sand flat facies, a zone of large dog-tooth crystals of mirabilite occurs (Fig. 8). These crystals grow displacively downward into the soft, water-saturated sediments of the mudflats. Upon complete desiccation, the crust of this subfacies is distinctly stratified. Within and directly on top of the mud flat sediment are aggregates of equant mirabilite crystals usually with abundant mud inclusions. The pyramidal dogtooth crystals of mirabilite overlie this. On top of these pointed crystals a thinner section of interlocking hopper and bladed mirabilite or thenardite crystals occur. Finally, at the top of the crust a very thin (< 20 mm) veneer of fine acicular bloedite crystals is found. The thickness of the entire crust ranges from 0·1 to 0·35 m. This type of mineralogical and morphological stratification of the evaporites has been found in many of the salt playas of the region and is described in detail elsewhere (Last, 1984). In Ceylon Lake the dogtooth crystal subfacies is found only in a relatively narrow band along the margin of the salt pan where the evaporitic crusts directly overlie mud flat clastics.

The evaporites on the floor of much of the salt pan away from the marginal areas consist mainly of a mosaic of large, interlocking, bladed crystals of mirabilite and thenardite. Single crystals up to 1·5 m in length have been found. These long, narrow and thin crystals form a reticulate to dendritic pattern over much of the salt pan floor (Fig. 9). In places aggregates of hopper and acicular crystals interrupt the network of bladed crystals. Although there is no distinct zone of hopper shaped crystals, the western and central portions of the basin consistently seem to have the greatest abundance. This is probably due to a wind shadow effect. The brine at the western edge of the lake, protected from the predominant westerly winds by the abrupt slopes of the basin, stays calm enough to allow floating rafts of hopper and acicular crystals to develop at the air–water interface. These rafts can move only short distances on the brine surface before sinking and being incorporated into the normal subaqueous precipitates. Hopper-shaped crystals and rafts of halite are a common occurrence in playas and sabkhas elsewhere (e.g., Teller, Bowler & Macumber, 1982; Shearman, 1978).

In areas of the salt pan that have slightly deeper brine, magnificent large aggregates of crystals can develop subaqueously. These crystal aggregates show radial and upward growth from the lake bottom. Upon complete drying of the basin, the aggregates are exposed, desiccated and somewhat eroded, leaving isolated lumps or mounds on the lake floor. In places on the salt pan these mounds can be so numerous as to give an undulating and hummocky appearance to the otherwise flat lake bed.

## Mirabolite Shoal Facies

Last (1984) described the occurrence and genesis of rounded accretionary mirabilite grains (pisolites and spherulites) that commonly form in the shallow salt lakes of the region. Several areas of these pisolites (termed mirabolites) occur in the central and southern parts of the basin. This facies generally consists of 0·05–0·2 m of loosely packed, well sorted accretionary grains. In some cases the grains are arranged in large-scale bed forms such as megaripples and low dunes.

**Fig. 7.** Low, indistinct beach developed at the south end of Ceylon Lake. Beach is composed mainly of rounded salt crystals and grains.

Most often, however, they occur simply as sheet-like accumulations with no obvious bed form character.

The grains themselves are relatively large (5–15 mm diameter), spherical to ellipsoidal, and have a blocky or platy surface texture. Most are true spherulites, lacking any observable nucleus. Because a shallow, saturated, and agitated brine is necessary for the formation of mirabolites, this facies is most often found in the downwind portion of the basin. Commonly subaqueous mirabolite shoals grade laterally into beach facies. Accumulations of mirabolites can occur on the salt pan or on the mud flat/sand flat facies.

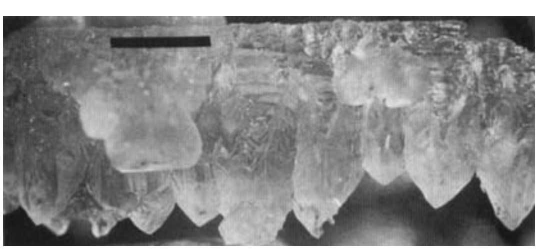

**Fig. 8.** Dogtooth crystals of mirabilite. Scale bar is 20 mm.

**Spring Orifice Facies (Fig. 10)**

In addition to diffuse ground water drainage into the basin and the occurrence of numerous springs on the valley slopes surrounding Ceylon Lake, there are several springs discharging directly into the lake. The sediments and evaporites associated with these springs are mineralogically and morphologically the most complex facies in the basin. Because the water of the sub-lacustrine springs is usually considerably cooler than the brine, large quantities of salts are precipitated around the spring openings. Mounds and pinnacles of mirabilite and bloedite up to 2 m high form on the floor of the lake (Cole, 1926; Last, 1988). Low ridges composed of a variety of carbonate and sulphate salts form in association with the spring orifices. Although most of the spring water is clean with little suspended sediment, some of the springs issue water highly charged with fine grained clastics. This clastic material quickly flocculates upon exposure to the saline brine and is deposited in mud mounds around the spring hole. These mud mounds can reach several tens of square metres in area and be up to 0·5 m high. During winter some of the springs remain active and build large cones of ice and salt on the surface of the frozen playa.

Fig. 9. Reticulate crystal pattern on the floor of the salt pan. Scale bar in foreground is 0·3 m.

Fig. 10. ridges of carbonate and sulphate minerals in the vicinity of spring openings. Width of ridge in foreground is approximately 0·1 m.

## SUBSURFACE SEDIMENTS

The postglacial sediments and stratigraphy of Ceylon Lake are known from 5 cores and 24 auger holes drilled in the basin. Some of the preliminary results of this stratigraphic sequence have been discussed elsewhere (Last & Slezak, 1988) and only a review will be presented here.

The postglacial sediment fill ranges from loose, unconsolidated sands and gravels to massive, well consolidated salt (Fig. 11). The nature and occurrence of these sediments is similar to that summarized by Last (1984) as a general facies model of salt playas in the Northern Great Plains.

### Till

The lowermost sediment penetrated in the basin is a gravelly clay loam diamicton. The poor sorting and non-laminated nature of this material suggest that it is ice laid (till). Similar sediment can be found underlying present day colluvium and soils on the slopes of the basin.

### Coarse sand and gravel

The sediments of this unit lie directly on top of the basal diamicton. They are generally brown to grey in colour, well sorted, and overall coarse-grained with little organic matter. This unit reaches a maximum thickness of greater than 2·5 m in the centre of the basin and pinches out laterally toward the east and west margins of the lake.

### Calcareous clay

This unit consists of grey to greenish grey clay and silt. Although not a marl, the sediment has up to 30% calcite and aragonite. Most of this carbonate material is bioclastic in nature and consists of fragments of ostracods, gastropods and Chara. The unit also contains some tufa and irregularly spaced carbonate

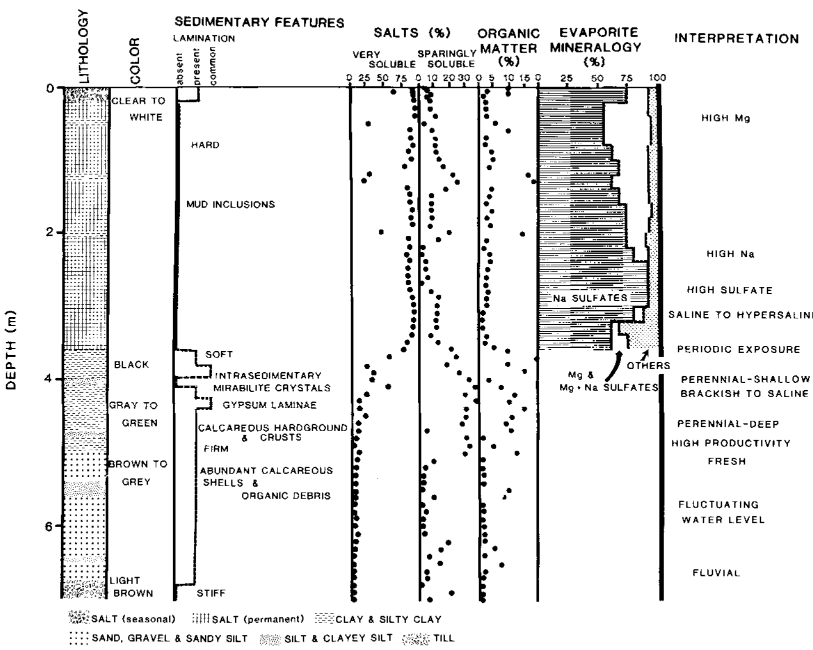


**Fig. 11.** Typical postglacial stratigraphic sequence from Ceylon Lake.

hardgrounds and crusts and gypsum laminae. Thickness ranges from 0·2 m near the basin margins up to 0·75 m in the lake centre.

### Black mud

The sediments of this unit are black, anoxic, fine-grained sand, silt, and clay. Very high moisture contents (50–80%) prohibit good core recovery. Intrasedimentary crystals of mirabilite and gypsum are abundant. Organic contents are high and the sediment has a strong $H_2S$ odour. This unit directly underlies and interfingers with the salt unit and can be traced laterally into the modern mud flat/sand flat facies of the nearshore complex.

### Salt

Volumetrically, this is the most abundant postglacial stratigraphic unit within Ceylon Lake. Similar to the modern salt pan sediments, it is composed of mainly mirabilite and thenardite but also contains appreciable amounts of gypsum, bloedite and epsomite. Natron and halite occur in trace amounts. The proportion of mirabilite plus thernardite decreases upward in the section from about 80 to 55% of the total soluble salt fraction. In contrast, the amount of Mg-bearing salts increases from less than 5% at the base to 25% near the top of the section. The salt is coarsely crystalline and massive.

## POST-DEPOSITIONAL MODIFICATION

In addition to facies control, several post-depositional processes are important in influencing the type, distribution and occurrence of sediment in the Ceylon basin. These additional controls are: (a) salt karsting and infilling of solution chimneys, and (b) mud diapirism. These processes are important because they can significantly disrupt large sections of the postglacial sediment fill in the basin, thereby making it very difficult to use a recovered stratigraphic sequence as a palaeolimnological tool (Slezak & Last, 1985b).

### Salt Karsting

Dissolution of the soluble crystal bed in Ceylon Lake by relatively dilute groundwater can create solution pits or chimneys in the salt unit. Seven such chimneys have been identified in the basin (Fig. 4). They range from 2·1 to 8·9 m in depth and from 9 to 46 $m^2$ in

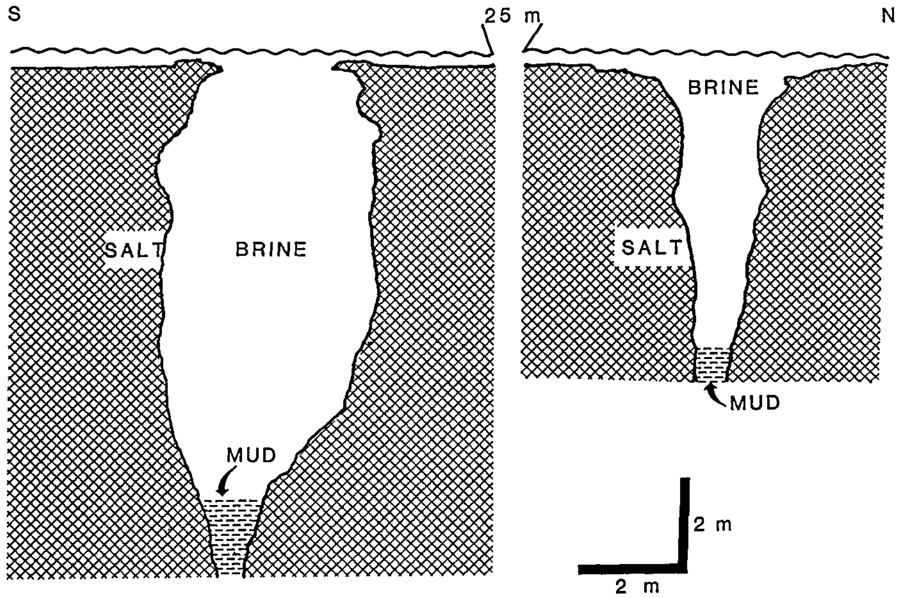


Fig. 12. Cross sections of the two salt karst chimneys located in the southernmost part of the basin.

Fig. 13. Mud dyke in Ceylon Lake.

surface area. Three of the seven pits have vertical walls with overhangs and ledges developed at depth (Fig. 12). The others have steeply sloping (but not vertical) walls.

Monitoring since 1981 shows that solution and refilling of these pipes can be extremely rapid and rather complex in detail. The chimneys can be filled with either freshwater or highly saline brine depending on the time of year and the hydrologic conditions of the basin. Likewise, the water columns within the chimneys can be either well mixed or thermally and chemically stratified. Two of the pits have formed within an 18 month period during 1983–1985. Conversely, one of the chimneys, originally 7·5 m deep, has been filled in with over 5 m of crystal and mud in a two year period.

## Mud Diapirism

Dykes and mounds composed of poorly sorted clastic material are present in the salt pan facies of Ceylon Lake. The dykes occur in a range of sizes, with widths from several centimetres to up to about one metre (Fig. 13). They are usually straight or very slightly curved, non-intersecting, and show a random orientation. The coarsest clasts in the dyke invariably show a preferred vertical orientation.

The intrusive mud mounds are less common than dykes in Ceylon Lake. They are usually small ($<30\ m^2$), low ($<0{\cdot}5$ m) and roughly circular in shape on the floor of the salt pan. Unlike the dykes, the clasts in the mounds normally do not show a vertical fabric.

The poorly sorted sediment of both the dykes and mounds can be modified when brought to the surface of the playa. Sorting by wave action during high water levels and by wind and sheetwash during subaerial exposure leaves a relatively coarse, well sorted gravel lag deposit on top of, and immediately adjacent to, the intrusion and a sheet-like deposit of finer clastics away from the site. This blanket of fines can cover large areas of the salt pan and can be up to several centimetres thick.

Although detailed excavation and analyses of these deformation structures is not yet complete, they are likely to be the result of liquefaction or fluidization of a water-saturated unit beneath the salt bed. The low permeability of the salt prevents normal diffusive pore fluid escape and sediment compaction. With continued deposition and loading of this underconsolidated unit, weaknesses in the salt are eventually exploited, and the liquefied sediment is injected into the salt bed until excess pore fluid pressures are dissipated.

## HISTORY AND EVOLUTION OF CEYLON LAKE

It is not yet possible to quantitatively reconstruct the water-level history or geochemical evolution of Ceylon Lake. The sediment fill in the basin is the result of a complex interplay of varying evaporation: precipitation ratios, quantity and chemistry of groundwater inflow, surface runoff and drainage basin characteristics, and major postglacial deformation. In particular, the implications of salt karsting and mud diapirism to stratigraphic interpretations have not been fully realized. However, the stratigraphy does record, in a general way, considerably differing depositional and hydrologic conditions and fluctuating water chemistries.

The Ceylon Lake basin originated as a glacial meltwater spillway about 15 000 years ago (Christiansen, 1979). The well sorted, coarse clastics immediately overlying ice laid deposits in the basin were probably deposited in this fluvial environment.

Due to slumping of the valley walls, differential isostatic rebound and decreased melt water flow, water gradually became ponded in the basin and lacustrine sedimentation began. The presence of calcite and the absence of Mg-bearing carbonates and other salts in the calcareous clay at the base of the lacustrine section suggests a relatively fresh low Mg/Ca ratio brine. High organic matter contents, abundant shell material, and a general lack of lamination indicate high levels of productivity and the presence of bottom dwelling organisms in this early phase. Carbonate-rich springs discharging into the lake probably built small tufa mounds and carbonate debris blankets in the basin.

With increasing aridity, the lake gradually became shallower and more restricted. The occurrence of carbonate hardgrounds, gypsum laminae and intrasedimentary salts suggest periodic desiccation and exposure. The increase in soluble salts versus clastics upward in the cores also points toward increasing salinity with time. The change from black silty clay upward into the salt unit marks the transition from a mud-dominated playa to a salt playa. The upward increase in Mg-bearing epsomite and bloedite at the expense of mirabilite suggests a shift in overall brine chemistry from a Na-dominated system to one of mixed Mg and Na. Because chronological control has not yet been established, little can be said of the temporal duration of these changes. However, the presence of a relatively thick salt unit implies hypersaline playa conditions have existed in the basin for some time.

## SUMMARY AND CONCLUSIONS

The Northern Great Plains of western Canada and northern United States exhibit a wide spectrum of saline lake types, ranging from shallow, ephemeral playa basins to deep perennial salt lakes. Ceylon Lake represents one end-member type in this continuum: a salt dominated playa. The sedimentological and geochemical study of this salt-dominated playa demonstrates the complex interaction that exists between the surface and groundwaters, and between the aqueous and mineral phases in this type of continental depositional setting. Although Ceylon Lake is one of only a few saline environments in this region that has been studied in detail, the sedimentary processes and resulting facies are probably representative of a large number of salt lakes in western Canada and northern United States, as well as of other semi-arid regions of South America, Africa, Asia and Australia. The major points summarizing this paper are as follows:

(1) The lake undergoes a distinct annual cycle

consisting of high water levels and salt dissolution during spring and early summer, followed by increasing brine concentration and eventual mineral precipitation during late summer–fall. Upon complete drying and desiccation, dehydration and mineral dissolution–reprecipitation in the upper several centimetres of sediment can create an impermeable cap which prevents further moisture loss by evaporation.

(2) During the period of study (1981–1987), the brine showed a considerable range of concentrations, compositions, and ionic ratios. In general, Ceylon Lake water is dominated by magnesium and sulphate. However, significant seasonal and spatial variations exist.

(3) The modern sediments in the basin can be divided into six distinct microfacies: (i) colluvium, (ii) mud flat/sand flat, (iii) beach, (iv) salt pan, (v) shoal, and (vi) spring orifice. The salt pan occupies nearly 80% of the total area of the basin and consists mainly of soluble Na, Na–Mg, and Mg sulphates.

(4) The general stratigraphic sequence of the postglacial fill in the basin consists of a lower coarse sand and gravel unit immediately overlying till, followed by calcareous clay, black mud, and, finally, a thick sequence of salt at the top of the section.

(5) Large-scale post-depositional modification of the sediments in the Ceylon basin has occurred. Salt karsting-infill and mud diapirism are the most important processes.

## ACKNOWLEDGMENTS

This sedimentological research on Ceylon Lake is supported by grants from the Natural Science and Engineering Research Council of Canada, Energy, Mines and Resources of Canada, and Canadian Plains Research Center. Thanks are also extended to L. Slezak for valuable discussions and assistance in the field and laboratory. Earlier versions of this paper were improved by the comments of Drs P. De Deckker, H. Dronkert, and B. C. Schreiber.

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*(Manuscript received 11 November 1987; revision received 27 April 1988)*