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S. McLaren ^a; M. W. Wallace ^a; B. J. Pillans ^b; S. J. Gallagher ^a; J. A. Miranda ^a; M. T. Warne ^c

^a School of Earth Sciences, University of Melbourne, Vic, Australia ^b Research School of Earth Sciences, Australian National University, ACT, Australia ^c School of Life and Environmental Science, Deakin University, Burwood, Vic, Australia

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Revised stratigraphy of the Blanchetown Clay, Murray Basin: age constraints on the evolution of paleo Lake Bungunnia

S. McLAREN¹*, M. W. WALLACE¹, B. J. PILLANS², S. J. GALLAGHER¹,
J. A. MIRANDA¹ AND M. T. WARNE³

¹*School of Earth Sciences, University of Melbourne, Vic. 3010, Australia.*

²*Research School of Earth Sciences, Australian National University, ACT 0200, Australia.*

³*School of Life and Environmental Science, Deakin University, 221 Burwood Highway, Burwood, Vic. 3125, Australia.*

Paleo Lake Bungunnia covered more than 40 000 km² of southern Australia during the Plio-Pleistocene, although the age and origin of the lake remain controversial. The Blanchetown Clay is the main depositional unit and outcrop at Nampoo Station in far-western New South Wales provides the most continuous lacustrine section preserved in the basin. Here the Blanchetown Clay represents the maximum lake fill and comprises: (i) a basal well-sorted sand with interbedded clay (Chowilla Sand), representing initial flooding at the time of lake formation; (ii) a thick sequence of green-grey clay comprised dominantly of kaolinite and illite, with the apparently cyclic occurrence of illite interpreted to represent cool and dry glacial climatic intervals; and (iii) a 2.6 m-thick sequence of finely laminated silt and silty clay, here defined as the Nampoo Member of the Blanchetown Clay. New magnetostratigraphic data constrain the age of the oldest lake sediments to be younger than 2.581 Ma (Matuyama-Gauss boundary) and probably as young as 2.4 Ma. This age is significantly younger than the age of 3.2 Ma previously suggested for lake formation. The youngest Blanchetown Clay is older than 0.781 Ma (Brunhes-Matuyama boundary) and probably as old as 1.2 Ma. The Nampoo Station section provides a framework for the construction of a regional Plio-Pleistocene stratigraphy in the Murray Basin.

KEY WORDS: Blanchetown Clay, climate, lacustrine sediments, Lake Bungunnia, magnetostratigraphy, Nampoo Member, Plio-Pleistocene.

INTRODUCTION

Tate (1885) was the first to identify the existence of a large intracontinental, Pleistocene paleo-lake in the Murray Basin of southern Australia. Browne (1945) named this feature Lake Nawait, but it was later renamed Lake Bungunnia by Firman (1965) and this name remains in use today. The evolution of Lake Bungunnia has been used by previous workers to make inferences on the nature and timing of climate cycles. In particular, the timing of the lake's demise has been used widely to indicate the onset of an arid climatic regime in the Australian continent.

Estimates of the size of Lake Bungunnia have been based on geomorphic and stratigraphic criteria (Browne 1945; Firman 1965; Bowler 1980). New-generation topographic data from the NASA Shuttle Radar Topographic Mission (SRTM) provides unprecedented opportunity to establish the lake geometry including the location of lake shorelines. Following Stephenson

(1986), the regional 60 m contour is generally accepted as the maximum extent of the lake fill. Using these criteria with the SRTM topographic data suggests lacustrine sediments covered an area of more than 40 000 km². As such, Lake Bungunnia is one of the largest known paleo- or modern lakes in an intracontinental setting.

Lake formation appears to follow a period of marine regression which extended through the Late Miocene and Early Pliocene leaving a record of stranded beach dunes across the Murray Basin represented by the Loxton-Parilla Sand (Ludbrook 1961; Blackburn 1962). The lake sediments comprise the variable (<40 m) thickness Blanchetown Clay and a thin (1–3 m) overlying lacustrine carbonate unit, termed the Bungunnia Limestone (Firman 1965) which is quite restricted in distribution and confined to the western portions of the basin (Stephenson 1986; Brown & Stephenson 1991). In the central and eastern portions of the basin lacustrine sediments unconformably overlie ferricrete of the

*Corresponding author: mclarens@unimelb.edu.au

Karoonda Surface developed on both the Miocene–Pliocene Loxton–Parilla Sand and Miocene marine limestones of the Murray Group. In the western portion of the basin the unit overlies the upper Norwest Bend Formation (Miranda *et al.* 2008) often infilling depressions on an irregular karst surface. Development of the Karoonda Surface as well as the well-developed karst topography in the upper Norwest Bend Formation imply a significant period (perhaps a million years) between marine regression and lake formation.

Previous workers have suggested that lake formation was driven by either: (i) uplift on the Padthaway High in South Australia (Firman 1965); (ii) uplift along the present course of the Murray near modern-day Swan Reach (Twidale *et al.* 1978); (iii) movement along the Marmon–Jabuk Fault causing uplift of the Pinnaroo Block (Stephenson 1986); or (iv) as a consequence of barrier formation at the mouth of the ancestral Murray (Belperio & Bluck 1990). Regardless of any proposed mechanism for formation or demise, the age and stratigraphic architecture of the lake remain poorly constrained. In part this is because the low average topography of the region means the lake sediments are only exposed in discontinuous outcrop, mainly along the modern river valley, and because of a general absence of useful dating material, such as fossil assemblages. This paper is concerned with stratigraphic and age constraints on the Blanchetown Clay, the major depositional unit of Lake Bungunnia.

BLANCHETOWN CLAY

The Blanchetown Clay, first formally defined by Firman (1973), is composed dominantly of green-grey, red to brown clay (Brown & Stephenson 1991). As noted by Stephenson (1986) the distribution and thickness of the Blanchetown Clay are largely controlled by the existing topography of the underlying Miocene and Pliocene sediments at the time of lake formation. Typically the entire unit is only 1–10 m thick in the western part of the Lake Bungunnia basin, but it does reach thicknesses in excess of 20 m in the area between the South Australian border and Lake Victoria in New South Wales.

The basal Blanchetown Clay, where exposed, comprises a well-sorted sand unit, termed the Chowilla Sand by Firman (1966) and Gill (1973). Firman (1973) suggested that the Chowilla Sand be considered a separate stratigraphic unit beneath the Blanchetown Clay whereas Gill (1973) found the sand interbedded with Blanchetown Clay and preferred to include the lithology as part of the Blanchetown Clay. Gill (1973) showed that the Chowilla Sand exhibits a similar grainsize distribution to the underlying Loxton–Parilla Sand and Firman (1973) interpreted the unit to represent reworking of this sediment in fluvial channels. The Chowilla Sand, as defined by Gill (1973), is interpreted by Brown & Stephenson (1991) to be equivalent to the Irymple Member of the Blanchetown Clay defined by Lawrence (1975).

Above the Chowilla Sand, the main thickness of Blanchetown Clay commonly exhibits local variations in lithology. Although dominantly pure clay, considerable grainsize variation is observed with clay grading to reddish sandy-clay in many places. The unit also contains thin sand interbeds, and Brown & Stephenson (1991) reported local gypsiferous layers. McKenzie & Gill (1968) reported local ostracod sand and noted the presence of four athalassic species *Ilyocypris* sp., *Diacypsis* sp., *Candonocypris* sp. and *Cypretta* sp. in cliff sections near Moorna Station, west of Wentworth. McKenzie & Gill's (1968) observation of the co-occurrence of *Ilyocypris* cf. *australiensis* Sars and *Diacypsis* sp. in Bed 4 of their Moorna Station measured section suggests that Lake Bungunnia was slightly saline for at least part of its history. The clay contains rare macrofossils, specifically fish spines and vertebrae and marsupial bones, principally in the region around Lake Victoria in New South Wales (Gill 1973; Lawrence & Goldberry 1973).

In this paper we focus on the section of Lake Bungunnia sediment outcropping at Nampoo Station, near Rufus River in western New South Wales (Figure 1). At this location, excellent exposure provides a sequence more than 34 m in thickness (Figure 2), almost certainly the best section of Lake Bungunnia sediments exposed anywhere in the basin.

Nampoo Station section

LITHOLOGY

A measured stratigraphic section of Lake Bungunnia sediments at Nampoo Station is shown in Figure 3. Local datum for the section is taken from river level. Accurate, high-precision GPS observations place the top of the Nampoo Station section at an absolute elevation of 56.6 ± 0.5 m above mean sea-level. Thus, the sediment package is likely to represent the record of maximum fill of the lake basin.

The basal Blanchetown Clay comprises a total thickness of 13.15 m, including a lower sand (7 m) and an upper sand (3.4 m), separated by a non-calcareous green clay (2.75 m). The upper and lower sand units both consist of a fine very well-sorted white to yellow quartz sand. The upper sand includes a prominent red mottled zone. We assign the total 13.15 m basal unit to the Chowilla Sand Member of the Blanchetown Clay.

This basal sand-dominated package is overlain by a 12.1 m-thick sequence of green-grey clay. The lower sequence of clay is finely laminated and contains thin interbeds of laminated well-sorted sand as well as a sequence of three thin laminated silt and silty-clay interbeds. Above the silt, the clay is non-laminated and contains a prominent laminated fine well-sorted cross-bedded sand (Figure 2). The 12.1 m-thick clay sequence is calcareous at its base and grades to slightly calcareous up-sequence.

Above this clay sequence is a sharp boundary to a distinctive often finely laminated white-grey chalky silt 2.6 m in thickness, containing some clay interbeds and a discontinuous well-sorted sand (Figures 2, 3).

Figure 1 (a) Location of Murray Basin in southeastern Australia; box shows location of (b). (b) NASA Shuttle Radar Topographic Mission (SRTM) image showing extent of Lake Bungunnia, with the maximum lake fill at the present-day 60 m elevation contour (dotted line) (Stephenson 1986) (c) interpretation of SRTM image, showing the extent of Lake Bungunnia in dark grey, the courses of the modern Murray and Darling Rivers, and the position of both lake and marine strandlines. Nampoo Station is shown by the star.

The unit is pure quartz silt at its base but shows increasing clay content at higher stratigraphic levels. The silt is medium to fine grained with major mode $\sim 5\text{--}20\text{ }\mu\text{m}$; it is poorly sorted and comprised

dominantly of very angular to subangular grains (Figure 4). This unit is very distinctive and has been noted elsewhere in the Lake Bungunnia sediments from around Renmark in the west to Lake

Figure 2 (a) Devils Elbow cliff section on Nampoo Station, viewed from the Murray River; arrow shows location of section shown in (b). Cliff is ~37 m high. (b) Composite view of Nampoo Station section showing: 1, lower Chowilla Sand; 2, upper Chowilla Sand including prominent mottled horizon; 3, lower silt; and 4, Nampoo Member silt. Three people indicated for scale in uppermost right corner and the upper Chowilla Sand indicated at (2) is 3.35 m thick. (c) Fine well-sorted and cross-bedded sand within green-grey clay at 24.2 m. (d) View of Nampoo Member (base is shown by arrow), overlying clay and calcrete capping; the total thickness of the Nampoo Member is 2.6 m.

Tyrrell in the east (Figure 1). We define this unit as the Nampoo Member of the Blanchetown Clay (Appendix 1).

A further 4.2 m of non-laminated, non-calcareous green clay overlies the silt and silty-clay. This is in turn overlain by well-sorted sand and a mottled red clay

Figure 3 Stratigraphic section of Blanchetown Clay at Nampoo Station. Levels refer to heights as measured above river level. The top of the section is at an absolute elevation of 56.6 ± 0.5 m above mean sea-level, as determined by precise GPS observations. NM, Nampoo Member.

Figure 4 Scanning electron microscope photomicrograph of broken surface of Nampoo Member quartz silt showing dominantly angular clasts, moderate to poor sorting and absence of cement.

horizon. The section is capped by a well-developed 4 m-thick calcrete.

MINERALOGY AND GEOCHEMISTRY

Samples for chemical and X-ray diffraction (XRD) analysis were collected at 0.2–0.5 m spacing throughout the Nampoo Station section. Whole-rock samples were dried overnight at 40°C and then prepared by grinding and crushing in an agate mortar and pestle to form a fine powder, with particle diameter in the range 5–10 μm . Whole-rock sample powders were subject to both XRD and bulk-chemical analysis using the EDS facility on the scanning electron microscope at the University of Melbourne. In addition to whole-rock analysis, the clay fraction ($\sim 2 \mu\text{m}$) from clay-rich samples was separated by settling and subject to additional XRD analysis.

XRD analysis of both whole-rock and clay samples was performed in the Department of Chemical and Biomolecular Engineering at the University of Melbourne using a Phillips PW1800 diffractometer. As the samples contained dominantly clay minerals, smear mounts were chosen in preference to random cavity mounts. Whole-rock samples were analysed under the following operating conditions: (i) copper $\text{K}\alpha$ X-ray target tube ($\lambda = 1.5418\text{\AA}$); (ii) step increment 0.05° ; (iii) count time of 2 s; (iv) sample spinner speed of 4 s/revolution; and (v) the scan was performed from 1 to 40° . Clay samples were also analysed with the above operating conditions except with an increased count time of 4 s. X-ray diffractograms were interpreted using the freeware program MacDiff 4.2.5 (<http://servermac.geologie.uni-frankfurt.de/Pub/MacDiff/>).

The whole-rock XRD analyses proved most useful in delineating the presence of major non-clay minerals, such as quartz, halite and calcite, while XRD analysis of the separated clay fraction was required to establish a time series of variations in clay mineralogy. Owing to severe problems with peeling samples, samples were not able to be glycolated or heated, and identification of the major clay minerals was based on the presence and absence of key peaks in an air-dried room-temperature smear mount only. A summary of the results of both whole-rock and clay mineral interpretation is shown in

Figure 5a. Calcite is present only between 13.15 and 24 m. Halite is present discontinuously through the section below 24.6 m, and may reflect primary salt or secondary salt precipitation due to groundwater flow. No other evaporitic minerals, such as gypsum, were observed.

Observed variations in the clay-mineral diffractograms (Figure 6) very closely match standard JCPDS powder diffraction data and are best explained by the presence of kaolinite-1A and/or illite-2M1. Kaolinite-1A appears to be present in all the samples analysed whereas illite is present only within interbedded clay of the Chowilla Sand, and between 13.15 and 14.0 m, 17.65 and 18.0 m, 24.2 and 28.8 m of the main Blanchetown Clay sequence.

Whole-rock analyses (Figure 5b–f) show variations in chemistry reflecting variations in grainsize as well as the observed variations in clay mineralogy. For example, the higher average K content of illite-bearing clay compared with kaolinite-bearing clay as a consequence of the presence of interlayer cations is reflected in the section. Clay in the Chowilla Sand is characterised by relatively high average Na and K contents (4.3 and 2.9%, respectively) when compared with the main thickness of Blanchetown Clay from 13.15 to 32.9 m. This main interval of clay appears to comprise two sequences of different chemistry, above and below a stratigraphic level of 24 m (Figure 5). Clay from 13.15 to 24 m is calcareous, as shown by both whole-rock XRD and chemical analysis, and is characterised by higher average magnesium content ($2.6 \pm 0.3\%$) compared with the non-calcareous clay above 24 m ($1.8 \pm 0.5\%$). Further, there appears to be a trend to slightly higher K and Si contents above 24 m; the latter reflecting the presence of the silty-clay of the Nampoo Member above 24.6 m (Figure 5). The transition between sequence A (below 24 m) and sequence B (above 24 m) is marked by a 20 cm-thick laminated, fine, well-sorted sand with planar cross-beds (Figures 2, 3).

PALEONTOLOGY

No macrofossils were observed in the Nampoo Station section. However, calcareous clay between 13.15 and

Figure 5 (a) Whole-rock and clay mineral XRD interpretation. Black boxes represent major minerals present, grey boxes represent minor minerals. (b–f) Bulk chemistry data for Nampoo section as determined by EDS on the scanning electron microscope for Mg, Na, Ca, K and Si abundances. Data are calculated percentage values as compounds with oxygen (cpd%). Each analysis is the average of three analyses of individual sample powders and average standard deviations are: Mg $\pm 0.13\%$, Na $\pm 0.23\%$, Ca $\pm 0.14\%$, K $\pm 0.11\%$, Si $\pm 0.80\%$.

15 m and between 19 and 23.5 m yielded a very well-preserved ostracod fauna. Only one species, *Ilyocypris australiensis* Sars, was recovered (Figure 7). However, two additional unidentified species were originally reported from the Nampoo Station area by McKenzie & Gill (1968). Both adult and juvenile forms of *I. australiensis* were identified (Figure 7). *I. australiensis* is reported to be euryhaline by De Deckker (1981a) and in modern Australia is reported to live in temporary freshwater ponds, saline inland lakes and the lower salinity reaches of estuaries. It mainly lives in water in the salinity range of 4–7‰ but can tolerate salinity up to 11‰ (De Deckker 1981b). No stenohaline freshwater ostracod species were recovered from the Nampoo Station section in this study.

MAGNETOSTRATIGRAPHY

Few geochronological constraints have previously been available for the sediment of Lake Bungunnia and the timing of lake formation and demise continue to be debated. Bowler (1980) and An *et al.* (1986) used the apparent pattern of magnetic reversals recorded in Blanchetown Clay sections at Chowilla in South Australia and Lake Tyrell in Victoria (Figure 1) to infer a formation age of 3.2 Ma. Bowler (1980) reported an age of 700 ka for the youngest lake sediment.

Paleomagnetic sampling of the Blanchetown Clay was performed on the Nampoo Station section (Figure 1). Holes at least 1 m deep were dug to expose fresh clay from which orientated 1.8 cm $\times$ 2.5 cm $\times$ 2.5 cm samples

Figure 6 Representative X-ray diffractograms for clay fraction from samples in the Nampoo Station section. (a) 8.0 m, (b) 15.5 m, (c) 17.65 m, (d) 20.0 m, (e) 25.6 m, (f) 30.0 m. Dark-grey bands represent peaks from kaolinite; light-grey bands represent peaks from illite. Peaks around 26.7, 20.9, 36.6 and 39.5 $2\theta^\circ$ represent quartz diffraction (note that 26.7 peak includes a contribution from both quartz and illite); peak at 31.7 $2\theta^\circ$ represents halite.

were cut for paleomagnetic analysis. The average sample spacing was 0.75–1 m with triplicate samples taken from each level. Samples were stored in magnetically shielded containers to minimise acquisition of any modern magnetic-field components. Samples were kept moist until paleomagnetic measurements were made at the Australian National University Black Mountain Paleomagnetic Laboratory, Canberra. Natural Remanent Magnetisation (NRM) directions were measured on a ScT 2-axis cryogenic magnetometer. Stepwise alternating field (AF) demagnetisations were performed using a Schonstedt tumbling demagnetiser. For specimens with low magnetic intensities magnetic remanence directions were determined after each demagnetisation step. For specimens of higher intensity, magnetic remanence directions were measured on a 2G 3-axis magnetometer with built in automatic AF demagnetisation to maximum fields of 160 mT. Magnetic susceptibilities were measured on a Digico bulk susceptibility bridge. NRM intensities varied by two orders of magnitude, from <0.1 to >10 mA/m. A broad correlation between magnetic susceptibility and intensity is consistent with varying concentrations of a similar magnetic mineral suite, probably dominated by magnetite.

Identification of characteristic remanent magnetisations (ChRMs) and magnetic polarity assessment was undertaken with the aid of demagnetisation vector plots and principal-components analysis (PCA) of linear segments (Kirschvink 1980). Specimens were given a

reliability ranking (Class A, B or C), based on their demagnetisation behaviours.

Class A. Stable magnetic directions, as evidenced from linear demagnetisation vector plots, with little angular scatter. ChRMs were identified by PCA. Only linear segments with a mean angular dispersion (MAD) of <10 were accepted. Reliable polarity identification of ChRM at intermediate and high AF fields (>30 mT).

Class B. Demagnetisation vector plots and PCA do not yield linear components, although magnetic polarity can be assigned on the basis of consistency of directions (e.g. directions are confined to a single quadrant on the vector plot, or demagnetisation directions show a consistent trend towards a reversed polarity. Representative declination and inclination values were selected from AF results >30 mT.

Class C. Unstable, weakly magnetised samples displaying erratic directions on vector plots, or directions only stable at low AF demagnetisation levels (<30 mT). Some samples have low field (<30 mT) components of normal polarity, representing a recent viscous overprint. Identification of ChRM for Class C samples is not possible.

Results of the paleomagnetic analyses are shown in Figure 8. The time-scale of Gradstein *et al.* (2004) and magnetic-field reversal data of Ogg & Smith (2004) are used throughout this section. The inclination and declination changes observed in the Nampoo Station clay sequence reveal a relatively simple pattern of

Figure 7 *Ilyocypris australiensis* Sars from the Blanchetown Clay at Nampoo Station. (a) External view of fragmented right valve of late stage juvenile. (b) External view of fragmented right valve of adult female. (c) External view of early stage juvenile female. (d) External left valve view of carapace of early stage juvenile male.

reversed and normal polarity. The lowermost clay in the Chowilla Sand (7.15–9.8 m), as well as the overlying clay (13.1–18 m) record reversed polarity. The overlying clay between 18 and 21.3 m records normal polarity. The remainder of the section from 21.3 to 29.7 m records reversed polarity. Clay above 29.7 m was heavily mottled and was not sampled for paleomagnetic analysis given the high likelihood that any original polarity record would have been overprinted.

This dominantly reverse polarity record suggests that the Blanchetown Clay was deposited entirely within the Matuyama Reversed Chron. Thus, Blanchetown Clay from the entire Nampoo Station section must be no younger than 0.781 Ma (Brunhes–Matuyama boundary) and no older than 2.581 Ma (Matuyama–Gauss boundary).

The normal interval between 18 and 21.3 m could be interpreted as either (i) the Jaramillo Normal Chron or (ii) the Olduvai Normal Chron. If a Jaramillo interpretation is correct, this would imply that the entire Blanchetown Clay sequence is younger than 1.778 Ma. Given that this is a time of generally dry climate

elsewhere in southern Australia (Martin 2006) we consider it unlikely that a lake of this size could have only formed at this time. Therefore, we prefer to interpret the normal polarity sediments as representing deposition during the Olduvai Normal Chron between 1.945 and 1.778 Ma.

If this interpretation is correct it implies an approximate sedimentation rate of ~25 m/Ma, allowing 20% compaction following sedimentation. Assuming this sedimentation rate is constant throughout the clay sequence gives an age of 1.2 Ma for the youngest Blanchetown Clay sediment at the top of the Nampoo Station section. However, given that the sedimentation rate of the sand units and the silt-dominated Nampoo Member are likely to be somewhat higher than the sedimentation rate in the clay, this age represents a minimum estimate for the age of the top of the sequence. Similarly, if we extrapolate to the base of the sequence we estimate the age at the top of the Chowilla Sand to be 2.2 Ma. In order to estimate the age of the oldest Chowilla Sand in the Nampoo Station

section we have assumed that the sedimentation rate in the sandy intervals of the Chowilla Sand is twice the sedimentation rate in the clay, i.e. 50 m/Ma. These

assumptions give our best estimate of 2.4 Ma for the oldest lake sediments in the Nampoo Station section (Figure 8).

Figure 8 Record of magnetic inclination, declination and susceptibility for Blanchetown Clay from Nampoo Station. Closed symbols denote Class A measurements; open symbols denote Class B measurements. Datums for magnetic field reversals from Ogg & Smith (2004).

Figure 9 Chronostratigraphic relationships for sediments in the Murray Basin. Blanchetown Clay and Bungunnia Limestone (BL) comprise the Lake Bungunnia sedimentary fill. NMbr, Nampoo Member; CS, Chowilla Sand. UNBF, upper Norwest Bend Formation; LNBF, lower Norwest Bend Formation (Miranda *et al.* 2008); BB, Bookpurnong beds. Time-scale of Gradstein *et al.* (2004).

DISCUSSION

The Nampoo Station section provides the most complete sedimentary record of the evolution of Lake Bungunnia. The preserved >34 m exposure of Blanchetown Clay is thicker than any other outcropping section and allows redefinition and refinement of the existing stratigraphic relationships (Figure 9). Furthermore, the new age and stratigraphic constraints provide a framework for the establishment of a regional stratigraphy in Plio-Pleistocene sediment of the Murray Basin. Discontinuous and limited exposures have previously hindered this reconstruction.

From the observations reported here, we define the Blanchetown Clay as a single stratigraphic unit containing two members: (i) the basal Chowilla Sand, representing early fluvial fill to the developing lake (Firman 1973); and (ii) the silt-dominated Nampoo Member. Preliminary observations from elsewhere within the basin suggest the Nampoo Member is a basin-wide unit and is likely to be very useful in establishing a regional stratigraphy. The average fine grain size, poor sorting and angular clasts suggest the Nampoo Member silt represents eolian-lacustrine deposition, and, if the unit can be mapped across the basin, it may have important implications for understanding climatic variation at this time.

The apparently cyclic presence of illite-group clay in the Blanchetown Clay may also reflect climatic change. Lacustrine clay may be either authigenic, products of neoformation, or detrital, products of weathering in adjacent watersheds. Given that Lake Bungunnia would have constituted a major sedimentary depocentre for material eroded from both the Australian Eastern Highlands and the Mt Lofty and Flinders Ranges, and that the sedimentary fill has seen no post-depositional heating, we prefer to interpret the clay in the Blanchetown Clay as detrital. Moreover, as the source rocks in these watersheds are unlikely to have changed from the time of lake formation to the time of lake demise, we

suggest that the variations in clay mineralogy can be interpreted in terms of changes in weathering conditions in the source areas. Kaolinite is thought to be derived from chemical weathering under warm and humid conditions, particularly in acid tropical soils where leaching is intensive (Weaver 1989). The absence of illite during particular intervals of lake sedimentation may simply be due to retroformation as a result of extreme weathering intensity, rather than an absence of illite in the source region. Fagel *et al.* (2003) generalised this observation to suggest that crystalline illite-group clays represent colder and/or drier climatic periods. Following this interpretation, we suggest that intervals of illite in the Blanchetown Clay may represent glacial episodes between wet and humid interglacial intervals. The occurrence of illite also correlates with the presence of silt units in the clay (including the Nampoo Member) suggesting the silt may represent eolian-lacustrine sedimentation under arid environmental conditions.

The dominantly reversed polarity record of the Blanchetown Clay section reported here supports the range of ages between 2.5 and 0.7 Ma originally suggested for Lake Bungunnia sediments by Stephenson (1986). This result is significantly younger than the 3.2 Ma age previously reported for the oldest Blanchetown Clay by An *et al.* (1986). This new age constraint, together with the reported lithostratigraphy, have significant implications for our understanding of Plio-Pleistocene climate evolution in southern Australia.

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APPENDIX 1: STRATIGRAPHIC NOMENCLATURE

The following definitions and descriptions apply to the new unit of the Blanchetown Clay described in this paper:

Nampoo Member (new name)

Type section Nampoo Station, Rufus River, New South Wales. 34°03'12.2"S, 141°09'27.5"E; MGA (Zone 54) 514549.7E, 6231912.1N (Figure 2: RL +18.9 m to +56.5 m).

Designation The highest unit within the Blanchetown Clay.

Thickness 2–3 m.

Description White-grey chalky quartz silt, often finely laminated. The unit contains some clay interbeds, with increasing clay content at higher stratigraphic levels, and a discontinuous well-sorted sand. Medium to coarse grained (average grain size ~5–20 µm), poorly sorted and comprised dominantly of very angular to subangular grains.

Boundary contacts Lower boundary defined by conformable sharp contact with green-grey clay. Upper contact defined by gradational change from silty clay to pure green-grey clay.

Age Early Pleistocene (1.6–1.4 Ma).