Palaeogeography, Palaeoclimatology, Palaeoecology, 76 (1990): 215 240
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa

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(Received August 14, 1989)

Abstract

Teller, J. T. and Last, W. M., 1990. Paleohydrological indicators in playas and salt lakes, with examples from Canada, Australia, and Africa. Palaeogeogr., Palaeoclimatol., Palaeoecol., 76: 215–240.

The sedimentary records of playas and salt lakes provide some of the best evidence for hydrological change in a region. These records are comprised of siliciclastic sediments and chemically-precipitated minerals that typically vary temporally and spatially. In some cases, the interpretation is straightforward, with mineralogical sequences related to changing brine concentrations and hydrology, as well as to climate. In other cases, it is difficult to identify the controlling factors, which include climate, groundwater, geological setting, and basin morphology. In addition, diagenesis commonly affects the sedimentary record.

Models of lake level fluctuations are given for basins in the Canadian Prairies and southeastern Australia. The Lake Manitoba model is based mainly on secondary changes associated with pedogenesis that alters the deeper-water sediment during low water stages. Smaller Canadian lakes in more arid regions display a larger variety of diagnostic paleohydrological indicators, such as specific carbonate and salt mineralogy, nature of bedding, grain size, and secondary alterations. Decreasing water levels in shallow lakes tend to show a progression from clastics to carbonates, to salts, and then back to clastics as groundwater levels fall below the lake floor. Similar parameters are used in Australian lakes. The hydrological model for the Lake Tyrrell playa in Victoria, whose present ionic composition is similar to seawater, shows clastics being deposited when average lake levels are high, followed by deposition of primary carbonates, gypsum, and halite; once seasonal drying on the lake floor begins, secondary gypsum grows within already-deposited sediment, and clay pelletization in the capillary fringe of surface sediment leads to basin deflation and the accumulation of adjacent eolian lunettes. Continued water level decline leads to pedogenesis. Subsequent lake level rises in all of these models may initiate sedimentation in any part of the hydrological cycle, and a complete cycle in the sedimentary record appears to be uncommon.

Introduction

Lakes with chemical concentrations of greater than 3 g l^{-1} (brackish to hypersaline) occur on every continent and have a volume similar to that of freshwater lakes (Williams, 1986). Most of these lakes lie in closed basins — those depressions that have no surface outlet and which are "terminal" in terms of runoff within a catchment — and occur in arid to subhumid regions where evaporative concentration is greatest. As a consequence of hydrological "closure", lake levels fluctuate, sometimes rapidly, and the sediments in such basins commonly are sensitive records of climatic conditions. Although the literature on the sedimentology and history of brackish to hypersaline (salt) lakes is small compared to that of freshwater lacustrine environments, considerable advances have been made within

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the past several decades. Studies of modern saline systems have furthered our understanding of the physical, chemical, and biological processes in these lake basins and have led to the interpretation of the ancient records of playas and saline lake basins.

The aim of this paper is to illustrate, with examples from Canada, Australia, and Africa, how selected physical, chemical, and mineralogical parameters of playa and salt lake sediments can be used to interpret past hydrological conditions in the basin, and to highlight some of the limitations that are inherent in evaluating the non-biological record in these basins.

Our examples span a variety of common perennial and ephemeral brackish to saline lake types, and include systems dominated by detrital (mainly siliciclastic) material and those dominated by minerals formed chemically within the basin such as carbonates and gypsum. The stratigraphic record of most ephemeral lake basins consists of a variety of sediment types, and clastics, carbonates, and salts commonly change in relative proportion through time in the sequence. In some cases the components change spatially within the basin, reflecting differences in water depth or circulation, surface runoff, local or regional groundwater contributions, turbidity, organic activity, or geological province.

Examples are selected mainly from our own research; they certainly are not the only examples of a particular geological, geochemical, and hydrological environment, and may not even be the best. We do feel, however, that they represent a spectrum of lacustrine conditions from some of the more common physico-chemical systems of playas and salt lakes. The literature on this subject is growing exponentially, and our discussion of environmental indicators is only intended to familiarize the reader with some of the possible ways to recognize paleohydrological changes in perennial and ephemeral salt lake basins where evaporation losses normally exceed additions by runoff and precipitation. To attempt more would require a discussion of textbook proportions.

Paleohydrological indicators

A number of recently published research papers and symposia volumes have reviewed the field of paleohydrology (e.g., Gregory, 1983; Berglund, 1986). As pointed out by Dearing and Foster (1986), historically much of the paleohydrological effort has been directed toward fluvial deposits and river channel morphology. However, because lakes are more or less continuous sinks for sediment they can likely provide the most detailed paleohydrological stratigraphic record of all terrestrial environments (Dohrenwend et al., 1986).

There is a wide variety of evidence that has been used to reconstruct the hydrological cycle and budget in lacustrine systems (see, for example, Richardson, 1969; Eugster, 1982; Haworth and Lund, 1984; Street-Perrott and Harrison, 1985; Torgersen et al., 1986; Gray, 1988). Complex geochemical systems and evaporite mineralogies have been discussed by many (e.g., Hardie et al., 1978; Nissenbaum, 1980; Watson, 1983; Eugster and Kelts, 1983; Sonnenfeld, 1984; and Hardie, 1984), and some have been related to the climate and hydrology of the lake basin. Because our objective is primarily hydrological, not geochemical, we use the specific mineralogies of lacustrine sequences mainly to help decipher lake level fluctuation.

Parameters commonly used to interpret hydrological changes in lake basins include geomorphological indicators of lake level changes, such as raised or submerged strandline features and the elevation of lacustrine sediment, allochthonous and autochthonous sediment character (including grain size, sorting, mineralogy), and facies patterns.

The sedimentary record of a lake basin is a function of many physical, chemical, climatic, and hydrological factors. Furthermore, short term, rare events may play a major role in the hydrology of a lake and, in turn, may greatly affect its sedimentary record. Although commonly regarded as continuous, lacustrine records in saline and ephemeral systems probably are only representative of a fraction of the history of the basin. Periods of non-deposition and deflation during desiccation, as well as re-solution of salts, are known in many playa basins to have resulted in unconformities. The record in deep parts of the basin, where water may remain for long periods of time, normally will be different from that in shallower areas, which are subjected to more frequent drying as well as different energy conditions. In basins with flat floors, the stress of wind shear over shallow bodies of water may maintain a brine in one end of the basin during a given period of salt precipitation, while preventing any record of that period from forming at the other end (see Teller et al., 1982, figure 6; Torgersen, 1984; Longmore et al., 1986). Localized geochemical conditions within a lake, such as at river mouths or spring sites may lead to localized mineral precipitation or biological activity (Dean and Fouch, 1983; Renaut et al., 1986).

Post-depositional alteration of a sedimentary sequence by, for example, oxidation of organics, sulfate reduction by bacteria or the activity of other micro-organisms, diffusion, solution, and various diagenetic processes is increasingly being recognized as important (Gauthier, 1986; Drever, 1988).

In some basins, sedimentation is controlled largely by events far removed from the lake, such as in the headwaters of rivers, or, in the case where regional groundwater systems are involved, even in areas far outside of the river catchment itself. Furthermore, closed basins underlain by permeable beds and a deep groundwater table may never allow chemical precipitates to form because any brine formed may sink below the basin surface before crystallization can occur; thus, many playas contain only siliciclastic sediments. Lake Chad, for example, even though now only a fraction of its former size, is not highly saline, probably because the dense brine infiltrates its permeable bed (Greer, 1977).

Not withstanding these problems, the geochemical and mineralogical records in closed continental lacustrine basins have been shown to be useful indicators of changes in the ionic composition and concentration which are commonly related to fluctuations in the hydrological budget of the lake (e.g., Cerling, 1979; Smith, 1979; Spencer et al., 1985). It is important to remember, however, that most geochemical techniques assume a direct relationship between lake volume and salinity, which during a hydrological "cycle" may deviate substantially (Street-Perrott and Harrison, 1985). Compositional reconstructions of lake water can be particularly explicit when based on combined geochemical and mineralogical investigations, as demonstrated by Smith (1979), Smith et al. (1983), Eugster (1986), and Tiercelin et al. (1987). It must be emphasized that *saline* lake sediments are very attractive in this regard because not only are the composition and mineralogy of these endogenic and authigenic evaporites useful, but even their mere *presence* can provide specific and unambiguous data on the chemical composition of the formative lacustrine brine or pore water (Wasson et al., 1984). However, differentiating between endogenic and authigenic precipitates is both difficult and necessary. Radiometric and stable isotope data can sometimes be used to assist in making this crucial distinction (Talbot and Kelts, 1986). Equally important, isotopic studies have been frequently applied to lacustrine sequences in order to evaluate biological productivity, temperature, evaporation/precipitation ratio, and source of lake waters (Pearson and Coplen, 1978).

Even seemingly simple physical hydrological relationships, such as between grain size and water depth, must be used with caution. Although grain size and sediment distribution in a lake basin may be controlled by water depth, other factors commonly come into play because they influence current and wave energy distribution; these may result from either shallowing or deepening of waters. Water depth itself need not be related to climatic change, with which it is so commonly associated, and changes in size of the catchment, erosion of the overflow outlet, or progressive sediment infilling of the basin may be the governing factors.

Therefore, an increase in grain size in a sedimentary sequence may represent any one of many possible changes in the system which leads to greater energy being imparted to the lake floor, and may or may not be linked to shallowing water: (1) an increase in aridity, (2) infilling by sediment, (3) erosion of the basin outlet, (4) an increase in wind strength, or (5) a greater wind fetch resulting from a deepening of water, shift in wind direction, or erosion of morphological impediments (island, headland, rooted organics). Of course, an increase in surface runoff may also produce an increase in grain size, but even simple relationships between increased rainfall and influx of sediment to the lake basin are only possible in arid regions because of the increasing role that healthy vegetation plays in retarding sediment yield from a watershed in a wetter climate (e.g., Langbein and Schumm, 1958; Schumm, 1965).

Brackish to saline lakes of the Canadian Prairies

Introduction

The Great Plains of western Canada and northern United States form a unique setting for thousands of brackish, saline, and hypersaline lakes. Salinities range from nearly fresh in the wetter (eastern) and cooler (northern) areas to hypersaline in the most arid southwestern part of the region. Many of the lakes are small (<1 km^2), but the region also contains several of North America's largest inland salt and brackish water bodies. Because these saline and brackish lakes are frequently the only surface water present in the region, they have been the subject of substantial research efforts from biologists, limnologists, and water resource managers (e.g., Rawson and Moore, 1944; Rutherford, 1970; Crowe, 1972; Whiting, 1977; Hammer, 1978; Hammer and Haynes, 1978; Lieffers and Shay, 1983; Kenny, 1985; Hammer and Heseltine, 1988). Similarly, due to the presence of thick deposits of evaporitic salts and commercially extractable brines, mineral resource experts have actively investigated the lakes (Cole, 1926; Tomkins, 1954; Grossman, 1968; Rueffel, 1968; Broughton, 1984; Last and Slezak, 1987). Only recently have investigators been turning their attention toward the stratigraphic records in these basins in an effort to interpret past hydrological conditions of the lakes and watersheds.

Last and Slezak (1988) provide an up-to-date synopsis of paleolimnological research in the Great Plains region of western Canada. The Holocene sediment records from Lakes Wabamun, Ste. Anne, Isle, and Hastings, all located near Edmonton, Alberta, have been subjected to some of the most detailed paleolimnological analyses in North America. The geochemical, biostratigraphic, and isotopic sequences from these lakes have been interpreted in terms of fluctuating water levels, rates of organic productivity, and watershed stability (e.g., Hickman et al., 1984; Holloway et al., 1981; Fritz and Krouse, 1973; Hickman and Klarer, 1981; Forbes and Hickman, 1981; Vance et al., 1983).

The sedimentary record of lakes in the Canadian Prairies is largely a function of the modern and past climatic history of the region. Climate has controlled sedimentation in nearly all basins, beginning with the early postglacial clastics deposited as the Laurentide Ice Sheet retreated from the region 10,000–15,000 years ago (e.g., Teller, 1987) and continuing through the mid-Holocene dry period (Hypsithermal) and the more recent slightly cooler and wetter phase. The climatic changes in the Prairies and the adjacent northern Great Plains of the United States have long been known from pollen studies (e.g., Wright, 1970; Ritchie, 1976; Bernabo and Webb, 1977; Delcourt et al., 1982; Webb et al., 1983) and from general sediment characteristics such as pedogenic horizons.

In the western Prairies, which have throughout the postglacial period been more arid, lake waters have tended to be more saline, and some basins have remained dry for long periods, whereas to the east, basins only occasionally were desiccated and most remained brackish or even fresh throughout the postglacial period. The chemical nature and concentration of waters in most of these lakes has been a function of climate and, in some cases, of groundwater. Where the upper aquifer of an area influenced lake hydrology, climate may have had a direct influence on the brine concentration and chemistry. Deeper, regional aquifers, however, contain waters originating many hundreds of kilometers away that have passed through several geological provinces over thousands of years of time (Fritz et al., 1974), so they cannot be used to decipher short-term temporal climatic changes in the lake and its catchment.

We have chosen several examples of lake basins that have responded to climatic and hydrological changes in the Prairies, and which exemplify several types of geochemical systems and sedimentological regimes (Fig.1). Lake Manitoba is a large lake in the wetter eastern part of the region, whose waters have remained brackish throughout much of its history. The sedimentary record of this basin has been studied in detail, and the hydrological history of the basin has been well established using that record. To the west, Ceylon Lake is a typical example of a much smaller Prairie playa in the drier region that has been more responsive to hydrological changes. Waldsea Lake, in central Saskatchewan is also small, but is contrastingly deep and is chemically stratified (meromictic). Nearby Deadmoose Lake is similar in many ways to Waldsea Lake, but is used to illustrate how sedimentary records can be quite different under seemingly similar hydrologic conditions.

Lake Manitoba

Lake Manitoba lies in the eastern part of the Prairies (Fig.1) in an area which today receives 500 mm of precipitation, and has 600–700 mm of pan evaporation (CNC/IHD, 1978). It is one of the largest lakes in North America (4706 km^2), but is extremely shallow, having a maximum depth of 6.3 m and a mean depth of only 4.5 m.

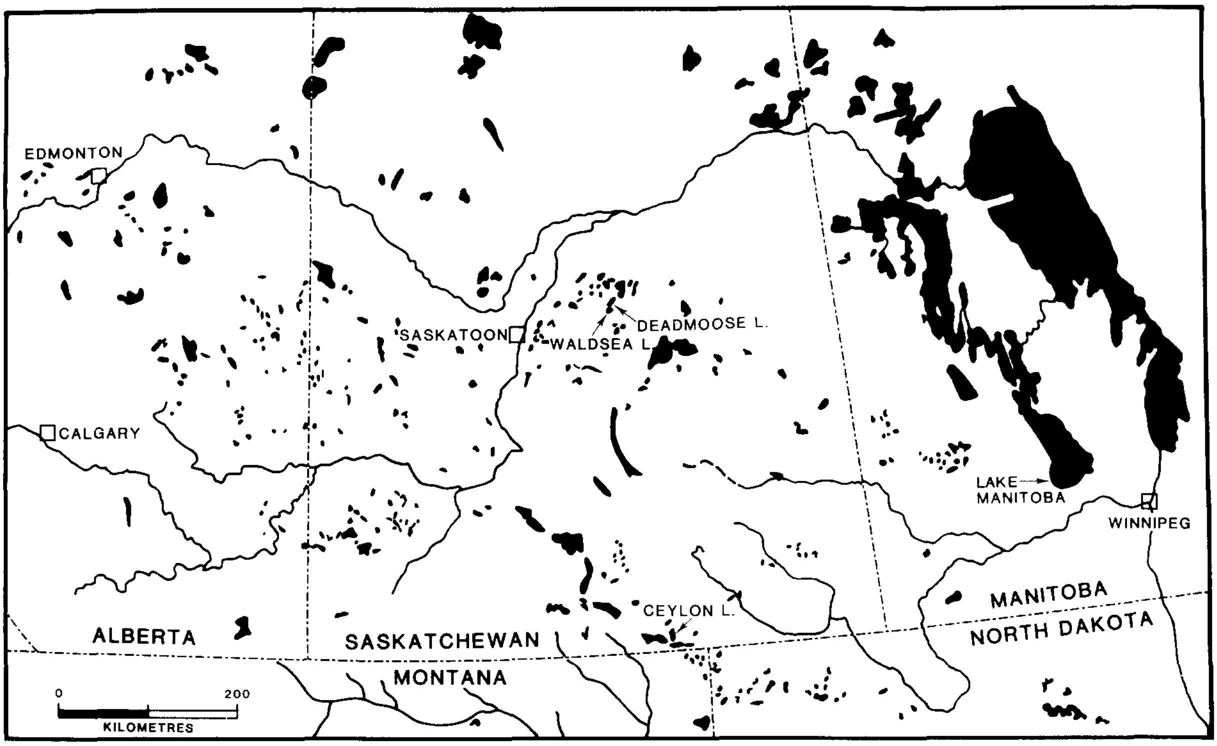

Fig.1. A map of the western Canadian Prairies showing the locations of the lakes discussed in this paper.

Its catchment extends from central Saskatchewan, 400 km to the west, and covers over 80,000 km^2. Today the lake is brackish (3 g l^{-1} TDS), with groundwater supplying only 6% of its water budget (International Garrison Diversion Study Board, 1976) but substantially influencing the ionic composition of the lake. The 12,000-year stratigraphic record of Lake Manitoba, which began when the lake was part of giant proglacial Lake Agassiz, has been studied in detail by Teller and Last (1979, 1981), Last and Teller (1983), Last (1982), and Nambudiri and Shay (1986). A number of sediment parameters have been used to deduce the hydrological history of the basin and to relate it to paleoclimatic changes known from elsewhere in the region.

One physical parameter used to identify low water stages in this shallow basin was low moisture content in the silty clay sequence. Distinct declines in pore water content, typically 30–40%, are scattered throughout the early to mid-Holocene period, 9000 to 4500 yr B.P. and are associated with blocky to granular structure, gleying, and a gradational lower contact. These "dry zones" were interpreted as weakly developed soil horizons that formed during periods of very low water or dry stages (Figs. 2 and 3) (Teller and Last, 1982).

The occurrence of coarser-grained shallow-water and fluvial sediments in the offshore part of the basin was also used to help identify lower water levels and a more arid hydrological setting, although the variable history of a major tributary to the lake, the Assiniboine River, has complicated the interpretation (Teller and Last, 1981). A declining influx of feldspars and clastic carbonate material through postglacial time indicates that the stability and depth of weathering in the watershed were increasing.

Last (1982) used the stratigraphic variation in the amount of magnesium in high-Mg calcite as an indicator of the Mg/Ca ratio of the lake water. The fluctuation in this parameter is interpreted as mainly reflecting the relative contribution of the shallow groundwater aquifer to the lake, because this aquifer contains a greater proportion of Mg than do either the deeper, regional groundwaters or the surface runoff (Last, 1984a). During dry periods when the Mg-rich shallow groundwater influx dimin-

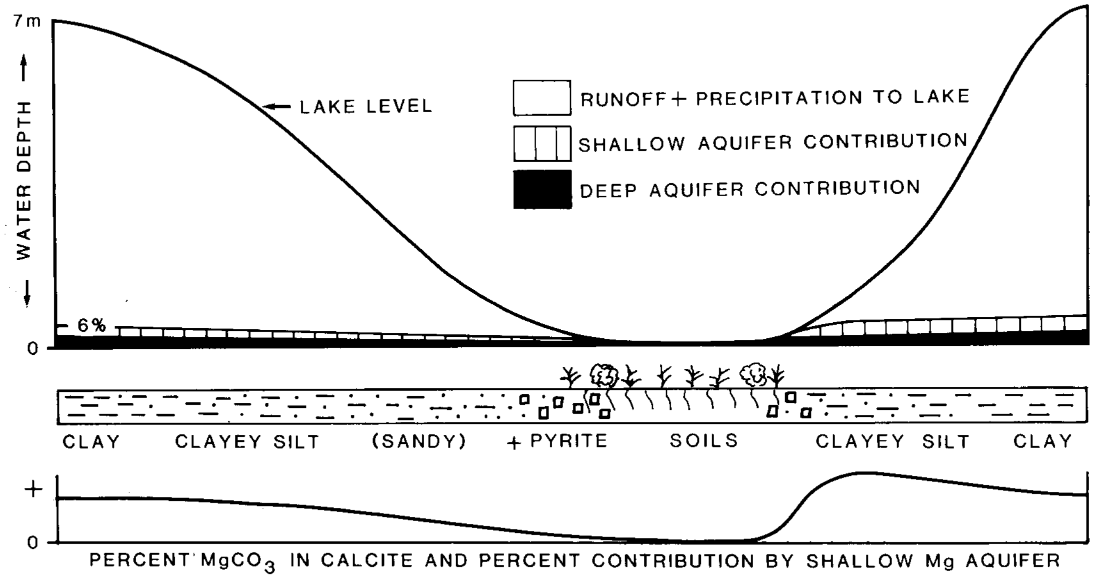

Fig.2. Lake level and relative contributions from runoff and precipitation, shallow groundwater, and deep groundwater during a hypothetical hydrological cycle of Lake Manitoba, showing the nature of sediment deposited and diagenetic changes. Lower graph shows rise and fall of magnesian calcite and of Mg contributed by shallow aquifer during the cycle.

ished, as did surface runoff, the basin was dominated by the deep, regional aquifer, and the lake brines and associated calcite were relatively low in magnesium (Fig.2). As conditions became wetter, there was an abrupt rise in the relative contribution from the shallow aquifer, and the amount of magnesium in the calcite rose. As the proportion of surface runoff increased, there was a slight decrease in this magnesium content.

Stratigraphic variation in the abundance of authigenic pyrite in the Lake Manitoba sequence was interpreted to reflect changing chemical conditions in the near-surface muds. Specifically, higher pyrite content probably was associated with relatively high organic content and anoxic and slightly acidic conditions — all related to low lake levels that allowed plants to take root on the lake floor and generate a low energy marsh environment (Fig.3) (Last and Teller, 1983).

Although postglacial differential isostatic rebound, and the changing history of one of its major tributaries complicate the hydrological reconstruction of the Lake Manitoba basin, palynological studies within the basin (Nambudiri and Shay, 1986), as well as in the surrounding region (e.g., Ritchie, 1976, 1983), support the general paleohydrological interpretations based on the study of the physical and mineralogical nature of the sediment.

Ceylon Lake

In the western part of the Canadian Prairies, there are thousands of small, closed-basin saline lakes. Most of these lakes are ephemeral, filling with water during the spring and drying completely by late summer. Ceylon Lake, located in southern Saskatchewan (Fig.1), is typical of many of these shallow ephemeral lacustrine basins. The present-day brine, dominated by Mg, Na, and SO_4 ions, shows a wide variation in composition and concentration on both a temporal and a spatial basis (Last, 1984b). The modern sediments, however, exhibit relatively simple facies relationships. An outer ring of coarse-grained (sandy) shoreline and colluvial clastics surrounds a zone of mixed fine-grained clastics and salts and, in the center of the basin, salt pan evaporites composed mainly of mirabilite, thenardite, and bloedite (Last, 1989). Present-day salt precipitation is controlled on a seasonal basis by evaporitive concentration of the brine during the warm summer months, and on a daily basis by diurnal heating (causing dissolution) and cooling (causing precipitation).

The postglacial sequence recovered from this salt playa can be subdivided into four lithostratigraphic units. The lowermost non-glacial sediment penetrated in the basin consists of up to several meters of coarse-grained sand and gravel. Overlying this are: (1) calcareous clay interbedded with thin beds of silty sand, (2) black, anoxic, nonlaminated, organic-rich mud with abundant intrasedimentary gypsum and mirabilite crystals, and, at the top of the section, (3) salt with thin beds of black, silty clay. The salt unit (3) can be up to 9 m in thickness and is comprised mainly of sodium sulfate salts (mirabilite and thenardite), with variable proportions of gypsum, bloedite, epsomite natron, halite, and insoluble clastic detritus (see Table I).

Although a number of postdepositional processes have altered the nature and stratigraphic relationships in the basin (Slezak and Last, 1985; Last, 1989), the sediment fill does record, in a general way, fluctuating depositional and hydrological conditions. In addition, discontinuous strandline features and a wave-produced boulder lag above the present-day level of the lake indicate that there have been periods with a more positive water balance.

The postglacial stratigraphic sequence of Ceylon Lake is typical of many of the salt-dominated playa lakes in the region (see Cole, 1924; Last, 1984b). The Ceylon Lake basin, as well as many other riverine valleys in the region, originated as a glacial meltwater spillway between 10,000 and 15,000 years ago. The basal, well sorted, coarse clastics immediately overlying glacier-laid sediments in the

TABLE I

Composition of carbonate, sulfate, and chloride minerals discussed in this paper.

Aragonite	$CaCO_3$
Calcite (low-Mg)	$CaCO_3$ with <4 mole % $MgCO_3$
Hi-Mg (Magnesian) Calcite	$CaCO_3$ with >4 mole % $MgCO_3$
Monohydrocalcite	$CaCO_3 \cdot H_2O$
Dolomite	$CaMg\ (CO_3)_2$
Magnesite	$MgCO_3$
Hydromagnesite	$Mg_4\ (OH)_2\ (CO_3)_3$
Natron	$Na_2CO_3 \cdot 10H_2O$
Gypsum	$CaSO_4 \cdot 2H_2O$
Mirabilite	$Na_2SO_4 \cdot 10H_2O$
Thenardite	Na_2SO_4
Bloedite	$Na_2Mg(SO_4)_2 \cdot 4H_2O$
Epsomite	$MgSO_4 \cdot 7H_2O$
Halite	NaCl

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 low-Mg calcite and the absence of Mg-bearing carbonates (dolomite, magnesite, high-Mg calcite) 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 mollusc shells, and a general lack of lamination indicate high levels of productivity and the presence of bottom-dwelling organisms in this early phase.

The occurrence of thin carbonate-cemented beds, gypsum laminae and intrasedimentary salts in the overlying black, organic-rich mud unit suggest increased brine concentration as the lake became shallower and more restricted during periods of increased aridity (Fig.3). Typically, the increase in soluble salts versus clastics upward in a stratigraphic section would suggest increasing salinity and a more arid hydrological setting with time. However, on the basis of pollen studies in the Prairies, the late Holocene climate has become wetter, not drier, so an alternative explanation must be sought. It is possible that in Ceylon Lake as well as other saline playas of the region, during periods of maximum aridity the watertable in the basin dropped below the level of the lake floor, resulting in downward leaching of soluble surface salts, precipitation of intrasedimentary salts, desiccation and deflation, and loss of some of the previous sediment record. In contrast, under less arid conditions, the groundwater level was high enough to permit a shallow body of water to persist on at least a seasonal basis. Evaporative concentration of this brine year after year gave rise to the thick section of bedded evaporites in the upper 9 m of the lacustrine sequence. Thin beds of silt and clay within this salt may represent: (1) inwash during increased runoff, when the lake may have become deeper and fresher, (2) dissolution of part of the salt sequence during more dilute stages which allowed clastics dispersed in the salt to be concentrated as a lag, or (3) eolian influx.

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. Although this change may, in part, be due to the natural evolution of the brine system (see Eugster and Hardie, 1978) and, therefore, unrelated to any hydrological variation, it is also possible that the high magnesium content

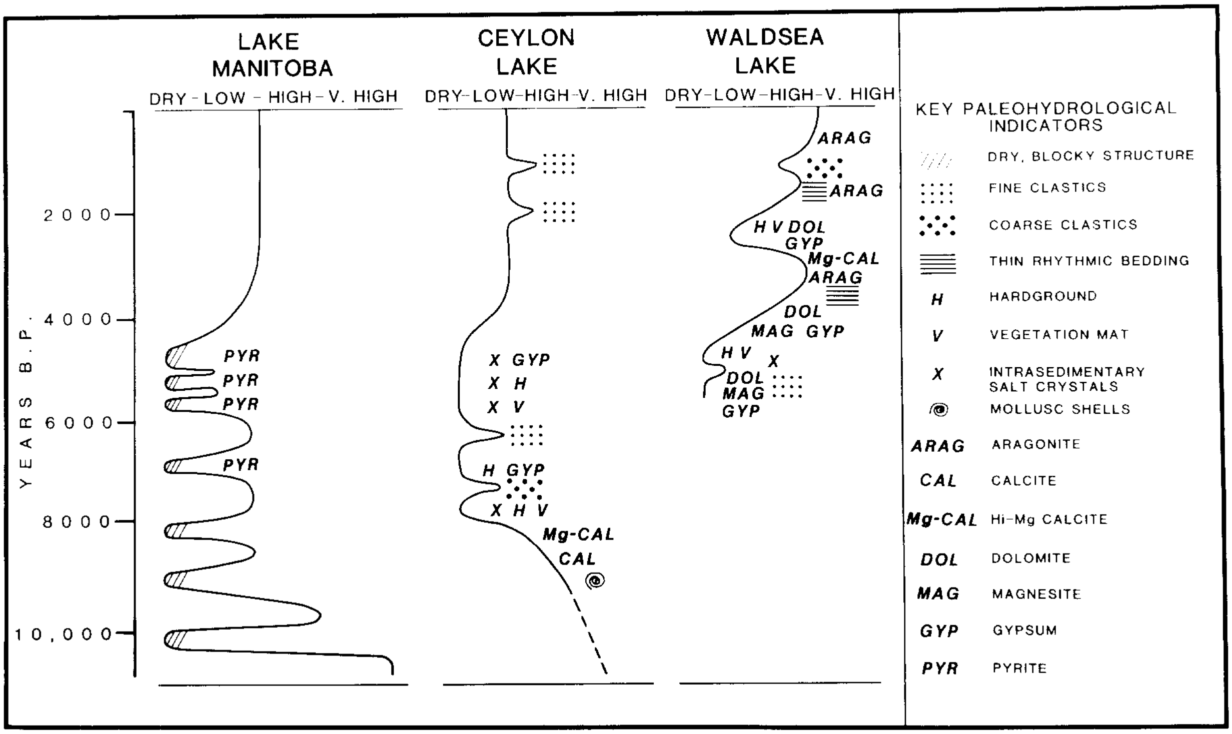

Fig.3. Interpreted water level curves for Lakes Manitoba, Ceylon, and Waldsea.

may be a reflection of a more humid climatic regime. Specifically, under higher rainfall conditions, it is possible that there would be more dissolution of dolomite from the Pleistocene tills in the watershed, resulting in a net increase in the Mg/Na ratio of the ponded brine.

Waldsea and Deadmoose Lakes

The vast majority of salt lakes in the northern Great Plains are shallow and ephemeral basins (i.e., playas) like Ceylon Lake. Only about 10% of the lakes contain more than 3 m of water. Of these deeper lakes, several have been identified as containing a chemically stratified (meromictic) water column. As emphasized by Anderson et al. (1985) and Anderson and Dean (1988), the absence of complete circulation of the stratified water column and the development of relatively permanent anoxia at the sediment–water interface can lead to a very detailed and explicit paleolimnological record.

Waldsea Lake is a deep (maximum depth 14.5 m) lake, located about 100 km east of Saskatoon, Saskatchewan (Fig.1), that has been one of the most intensively sampled and studied salt lakes in Canada. The basin is attractive for detailed study because of its small size, excellent accessibility, and interesting meromictic character. Similarly, nearby Deadmoose Lake, which is up to 40 m deep, is presently undergoing detailed sedimentological and geochemical study. In many respects the two lakes are quite similar. They are both saline and meromictic; they both contain phototrophic bacterial plates; they both precipitate aragonite and contain finely laminated stratigraphic sequences. However, other aspects of the basins are quite different. The Deadmoose basin is much more complex than Waldsea in terms of morphology and modern sedimentary facies and processes, and its history is more complicated.

The limnology and modern sedimentology of Waldsea and Deadmoose Lakes have been discussed elsewhere (Hammer et al., 1978;

Parker et al., 1983; Schweyen and Last, 1983; Last and Slezak, 1986). Briefly, the modern sediments of the two lakes consist mainly of organic-rich, silty clay and clayey silt in the offshore portions of the basins that grade to coarser clastics (sands and gravels) in the nearshore areas. The modern mineral suite in each lake is roughly similar: mainly allogenic clay minerals, endogenic carbonate and sulfate minerals, and authigenic pyrite. The modern sedimentology of these two lakes is controlled mainly by the interaction of: (a) evaporative concentration and organic productivity which create highly supersaturated conditions and precipitation of endogenic carbonate minerals, and (b) detrital influx by wind and streamflow.

This relatively simple modern facies assemblage does not persist throughout the Holocene record. Rather, the stratigraphic sequences preserved in the basins reflect significant fluctuations in lake levels and chemical conditions. Last and Schweyen (1985) used the distinctive mineral suite (gypsum, dolomite, mirabilite), and the morphologies and textures of these components in the lower part of the lacustrine record from Waldsea Lake (Fig.3) to demonstrate that deposition occurred in a saline, clastic-dominated playa, where water levels fluctuated on a seasonal basis. When there was ponded water in the basin, it was dominated by Na and SO_4 ions. Concentrations in the shallow playa probably exceeded 200 g l^{-1} as indicated by the pore water chemistry, and seasonal precipitation of mirabilite and other evaporitic salts occurred. The mudflats surrounding this shallow lake were sites of abundant gypsum and carbonate precipitation. The intense evaporation on the mudflats created a dynamic diagenetic environment and much of the original calcium carbonate was quickly altered to dolomite in response to the high Mg/Ca ratios of the pore water. When water levels were even lower, algal mudflats and vegetation mats covered most of the basin.

An overlying unit of fine, undisturbed carbonate laminae alternating with organic-rich muds suggests deposition in a relatively deep, probably meromictic lake, as the hydrological budget became increasingly more positive (Fig.3). High pore water salinities indicate that the lake was still hypersaline during this high water phase. Deposition of pure aragonite laminae was most likely related to carbonate "whitings" which were triggered by dilute inflow water periodically entering the basin and mixing with the highly alkaline and Mg-rich saline lacustrine brines. In addition to this endogenic precipitation of aragonite, high but fluctuating Mg/Ca ratios in the lake are recorded by the complex assemblage of early diagenetic carbonates including high-Mg calcite, dolomite, and magnesite (see Table I).

The lake became shallow once more between 2800 and 2000 yr B.P., and mudflat-playa conditions returned to the basin as evidenced by gypsum laminae, dolomite crusts, and organic fiber mats. During the last 2000 years, deposition in the Waldsea basin was dominated by finely laminated aragonite–clay couplets, which probably formed in a relatively deep water, stratified basin. Either a lowering of the lake or a loss of vegetative ground cover occurred abut 1000 years ago as indicated by the occurrence of a thin but basin-wide coarse silt-sand unit (Fig.3).

Because of its irregular basin morphology, the stratigraphic sequence and facies relationships in nearby Deadmoose Lake (Fig.1) are more complex (Last and Slezak, 1986). Conditions within the main (deep) part of the basin were probably roughly similar to that of today for much of the mid to late Holocene. Fine, undisturbed laminae of aragonite and the lack of carbonate-cemented crusts, intraclasts, and fiber mats suggest the existence of a permanent, relatively deep, stratified water body. The presence of aragonite throughout this deep water facies points toward high and probably stable Mg/Ca ratios. Stable oxygen isotope data on this endogenic aragonite indicate a warmer, more evaporitic regime at the base of the section grading upward to cooler conditions at the top of the sequence (Last and Slezak, 1986). A sandy facies found at the northern end of the basin was part of a shoreline/delta complex that was active about

1500 years ago, when the lake was 10 m lower and much smaller than today. The presence of coarse clastics, carbonate-cemented laminae, vegetation mats, and gypsum beds in the relatively shallow margins of Deadmoose also confirms this lower lake level. Last and Slezak (1986) show that several satellite basins, which are now part of Deadmoose, were probably separate lakes during much of the mid to late Holocene. With higher water levels and a transgressing shoreline beginning about 1000 years ago, the nearshore coarse clastics and mudflat deposits were drowned, and deeper water (aragonite laminated) sediment was deposited on top of the shallower water clastics.

Salt lakes and playas of southeastern Australia

Introduction

Australia is particularly well suited for interpreting the paleohydrological history of a region from its lacustrine sediments. The continent has a larger proportion of its area in closed (endoreic) drainage basins than any other in the world (Greer, 1977). It has a wide range of climatic conditions, from warm, tropical monsoonal regions of north Queensland to semi-arid climates of central and western Australia. Even on a more local scale, significant climatic gradients exist between the generally high-rainfall fringe along the northern, eastern, and southeastern coasts and the much drier semi-desert areas a relatively short distance inland. In addition, there is a spectrum of closed-basin lake types that are suitable for paleohydrological investigation, including large and small playas, volcanic crater basins, and coastal lakes (De Deckker, 1982a, 1988).

Some of the lakes of southeastern Australia have already attracted considerable attention from paleolimnologists. The sediment fill in Lake Keilambete, a small volcanic maar basin in western Victoria, is one of the best studied and documented late Pleistocene and Holocene continental sequences in Australia. In that basin, brine salinities, chemistries, and temperatures, paleo-lake levels, and local vegetation history have been deduced from detailed examination of sedimentary structures, grain size, mineralogy, and strandlines (Bowler, 1981), palynology (Dodson, 1974), invertebrate stratigraphy (De Deckker, 1982b), and ostracod shell chemistry (Chivas et al., 1985). In addition, the sedimentary sequence in this small basin, as well as that of a nearby maar Lake Terang, have been subjected to intensive paleomagnetic studies (Barton and McElhinny, 1981; Barton et al., 1987). The changes in lake level and salinity of three other maar basins in western Victoria, Lakes Bullenmerri, Gnotuk, and Purrumbete, have been inferred from a variety of paleontological investigations (Churchill et al., 1978; Dodson, 1979; De Deckker, 1982b). Currey (1964) used preserved Pleistocene strandlines and the distribution of offshore lacustrine deposits to evaluate the drainage evolution and water level fluctuations of nearby Lake Corangamite, the largest permanent inland water body in Australia. Lake George, a large lake in a closed basin northeast of Canberra, has been studied in considerable detail by Singh et al. (1981). A core from Lake George, spanning more than 4 million years, displays a largely siliciclastic sequence, but pedogenic horizons, grain size, pollen, and plant macrofossils have allowed many major lake level oscillations to be identified, including more than a dozen periods when the lake was ephemeral or dry. In the drier areas of southeastern Australia, the associated stratigraphy of aeolian deposits (lunettes) bordering playas (and derived from them) have been used to identify paleoclimatic and paleohydrological events during the Quaternary (Bowler, 1971, 1976).

The four lakes we discuss below (Lakes Tyrrell, Beeac, East Basin, and West Basin) demonstrate the range and diversity of paleoenvironmental indicators that can be investigated in lacustrine settings of the region. Lake Tyrrell and Lake Beeac illustrate the type of hydrological interpretations that can be deduced from the physical and mineralogical records of shallow playa basins; East and West Basin Lakes show how the stratigraphic records in deep, perennial lakes can be used.

Lake Tyrrell

Lake Tyrrell is a large, 185 km^2, elongated playa basin located about 300 km northwest of Melbourne, Victoria (Fig.4). Although it is the largest salt lake in southeastern Australia today, there are many similar smaller basins in the region. The climate in the area is semiarid, with the 325 mm, winter-dominated annual rainfall exceeded substantially by the 1350 mm annual pan evaporation (Bowler and Teller, 1986).

The floor of the lake basin is flooded each year to a depth of less than a meter during the cooler and wetter winter months. Water is supplied by infrequent brief floods down the major tributary valley (Tyrrell Creek), direct precipitation, overland flow, and groundwater discharge (Teller et al., 1982).

As in many lake basins in southeastern Australia and elsewhere, aeolian lunettes, comprised of sediment deflated from the playa floor, lie along the eastern side of Lake Tyrrell, reflecting paleowind directions during specific past hydrological conditions (Bowler, 1973, 1976, 1983). For this reason, part, perhaps a large part, of the sedimentary record of Lake Tyrrell (and probably of other lunette-fringed basins) is missing (Bowler and Teller, 1986).

A thin (< 10 cm) crust of halite, with minor amounts of gypsum, thenardite, and mirabilite, are precipitated each year as the shallow brine evaporates. These salts are redissolved by the

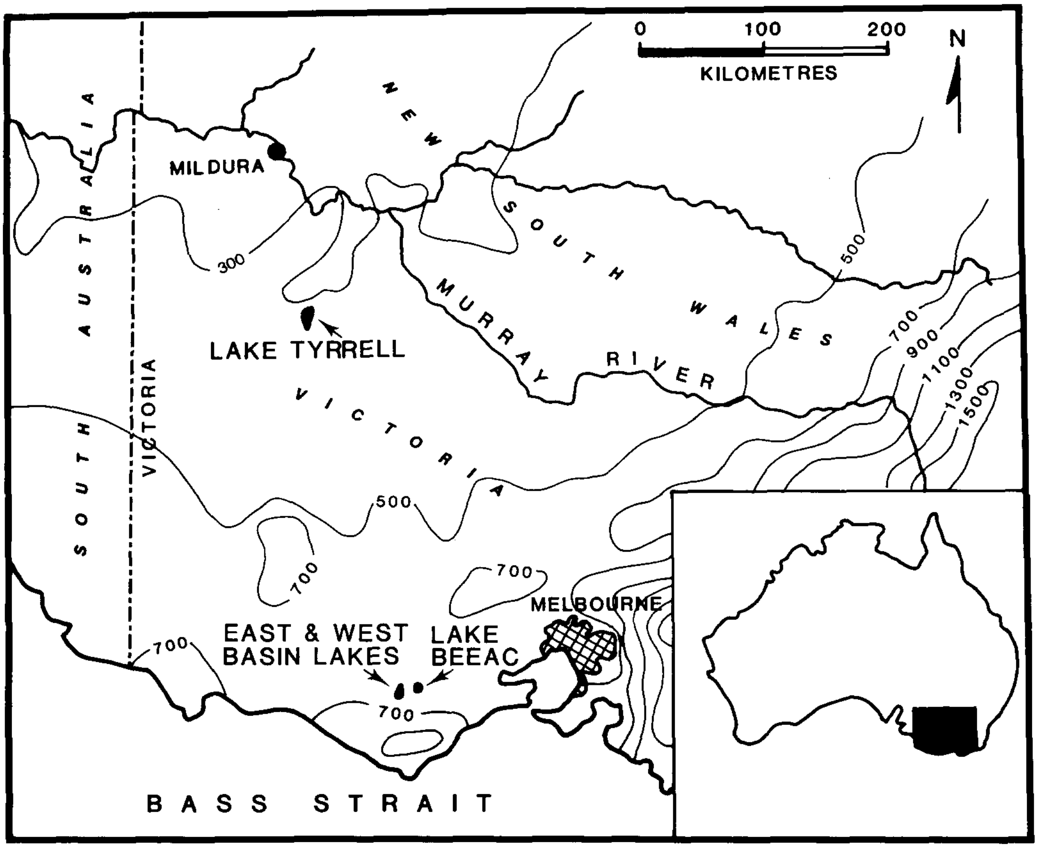

Fig.4. Map of southeastern Australia showing the locations of the lakes discussed in this paper. Contour interval of precipitation isohyets is 200 mm. Boxed area on inset map indicates location.

annual influx of freshwater, and then re-precipitated as the water evaporates. There is no halite preserved in the sedimentary record. Teller et al. (1982) and Macumber (1983) describe the three different groundwater types of the Tyrrell basin, each with distinct salinities, and describe the refluxing cycle involved in the transfer of salts into and out of the basin in the groundwater systems.

A model of paleohydrological conditions in the Tyrrell basin, based on cores through the > 700,000-year-long sedimentary sequence, was proposed by Bowler and Teller (1986). A cycle of surface and groundwater-level oscillation was used to explain the typical repetitive sedimentary sequence in terms of the controlling chemical, physical, biological, hydrological, and diagenetic conditions on the lake floor and in the sediments below. Major sediment parameters used as paleohydrological and paleoenvironmental indicators in the Tyrrell basin were: (1) presence of detrital clay particles and their fabric, (2) presence of clay pellets, (3) presence of carbonates, (4) presence and crystal structure of gypsum, (5) presence of pedogenic horizons, and (6) spatial and temporal associations of the above sedimentary types. In addition, there are scattered beach remnants around the lake indicating water depths before 30,000 yr B.P. had been more than 13 m (Macumber, 1983).

Figure 5 depicts the hydrological model proposed by Bowler and Teller (1986) for the Lake Tyrrell basin, and it is thought to be representative for other basins where the ionic composition of the brine is similar to that of seawater, as it is in Lake Tyrrell. This cycle may be repeated many times during the life of a playa, and may represent long or short periods of time. Erosion and hydrological reversals, as well as the actual rates of change, may result in missing intervals and complex sedimentary sequences.

In Stage I of the model, lake water is deep and salinities are low. Sedimentation in this chemically undersaturated water is related to the influx of clastics, which in the Tyrrell basin has mainly been clays. Bioturbation of these clays by benthic fauna is indicated by a random grain orientation in the depositional clay fabric (Bowler and Teller, 1986).

As average water levels decline through

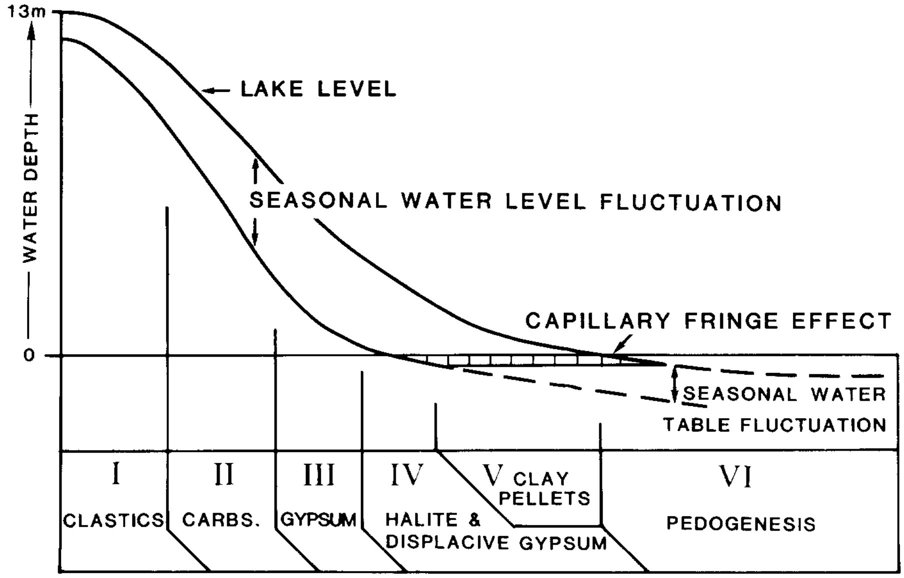

Fig.5. Lake and groundwater level change during a Lake Tyrrell hemicycle of drying, showing potential seasonal fluctuations. Stages of sedimentation and diagenesis (I–VI) related to the changing hydrology are also shown (after Bowler and Teller, 1986).

time, and the brine becomes more concentrated, carbonates (Stage II) and then primary gypsum (Stage III) are precipitated. Interlaminated and bedded clays represent phases of lake freshening by muddy floodwaters. When these detrital clays have an oriented fabric, as they typically do in the Tyrrell sediments, it is interpreted to mean that benthic fauna were not present to cause bioturbation; this is possibly a function of elimination by preceding high salinity events.

Increasing aridity produces ephemeral or seasonally dry conditions in the basin, and halite is precipitated (Stage IV). Under conditions like those in the Tyrrell basin today, this salt is repeatedly redissolved and eventually added to the dense pool of groundwater brine below the basin (Macumber, 1983), rather than being preserved in the sedimentary record. During this stage, and continuing until the groundwater table falls well below the playa floor, displacive (hemipyramidal) gypsum grows within already-deposited sediment as long as sulfate-reducing bacteria are not present. One factor contributing to the scarcity of *primary* gypsum (Stage III) in the sequence is believed to be the activity of such bacteria just below the sediment–water interface (Teller et al., 1982).

As the length of the seasonally dry period increases, the generation of pelletal clay aggregates on the floor of the basin becomes significant (Stage V), although halite precipitation and displacive gypsum growth continue. These clay pellets develop as soluble salts such as gypsum, halite, mirabilite, and thenardite crystallize in and fragment the cohesive clayey sediments within the capillary fringe. A "puffy", easily eroded surface develops that can be readily deflated by the wind. Clay lunettes along the basin margin were formed in this way, as well as clay pellet islands in the lake and the beds of pelletal clay within the lacustrine sequence. It is during this stage that most deflationary loss occurs.

A continued decline in groundwater level results in the downward leaching of soluble salts and the formation of soils (Stage VI). This ends the ideal cycle. A return to wetter conditions may initiate sedimentation belonging to any of the previous stages.

Lake Beeac

Lake Beeac is one of many small saline playa basins located in the Western Plains volcanic region of southeastern Australia (Fig.4). In contrast to Lake Tyrrell, Lake Beeac brine is highly alkaline with a pH usually greater than 8.5 (Williams and Buckney, 1976). The saline, evaporitic conditions, high alkalinities, and elevated Mg/Ca ratios are conducive to Mg-carbonate precipitation. Both magnesite and dolomite with an excess of magnesium (high-Mg dolomite) occur as primary precipitates in the modern sediment of the basin (De Deckker and Last, 1988). The surficial sediment also contains an allogenic component comprised mainly of smectitic clays and quartz.

The late Pleistocene and Holocene stratigraphic record from Lake Beeac consists of about 1.3 m of fine-grained, generally nonbedded, nonfossiliferous, calcareous clay and silty clay. On the basis of mineralogy, texture, sedimentary structures, and color, three units can be identified (Fig.6). The lowermost half meter of sediment penetrated in the basin (Unit I) is a firm gray clay with a relatively high content of Mg dolomite and low content of magnesite. The unit exhibits a crumbly to blocky and granular pedogenic structure and has a very low moisture content. Abruptly overlying this is a 25-cm thick unit (Unit II) of structureless, mottled, pelletal, light-gray to dark-gray silty clay and clayey silt with a high magnesite and low dolomite content relative to the basal unit. Grading upward, the sediment of Unit III consists of Mg-enriched dolomitic mud, and is characterized by a diverse array of structures and varying textures; burrows, roots, mudcracks, ooids, fecal pellets, and mottling are present. Finally, the upper 3–10 cm of the sequence consists of very soft to gelatinous magnesite–dolomite clay.

Even though the stratigraphic record of Lake Beeac is dominated by fine-grained mud

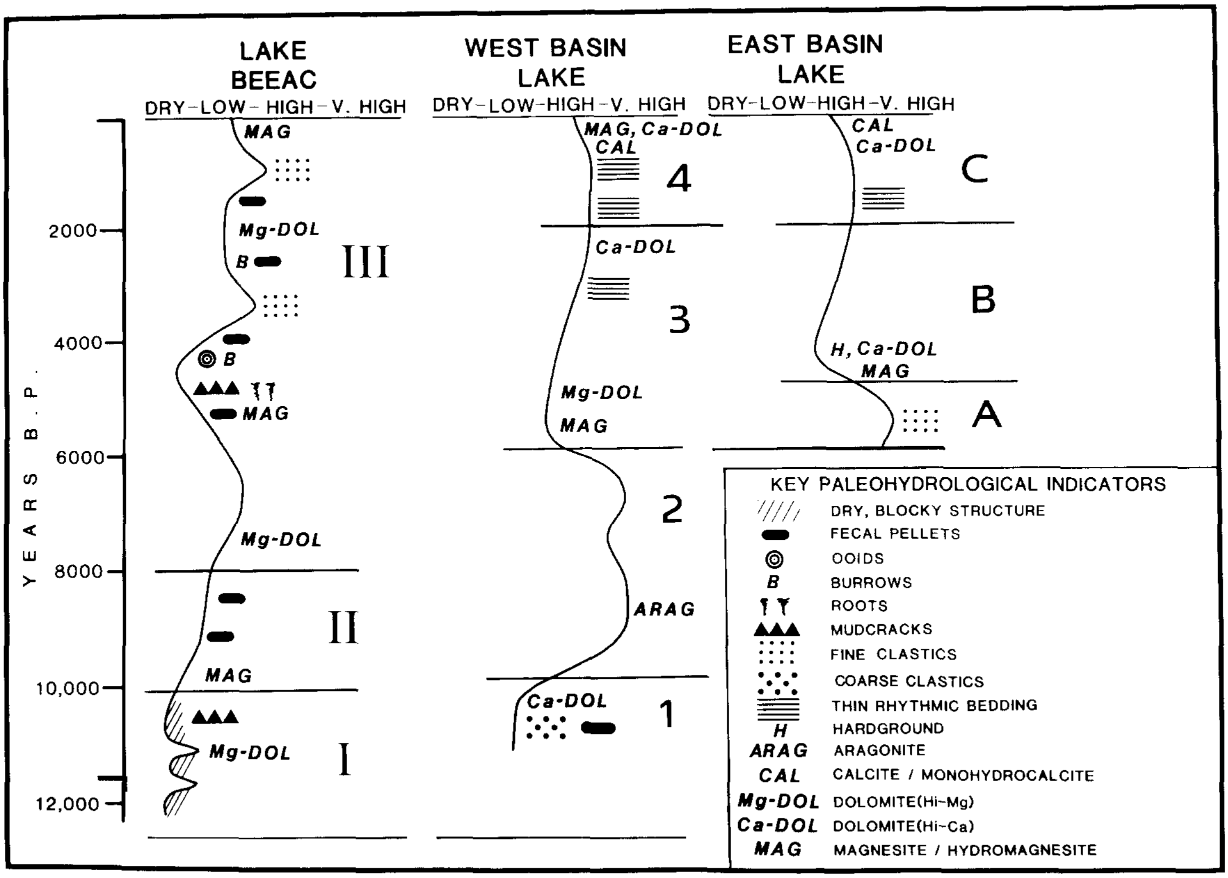

Fig.6. Interpreted water level curves for Lakes Beeac, East Basin, and West Basin.

there is no indication that the Beeac basin ever contained a deep-water lake. Shallow water and oxygenated bottom conditions were present throughout much of the Holocene (Fig.6) as indicated by the light grey color of the mud and the occurrence of ooids, pellets, burrows, low organic content, and absence of bedding. The low moisture horizon with blocky, pedogenic-like structure at the top of Unit I has been dated at about 10,500 yr B.P. (De Deckker and Last, 1989) and probably represents a period of complete basin desiccation and lake-floor exposure during the late Pleistocene. This period of aridity is also recognized in other lacustrine records in the region (e.g., Bowler, 1981; De Deckker, 1986; Bowler and Teller, 1986; De Deckker et al., 1987).

Because of a lack of visual microscopic or macroscopic evidence of replacement fabrics, De Deckker and Last (1989) conclude that the dolomite and magnesite in Lake Beeac are primary (endogenic) components derived either by direct nucleation from the lake's water column or precipitation from pore solutions in the surficial sediment. Thus, as primary or very early diagenetic material, these Mg-carbonates can provide a wealth of information on the nature and chemical composition of the lacustrine brine.

In addition, because both the high alkalinity and the distinctive Mg/Ca ratio of today's lacustrine brine are likely derived from groundwater sources as opposed to surface runoff (De Deckker and Last, 1989), the varying carbonate mineralogy of the Beeac section can also be interpreted in terms of fluctuations in the relative contribution of surface runoff versus groundwater influx to the lake's hydrologic budget. Specifically, during periods in which the groundwater contribution was dominant, the brine was highly alkaline and relatively enriched in magnesium, and magnesite was the dominant carbonate mineral precipitated. This is the situation in the basin today and probably was the condition that prevailed during deposition of Unit II, immeditely after the late-Pleistocene drying event about 10,500 years ago (Fig.6). In contrast, when both groundwater and surface water were contributing to the hydrological budget, the brine had a somewhat lower Mg/Ca ratio and dolomite was the dominant carbonate precipitate. This was the case for much of the time during the deposition of Units I and III. At times when surface runoff became dominant, such as during extended wet periods, chemical conditions were not conducive for either dolomite or magnesite nucleation,and the sediment deposited was mainly fine grained siliciclastics. This appears to have occurred for only brief periods during the deposition of Unit III.

Thus, even though Lake Beeac and Lake Tyrrell lie in a similar climatic region today and probably underwent similar hydrological "cyclicity" during their history, the sedimentary records are different in many ways. The explanation lies mainly in the brine chemistry. In Lake Beeac, the high alkalinity and elevated Mg/Ca ratio allowed various Mg-bearing evaporitic carbonates to form; the low sulfate content prohibited the formation of gypsum. In contrast, the higher sulfate content and lower alkalinity of Lake Tyrrell was conducive to gypsum crystallization. In both basins, blocky to pelletal aggregates in the clayey sediment indicate very low water to dry conditions on the lake floor, as do other pedogenic features such as roots and mudcracks. Relatively deeper water and oxygenated conditions are suggested by burrowed and poorly-laminated sediment with fecal pellets, ooids, and a paucity of soluble evaporitic minerals.

East and West Basin Lakes

The Basin Lakes are two adjacent small volcanic-maar lakes west of Melbourne (Fig.4). Both basins contain permanent saline water bodies. East Basin Lake has a mean depth of 4.5 m; West Basin about 5.8 m. Timms (1972) and Timms and Brand (1973) examined the physical and chemical limnology of the present-day lakes. West Basin Lake is meromictic. Its mixolimnion averages 75 g l^{-1}; the monimolimnion has a salinity of 89 g l^{-1}, with a chemocline occurring at 3.5 m depth. East Basin is not presently chemically stratified, and has an average salinity of 49 g l^{-1}.

The modern sedimentary facies and processes operating in these two basins are surprisingly complex considering the relatively simple morphology and modern hydrological setting. In West Basin, part of this complexity is due to the meromictic nature of the water column, which makes deciphering mineral precipitation and dissolution processes difficult. Development of seasonal thermal stratification in both basins can further influence modern facies characteristics. In addition, both East and West Basin lakes contain a great variety of algal-generated and evaporitic carbonate hardgrounds and stromatolitic features which occupy the fringes of the basins to a water depth of approximately 2 m. These carbonate fringes exhibit a complex array of fabrics, geometries, and mineralogies (Last and De Deckker, 1987a) and grade basinward into coarse clastics and organic-rich, laminated clays.

East and West Basin lakes offer a treasurehouse of paleoenvironmental information. Wave cut notches and strandlines are recorded as breaks in slope on the inner flanks of the craters. Although these strandlines can be traced along the entire circumference of the basins, they are generally poorly developed, suggesting that the high water level periods were relatively short in duration. Carbonate hardgrounds, boundstones, and stromatolites that are exposed above the present-day lake levels in the basins similarly provide important information about water depth, and, as shown by Hillaire-Marcel et al. (1986) in several East African salt lakes, they can also be used to decipher chemistry, salinity, and isotopic composition of the brine. Finally, because of the saline conditions and the ease with which "permanent" chemical stratification (meromixis) can develop in water columns of basins such as these, the stratigraphy of the sedimentary fill in the lakes should be a valuable record of paleolacustrine conditions.

Despite their close proximity, similar modern characteristics, and identical basin origins, the stratigraphic records of the two lakes are considerably different. The Holocene record from West Basin can be subdivided into four major stratigraphic units (Fig.6). The lowermost unit (Unit 1) is a laminated, relatively coarse-grained (silty sand to clayey silt) dolomitic mud. Laminae consist of concentrations of fecal pellets alternating with organic-rich silts. Overlying this is Unit 2, a finer-grained (clayey silt to silty clay) sediment characterized by fine but irregularly spaced aragonite laminae. This is overlain by 3 m of Unit 3, which is a poorly bedded mud containing dolomite and magnesite as the major carbonate minerals. The dolomite content of Unit 3 increases upward and shows a gradation from Mg-rich at the base to increasingly Ca-rich at the top. Finally, this grades upward into the sediment of Unit 4 which contains packages of multicolored (brown, red, green, gray), very finely- and rhythmically-laminated sediment alternating with zones of non-bedded material. This unit contains Ca-rich dolomite, hydromagnesite, and calcite. The recovered stratigraphic section from West Basin Lake spans about 10,000 years.

The sedimentary sequence recovered from East Basin spans only about 6000 years, and is, in general, less distinctly laminated than that of West Basin, although the section does show gross color banding and some rhythmic bedding. The lowermost 2 m (Unit A) is non-bedded, non-calcareous, organic-rich clay. This grades upward into a poorly bedded clayey silt (Unit B) with relatively high dolomite and magnesite contents and numerous hardgrounds and lithified horizons. Finally, the upper 2 m of East Basin sediment (Unit C) is generally non-bedded with occasional thin (1–5 cm) zones of rhythmically laminated material similar to Unit 4 in West Basin. Unit C is also characterized by a distinctive carbonate mineral suite of dolomite–calcite–monohydrocalcite.

Last and De Deckker (1987b, 1989) and De Deckker et al., 1987) have interpreted the litho- and biostratigraphic changes in these basins in terms of variations in water level, brine chemistry, detrital input, and water column stratification conditions. The detailed chronology presented by Last and De Deckker (1989) shows that these lakes experienced highest clastic sedimentation rates during early to mid-Holocene, after which decreased rates of supply of detrital material led to lower overall sedimentation rates and a higher proportion of chemical precipitates. These changes likely reflect stabilization of the watershed slopes. The maars and associated volcanic features of the area are very young (late Pleistocene to early Holocene; Ellis and Ferguson, 1976). Thus, formation of soils on the crater slopes reduced the influx of clastic material to the Basin Lakes. In addition, these changes may also be associated with an increasing precipitation/evaporation ratio: with increased rainfall, vegetation will retard detrital sediment yield from the watershed, thereby resulting in a basin fill dominated by chemical precipitates.

Although both basins have experienced significant fluctuations in water levels (Fig.6), there is nothing to indicate that either lake has undergone complete drying and desiccation. The relatively coarse grain size and the abundance of fecal pellets in Unit 1 of the West Basin section suggests that lower water levels prevailed during the early part of the Holocene. However, by about 9000 yr B.P., more humid conditions gave rise to higher water levels in West Basin as indicated by the finer grain size and the finely laminated nature of the overlying Unit 2. The hydrological budgets of both lakes were probably dominated by surface runoff (low Mg/Ca ratio) versus groundwater influx (high Mg/Ca ratio) for the next few thousand years as suggested by the aragonite–calcite carbonate mineralogy of Unit 2 in West Basin and the paucity of any type of carbonates in Unit A of East Basin.

Beginning about 6000 yr B.P. in West Basin and shortly after that in East Basin, aridity increased, initiating lower water levels and more saline conditions. This is reflected in the sediment records of the two basins by the presence of magnesite and dolomite, hardgrounds and lithified crusts, and the general absence of lamination in Unit B of East Basin and Unit 3 of West Basin. A similar mid-Holocene aridity is indicated in the lacustrine records of other volcanic maars of the region (De Deckker, 1982b; De Deckker et al., 1987).

A subsequent decrease in magnesite and increase in dolomite in the upper part of Unit 3 in West Basin, as well as the change from Mg-rich to Ca-rich dolomite at the top of this unit, suggest freshening conditions and a trend toward greater influence of surface runoff (versus groundwater) in the hydrological budget of the lake. A deep, stratified water column has persisted in West Basin Lake for much of the last 3000 years, allowing the very fine rhythmic laminae of Unit 4 to accumulate. At times during the past 3000 years, however, a somewhat more positive hydrological budget prevailed, giving rise to slightly fresher water conditions and the deposition of mainly calcite, organic matter, and clay minerals. During most of this 3000-year period, however, a saline water body existed in West Basin, as evidenced by the dolomite–hydromagnesite carbonate mineral assemblage. In contrast, the general lack of bedding in the sedimentary fill of East Basin suggests that this lake's water column has remained mainly nonstratified throughout much of its 6000 year history. The presence of calcite and monohydrocalcite in Unit C of East Basin points toward overall fresher water conditions and a lower Mg/Ca ratio during the past 2500 years relative to that of the previous several thousand years of deposition in the basin.

Playas in the Namib Desert of southwestern Africa

Introduction

In some settings, playas lie in areas where aridity is extreme, and the hydrology of these ephemeral lakes is largely controlled by events in wetter areas beyond their margins. Many of the "pans" of the arid to hyperarid Namib Desert of southwestern Africa are examples, as are some oases in the Sahara Desert. Water levels in intermontane basins in the western United States that experience very little precipitation on or near the playa itself commonly respond to rainfall and snow melt events in adjacent mountains (e.g., Benson and Thompson, 1987). For example, lake level fluctuations in Searles Lake, California, through the past several million years are attributed to varying runoff in mountains surrounding the basin (Smith et al., 1983). In some basins in the southwestern United States, lake levels have responded to an increase in runoff from the surrounding watershed only when adjoining "upstream" basins overflowed (see Smith and Street-Perrott, 1983). A similar situation has been documented in the Willandra Lakes of New South Wales, Australia, where increased Pleistocene runoff from the headwaters of the catchment increased flow, in sequence, to a series of "terminal" playa basins. When the volume of runoff was relatively small, only the most headward basins (e.g., Lake Mungo) received water; when runoff increased or persisted for long periods, these headward basins overflowed into basins farther "downstream" (Bowler, 1971; Bowler and Wasson, 1984). Today all of these basins are dry.

Where groundwater is the dominant component in the hydrological budget of a basin, as it appears to have been in many playas of the Namib Sand Sea, even precipitation events outside of the surface catchment area may control water levels in the playa. As previously noted, this is the situation in some basins in the Canadian Prairies, with the age of the water in the eastern (downflow) end of the deep

Prairie aquifer being at least 10,000 years old (Fritz et al., 1974).

Interdune depressions in the Namib Sand Sea

The Namib Desert is an area along the western coast of southern Africa that extends about 2000 km from southern Angola to about the southern border of Namibia. The region slopes west toward the Atlantic Ocean from a divide that lies 100–200 km inland (Fig.7A). Precipitation gradually increases inland from the hyperarid zone (< 50 mm rainfall) along the coast to the semiarid region along the divide, where more than 200 mm of rain falls.

Runoff from the wetter uplands only occurs periodically, and river flow in most valleys rarely reaches the coast. Along a 300-km stretch of this desert, all runoff is intercepted by the Namib Sand Sea — a 100-km wide coastal zone of north–south oriented active linear dunes. Today a number of valleys terminate in playas along the eastern side of the Sand Sea, such as Tsondab Vlei, Sossus Vlei, and Koichab Pan (Fig.7A). The calcareous clays, silts, and sands in these modern playas are dated at younger than 10,000 yr B.P. (Vogel and Visser, 1981).

West of Tsondab Vlei (playa), isolated within the active dunes of the Sand Sea (Fig.7B), lie a number of fresh to brackish water playa deposits of calcareous silt and fine-sand beds, many of which are lithified; sandy limestones are interbedded at some locations (e.g., Ward, 1987; Teller et al., 1988, in press). These interdune exposures are generally less than a meter thick, although thicknesses of up to 25 m have been measured at one location where alternating episodes of lacustrine and eolian deposition have occurred (Teller and Lancaster, 1986a). The known areal extent of these deposits is rarely more than a few square kilometers.

Low magnesian calcite is the dominant chemical precipitate in these beds, with lesser amounts of dolomite, aragonite, high magnesian calcite, and halite (Teller et al., in press). Calcified reed casts, gastropods, and diatoms are present in many playa sequences, indicating that waters were mainly fresh to brackish at the time of deposition (Teller et al., 1988). At some locations, limestones lie in the center of the basin and carbonate-cemented sands and silts, containing calcified reeds and overlying bleached and mottled dune sands, occur at the basin margin (Lancaster and Teller, 1988). As Teller et al. (in press) conclude, individual calcareous beds that contain more than one carbonate type represent either multi-stage crystallization from a single brine (i.e., single wet phase) and/or diagenetic evolution from an original carbonate mineral that may have resulted from a number of wet phases. The complicated geochemistry of carbonate precipitation (e.g., Scoffin, 1987) plus the difficulty in even distinguishing primary from secondary crystallization, poses problems in interpreting the hydrochemical history of these, as well as other, lacustrine deposits.

The lacustrine beds in the Namib Sand Sea are isolated from all modern rivers and drainage lines by linear and star dunes that are typically more than 100 m high. Modern ponding of the infrequent overland flow in the interdune depressions of the hyperarid region where these deposits are found is unknown. Radiocarbon dates on the carbonate in these playas range between 11,000 and 40,000 yr B.P. (Vogel and Visser, 1981; Teller and Lancaster, 1986a). Therefore, the origin of these fresh to brackish water playa deposits requires a different hydrological regime from that of the present.

Four possible scenarios for the development of standing water at these sites have been proposed.

(1) Terminal lakes may have formed at the end point of the Tsondab River when it extended farther west into the Sand Sea, prior to the isolation of the depressions by migrating dunes (Seely and Sandelowsky, 1974; Teller and Lancaster, 1986a; Teller et al., in press). Deposits with this possible origin lie northwest of the modern teminal playa at Tsondab Vlei, such as at Narabeb (Fig.7B). Then, as today, runoff to the river terminus would have been

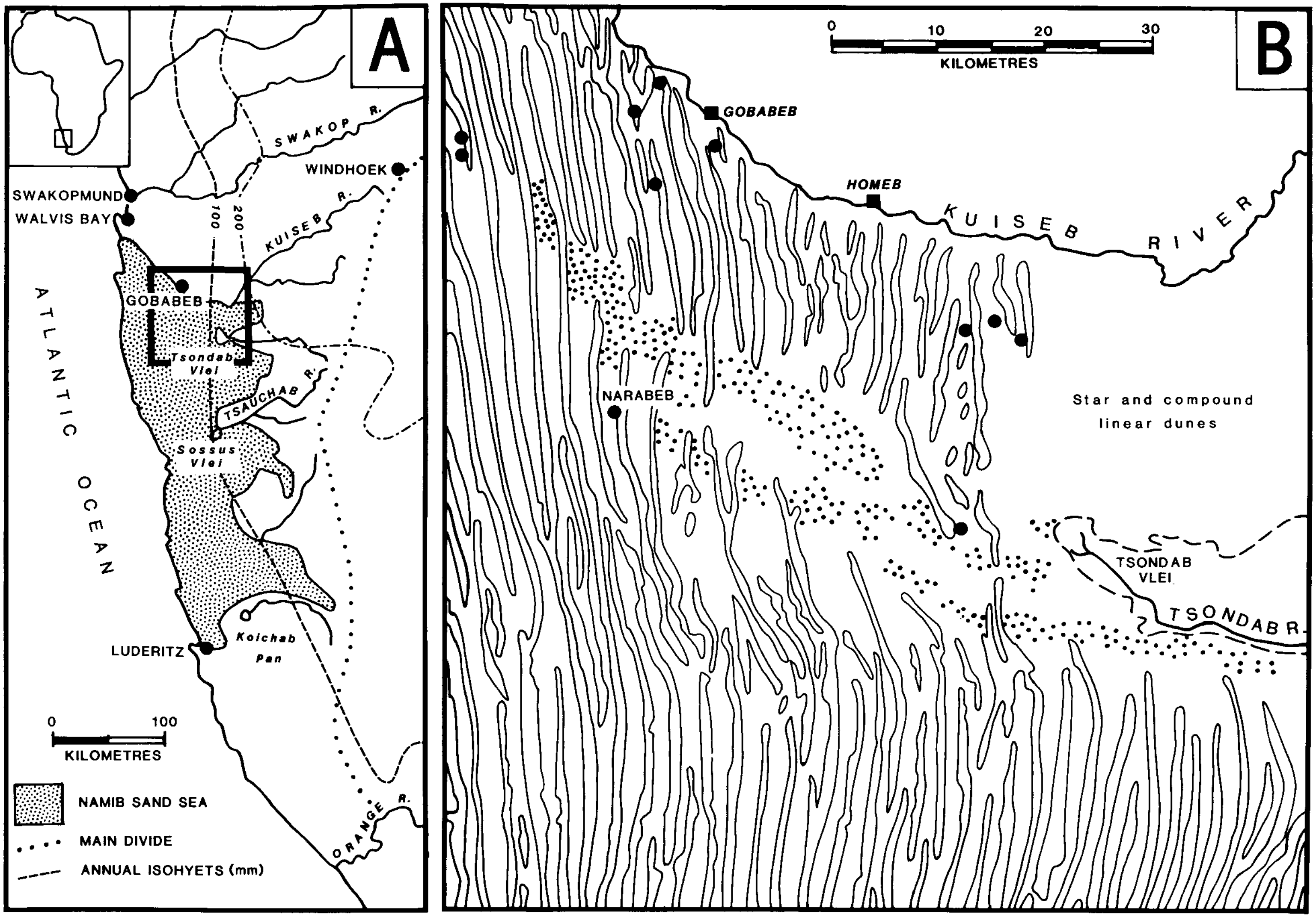

Fig.7A. Namib Sand Sea (stippled) along the southwestern coast of Africa, showing precipitation isohyets and drainage divide (after Marker, 1977). Area shown in B boxed. B. Location of calcareous lacustrine deposits (large dots) between north–south linear dunes in the northern part of the Namib Sand Sea. Pleistocene fluvial deposits west of modern playa (Tsondeb Vlei) shown by coarse stipples (after Teller and Lancaster, 1986a; Lancaster, 1984).

mainly the result of precipitation in the wetter areas to the east.

(2) Flooding along ephemeral water courses such as the Kuiseb and Tsondab valleys (Fig.7B) may have caused lateral flooding into the interdune corridors (Teller and Lancaster, 1986b,c).

(3) There may have been groundwater seepage into interdune depressions from a regional aquifer such as the Tsondab Sandstone Formation, which underlies much of the Sand Sea, or through confining dunes that isolate the depression from ephemeral rivers (Teller and Lancaster, 1986b,c; Ward, 1987; Teller et al., 1988).

(4) There may have been an increase in precipitation over the Sand Sea.

In all four possibilities, an increase in precipitation (or in the precipitation/evaporation ratio) would increase the chance of ponding. Furthermore, any increase in precipitation may only have occurred in the uplands to the east, and the Sand Sea where the playas are located may have remained hyperarid throughout the Cenozoic.

In the now-dry interdune depressions of the Namib Sand Sea, the sedimentary record is mainly used to identify and date previous episodes when there was a positive hydrological budget. The biological record indicates that fresh to brackish water conditions existed prior to desiccation. Because the total thickness of calcareous beds at each site rarely exceeds a meter, it seems likely that the total length of time of ponding during the interval between 40,000 and 10,000 yr B.P. was short. It is possible that each of these thin beds may represent several wet phases, which may have led to incremental additions to the deposit and to progressive and variable diagenetic changes in the carbonate mineralogy.

Summary and conclusions

The sedimentary record of lakes in closed basins can be used to decipher the hydrological history of the lake and catchment. The details of this record may be used to help resolve the details of water level fluctuations and related brine chemistry, as well as paleoclimate, but they commonly pose difficult interpretive problems. Energy variables, brine geochemistry, watershed and hydrological characteristics, and varying contributions from surface runoff and aquifer(s) are only a few examples of factors that commonly contribute to generating the sedimentary sequence of playas and salt lakes.

As a first step in developing hydrological interpretations, simple relationships should be considered, such as that shallowing water leads to coarsening of clastics and to the precipitation of increasingly soluble minerals (e.g., calcite⇒gypsum⇒halite⇒other soluble salts). Indeed, certain sediment types or sequences probably are fairly reliable indicators of hydrological conditions. Primary calcite, gypsum, and some salts are indicative of specific brine concentrations; other contemporary lakes in the region, however, may have quite different mineralogies if surface inflow, groundwater supply, or geology are different, even if controlling climatic factors are the same. Low-water to dry conditions on the lake floor are suggested by secondary changes to the sediment such as pelletization of clays, pedogenesis, and the growth of secondary minerals. The occurrence and specific grain size of clastics in the sequence are mainly a function of energy imparted to the lake floor or sediment influx, and clastics tend to be dominant during (1) deep-water, low-salinity periods when river influx is high and chemical precipitation is low, (2) shallow water periods when energy reworks sediment from the margins on to the lake floor and overwhelms any chemically precipitated minerals, and (3) dry-lake stages when clastics may accumulate as a lag after dissolution of soluble minerals or by periodic influxes of fluvial or eolian sediments. Therefore, in basins undergoing an increase in aridity, both the wettest and the most arid periods commonly are represented by siliciclastics, whereas "intermediate" hydrological stages generate beds dominated by primary mineral precipitates. Furthermore, basin drying commonly leads to deflation and loss of part of the previously deposited sequence; adjacent eolian deposits such as lunettes can be used to supplement the paleohydrological interpretation based on the lacustrine sequence. Post-depositional events may also change the primary mineralogy, and in some cases the diagenetic mineralogy can be used to better understand the hydrological (or geochemical) history of the basin.

It is always a challenge to deduce the hydrological history of a lake basin from its sedimentary record. Not only must we understand the role that various physical and organic processes can play, and be familiar with the geochemical complexities of evaporating a given brine but we must also understand that interruptions and reversals may occur in any depositional model. Playa and saline lake sediments, however, probably provide the best record of changing hydrological conditions in arid and semiarid regions.

Acknowledgements

Much of the research discussed in this paper was supported by grants from the Natural Science and Engineering Research Council of Canada. Lake Manitoba research was also supported by the Environmental Management Division of the Manitoba Department of Mines, Natural Resources, and Environment. The University of Manitoba, Australian National University, Monash University, Geological Survey of SWA/Namibia, and Inland Waters Canada provided financial and logistical support on several projects.

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