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PALEOHYDROLOGY AND PALEOCHEMISTRY OF LAKE BEEAC, A SALINE PLAYA IN SOUTHERN AUSTRALIA

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ABSTRACT

Lake Beeac is one of a large number of playa lakes located in the semi-arid Western Plains region of Victoria, Australia. The late Pleistocene and Holocene sediment fill in the basin consists of generally non-bedded, fine grained, organic-rich pelleted carbonate muds. Three lithostratigraphic units can be recognized on the basis of mineralogy, texture, sedimentary structures, fabric, and colour. Stratigraphic fluctuations in the endogenic Mg-bearing carbonates provide detailed insight into changes in the chemical composition of the brine during the past 13,000 years. These changes, in conjunction with variations in sedimentary structures, organic remains, and the ratio of detrital to endogenic components, can be used to reconstruct a lake history that follows a general pattern similar to that deciphered from perennial lakes in the region. Because the Beeac basin is a regional groundwater window however, the preserved stratigraphic sequence in the lake offers a more detailed and sensitive record of past hydrologic and climatic changes.

INTRODUCTION

Lake sediments are very responsive to changes in regional and local hydrology, lake water chemistry, and watershed weathering characteristics. Because lakes that occupy topographically closed drainage basins are more sensitive than any other terrestrial depositional system to climatically induced environmental fluctuations, it is no surprise that the sediments of these closed basins are attractive targets for paleoclimatic and paleolimnological research. Recently, considerable effort has been made to use the sediment records of playas and shallow salt lakes to interpret the paleochemistry and evolution of the brine and the paleohydrology of the basin (e. g., Wasson et al. 1984; Bowler and Teller 1986; Smith et al. 1987).

The Western Victorian Plains region of southeastern Australia contains many closed basin lakes. The purpose of this paper is to summarize the results of a reconnaissance paleoenvironmental study of one of these basins, Lake Beeac, based on analysis of a variety of physical, chemical, mineralogical, and biological parameters from sediment cores and subsurface samples. Closed basin playa lakes like the one described here function as groundwater windows: the regional groundwater table is close enough to the topographic surface so that at times the floor of the lake occurs below the water table and the basin is periodically flooded by groundwater. This is in contrast with many other playa lakes and wetland depressions which lie over a water table several meters to several hundreds of meters below the surface (e. g., Lake Eyre, Lake Torrens in Australia and many playas in southwestern United States). During short wet periods, these latter depressions fill with water to form a lake, but there is little interaction with the groundwater below. Commonly, the water in these lakes is only slightly saline or even fresh, and taxa living in the lakes are characteristic of temporary pools or ephemeral ponds, but are definitely not the same as those habiting the groundwater-charged playas and salt lakes. It is our contention that the sediment records in lakes such as Beeac are extremely valuable in attempting to decipher paleoenvironmental fluctuations in semi-arid regions because these lakes may be the *first*, and sometimes only, sites to register even minor changes in the hydrologic/climatic setting.

REGIONAL SETTING

The Western Victorian Plains physiographic province is a large 40,000 km^2 area of flat to gently rolling terrain located in southeastern Australia (Figure 1). The area experiences a warm, semi-arid to subhumid climate. The mean annual temperature is 15.5°C (Thompson 1971) and the average annual rainfall ranges from about 1000 mm in the south to less than 500 mm in the northern part of the region (Lee, 1982). High evaporation rates during the summer give annual evaporation/precipitation ratios of generally one to two.

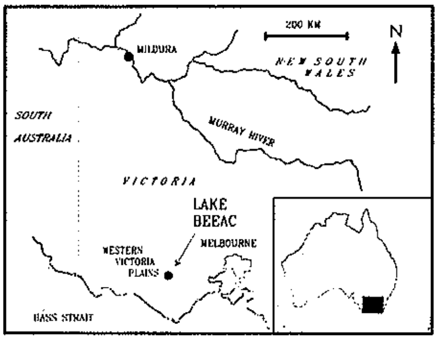

Figure 1. Map of southeastern Australia showing the location of Lake Beeac and the Western Plains region of Victoria.

The flatness of the region is the result of Quaternary and Tertiary volcanism. This volcanism and the resulting landforms have been the subject of considerable research (see summaries of these studies in Clark and Cook (1988) and Douglas and Ferguson (1988)). The igneous activity created an extensive plain of basalt interrupted only by occasional rough and jumbled topography of individual lava ridges (stony rises) and the numerous eruption points that can reach up to 160 m above the surrounding plain. The most recent volcanism in the region occurred about 7000 years ago (Jenkin 1988). In most of the area around Lake Beeac the basaltic bedrock is mantled with a poorly developed, thin, stony, brown to grey, solodic soil. The natural vegetation of the region consisted of grasses and mixed grassland-woodland. However, today most of the land is cropped or used for grazing.

The region is characterized by poorly developed drainage and an abundance of lakes. Many of these lakes occur in topographically closed basins. Most of the lakes are saline. There is a wide variety of lake basin types and morphologies, with lakes ranging in size from Lake Corangamite (Figure 2), the largest inland permanent water body in Australia, to small ephemeral ponds less than 1 km^2 in area. Most of the smaller lakes simply occupy local depressions in the lava field surface, whereas some of the larger lakes have formed in basins behind lava flow dams. Finally, many of the volcanic cones and eruption centres (forming maars) also contain small but often deep lakes.

METHODS

This report is based on analyses of surficial and subsurface sediment samples taken from the Lake Beeac basin from 1987 to 1989 (Figure 2). Subsurface samples were acquired by coring using a modified Livingstone piston corer and by hand augering. Pits and trenches were also dug at numerous locations in the basin in order to examine and better describe the details of stratification.

After visual observations of the sediment were logged, subsamples were analyzed for bulk mineralogy, clay mineralogy, and detailed carbonate and evaporite mineralogy using standard X-ray diffraction techniques. Details of these analytical procedures, sample preparation, and X-ray data interpretation can be found elsewhere (Last and De Deckker

1990; De Deckker and Last 1989; Wright 1988). Wet chemical analyses were used to confirm the composition of the dolomite derived by XRD. Grain size was evaluated using a laser particle counter (Brinkmann PSA 2010). Organic matter content was determined by loss-on-ignition (Dean 1974). Standard laboratory techniques were used to prepare and examine sediment subsamples for microfossil remains (De Deckker 1982). Selected samples were also examined using a scanning electron microscope (SEM) coupled with an energy dispersive analytical system (EDS).

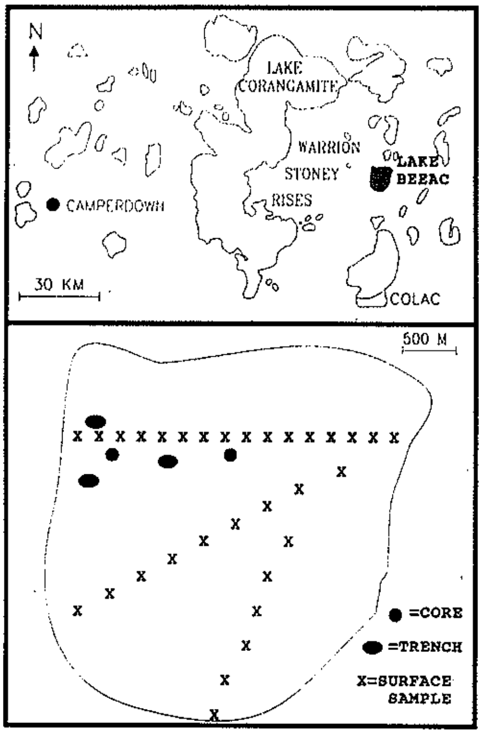

Figure 2. Map of Lake Beeac showing core and sample locations.

THE MODERN LAKE BEEAC

Lake Beeac, located about 15 km north of Colac, Victoria, has a surface area of 6.47 km^2 when full (Figure 2 and Table 1). The lake is one of the largest of the many shallow playa lakes in the region. It occupies a topographically closed basin situated at the eastern edge of a large field of stony rises and scoria cones. Quaternary alluvial and lacustrine sediments occur at the surface to the east and north of the Beeac basin. Immediately adjacent to the eastern shoreline of Beeac is a long, topographically distinct, north-south oriented ridge (lunette) composed of aeolian sands, silts, and clays.

As with most of the playas and ephemeral lakes of the region, the water levels in Beeac vary greatly, usually on an annual basis. Maximum water depths of 0.5 to 1 m normally occur during the wet winter season; the lake usually dries completely during the summer. According to Thompson (1971), salt has been harvested from the lake bed during particularly dry years.

There are no major perennial streams entering the lake, but four very small ephemeral creeks drain a watershed area of about 25 km^2. The discharge of these creeks has not been quantified but is assumed to be minor relative to the contribution of groundwater into the lake basin. Details of this groundwater flow in the immediate drainage basin area and the magnitude of the groundwater contribution to the hydrologic budget of the lake have not yet been fully established. Thompson (1971) suggests that Lake Beeac, as well as several other playas in the area, is maintained by groundwater derived from the Warrion lava flow east of the basin (Figure 2). Similarly, Gill (1987) shows that groundwater movement is eastward toward the Beeac basin from a groundwater drainage divide located about 10 km west of the lake. This groundwater input to Lake Beeac occurs as diffuse seepage through the low permeability lake sediments. No discrete groundwater springs have been found in the basin. Thus, Lake Beeac is a groundwater window. The water table is located close to the floor of the lake such that during the wet (winter) season the playa is thought to become flooded primarily by groundwater seepage. During the summer, high evaporation

Table 1. Morphometric, hydrologic, and chemical characteristics of Lake Beeac.

Maximum length	3.38km
Maximum width	3.01km
Maximum depth	0.89m
Area	6.47km^2
Volume	3918m^3
Drainage area	24.12km^2
Length of shoreline	10.10km
Estimated annual precipitation	600mm
Estimated annual evaporation	1100mm
Brine Composition (average of all available data, 1960-present)	
K^+	2.2ppt
Na^+	43.9ppt
Ca^{2+}	0.1ppt
Mg^{2+}	1.9ppt
HCO_3^-	1.3ppt
CO_3^{2-}	< 0.1ppt
Cl^-	64.6ppt
SO_4^{2-}	3.1ppt
TDS	90.7ppt

rates decrease surface water levels and cause desiccation of the lake. Even during the summer, however, the water table is at or near the surface of the playa; auger holes and pits dug in the dried playa are readily filled with water.

Because of concern about soil salinization in this intensely cultivated area of Victoria, a considerable effort has been placed on documenting the hydrochemistry of the groundwater in the region. Thompson (1971) summarizes the chemical data available from over 140 wells in the area. He notes that the shallow groundwater undergoes a dramatic increase in salinity, and an enrichment in Na^+ Cl^-, and Mg^{2+} with distance away from the recharge area (i. e., the Warrion stony rises). The salinity of shallow groundwater in wells immediately adjacent to Lake Beeac ranges from about 1000 to 3000 mg l^{-1} TDS and has typical ionic ratios of $Na^+ >> Mg^{2+} > K^+ > Ca^{2+}$ and $Cl^- >> SO_4^{2-} > HCO_3^- > CO_3^{2-}$.

A lot of water chemistry data exists for Lake Beeac (see compilations in Williams and Buckney 1976; De Deckker and Last 1989). The Beeac brine is saline (55 to greater than 300 ppt TDS), alkaline (average pH = 8.7), and strongly dominated by Na^+ and Cl^- ions, with secondary abundances of Mg^{2+} and SO_4^{2-} (Table 1). The water is supersaturated with respect to dolomite, magnesite, and hydromagnesite at all times of the year, but is generally undersaturated with respect to more soluble salts such as gypsum and halite. De Deckker and Last (1989) show that the brine is at or slightly undersaturated with respect to calcite and aragonite.

The surficial sediments of Lake Beeac have been described by Last (1990), De Deckker and Last (1988, 1989), and Wright (1988). The modern offshore sediment in the basin is a fine grained, white to grey, semifluid mud. This soft, gelatinous mud can be easily resuspended by even mild wave agitation, thereby giving the lake water a very distinctive white colour and low transparency. Mean grain size ranges from 9 to 26 microns, with very poor sorting characteristics. Because of the shallowness of the lake and the mobility of the muds, there is no consistent spatial trend in grain size, although the "nearshore" sediment tends to be more poorly sorted than the sediment from basin centre.

The modern sediment (i. e., upper 1 cm) is composed mainly of clay minerals, carbonate minerals, and organic matter, with minor amounts of quartz and feldspars. When dried, the surficial samples can also contain halite. The carbonate fraction of the sediment consists of an approximately equal mixture of dolomite and magnesite. Both of these carbonates occur as very small subhedral to anhedral crystals and microcrystalline aggregates. The dolomite is poorly ordered, with compositions ranging from Ca-rich to Mg-rich. The magnesite is also unusual in that it exhibits an enlarged crystal lattice on XRD patterns, presumably due to slight hydration of the $MgCO_3$ precipitate.

On the basis of petrographic and isotopic evidence, De Deckker and Last (1989) conclude that the origin of the carbonate fraction of the modern sediment in Beeac is direct, primary precipitation from the lake brine. The high alkalinity and high salinity coupled with elevated Mg/Ca ratios in the lake water give rise to greatly supersaturated conditions with respect to dolomite and magnesite, resulting in nucleation and precipitation from either the shallow water column or from the saturated pore solutions at the sediment-water interface. Thus, Lake Beeac occupies a unique position in the realm of carbonate sedimentology. It is not only one of the very few modern, nonmarine localities in which dolomite is actively forming, it is also one of only three reported occurrences of Mg-rich dolomite precipitation. The noncarbonate fraction of the sediment, except for halite, is interpreted to be allogenic in origin, derived from weathering of the basalts and erosion of the soils of the watershed. Halite is interpreted to be an artifact of drying and sample preparation.

STRATIGRAPHY

Lithostratigraphy

General

Overall, the upper 1 to 1.5 m of sediment in Lake Beeac is similar in appearance, texture, and composition to that of the surficial sediment. In general, the subsurface sediment is non-bedded, medium to dark grey, calcareous, organic-rich silt and clayey silt. The mean grain size of the sediment shows an increase upward in the section from an average of 9 microns at the base to about 20 microns at the top. The uppermost gel is usually finer grained (average of 15.6 microns) than the firmer material immediately below it. Coarser-grained sandy silt and silty sand occur at the basin margins and are sporadically distributed throughout the sampled section. Sediment colours are generally medium to dark grey, with abundant lighter and darker mottling. Horizons, streaks, and lenses of dark brown to reddish brown to black coloured sediment also occur. Indistinct light to dark colour banding on a scale of several tens of centimetres is evident in freshly exposed sediment of the pits. In all the pits and cores, the upper several centimetres to as much as 40 cm is very soft to gelatinous. Below this the material becomes gradually firmer and more compact and plastic with depth. Moisture content can be as high as 85% in the soft gelatinous surficial sediment, but this decreases to values of generally 30 to 50% at depth. Organic matter content ranges from 5 to 40% but does not exhibit any consistent trends with depth. Overall, the subsurface sediment is structureless, although the cores do show an indistinct pelleted fabric and granular to blocky structure in places. In one of the cores, small iron-stained root-like structures and indistinct burrows were observed. Core and auger penetration was limited throughout the basin by the presence of an impenetrable hard, dense horizon. Where sampled in pits nearshore this horizon consists of light brown, indurated sediment with abundant dark brown to reddish brown staining and mottling.

Overall, the mineral suite of the older sediments in Lake Beeac is similar to that of the modern sediments. The detrital components consist mainly of clay minerals, feldspars, and quartz; the carbonate minerals, dolomite and magnesite, are interpreted to be entirely endogenic in origin. The morphology of the dolomite and magnesite crystallites is uniformly anhedral to subhedral with no consistent stratigraphic variation. Some of the subsurface samples also contain trace amounts (< 5%) of calcite and high-Mg calcite. This $CaCO_3$ is interpreted to be bioclastic material, derived from calcareous shells and tests of organisms such as ostracods. The detrital minerals show a general decrease upward in the cores, whereas the endogenic carbonates increase toward the top of the section.

In addition to these fluctuations in the percentages of dolomite and magnesite in the section, the amount of magnesium incorporated into the dolomite crystal lattice also shows stratigraphic variation. Dolomite in both modern and ancient sediments rarely has an ideal (stoichiometric) composition of $CaMg(CO_3)_2$; instead nearly all dolomite in sedimentary environments is nonstoichiometric and usually enriched in calcium. The dolomite in Beeac sediment ranges from 47% to 57% $CaCO_3$ (i. e., Mg-rich to Ca-rich).

Lithostratigraphic Units

On the basis of core and pit descriptions and on the variations in mineralogical composition, texture, sedimentary structures, moisture content, and organic matter content, three lithostratigraphic units are recognized in the Lake Beeac basin (Table 2). Unit 1 is the lowermost unit in the basin. It is a firm, compact, medium to dark grey, clayey silt with a high dolomite content and low magnesite percentages. The unit exhibits a blocky structure throughout and has a low moisture content. The sediment at the upper contact is very firm, crumbly, and dry.

Table 2. Summary of average mineralogical and physical parameter values of the three lithostratigraphic units in Lake Beeac.

Unit	Moisture (%)	Organic (%)	Sand (%)	Silt (%)	Clay (%)	Mean Size (μm)	S.D. (μm)
3	41.0	26.0	5.6	80.9	13.5	17.3	16.6
2	34.8	19.6	5.7	82.8	11.5	15.3	16.6
1	17.2	13.3	1.2	81.7	17.1	12.4	13.0

Unit	Quartz (%)	Feldspars (%)	Clay Minerals (%)	Calcite (%)	Dolomite (%)	Magnesite (%)
3	4.7	7.7	60.9	0.2	11.1	12.7
2	3.9	11.0	63.8	0.0	10.5	9.9
1	2.0	9.9	70.0	0.0	12.4	3.4

Overlying this is Unit 2, an indistinctly mottled light grey to dark grey, silt and clayey silt, with a high total carbonate mineral content due mainly to a substantial increase in the proportion of magnesite relative to that of the underlying unit. The contact between Units 1 and 2 is sharp and readily observed in cores and pits throughout the basin. The grain size of Unit 2 shows an overall increase upward in the section as do the proportions of quartz and feldspar minerals. Both dolomite and magnesite decrease toward the top of the unit.

Unit 3, the uppermost stratigraphic unit in the basin, consists of mainly light to medium grey silt with relatively abundant root structures, burrows, and an indistinct pelleted fabric. This unit ranges from soft at the base to gelatinous at the surface. Although the contact between Unit 3 and Unit 2 is difficult to recognize in the field, it is readily identified on the basis of sediment texture and mineralogical composition. At the contact, the detrital components of Unit 3 dominate the sediment making up nearly 80% of the total mineral suite, with the proportions of quartz and feldspars being particularly high. This detrital fraction shows a strong decrease in percentage upward in Unit 3, with both quartz and feldspars decreasing to less than 5% at the surface. The opposite trend is shown by the endogenic minerals in Unit 3: the total carbonate content increases from about 15% at the base of the unit to generally more than 40% at the top of the section. The dolomite is Ca-rich throughout much of the lower part of the unit, but gradually becomes Mg-rich at the top.

Biostratigraphy

Twelve subsamples from one core were analyzed for their microfossil content. Unfortunately, few recognizable organic remains were recovered from the stratigraphic section. The following saline ostracod taxa were found: *Platycypris baueri*, *Diacypris* sp., and *Reticypris* sp. In all cases the occurrence of these species was rare with no evident stratigraphic trends present; most valves were deformed. Faecal pellets were also recovered from the upper 30 cm of the section. These are most likely from brine shrimp of the *Parartemia* genus.

The paucity of carbonate-shelled remains and fossils in the sediment fill of Lake Beeac is surprising, particularly since ostracods abound in the lake today (P. De Deckker, pers. observations). The most likely explanation for this apparent discrepancy lies in the unique water chemistry of the basin. As pointed out above and discussed elsewhere (De Deckker and Last 1989), although Beeac water is strongly supersaturated with respect to the Mg-bearing carbonate minerals of dolomite and magnesite, it is frequently *undersaturated* with respect to calcite and aragonite. These undersaturated conditions explain the absence of gastropod fossils, such as the otherwise ubiquitous *Coxiella* sp. with its aragonite shell, as well as the lack of calcitic ostracod remains. Even though these halobiont organisms can and do live in the lake today, upon death their shells simply dissolve in the undersaturated brine and are not preserved in the stratigraphic record.

Chronology

The absolute chronology of the sedimentary sequence in Lake Beeac is known from two reconnaissance radiocarbon dates reported by De Deckker and Last (1989). These dates, one from the surficial gel (1040 ± 70 yr B.P.) and the other from Unit 1 (10,360 ± 100 yr B.P.), were obtained from the carbonate fraction of the sediment (i. e., the endogenic dolomite and magnesite). As discussed by De Deckker and Last (1989), the anomalously old ^{14}C age for the modern surficial sediment is probably due to either: (i) a "hard-water" effect (i. e., contamination of the present-day CO_2 pool with older bicarbonate ions derived from old carbonate bedrock), or (ii) a physical mixing of the "modern" sediment with somewhat older lacustrine deposits.

DISCUSSION

The most significant and useful stratigraphic variations in the sediment record of Lake Beeac occur in the carbonate mineralogy. As many other reports have already emphasized, lacustrine carbonate minerals are important paleoenvironmental tools. Carbonates are one of only a few mineral groups that commonly occur as detrital (allogenic), endogenic, and/

or authigenic components in lake sediments. Carbonate minerals occupy a unique position in lacustrine sedimentology because they can be readily derived by purely inorganic precipitation, by biologically-induced inorganic precipitation, and by purely organic precipitation. While it is often possible to differentiate between detrital carbonate material and endogenic/authigenic precipitates on the basis of texture, fabric, and grain morphology, it is much more difficult to recognize and separate endogenic carbonates from authigenic material. As pointed out by Talbot and Kelts (1986), it is imperative that this distinction is made.

Of the three main genetic types of carbonates, the least important in Lake Beeac is detrital calcium carbonate. The unique mineral saturation conditions of the Beeac water discussed above mean that any fine grained detrital calcite or aragonite derived from physical weathering in the watershed and transport to the lake would likely be dissolved in the brine. Furthermore, neither dolomite nor magnesite occur in the soils or near-surface bedrock surrounding the basin. Similarly, we conclude that carbonates of authigenic origin are relatively unimportant in Beeac sediments. With the exceptions of the indurated hardground at the base of the sequence and the few ostracod valves recovered from the upper part of the section, our examination of over 100 subsamples of Beeac core by SEM has provided no evidence of replacement fabrics, intragranular precipitation, or dissolution-reprecipitation phenomena.

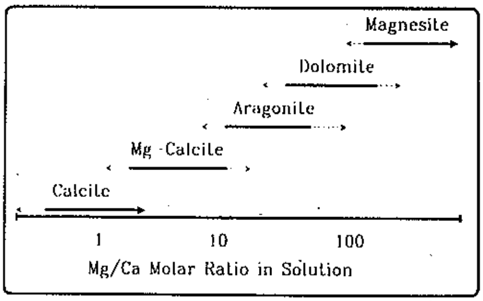

Figure 3. Effect of Mg/Ca ratio of the precipitating solution on the endogenic carbonate mineralogy (compiled from various sources; see text).

Having established the origin of most of the carbonate material in Lake Beeac as endogenic, it is possible to use the stratigraphic variation in the two Mg-bearing minerals to deduce the Mg/Ca ratio of the precipitating brine. It is generally held that the specific Ca-Mg-carbonate mineral phase precipitated from a saturated solution is controlled mainly by the Mg/Ca molar ratio of the water (see, for example, Usdowski 1968; Moller and Kubanek 1976; Müller et al. 1972; Last 1990). Although this subject is one of considerable controversy when applied to low temperature/pressure carbonate mineral formation, a generalized sequence is shown in Figure 3. It must be recognized our understanding of this mineral formation sequence is still incomplete. Many other factors, including total ionic strength, sulphate ion content, temperature, and the role of organisms, have been cited as important in dictating the specific carbonate species generated. The presence of endogenic carbonate minerals throughout the entire late Pleistocene and Holocene sediment record of Beeac indicates that the lake water has been alkaline and actively precipitating carbonates during much of its history. During deposition of Unit 1 the water was much more conducive to precipitation of dolomite than magnesite due, most likely, to a relatively low Mg/Ca ratio. The absence of calcite, high-Mg calcite, and aragonite indicate that this ratio was still greater than about 10. In contrast, during deposition of the overlying carbonate muds throughout most of the Holocene, the lacustrine brines were relatively rich in magnesium as shown by the abundance of magnesite and the occurrence of Ca-depleted dolomite (i. e., high-Mg dolomite) in Units 2 and 3. Indeed, the striking increase in the amount of magnesite relative to dolomite in the upper part of Unit 3 indicates that excessively high Mg/Ca ratios were achieved and have been maintained in the basin for some 1600 years.

Because Lake Beeac is a groundwater window and the distinct chemistry of the brine (high alkalinity and high Mg/Ca ratio) is derived from a shallow groundwater source, these fluctuations in carbonate mineralogy provide valuable insight into changes in the hydrologic budget of the basin. During episodes in the lake's history that were similar to that of today (i. e., a dominance of groundwater influx over surface inflow), the brine was highly alkaline, with probably greatly elevated Mg/Ca ratios like those today (see De Deckker and Last 1989). Carbonate mineral precipitation was dominated by magnesite and Mg-dolomite. However, when conditions were such that the surface runoff and the groundwater contributions were approximately the same, brines with somewhat lower Mg/Ca ratios prevailed and dolomite was the main carbonate being generated in the lake. Finally, if the hydrology of the basin was dominated by surface inflow with little or no contribution from groundwater sources, conditions may not have been conducive to the formation of either dolomite or magnesite, and sediment comprising mainly siliciclastics was deposited.

One of the most distinctive visual features of the stratigraphic sequence in Lake Beeac is the difference between Units 1 and 2. The very firm, dry, crumbly sediment of the upper part of Unit 1 contrasts sharply with the overlying soft, massive, moist material of Unit 2. This contrast is marked by an abrupt transition from the fine, angular blocky and granular structure of Unit 1 to the essentially structureless sediment above. As discussed above, there is also a sharp change in mineralogy. With depth in Unit 1, the structure gradually becomes less distinct, less angular, more pelletal, and the moisture content increases. We interpret this dry, structured sediment at the top of Unit 1 as representing relatively lengthy periods of lake desiccation. Subaerial exposure of the playa muds and possibly incipient soil formation would produce low moisture contents as well as a blocky and granular structure due to shrinkage and cracking.

The duration of this period of subaerial exposure and desiccation is not yet known. More closely spaced dating must be done of the late Pleistocene-early Holocene sequence. Teller and Last (1982) review the generation of pedogenic marker horizons such as this in several lacustrine sequences in North America. They conclude that pedogenic fabrics and structures like those found in Unit 1 of the Beeac sequence could form during periods of desiccation lasting only a few years or may represent a much longer (1000 years) hiatus.

The late Pleistocene date for this period of extended desiccation fits well with the general pattern of lake level fluctuations deduced from the sediment records of volcanic maars in the region. Several studies have recognized a similar period of aridity and low lake water levels at this time in western Victoria: Bowler (1981, 1970) and De Deckker (1982) in Lake Keilambete; De Deckker (1982) in Lakes Gnotuk and Bullenmerri; De Deckker et al. (1987) in West Basin Lake; and Bowler and Teller (1986) in Lake Tyrrell.

Stratigraphic fluctuations in the amounts of detrital minerals in Lake Beeac also provide some insight into varying geochemical and hydrologic conditions in the basin and watershed. Unfortunately, these fluctuations are much more difficult to interpret. The gradual decrease in abundance of detrital components and the concomitant increase in endogenic material towards the top of Unit 3 clearly points toward decreasing clastic sedimentation rates and an increasing importance of chemical sedimentation in the basin during the past five to six thousand years. This may be related, in terms of climate, to either an increase or a decrease in mean annual rainfall. The general relationship between surface runoff and detrital sediment yield is well known (Schumm 1968) and is a principle of fundamental importance in geology and geomorphology. This relationship, termed the Langbein-Schumm Rule, indicates that although increasing runoff will tend to increase the sediment yield for a drainage basin, the effect of increased surface vegetation at higher rainfalls will counteract this trend. The result is a decreased sediment yield with increased rainfall. Above a certain level of precipitation, however, the trend is again reversed, leading to higher yields with higher rainfall. The combination of these effects (Figure 4) shows that a greater clastic sedimentation rate in Lake Beeac during the mid-Holocene could be achieved either by: (a) decreasing annual precipitation in the area by about 50%, or (b) increasing annual precipitation by a factor of two. As pointed out by Wilson (1973) many factors in addition to annual precipitation make this relationship much more complex than is illustrated in Figure 4.

In contrast, the gradual decrease in clastic sedimentation in Lake Beeac over the past six millennia may not be directly related to any climatic parameter. Instead, this change may be reflecting a gradually stabilizing watershed due simply to soil development. Clastic sedimentation rates were likely very high immediately after the most recent volcanism in the region. The fresh basalts, tuffs, ashes, and scoria deposits could be easily weathered and eroded. However, with time the landscape would develop soils which effectively isolate the new igneous rocks and derived sediments from this rapid erosion, thereby decreasing the net clastic sedimentation rate in the basin. Colonization of the fresh bedrock and eruption detritus by plants would have a similar isolating effect. Although it is not yet possible to confidently interpret the significance of the fluctuations in detrital versus endogenic mineral components in the Beeac record, De Deckker et al. (1989) point out that the evidence from nearly every other site in southeastern Australia points to higher precipitation levels 5000 years ago. Thus, the most likely explanation for the decreasing clastic/chemical sediment ratio in Beeac over the past 5000 years is that of a gradually stabilizing watershed due to soil development probably in conjunction with decreasing annual rainfalls.

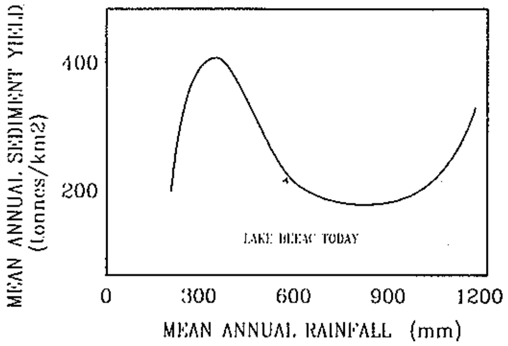

Figure 4. Relationship between sediment yield from a drainage basin and mean annual precipitation (after Leeder 1982).

CONCLUSIONS

Our reconnaissance study demonstrates that the sediment record in Lake Beeac can be used as a sensitive indicator in helping deduce past geochemical conditions in the basin and hydrologic changes on a regional as well as local scale. Lake Beeac, and playa basins like Beeac, respond very rapidly to such chemical and hydrologic changes because they are windows in the shallow groundwater table. One of the major features of importance of the sediment record from Lake Beeac is that it provides evidence of hydrologic fluctuations during a time that was more arid than today, and during which most of the deeper, perennial lakes of the region were completely dry. Once a more complete chronology becomes available for the late Pleistocene-Holocene record of Lake Beeac, it may be possible to obtain information on very subtle hydrologic changes. This information could not be obtained from other lake types in the region, especially crater lakes, which are often perched and not in direct contact with the regional groundwater.

It is very important to realize, however, that the interpretation of these hydrologic/geochemical fluctuations in terms of paleoclimate in a basin such as Lake Beeac is fundamentally different from many other lacustrine settings. A decrease in mean annual rainfall, for example, would likely be recorded in a typical volcanic crater lake in the region as decreased water levels. In the Beeac basin, however, the onset of a dry period would cause the disappearance of local arboreal/shrub vegetation. As a consequence of decreased evapotranspiration, the groundwater table should rise, thus causing the lake to fill up as a result of the water table becoming progressively higher across the landscape.

This phenomenon is commonly seen in western Victoria today as a result of clearing of the land by man (e. g., Macumber et al. 1989).

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