GEOCHEMISTRY AND MINERAL FORMATION IN THE EARTH SURFACE

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SEDIMENTOLOGY, GEOCHEMISTRY, AND EVOLUTION OF A SALINE PLAYA IN THE NORTHERN GREAT PLAINS OF 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 sulfate ions, shows wide variation in composition and concentration on both a temporal and 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 center 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 evaporties 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, filling with water during the wet season, but drying up during the summer and fall. Glauber's salt (sodium sulfate) 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 sulfate are produced per year from the playas in western Canada, with the total value of this product exceeding $40,000,000 annually (Slezak and Last, 1985).

Despite their economic importance, there is little modern sedimentological or geochemical data and essentially no stratigraphic information published on these playas. A knowledge of the sedimentary processes, mineralogy and post-depositional alterations of the sediment is essential not only to assist the present and future potential of the sulfate 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 the saline lakes is important for several other reasons. Saline and hypersaline lacustrine environments 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 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. 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 moblize these elements, thereby creating a potential environmental problem.

The purpose of this paper is to discuss the modern sedimentology and hydrochemistry 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.

1. 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

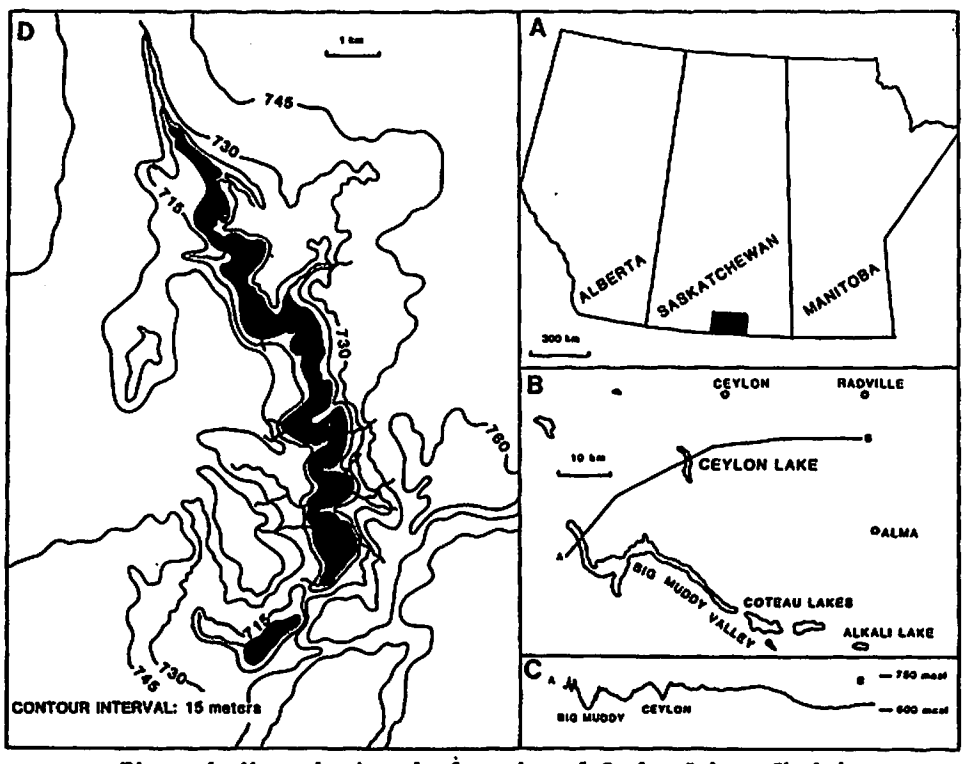


Figure 1: Maps showing the location of Ceylon Lake. Shaded area in A is enlarged in B. Surface elevation cross section (a-b) in B is shown in C. D shows topography surrounding the lake. North is to the top on all maps.

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 and Schweyen (1983) and Last (1984) describe the regional geological, climatic and hydrologic setting of the saline lakes (including Ceylon Lake) of the Northern Great Plains. Cole (1926) and Tompkins (1954) review the mineral extraction potential of Ceylon Lake.

TABLE 1 Morphologic, Hydrologic & 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

2. HYDROLOGY AND HYDROCHEMISTRY

As with most of the playas and intermittent 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 September or October. Any water remaining in the basin after October is frozen until the next spring thaw. The typical annual cycle is shown in Figure 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 sulfate 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

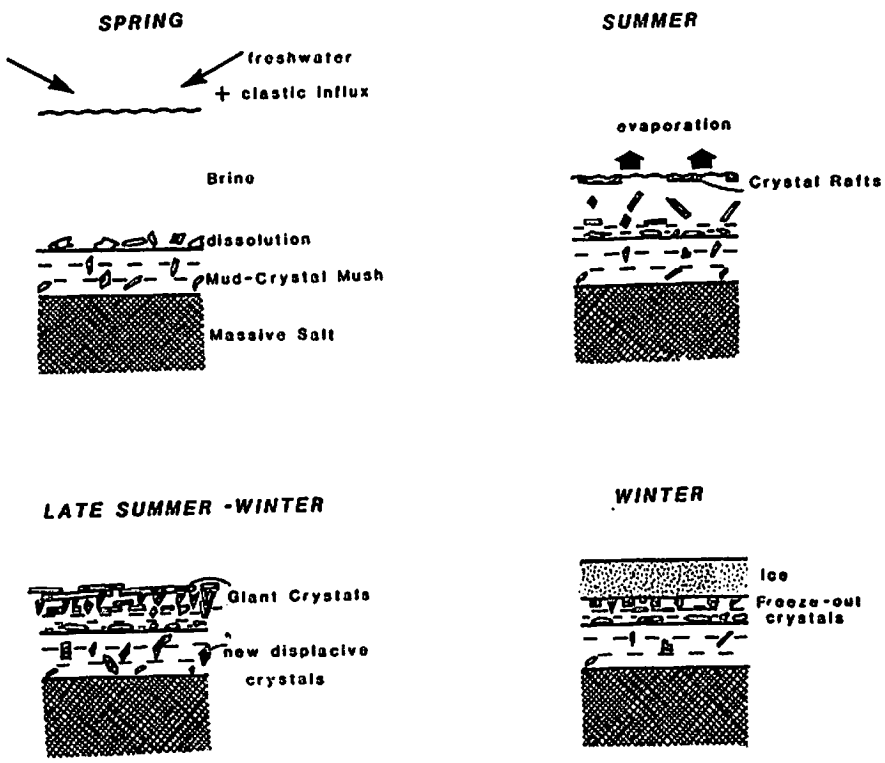


Figure 2: Typical annual cycle in Ceylon Lake.

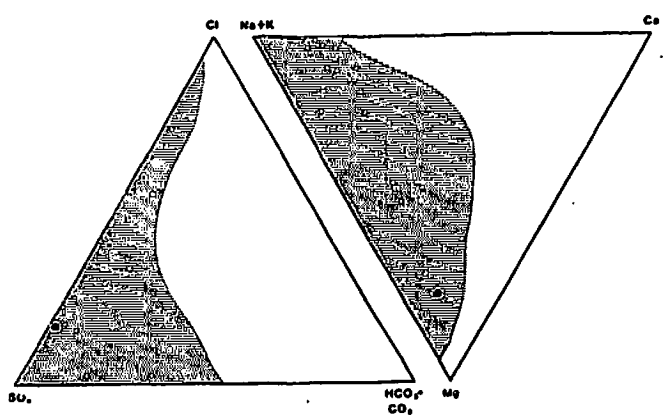


Figure 3: Triangular diagrams showing the average water composition (mol%) of Ceylon Lake (black dots) and the range of compositions (shaded) of the brine.

percent equivalent Ca and 35 percent 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 restricted 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 temperature and humidity conditions. At the end of a warm summer day in which the water temperature may reach 45°C, the brine concentration is at a maximum. With overnight cooling large amounts of hydrous sodium and magnesium salts precipitate. Crusts and crystalline aggregates up to 35 cm 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 structure 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 10-20 cm of this crust, effectively sealing the underlying sediment and salt from desiccation. This seal also prevents surface water from infiltrating into the substrate.

3. 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 sulfates, clastic material, and organic detritus (Fig. 4). Several major environmental zones can be easily recognized in the basin, giving rise to six distinct sedimentary facies. These facies can be defined on the basis of texture, mineralogy, organic content, evaporite to the clastic ratio, and crystal morphology. Although the facies are visually distinct and can be mapped (Fig. 5) facies boundaries are usually gradational.

3.1 Shoreline/Nearshore Complex

(a) Colluvium facies (Fig. 6a): 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 (< 25 cm), in places the colluvium can reach several meters in thickness. The upper several centimeters of the sediment is often coarse grained and well sorted and forms a thin cobble pavement at surface. The colluvium has low organic matter and moisture contents. Efflorescent crusts are rare. The mineral composition of the colluvium closely resembles that of the till: mainly detrial clay minerals, carbonates, quartz and feldspars. Minor amounts of diagenetic gypsum and calcite also occur.

(b) Mud flat/sand flat facies (Fig. 6b and c): 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. Mud flat facies dominate at the northern end of the

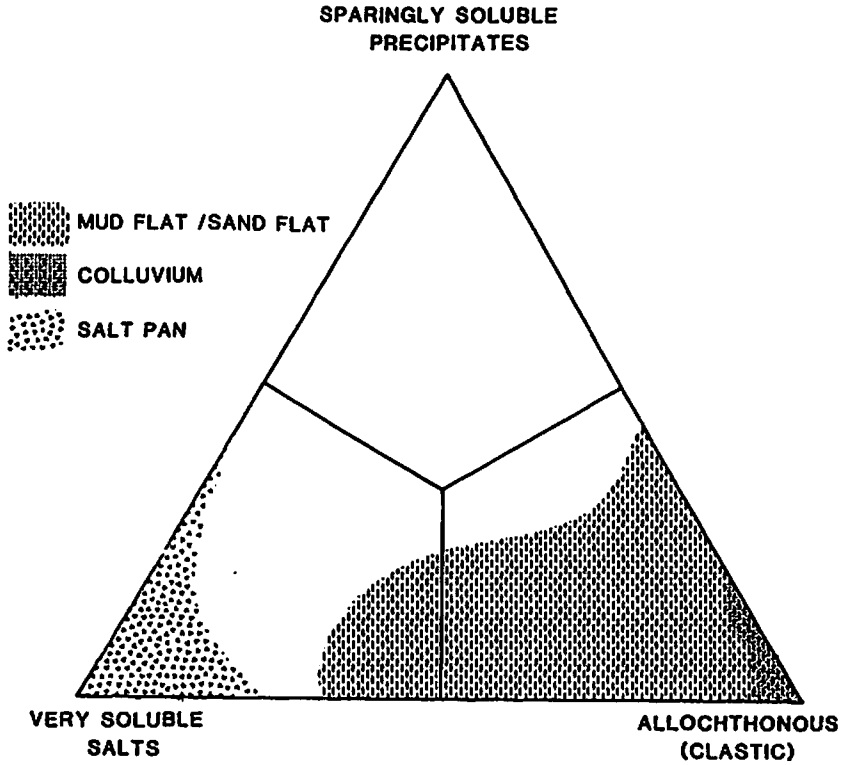


Figure 4: Triangular diagram showing the proportion of the main sedimentary components in various facies types of the modern sediment. Very soluble salts include any material soluble in warm water; sparingly soluble salts include any material which dissolves in dilute acid; allochthonous material is the residue after water and acid treatment.

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 25 cm 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 mats such as reported in other playas of the region (Last, 1984; Lieffers, 1981) do not occur at Ceylon Lake.

(c) Beach facies (Fig. 6d): Although distinct wave cut scarps and beach ridges occur on the steep walls of the valley several meters 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 salt grains and crystals, organic debris

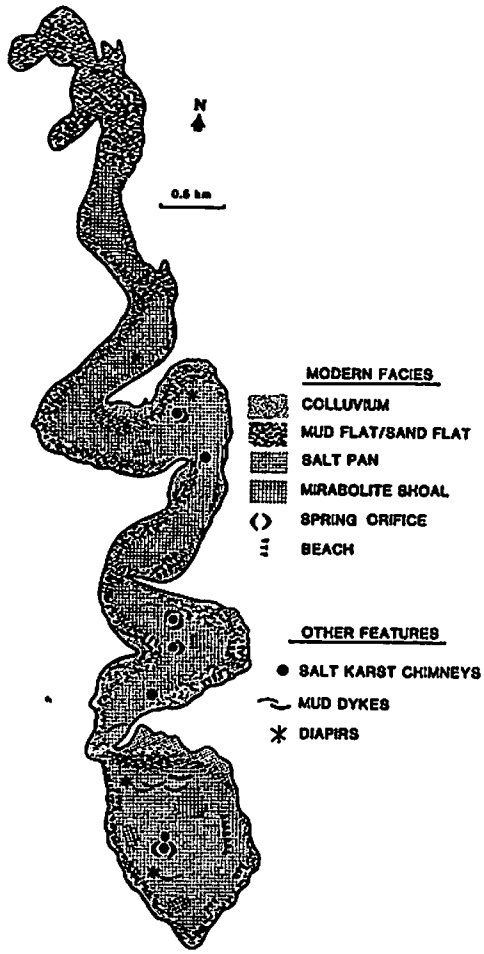


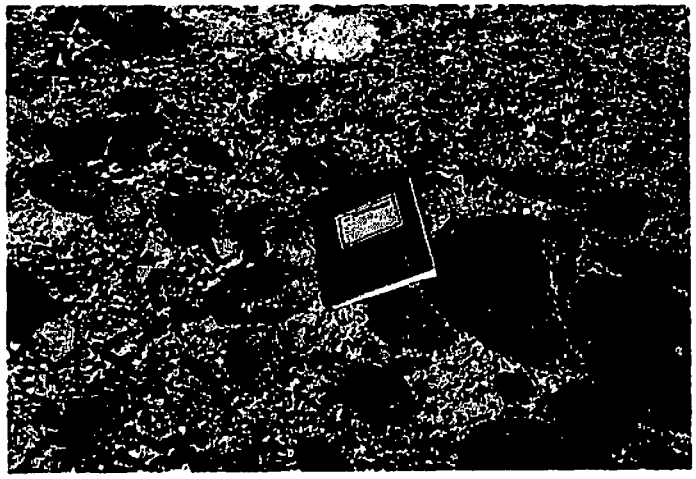
Figure 5: Modern sediment facies of Ceylon Lake. Also shown are occurrences of salt karst chimneys and mud dykes/diapirs.

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.

3.2 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, being 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 contents. The salt pan sediments grade laterly 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 (1-5 cm) of epsomite and hydrohalite



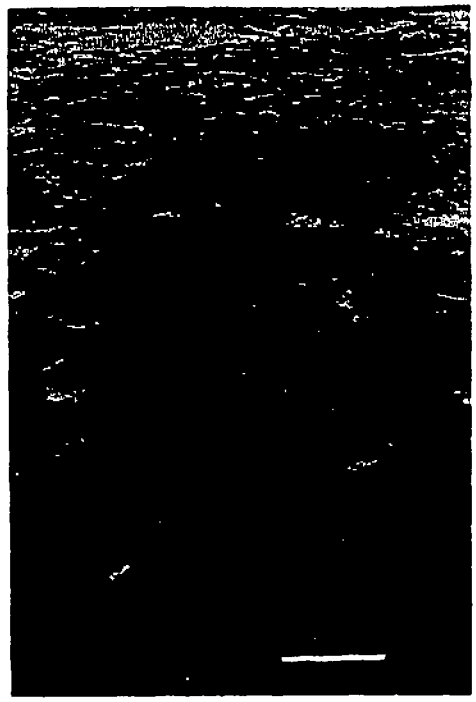


Figure 6: Examples of modern sediment facies in Ceylon Lake.
(A) Poorly sorted colluvium near the edge of the basin. Notebook is 25 cm long.
(B) Mud flat facies at the north end of Ceylon Lake showing abundant mudcracks.

Figure 6: Examples of modern sediment facies in Ceylon Lake.
(C) Efflorescent crust development on top of mud flat facies. Crust is 12 cm thick. Pole is 70 cm long.
(D) Low, indistinct beach developed at the south end of Ceylon Lake. Beach is composed mainly of rounded salt crystals and grains. Scale bar in foreground is 35 cm.

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. 7a). These crystals grow displacively downward into the soft, water saturated sediments of the mudflats. Upon complete desiccation, the

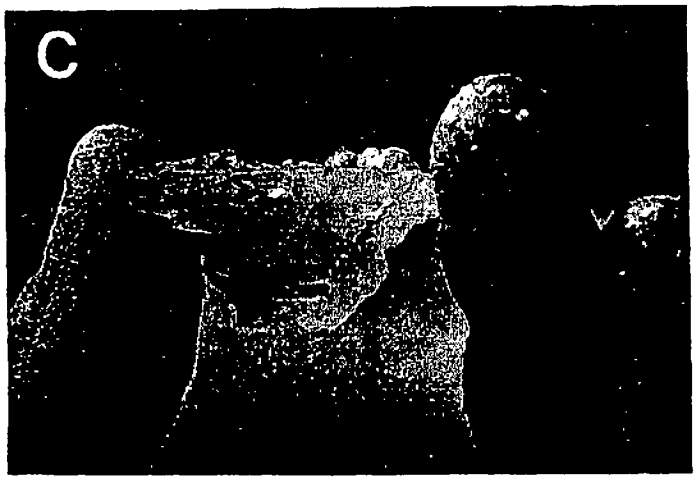
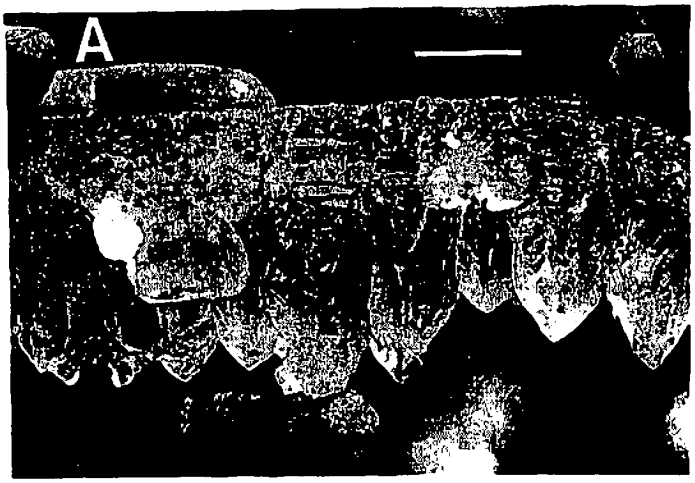


Figure 7 (con't): (C) Hopper-shaped mirabilite crystal. (D) Subaqueous crystals growth on the floor of the salt pan. Floating matchbook is 3.5 cm wide.



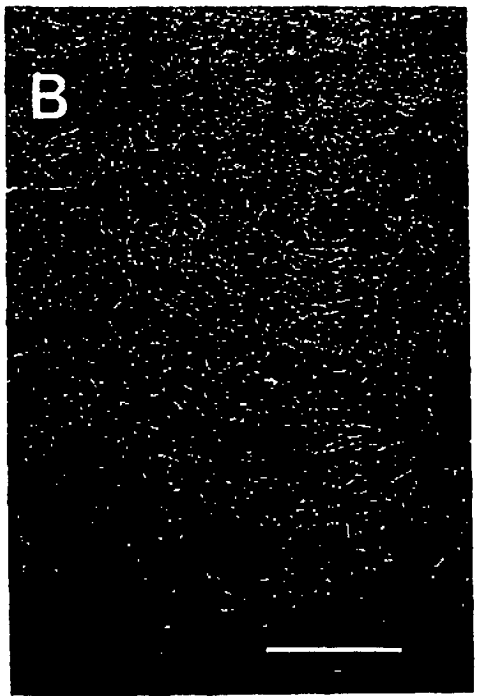


Figure 7: (A) Dogtooth crystals of mirabilite
(B) Reticulate crystal pattern on the floor of the salt pan.
Scale bar in foreground is 30 cm.

crust of the 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 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 (< 2 cm) veneer of fine acicular bloedite crystals is found. The thickness of the entire crust ranges from 10 to 35 cm. 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. 7b). In places aggregates of hopper and acicular crystals interrupt the network of bladed crystals (Fig. 7c). Although there is no distinct zone of hopper shaped crystals, the western and central portions of the basin seem to consistently 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 predominent 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.

In areas of the salt pan that have slightly deeper brine, magnificant large aggregates of crystals can develop subaqueously (Fig. 7d). 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 hummoky appearance to the otherwise flat lake bed.

3.3 Mirabolite Shoal Facies (Fig. 8a)

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 consist of 5-20 cm of loosely packed, well sorted accretionary grains. In some cases the grains are arranged in large-scale bedforms such as megaripples and low dunes. Most often, however, they occur simply as sheet-like accumulations with no obvious bedform character.

The grains themselves are relatively large (5-15 mm diameter), spherical to ellipsoidal, and have a blocky on 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. Often subaqueous mirabolites can occur on the salt pan or on the mud flat/sand flat facies.

3.4 Spring Orifice Facies (Fig. 8b)

In addition to diffuse groundwater 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. 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. Low ridges composed of a variety of

Figure 8: (A) Mirabilite shoal. (B) Ridges of carbonate and sulfate minerals in the vicinity of spring openings. Width of ridge in foreground is approximately 10 cm.

carbonates and sulfate 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 meters in area and be up to 50 cm high. During winter some of the springs remain active and build large cones of ice and salt on the surface of the frozen playa.

4. SUBSURFACE SEDIMENTS

The postglacial sediments and stratigraphy of Ceylon Lake are known from five cores and 24 auger holes drilled in the basin. Some of the preliminary results of this stratigraphic sequence have been discussed elsewhere (Last and Slezak, 1986) and only a brief review will be presented here.

The postglacial sediment fill ranges from loose, unconsolidated sands and gravels to massive, well consolidated salt (Fig. 9). 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.

(1) Till: The lowermost sediment penetrated in the basin is a gravelly clay loam diamicton. The poor sorting and nonlaminated nature of this material suggests that it is ice laid. Similar sediment can be found underlying present day colluvium and soils on the slopes of the basin.

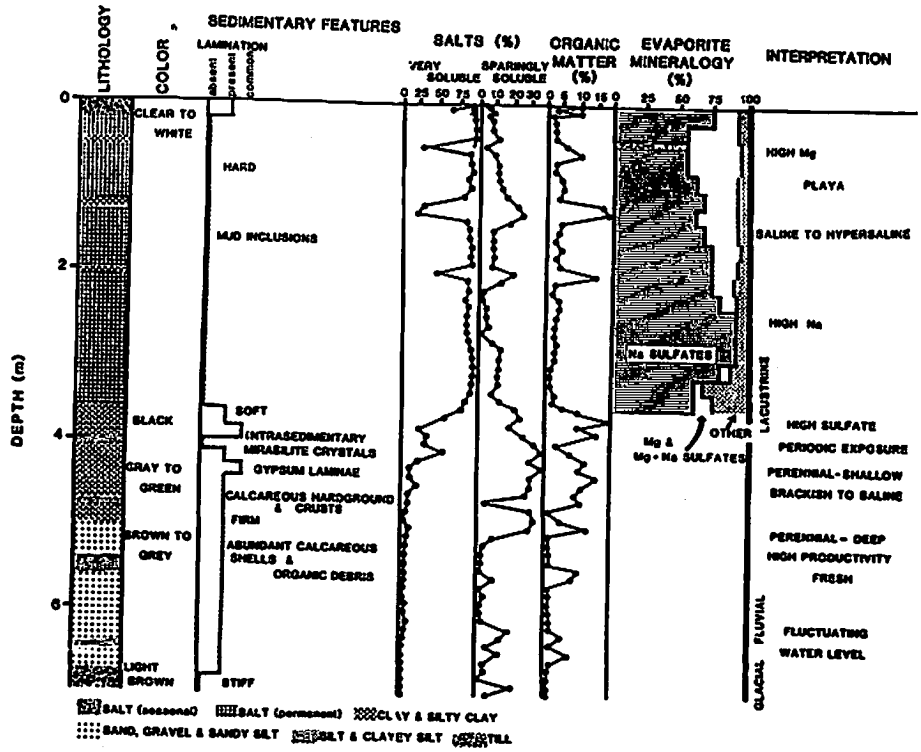


Figure 9: Typical postglacial stratigraphic sequence from Ceylon Lake.

(2) Coarse Sand and Gravel: The sediments of this unit lie directly on top of the basal diamicton. They are generally brown to grey in color, well sorted and overall coarse grained with little organic matter. This unit reaches a maximum thickness of greater than 2.5 m in the center of the basin and pinches out laterally toward the east and west margins of the lake.

(3) 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, consisting of fragments of ostracods, gastropods and Chara. The unit also contains some tufa and irregularly spaced carbonate hardgrounds and crusts, and gypsum laminae. Thickness ranges from 20 cm near the basin margins up to 75 cm in the lake center.

(4) 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 odor. 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.

(5) 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 thenardite decreases upward in the section from about 80% to 55% of the soluble salt fraction. In contrast, the amount of Mg-bearing salts increases from less than at the base to 25% near the top of the section. The salt is coarsely crystalline and massive.

5. POST-DEPOSITIONAL MODIFICATION

In addition to facies control, several post-depositional processes are important in influencing the type, distribution and occurence 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 paleolimnological tool.

5.1 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. 5). They range from 2.1 to 8.9 m in depth and from 9 to 46 m^2 in surface area. Three of the seven pits have vertical walls with overhangs and ledges developed at depth (Fig. 10). 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 juring 1983-1985. Conversely, one of the chimneys, originally 7.5 m deep, has been filled in with over 5 m of the crystal and mud in a two year period.

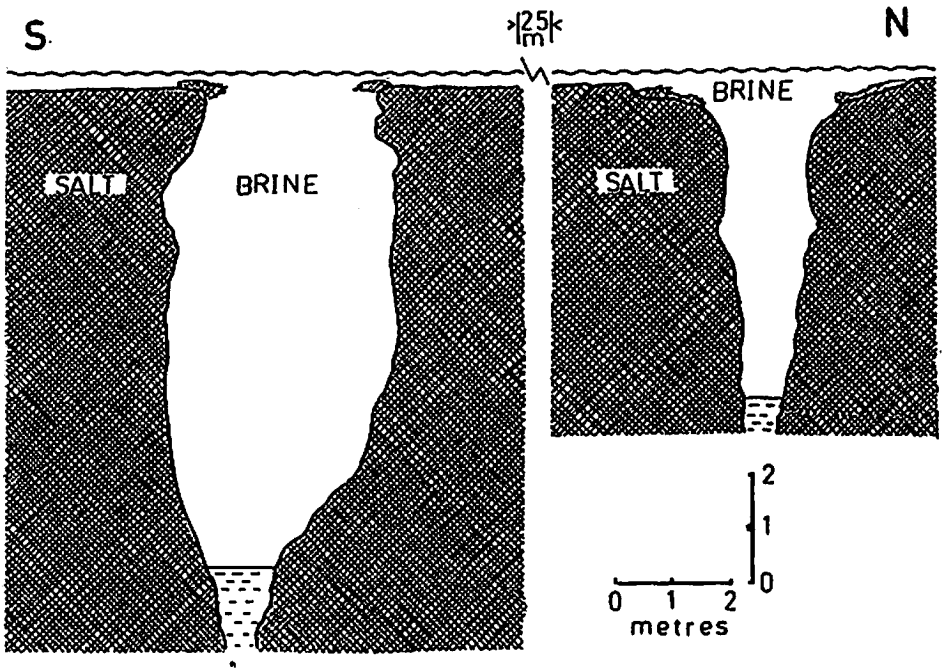


Figure 10: Cross sections of the two salt karst chimnys located in the southernmost part of the basin.

5.2 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 centimeters to up to about one meter (Fig. 11). 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 that dykes in Ceylon Lake. They are usually small (< 30 m^2), low (< 50 cm), 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 suaerial 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 centimeters thick.

Although detailed excavation and analyses of these deformation

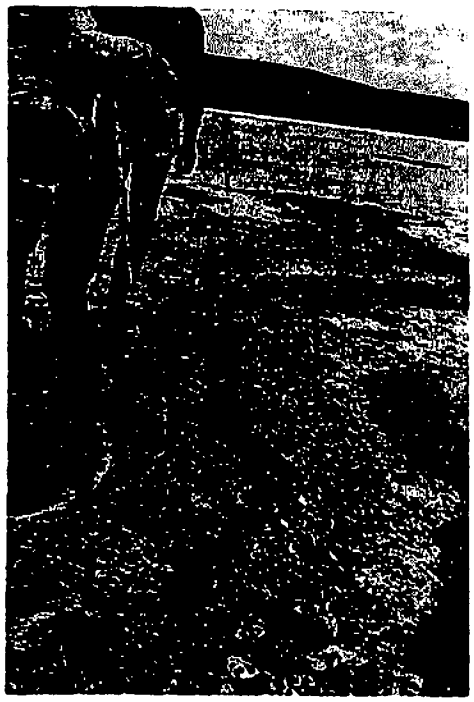


Figure 11: Mud dyke in Ceylon Lake

structures is not yet complete, they are likely the result of liquefaction or fluidisation 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 liquified sediment is injected into the salt bed until excess pore fluid pressures are dissipated.

6. HISTORY AND EVOLUTION OF CEYLON LAKE

It is not yet possible to reconstruct the water-level history or geochemical evolution of Ceylon Lake quantitatively. 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 meltwater flow, water gradually became ponded in the basin and lacustrine sedimentation began. The presence of calcite and 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 content, 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 core also points toward increasing salinity with time. The change from black silty clay upwards 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.

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