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THE PLEISTOCENE PALAEOENVIRONMENTAL RECORD OF LAKE BUCHANAN: AN ATYPICAL AUSTRALIAN PLAYA

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ABSTRACT

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Lake Buchanan is an "intermontane" playa located in subdued topography astride the Great Dividing Range in central Queensland. Undated multiple beach ridges on the western shore and cliffed lacustrine sediments on the eastern shore, both up to 5 m above the present lake-floor, attest to previous permanent-lake phases. Due to its position astride the continental divide for much of the Tertiary, Lake Buchanan probably escaped the acid weathering regime and attendant gypsum-formation of the continental interior.

Present surface- and groundwaters (140—210‰ salinity) are atypical of other Australian salt lakes which are commonly Mg^{2+}-rich and similar to evaporated ocean water. For Lake Buchanan, ionic $Ca^{2+}/Mg^{2+} \sim 1$, and the Sr^{2+} (~95 ppm) and F^- (~12 ppm) contents are very high, and Br^- exceedingly low (<0.02 ppm). The unusual water compositions are considered to reflect the chemical composition of the catchment rocks which are Mesozoic and Tertiary clay-rich sandstones. This relationship argues against the universal applicability of marine aerosol transport and marine-salt recycling as sources of salts for Australian playas.

Sediments cored from the lake floor are uniform non-laminated sandy clays composed of quartz (35 weight%), kaolinite (30%) and illite (25%). There is no primary chemically-precipitated carbonate or gypsum. Low-magnesium calcite occurs as a biogenic detritus of shelly fauna, charophyte gyrogonites and pedogenic nodules. Apart from the upper 20—50 cm, the sediment is devoid of organic carbon. A sequence of palaeosols indicates exposure of the lake floor during at least 13 episodes in the Pleistocene.

For a 15-m core (BU-1), palaeomagnetic analysis has identified the Brunhes-Matuyama boundary (0.73 Ma) at 5.0 m; and probably the top of Jaramillo subchron (0.92 Ma) at 6.3 m. An extremely slow sedimentation rate of ~7 m/Ma is indicated for the last 1 Ma. From 6.5 to 10.5 m in this core, intense iron-staining (pedogenesis) has confounded

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designation of palaeomagnetic polarity. Extrapolation might suggest an age of between 1.5 and 2 Ma for the base of this core.

Fossil biota from BU-1 and BU-9 include abundant ostracods and charophyte remains, and less commonly gastropods, fish fragments and foraminifers. Water depth is interpreted from ostracod and charophyte assemblages. For the last 0.73 Ma we recognize four major wet phases. The early history of BU-1 (below 12 m, ~1.6 Ma?) alternated between dry playa and shallow lake.

INTRODUCTION

The playa Lake Buchanan (21°36′S, 145°53′E) is situated in northeast Australia north of the Tropic of Capricorn, some 350 km west of Mackay (Fig.1). The lake is approximately 23 km long and 7 km wide, has a surface area of 117 km^2, and lies at an altitude of 289 m. The lake (for brevity, the term "playa" is omitted from the text) and its catchment area (2712 km^2) are situated in an "intermontane" depression astride the Great Dividing Range which runs almost parallel to the east coast of Australia. The ratio of lake area to catchment area is 1:23. Both the western and eastern margins of the catchment reach an altitude between 400 and 450 m. The area is characterized by an annual rainfall of ~550 mm/yr with most of the rain falling during summer, and February being the wettest month. The calculated annual mean temperature is 23.4°C, with a daily mean maximum of 30.9°C and a daily mean minimum of 15.9°C (H. A. Nix, personal communication, 1985).

When dry, the southeastern portion of the lake floor is covered with a thin halite crust. Dense macrophyte beds of the halophyte *Ruppia* sp. grow in the lake when water is present and abundant zooplankton, consisting mainly of crustaceans including ostracods, occur. There is no modern record of the periodicity of lake filling. In 1974, the lake was filled by ~5 m of water and expanded ~4.5 km beyond the eastern shoreline. Inspection of LANDSAT images for the last five years, indicates that the lake floor was nearly covered with water (the northwestern portion of the lake floor is the highest and last to fill) in March 1981 and again in April 1983. There have been recent periods of complete dryness, but the presence of a small pool, typically 4 × 2 km, near the southeastern shore, is the most common condition.

During the SLEADS (Salt Lakes, Evaporites and Aeolian DepositS) drilling program, a number of cores (Fig.1) were taken on the floor of Lake Buchanan and along its margin as part of an enterprise aimed at reconstructing the Late Cainozoic history of Australia. A light-weight piston and hollow-flight auger drilling-rig (Jacro 350) was used in September 1983 to take cores down to 15 m. Analyses of the core samples for chemistry, mineralogy, palaeomagnetism and fossil biota were performed in order to elucidate the lake's history.

PRESENT ENVIRONMENT OF LAKE BUCHANAN

Geology of the catchment area

Most of the catchment is composed of Quaternary sand and colluvium. The margins of the basin, along the Great Dividing Range, are defined by three outcropping units (Olgers, 1970). Along the eastern margin, the Warang Sandstone (Lower Triassic) is composed of kaolinitic quartz sandstone with minor ferruginous siltstone. The western margin is formed by the Ronlow Beds (Jurassic to lower Cretaceous) which are sandstones and mudstones, and unnamed Tertiary argillaceous sandstone. In the south the Moolayember Formation (middle to upper Triassic) is dominantly composed of mudstone and siltstone.

The abundance of these argillaceous sedimentary rocks in the catchment area strongly suggests that the clays deposited in Lake Buchanan are largely reworked from the basin margins rather than having an origin as authigenic or more recent weathering products.

Setting

The topography around Lake Buchanan is very characteristic; there is a set of ridges on the western side of the lake which runs almost parallel to its western shore (Figs.1 and 2). Some of the depressions between these ridges retain water at times, and in some places shallow lakes have developed; the largest of these is Lake Constant (Fig.1).

The ridges only occur on the western side of the lake as a result of the predominant easterly wind. On evidence so far obtained, they formed as beach ridges during high lake-stands. However, there is so far insufficient information to demonstrate that some of the ridges also contain aeolian material which could have been deflated from the lake floor during dry lake episodes. The highest surveyed ridge (J. M. Bowler, personal communication, 1983), which is ~1500 m from the western shore, is approximately 5 m above the present lake floor and has the same altitude as the top of a cliff consisting of lacustrine sediment. The latter was surveyed along a section in Dinner Creek on the eastern side of the lake (Fig.1). This further indicates that the western high ridge was formed when the lake was full.

Water chemistry

Chemical analyses of Lake Buchanan water have been available since Dunstan's (1920) publication. After 1965, when Bayly and Williams (1972) sampled the lake, chemical analyses have been made more frequently. A representative set of water analyses for Lake Buchanan is presented in Table I.

Lake Buchanan is dominated by NaCl, like the majority of saline lakes in

TABLE I

Chemical composition of Lake Buchanan waters. Results are reported in ppm and mmol/kg; salinity (total dissolved solutes) in parts per thousand

Date	Author or collector	Value[a]	Ca^{2+}	Mg^{2+}	K^+	Na^+	Cl^-	SO_4^{2-}	HCO_3^-	salinity (‰)
pre-1920	Dunstan (1920)	A	121	18	21	11,400	17,700	289	0	29.6
		B	3.0	0.7	0.5	498	500	3.0	0	
Jan. 1965	Bayly and Williams (1972)	A	1400	630	820	31,000	53,600	0	75	87.6
		B	34.9	25.9	21.0	1349	1512	0	1.2	
June 1981	De Deckker (coll.)[b]	A	128	93	700	20,500	32,400	640	94	55
		B	3.2	3.8	17.9	892	914	6.7	15	
July 1981	B. Timms (coll.)[b]	A	2060	1300	1160	45,100	75,000	1370	156	127
		B	51.4	53.5	29.7	1962	2116	14.3	2.6	
July 1983	B. Timms (coll.)[b]	A	747	352	325	13,800	23,300	593	28	39.5
		B	18.6	14.5	8.3	602	914	6.2	0.5	
Sept. 1983	De Deckker (coll.)[c]	A	2630	1290	1270	49,970	86,000	2450		144
		B	65.6	53.1	32.5	2174	2427	25.5		

[a] Value: A in ppm; B in mmol/kg. [b] Analyses by J. Caldwell and [c] E. Kiss.

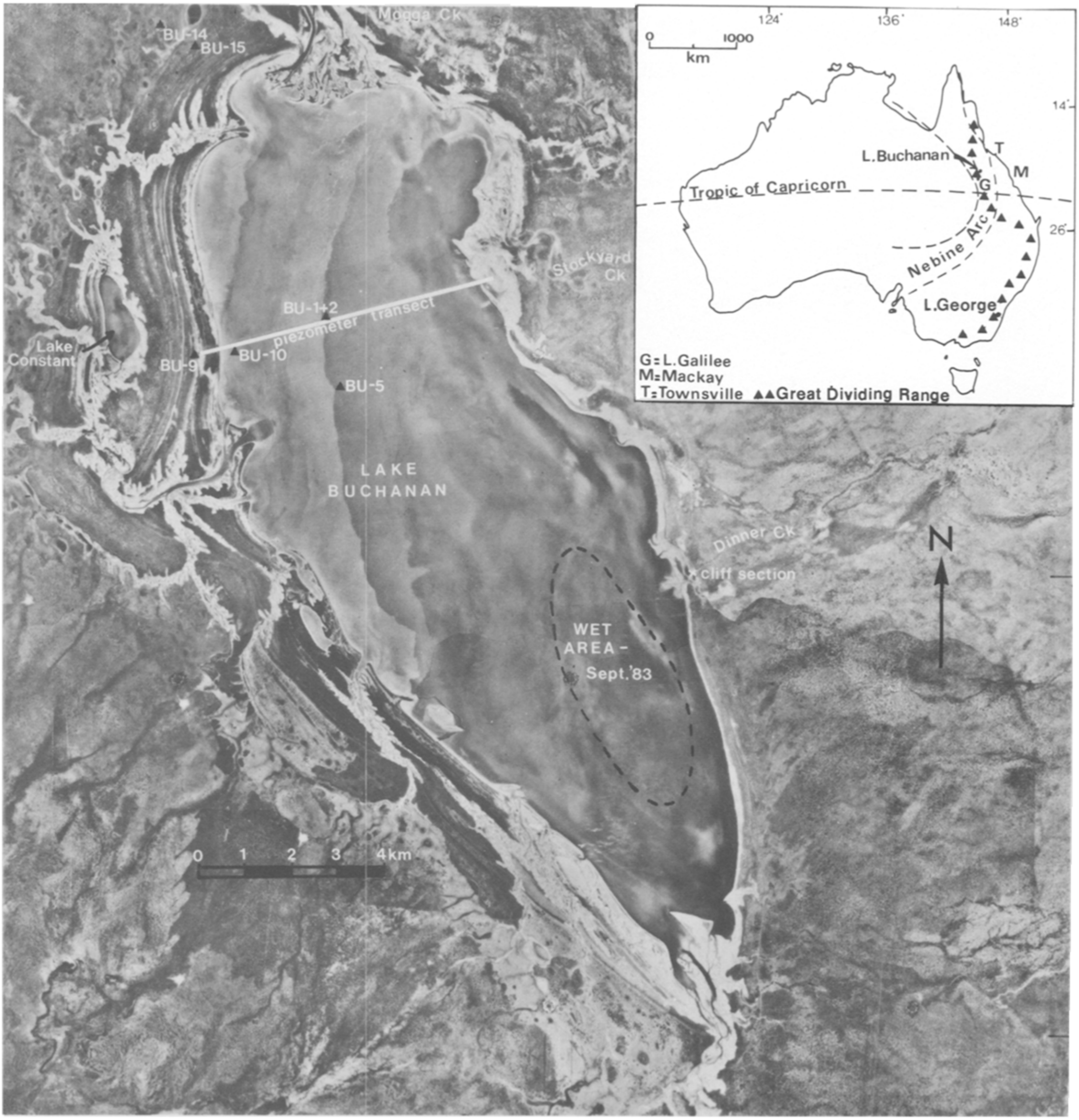
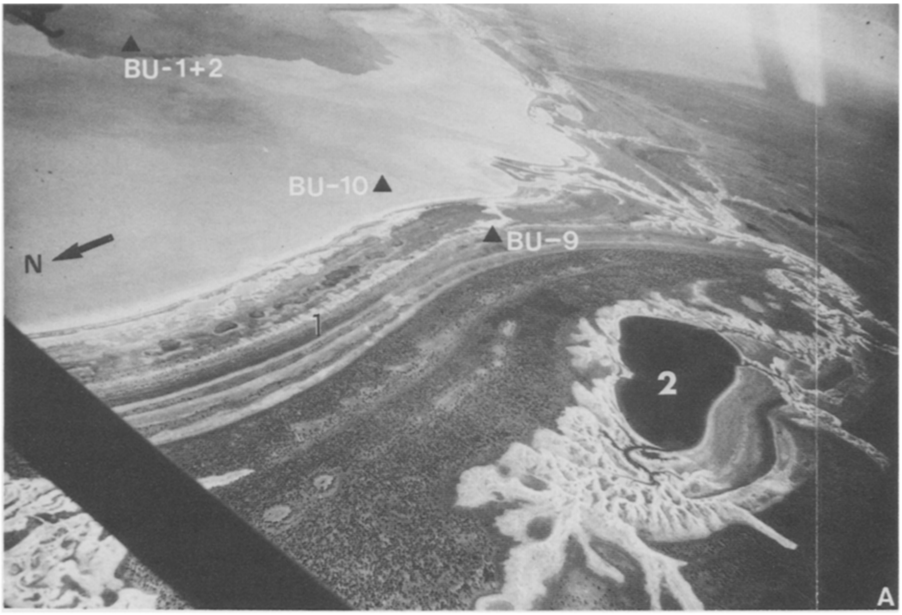


Fig.1. Composite aerial photograph (1971) of the playa Lake Buchanan showing coring sites (*BU-*) and the piezometer transect. Previous strand lines are visible on the lake floor. The area of surficial water during September 1983 is also indicated. Orthophotomap Bowie 8054 (1:100,000) is Crown Copyright and has been reproduced by permission of the Director, Division of National Mapping, Department of Resources and Energy, Canberra, Australia.



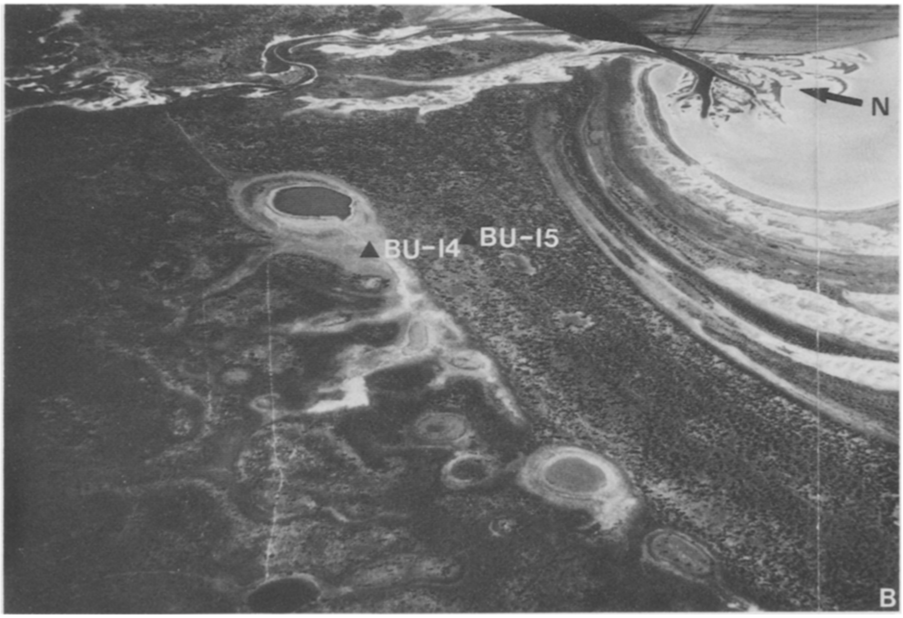


Fig.2. A. Oblique aerial photograph of the western shore of Lake Buchanan showing: (1) parallel beach ridges along the shore of the lake; (2) Lake Constant containing water; and coring sites. B. Northwestern shore of Lake Buchanan and Mogga Creek delta. Note parallel beach ridges and small pans situated in swales. Photographs courtesy of J. M. Bowler.

Australia. The ionic Ca^{2+}/Mg^{2+} of the water is close to unity and in some samples Ca^{2+} is slightly more abundant than Mg^{2+}. This is a surprising feature for Australian continental saline waters where the opposite is usually the rule. This composition (Ca/Mg ~ 1) is a regional feature since it also applies to all the saline waters (most often slightly saline) in the vicinity of Lake Buchanan including Lakes Galilee and Dunn, which are ~100 km south of Lake Buchanan. The sulfate content of Lake Buchanan water appears low compared to that of other Australian saline lakes.

Hydrology and groundwater chemistry

A set of piezometers was placed along a transect across the lake floor (Figs.1 and 3). Chemical analyses (Table II) of the waters from the piezometers indicate that the upper portion of the groundwater below the lake floor is similar to the lake water. The profile of the groundwater table (Fig.3), measured in September 1983, shows a small rise near the middle of the lake. This ridge of shallow groundwater probably forms a central axis within the lake, trending NNW from the small pool of surface water.

The trace-element compositions of the groundwater brines present several unusual features. The strontium content is very high (~95 ppm), as is fluoride (~12 ppm), whereas bromide is extremely low (<0.02 ppm) and molar Cl^-/Br^- is $>2 \times 10^6$—10^7. These abundances are in stark contrast to those of most other Australian lakes which typically exhibit major- and trace-element ratios very like those of ocean water (Sr^{2+} = 7.6 ppm, F^- = 1.3 ppm, Br^- = 67 ppm, Cl^-/Br^- = 650 and Ca^{2+}/Mg^{2+} = 0.19). Thus, the Sr^{2+}/F^- ratios of Lake Buchanan water are not unlike those of evaporated ocean water, but the Ca^{2+}/Mg^{2+} and Cl^-/Br^- ratios are very different. The low Br^- content, in particular, precludes even a minor contribution of ocean water to the Late Buchanan brines.

SEDIMENTOLOGY

The sediments recovered from Lake Buchanan consist of uniform non-laminated olive-green to beige sandy clays composed of quartz, kaolinite and

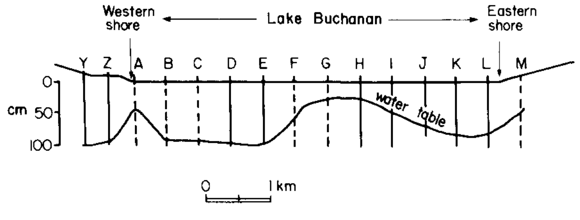


Fig.3. Profile of water table (September, 1983) within the northern portion of Lake Buchanan from the piezometer transect (see Fig.1). Letter symbols refer to each piezometer (most inserted to a depth of one meter, *J* inserted to 83 cm). Groundwater analyses (see Table II) are presented from those piezometers (*A*, *B*, *C*, *F*, *G*, *M*) that are represented by dashed lines.

TABLE II

Chemical composition of groundwater (Sept. 1983) from piezometers in the dry floor of Lake Buchanan compared with that of the lake water. Results are reported in ppm and mmol/kg; salinity (total dissolved solutes) in parts per thousand. All samples have <0.02 ppm Br.

Piezometer	Depth[a] (cm)	Value[b]	Ca^{2+}	Mg^{2+}	Sr^{2+}	K^{+}	Na^{+}	Cl^{-}	F^{-}	SO_4^{2-}	Salinity (‰)	field pH
BU-A	50	A	2600	1480	106	878	53,780	83,230	12.1	1790	144	6.45
		B	65	61	1.2	22.5	2340	2348	0.64	18.6		
BU-B	96	A	3414	2290	99	1318	72,630	126,100	17.9	2230	208	6.95
		B	85	94	1.1	33.8	3160	3558	0.94	23.2		
BU-C	96	A	3390	2200	94	1307	71,800	132,400	12.7	2350	214	6.75
		B	85	90.5	1.1	33.6	3123	3734	0.67	24.5		
BU-F	50	A	3100	1880	91	1274	59,490	114,600	11.2	2210	183	6.75
		B	77	77	1.0	32.7	2588	3233	0.59	23.0		
BU-G	34	A	3090	2270	93	1289	59,390	113,300	10.5	2237	182	7.05
		B	77	93	1.1	33.1	2584	3195	0.55	23.3		
BU-M	51	A	2770	1706	98	1101	54,220	95,000	8.9	1855	157	
		B	69	70	1.1	28.3	2358	2680	0.47	19.3		
Lake water		A	2633	1293	54	1266	50,000	86,000	12.9	2446	144	
Sept. 1983 (BUC)		B	66	53	0.6	32.5	2174	2427	0.68	25.5		

[a]Depth = height of water table below lake floor. [b]Value: A in ppm; B in mmol/kg. Analyses by E. Kiss. Ca^{2+}, Mg^{2+}, Sr^{2+}, K^{+}, Na^{+} by A.A.S., Cl^{-} by spectrophotometry; F^{-}, Br^{-}, SO_4^{2-} by ion chromatography.

illite. Thin sections of undisturbed sediments indicate that the quartz is largely present as angular grains, typically 0.05—0.1 mm across, but commonly up to 0.8 mm across. There is no primary chemically precipitated carbonate component within the sediment. Low-magnesium calcite occurs as a biogenic detritus of charophyte gyrogonites and fragments of stem encrustations, ostracod shells and less commonly the gastropod *Coxiella* sp. Strata that are rich in these components have a sandy texture, but a clay-sized matrix. A reconnaissance palynological study (J. Luly, personal communication, 1982) indicates that pollen is neither abundant nor well preserved. Apart from the uppermost 20—50 cm, the cores are devoid of organic carbon. Many analyses of whole sediments that are free of biogenic calcite, have <0.01% total carbon (Fig.4).

Mineralogy

Quantitative mineralogical analysis of core BU-1 and BU-2 was determined by X-ray diffraction using samples of consistent weight (25 mg) and grain size. X-ray peak intensities were related by algorithm, to binary and ternary mixtures of standards composed of sedimentary illite, kaolinite, quartz, aragonite and calcite. The abundances of quartz (typically ~35 weight %), kaolinite (~30%) and illite (~25%) are remarkably uniform (Fig.4). The isolated calcite peaks correspond to the presence of biogenic carbonate or pedogenic calcite nodules. Dolomite recorded between 12 and 15 m in the core may also have a pedogenic origin. Aragonite, smectite and gypsum were not detected. Halite, precipitated from pore waters during drying of sediment samples, is commonly detected. Nodules of celestite ($SrSO_4$) present in core BU-9 from 6.83 to 7.00 m reflect the strontium-rich nature of the lake system.

Palaeosols

The most striking feature of the sediments is the presence of segments containing abundant iron-staining and brown to orange colour-mottling. Commonly associated with the colouration are subvertical structures (interpreted as root casts), blocky fabric, ferruginous and calcareous micritic nodules (up to 5 mm across, but typically about 2 mm across) and manganese staining. These features are interpreted as indicative of palaeosols.

The abundance of palaeosols, which correlate among the three long cores suggests long and frequent episodes of desiccation, during which the lake floor was exposed. Unless the lake floor was rapidly vegetated at each period of exposure, some sediments may not have been preserved owing to aeolian deflation. Therefore, we can anticipate that portions of the sedimentary record are incomplete, but we are unable to specify how much and when this loss of material might have occurred.

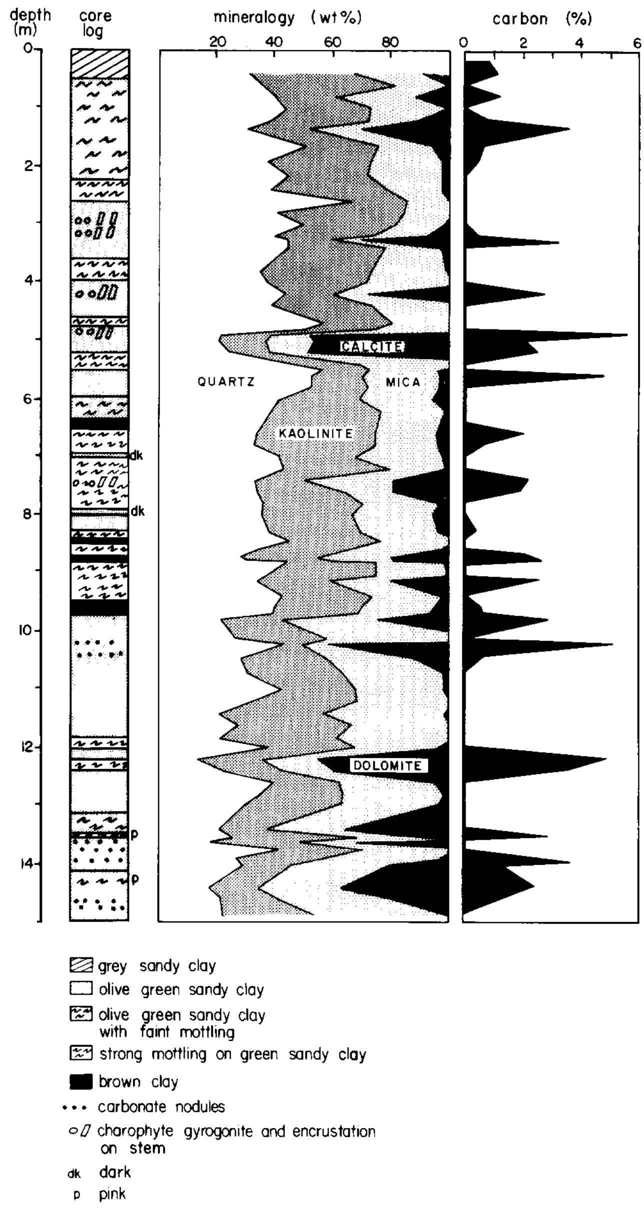


Fig.4. Lithology, modal mineralogy in cumulative weight % (by X-ray diffraction), and total carbon content of sediments from core BU-1. Carbon contents were determined by a Leco radio-frequency induction furnace and WR12 carbon determinator.

PALAEOMAGNETIC ANALYSIS

Cores BU-1 and part of BU-2 were sampled for palaeomagnetic analysis in January 1984, when the cores were moist and first opened for photography and chemical sampling. The oriented palaeomagnetic specimens were collected at approximately 20-cm intervals in transparent plastic boxes, 11.1 cc in volume, inserted in the face of the split core.

The natural remanent magnetization (*NRM*) was measured on a cryogenic fluxgate magnetometer (Goree and Fuller, 1976). All specimens were stepwise demagnetized, and measured after tumbling successively in peak alternating fields (McElhinny, 1966) of 50, 100, 200 and 300 Oe. Most specimens are only weakly magnetized (*NRM* = 0.06—2.7 $\times$ 10^{-6} emu/cc) and have median destructive fields (*MDF*) commonly less than 100 Oe indicative of their poor magnetic stability. Several specimens have a *MDF* less than or only slightly above 50 Oe, which represents very poor magnetic stability. The most stable magnetic components were obtained from the sequential cleaning data using modified Zijderveld plots (Zijderveld, 1967) to distinguish where vector rotation ceased and changes occurred only in intensity. For the 81 specimens, these end-points (2 at 100 Oe, 44 at 200 Oe, 27 at 300 Oe and 8 without a recognizable end-point) have intensities in the range 0.01—0.2 emu/cc $\times$ 10^{-6}. Owing to rotation of the cores during recovery, the declination measurements are of little value and magnetic polarity is assigned on the basis of palaeo-inclination (Fig.5). The expected geocentric axial-dipole inclination at Lake Buchanan is —38° and the measured 1980 inclination was ~—52°. Figure 6 represents a histogram of end-point inclination directions. Although there is a maximum at about —40°, there is a wide scatter of values. The lack of positive values especially near +38°, indicates scatter due to poor magnetic stability and a strong normal chemical remanent magnetization (*CRM*) overprint associated with palaeosol formation.

Designation of polarity is rendered difficult in some specimens by the scatter of directions and near-destruction of the magnetization during stepwise partial demagnetization. These specimens are identified in the reliability column of Fig.5. Another impediment to the determination of original polarity is the iron-staining and mottling present in the core. This is particularly intense between 6.5 and 10.5 m in BU-1. In this interval it is probable that after partial demagnetization at only 300 Oe alternating field, a secondary chemical magnetization component associated with the staining is largely preserved at the expense of the primary detrital remanent magnetization. Most of the specimens from this interval have a normal polarity, whereas a reversed polarity would be expected for the primary component. Two individual specimens at 8.58 and 9.35 m have reversed polarity.

Magnetic-polarity time-scale and rates of deposition

The magnetic-polarity sequence for the upper 6.5 m of core BU-1 consists of normal polarity from 0 to 4.82 m; reversed from 5.16 to 6.22 m; and

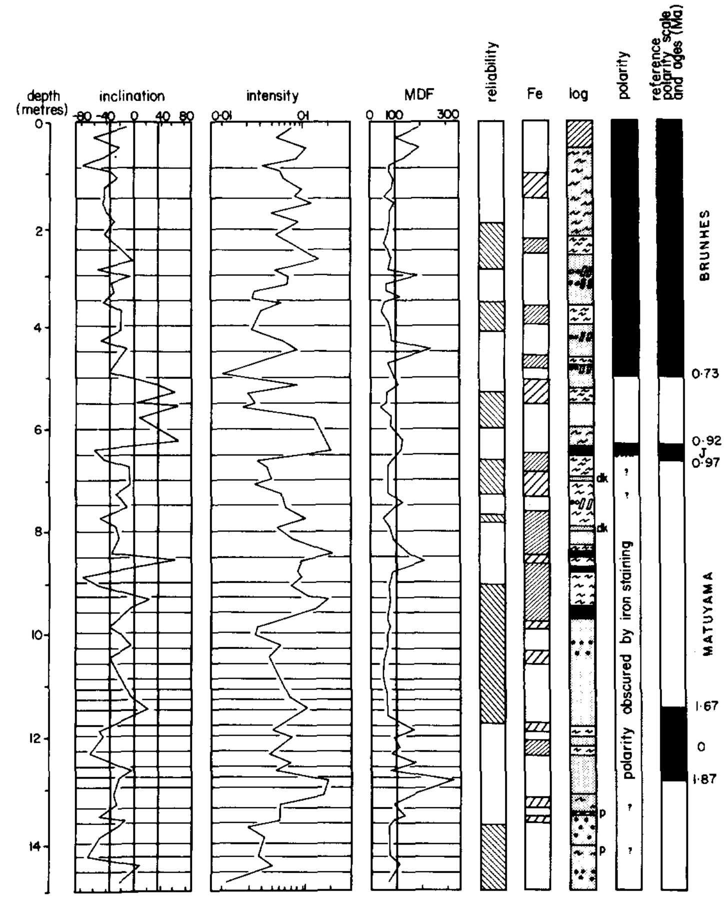


Fig.5. Palaeomagnetic results for cores BU-1 and BU-2. Results are essentially for BU-1 with a small interval of non-recovery (0.90—2.50 m) substituted by results from the adjacent hole BU-2. Horizontal lines indicate breaks between individual core segments. The intensity at stable end-points ("intensity") are in 10^{-6} emu/cc and the median destructive fields ("*MDF*") are in Oersted. Cross-hatched segments in the "reliability" column indicate poor reliability based on weak end-point intensities and low median destructive fields. Those specimens that are iron-stained or mottled are shown in the column labelled "*Fe*"; the closely hatched pattern indicates more intense iron staining. Symbols for the stratigraphic log as for Fig.4. The reference polarity time-scale is from Harland et al. (1982), and is at a scale of 6.9 m/Ma. *J* = Jaramillo subchron, *O* = Olduvai subchron, black is normal polarity, white is reversed polarity.

normal from 6.42 to the beginning of the iron-stained portion at 6.5 m. Designation of the first reversal at about 5.05 m as the Brunhes/Matuyama boundary (0.73 Ma) provides a mean rate of sedimentation of 6.7—7.1 m/Ma for the last 730,000 years. The magnetically reversed interval from about 5.05 to 6.35 m may represent either the upper part of the Matuyama chron to the Jaramillo subchron (0.92 Ma), or a more complete portion of the

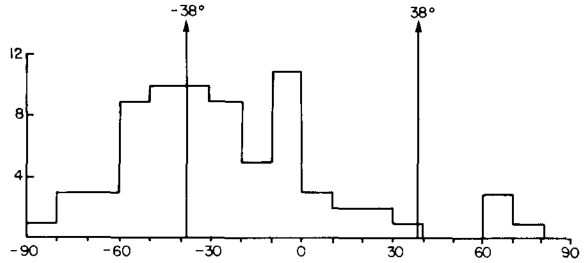


Fig.6. Histogram of end-point inclination directions for samples from cores BU-1 and BU-2. The expected geocentric axial-dipole inclination at Lake Buchanan is −38°. The wide scatter indicates that stepwise partial demagnetization has not completely removed the secondary component of magnetization that is caused by pedogenic iron-staining.

Matuyama chron, to the top of the Olduvai subchron at 1.67 Ma. The former interpretation is preferred as the mean sedimentation rate for the interval 6.35—5.05 m (i.e. 0.92—0.73 Ma) would be between 5.6 and 7.9 m/Ma, which is similar to that of the last 0.73 Ma. The second interpretation yields a mean sedimentation rate of 1.1—1.6 m/Ma for the interval 1.67—0.73 Ma.

Below 6.5 m, no clear interpretation of the polarity time-scale is possible if we discount the presence of three single-specimen reversals. An extrapolation of the mean sedimentation rate of 6.9 m/Ma for the first 6.5 m to the base of the core near 15 m, would place the top of the Olduvai subchron (1.67 Ma) at about 11.5 m. If there were originally a sequence with reversed polarity between 6.7 m and about 11 m, it is now overprinted by normally magnetized palaeosol development. The three single-specimen reversals may represent samples that escaped this overprinting, although more sampling would be needed to confirm this. Sediments from the base of the core may have an age of about 1.7—1.8 Ma.

Ages of pedogenesis

Magnetic polarities can be used to place some limited constraints on the ages of secondary iron deposition and thus timing of pedogenesis and exposure of the lake floor. Not all iron-staining or mottling is necessarily of pedogenic origin; some of the discrete ferruginous layers (e.g. at 12.2 m) might be original deposition features, or formed by iron-precipitation from groundwater springs. However, the larger volumes of iron-stained material have the appearance of a pedogenic origin. The numerous and nearly continuous mottled zones at 6.5—10.6 m in BU-1 have a normal magnetic overprint that indicates formation in the Jaramillo sub-chron (0.97—0.92 Ma) and/or during the last 0.73 Ma. There are four recognizable palaeosols in the last 0.73 Ma (upper 5.0 m of BU-1).

FOSSIL BIOTA

The Lake Buchanan cores and the cliff section at Dinner Creek were sampled for the study of microfossils. Cores BU-1 and 2 combined and BU-9 are particularly relevant (see location on Fig.1). A series of samples weighing 10 g each were treated (after De Deckker, 1982) for the recovery of ostracods and other microscopic remains, namely those of charophytes, foraminifers and vertebrates.

Ostracoda

The ostracods recovered from the cores are listed below in order of decreasing abundance; commonly occurring species: *Reticypris walbu*, *R. pinguis*, *Diacypris spinosa*, *D. whitei*; rarely occurring species: *Mytilocypris splendida*, *M. praenuncia*, *Ilyocypris australiensis*, *Trigonocypris globulosa*, *Trigonocypris* n.sp., (with dorsal overlap like *Cyprinotus*), *Platycypris baueri*, *Australocypris* sp. and *Ilyocypris* n.sp. (with nodes in the posterior area). Ecological information, principally salinity tolerances, for these ostracods can be obtained by referring to the list of publications mentioned in De Deckker (1983). All these ostracods indicate saline water conditions throughout the cores. Unfortunately, the salinity range of most of the abovementioned species is too broad to permit good definition of water salinity for most stratigraphic horizons. The new *Ilyocypris* and *Trigonocypris* species are assumed to be slightly saline species based on their association in the cores with other ostracod species indicative of such conditions. The noded *Ilyocypris* is found in association with dolomite, therefore indicating a possible different water chemistry for the lake water. This species has never been previously documented.

Variations in shell ornamentation and thickness were noticed on specimens of both *Reticypris* species. For example, some specimens of *Reticypris walbu* shells are extremely thin, finely reticulated and carry numerous spines dorsally along the shell periphery. Other specimens of the same species have thick shells, with a barely visible reticulation and commonly no spines. These two types of shells are thought to form under very different water conditions: thin shells form in deep (≥ 2 m) and most likely permanent water, and thick shells (nearly always found in association with charophyte remains) form in shallow water (<2 m) thought to be supersaturated in calcium carbonate. Further information is provided in the section on charophyte remains.

Foraminifera

One sample in each core yielded tests of the foraminifer *Ammonia beccarii*. The occurrence of this typically marine organism is not uncommon in saline lake deposits, especially in Australia where water composition in many salt lakes (with Na and Cl as dominant ions) is similar to that of the sea.

Cann and De Deckker (1981) and De Deckker and Geddes (1980) documented the occurrence of living and fossil foraminifers in Australian salt lakes and indicated that *A. beccarii* requires permanent water to grow and reproduce. It is thought also that when salinity in a lake is similar to that of the sea, *A. beccarii* numbers are high because optimal conditions for growth occur. Such conditions seem to have prevailed during the deposition of the foraminifer-rich layer in core BU-(1 + 2) (at 325 cm) and BU-9 (at 425 cm). Because this occurrence of foraminifers relates to a very specific event in the lake, these two layers are thought to be synchronous. This is confirmed by the fact that the BU-9 coring-site is one meter higher in elevation than the site of BU-(1 + 2), and that interpretations of water level for the lake above and below the foraminifer-rich layer in each core are identical.

Charophyta

Recently, Burne et al. (1981) documented the common occurrence of charophytes in saline waters. Therefore it is not surprising to find the fossil calcified female reproductive organs (gyrogonites) associated with fossil halobiont ostracods. The stems of charophytes may become encrusted with layers of calcium carbonate and those encrustations are also preserved in the sedimentary record, as is the case at Lake Buchanan.

Charophyte plants are never found at great depths in Australian salt lakes. Brock (1979) documented the occurrence of the charophyte *Lamprothamnium papulosum* only down to 2 m in the 4 m-deep saline Little Dip Lake in South Australia. Charophytes in salt lakes are therefore recognized as typical littoral organisms in Australian salt-lake deposits. In cores BU-(1 + 2) and BU-9, the common association of charophyte remains with thick-shelled *Reticypris* species with no spines is considered to represent a shallow water (<2 m) facies. The charophyte remains are never found associated with the thin-shelled *Reticypris*.

Gastropoda

The shorelines of moderately saline (≤100‰) playa lakes in Australia are characterized by thick layers of *Coxiella* shells. These gastropods are frequently reworked along the shore lines, but are usually very sparsely distributed on dry lake floors. The almost total absence of gastropod shells in core BU-(1 + 2) indicates that this site was rarely at the lake shore whereas the lake margin extended frequently to the site of core BU-9 between level 230 cm and the top of the core.

Vertebrate fragments

Fragments of bones, teeth and vertebrae, considered to be those of fish, plus fish scales are found in the cores. Vertebrate fragments occur most frequently in samples devoid of other fossils. They must originate from freshwater rivers which flow into the lake (e.g. Mogga and Cattle Creeks in the north and Dinner Creek in the east). These fossils commonly occur in association with sediments characteristic of a dry lake phase; they simply indicate occasional flooding by freshwater rivers into the dry lake basin.

PALAEOENVIRONMENTS AND INTERPRETATION

From analysis of the fossil biota recovered in cores BU-(1 + 2) and BU-9, several environments in the lake history can be recognized (Fig.7). A *deep* lake ($\geqslant 2$ m water) phase is interpreted from the presence of thin ostracod

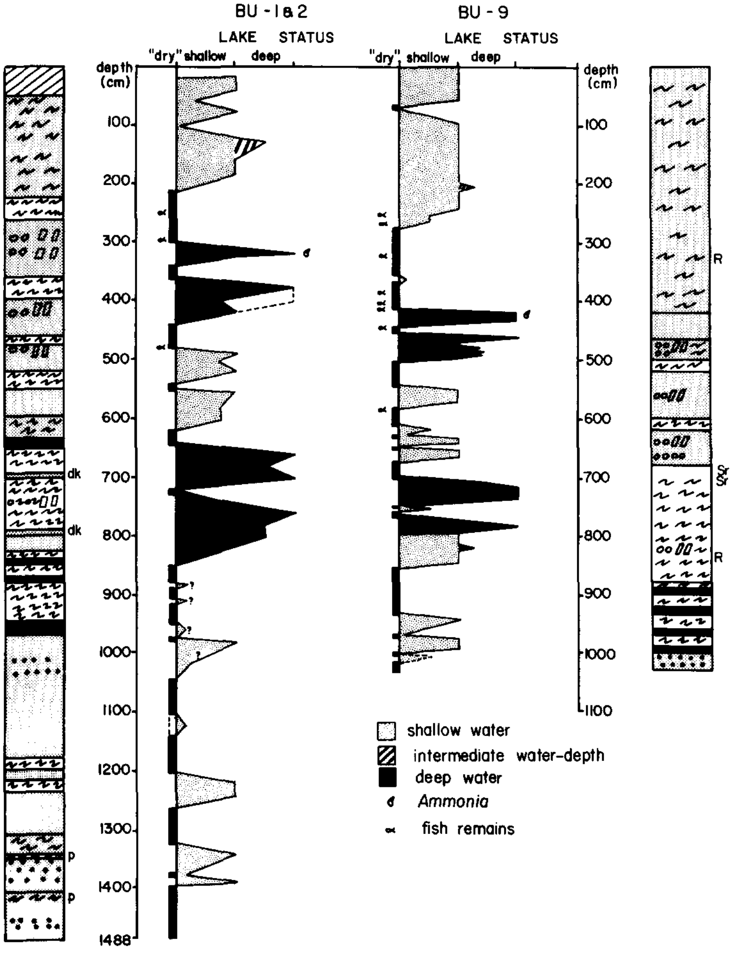


Fig.7. Lithologic logs (symbols same as those of Fig.4, *Sr* = celestite nodules, *R* = fossil roots) and interpreted past water-depths, based on ostracods and charophytes, for cores BU-1 and 2, and BU-9.

shells, and more especially the delicately ornamented and spiny *Reticypris* specimens. Charophyte remains are absent in these samples. *Shallow* lake (<2 m water) phases are recognized by the presence of charophyte remains, numerous and usually thick ostracod shells, and *Reticypris* species which are coarsely reticulated and with few or no spines. An *intermediate* phase can also be detected between the two previous ones where charophyte remains are few and varyingly ornamented ostracods belonging to the same species are found. It is assumed then that lake level fluctuated between shallow and deep.

For the portions of the core where ostracods are absent, we have little information on the lake environment. Ostracods could have even been present in the lake at the time of deposition of those strata or present and subsequently destroyed (mainly by dissolution) during pedogenesis. On the other hand, samples of olive-green sandy clay with no mottling found in core BU-(1 + 2) below 12 m exhibit no evidence of pedogenesis nor of laminations (such as those formed under aqueous conditions). So far, we cannot provide a satisfactory environmental interpretation for these strata. However, we assume that for some such strata the lake was *dry* at some stage, as indicated by pedogenesis. These problematical strata are labelled "dry" without a question mark in Fig.7.

The possibility that lacustrine sediments were deflated from the lake floor during dry phases cautions that some episodes in the history of Lake Buchanan may be missing from the record obtained by coring. Deflated material for example, if indeed deflation did occur, ought to be found outside the lake proper, perhaps as a mantle on, or interbedded with some of the beach ridges on the western shore.

The following lake history is recognized from a study of two cores (BU-(1 + 2) and BU-9) (see Fig.7). For the last period of normal polarity (viz. the last ~730,000 years), four major wet phases are recognized. During the first two phases, the lake was deep (≫2 m), whereas for the last two phases the lake was shallower. The first two phases were separated by a dry interval. The two deep-water phases were only separated by what seems to be a short dry episode. Prior to 730,000 years, there is an alternation of wet and dry episodes.

Below 12 m in core BU-1, which may correspond to ~1.6 Ma, environments at Lake Buchanan alternated between a dry playa and a shallow lake. Water chemistry was also different as shown by the different ostracod fauna associated with the presence of dolomite. The dolomitic horizons, recovered only from BU-1 are commonly associated with pedogenetic structures, but ostracods are still present in them, indicating that prior to pedogenesis, a wet phase did occur.

There are no palaeoenvironmental data available from other Pleistocene continental sedimentary sequences in tropical (northern) Australia that can be compared with the Lake Buchanan record. Singh et al. (1981) present data from Lake George (lat. 35°05′S; long. 149°25′E) that is situated

1500 km to the south (Fig.1, inset), in an area that presently experiences a temperate, winter-rainfall climate. Singh et al. (1981) recognized a series of 12 major wet episodes for the last 730,000 years in 17.5 m of sediment at Lake George. Only four major episodes are recorded at Lake Buchanan during the same time interval, but in 5.0 m of sediment. We are uncertain if this apparent difference reflects low climatic or hydrologic variability at Lake Buchanan, or if the Lake Buchanan sediments have not faithfully recorded all major environmental fluctuations. The Lake Buchanan sequence is condensed owing to a low sedimentation-rate and probable, but unknown, sediment loss by deflation and pedogenesis.

The fact that there is little authigenic-carbonate sediment found in the Lake Buchanan cores presents some interesting insight concerning the chemical evolution of the lake basin and its waters and sediments. Obviously, the water chemistry and carbonate mineralogy have remained fairly similar throughout the last ~1.6 Ma. This probably results from a periodic or continuous loss of brines from the basin either through overflow or leakage via the groundwater. On the other hand, since the majority of the sediments in the lake originate from the surrounding lithologies, there appears to be little control or effect by the brine pool below the lake. This would further confirm that Lake Buchanan is hydrologically open and remained so during the last ~1.6 Ma.

DISCUSSION OF MODERN BRINE COMPOSITIONS

There is presently much discussion on the origin of Australian inland salts and brines, because of their chemical similarity to ocean salts. One suggestion involves inland salt formation by cyclic processes, via marine aerosol transport. It could also be argued that central Australian modern lakes derive their salts from leaching and weathering of sedimentary rocks deposited during the Cretaceous marine transgression that inundated central Australia. Thirdly, much of Australia is covered by a weathered mantle (regolith) that evolved during prolonged exposure (50—90 Ma, in many areas). Thus it might be considered that the ultimate soluble weathering products (now gathered in terminal lakes) of a large portion of a continent may resemble global soluble weathering products (=ocean water).

The discovery that the Lake Buchanan area has brines that are compositionally very different from ocean waters argues against the universal applicability of the marine aerosol transport and marine-salt recycling suggestions. Our interpretation is that the unusual, but regional, brine compositions of Lake Buchanan ultimately reflect the chemical composition of the rock types in the Buchanan catchment area. These rocks comprise Mesozoic and Tertiary clay-rich sandstones that are not represented in the catchments of other Australian salt lakes. The Lake Buchanan area was located at the margin of the area affected by the Cretaceous marine transgression, and may have been thinly covered by marine sediments at this time, although the present groundwaters carry no evidence (via Br^- content) that soluble salts from the transgressive sequence remain in the modern environment.

CONCLUSIONS

A palaeomagnetic record spanning much of, and probably beyond the Pleistocene is found in the upper 15 m of sediments of the playa Lake Buchanan. This record indicates a very low sedimentation-rate in the lake, typically 7 m/Ma. For the last ~1.6 Ma, at least, the chemistry of the Lake Buchanan sediments remained surprisingly constant and yet different from most other Australian salt lakes. For example, at Lake Buchanan, there is a total lack of gypsum. In addition, it seems that the water chemistry and biota remained virtually unchanged during those ~1.6 Ma. Prior to this, dolomitic sediments, and a partly different ostracod fauna did occur.

The sediments testify to numerous wet and dry phases. At least four long wet phases occurred at the lake during the last ~730,000 years. The first two produced deeper water. Between these two deeper phases and the shallower ones, there was an extensive period during which the lake is thought to have been dry. Any record of a possible wet phase during this long interval may have been destroyed either by pedogenesis or by deflation.

The present Lake Buchanan occurs in a depression atop the Great Dividing Range, and is also included in an old lineament of the Nebine Arc described by Harrington et al. (1982). The Nebine Arc is considered to have been the continental drainage divide (Fig.1, inset) throughout much of the Tertiary. Due to the lake's position astride this divide for much of the Tertiary and Quaternary, Lake Buchanan probably escaped the acid weathering regime and attendant gypsum formation so common in the continental interior. Since the Pleistocene deposition rate has been so slow, Lake Buchanan is an ideal site for the preservation of a Neogene continental record and is worthy of investigation by deep drilling.

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