Paleosol record of Neogene climate change in the Australian outback

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Effects in Australia of a global spike of warm-wet climate during the middle Miocene (ca 16 Ma) have been controversial, with one faction arguing for inland rain forest and the other faction for dry woodland. This question is here addressed using the Oligocene–Miocene sequence of fossil mammal localities at Lake Palankarinna, South Australia, which includes numerous paleosols that have been dated by paleomagnetism, palynology, biostratigraphy, and radiometric methods to straddle this paleoclimatic event. Paleosols of the Oligocene–Miocene Etadunna and Pliocene Tirari Formations formed in arid paleoclimates and include pedogenic gypsum. The Maralji paleosol, developed on early Miocene Etadunna Formation and overlain by late Miocene–Pliocene Mampuwordu Sands, is middle Miocene in age based on mammal fauna at correlative horizons in nearby Lake Ngapakaldi. The Maralji paleosol has shallow calcareous nodules and stout root traces suggesting vegetation like dry woodland (mallee). Mallee vegetation now grows no closer than 1200 km to the southwest, so middle Miocene warm-wet climate enabled range extension of mallee and woody thickening of plants in the Australia outback. There is no evidence in the outback of middle Miocene rain forest, which may have expanded its range to form kaolinitic Ultisols near Sydney, Mudgee and Gulgong, all in New South Wales. Nor is there evidence so far inland of swamp woodlands and heaths like those producing brown coals in the Latrobe Valley, Victoria.

KEY WORDS: Miocene, paleosol, paleoclimate, mammals, mallee, rain forest.

INTRODUCTION

The middle Miocene thermal maximum was a period of past climate change similar in its global geographic scale and the extrapolated magnitude of temperature change to the change predicted to occur by the year 2100 (Alley et al., 2007; Retallack 2009). For example, benthic foraminiferal oxygen isotope records (Figure 1) reveal that middle Miocene deep ocean waters were 6°C warmer than present (Flower & Kennett 1994; Lear et al., 2000). Cooling from 15 Ma onwards coincided with the onset of glaciation in Antarctica (Zachos et al., 2001). As another example, paleosol records in central Oregon, USA (Figure 1), are evidence of paleotemperatures peaking at 15 ± 4.4°C and mean annual precipitation of as much as 1896 ± 181 mm (Retallack 2007a, 2008a), compared with 9.2°C and 340 mm, respectively, now in John Day, Oregon (Taylor 2005). The middle Miocene thermal maximum is characterised globally by extension of thermophilic plant and animal taxa to high paleolatitudes (Christensen 1975; Bown & Fleagle 1993; Wolfe 1994; Blisniuk et al., 2002; Bestland et al., 2008).

In the Australian outback, the magnitude of this global climatic change has proven controversial. Fossil mammal assemblages at Riversleigh, Queensland, have been used as evidence of middle Miocene rain forest expansion into the desert (Archer et al., 1991), although such dramatic paleoclimatic transformation of the Australian outback has been disputed (Megirian et al., 2004). The differences between soils of rain forest (Ultisols, Oxisols), woodland (Alfisols) and desert (Aridisols) are profound (Retallack 1997), and this study of paleosols is a test of these conflicting reconstructions of Miocene paleoclimate in central Australia.

In northern South Australia, Cenozoic sediments around the Lake Eyre basin, an extensive network of ephemeral salt-pan lakes (Figure 2), are famous for fossil vertebrates (Stirton et al., 1961, 1967; Woodburne & Tedford 1975; Vickers-Rich 1979; Wells & Callen 1986; Woodburne et al., 1993). Oligocene–Pliocene sediments are best exposed and most easily accessed at Lake Palankarinna, located at the southern extent of the Tirari Desert, surrounded by northwest-striking sand dunes. Lake Palankarinna is one of the most productive Australian localities for mammal fossils, and its sequence of fluviatile-lacustrine sediments has been previously dated by paleomagnetism, palynology, biostratigraphy, and radiometric dating (Woodburne et al., 1993), although its paleosols have not been studied until now.

This study presents new work on the paleosols from Lake Palankarinna that provides an understanding of landscape and ecosystem evolution during middle Miocene climate change in the Australian outback. Woody thickening has already been documented during 20th century warmer and wetter conditions in central...
Queensland (Krull et al. 2004), and our results provide a model for projected changes in delicate ecosystems of inland Australia with continued climatic warming.

MATERIALS AND METHODS

Paleosols were described and sampled during August 2006 within vertical stratigraphic sections in badlands at 28°45.77'S 138°24.129'E, including the best-known fossil quarry at Mammalon Hill (Figure 3). In addition, a paleosol was sampled in the Mampuwordu Sand 100 m south of Mammalon Hill in Lawson's quarry (28°45.794'S 138°24.107'E). Field descriptions included Munsell colour (Munsell 1975), grainsize, soil structure, horizonation, horizon boundaries, and the presence of other soil features such as root traces, nodules, animal or insect burrows, or fossils. Thickness of the calcic (Bk) or gypsic (By) horizon and depth to carbonate or gypsum nodules were measured. Detailed stratigraphic sections were also drafted in the field (Figure 4). Paleosols were classified into groups using the pedotype approach (Retallack 2001) which characterises different paleosol types using field criteria. Descriptive names were given to each pedotype from the local Dieri language (Schoknecht & Schoknecht 1997). Naming conventions for the paleosols in this study follow USDA Soil Survey (Soil Survey Staff 2000) nomenclature to soil-order level as well as the Australian soil nomenclature (Isbell 1998). A 35 m-section of drill-core (BMR Palankarinna-2) was examined, described, and sampled at Geoscience Australia, in Canberra in September 2006 (Figure 5). The very close correspondence of these sections is unsurprising considering that the drill site on the nearby plateau at 28°45.633'S 138°24.124'E is only 75 m northeast of the badlands outcrop sampled. The core was very helpful in revealing the nature of paleosols at depth, unencrusted with gypsum common in outcrop.

Samples were collected from every horizon within a type section for each pedotype for geochemical analysis of major and trace elements and analyzed by the Washington State University XRF laboratory in Pullman. Bulk composition is useful for investigating geochemical processes active during soil formation. Molecular weathering ratios, calculated from the weight percent of an element in its oxide form, are commonly used as proxies of compositional changes in a rock or soil due to weathering (Marbut 1935). These ratios can illuminate the dominant chemical reactions at work in a soil, such as hydration, oxidation, and leaching (Retallack 1997, 2001), and are also useful as paleoclimatic proxies (Table 1). Some widely used geochemical climofunctions based on North American soils (Sheldon et al. 2002; Sheldon & Tabor 2009) were not pursued here because of unreasonable calculated values: for example, near freezing temperatures in Oligocene paleosols containing fossil crocodiles (Kobera pedotype). Australian-specific soil climofunctions are not available and may be needed, because high soda is a feature that sets these and many Australian soils apart from North American soils (Northcote 1971; McKenzie et al. 2004). There is also the likelihood of inherited little-weathered clay from central Australian Neoproterozoic, Permian, and Cretaceous glacial deposits (Alley & Frakes 2003), and Paleogene bauxites and laterites (Firman 1994).

Oriented rock samples were collected from each diagnostic soil horizon for petrographic thin-sections, prepared under kerosene and with resin encasement needed for fractured smectitic clays (Tate & Retallack 1995). The thin-sections were then observed under a petrographic microscope to examine soil microfabrics (Brewer 1976; FitzPatrick 1993; Retallack 1997), genetic

![Figure 1](image1.png) Middle Miocene (16 Ma) thermal maximum from paleosols in Oregon (grey after Retallack 2007a, 2008), and from oxygen (A) and carbon (B) isotopic composition of foraminifera in the Southern Ocean (after Zachos et al. 2001).

![Figure 2](image2.png) Location of Lakes Palankarinna and Ngapakaldi, and mentioned fossil mammal sites in central Australia, with the modern distribution of mallee vegetation and mallee species, distinctive Australian aridland trees (after Hill 1989). Also shown is the 500 mm isohyet (mean annual precipitation, dotted) separating the dry outback from humid coastal regions (<http://www.bom.gov.au> accessed 4 November 2009).
soil features, and mineralogy, as well as to obtain accurate grain size and mineral distributions by point counting using a Swift automated point counter and stage.

Sample numbers and raw geochemical and petrographic data are tabulated in Appendix 1, along with measured Bk and By depths from these and other Australian Cenozoic paleosol sequences examined in reconnaissance fashion (Figure 2), including Kangaroo Well (Megirian et al. 2004: should be regarded as early Miocene confirming Rich et al. 1991; Long et al. 2002), Alcoota (Megirian et al. 1996), and Mungo Lake (Hope 1978).

GEOLOGICAL SETTING AND AGE

The oldest unit exposed around the lake and in the Palankarinna-2 core is the Paleocene–Eocene Eyre Formation, which is disconformably overlain by the Oligocene–Miocene Etadunna Formation (Table 2). The late Miocene Mampuwordu Sands, filling a paleochannel, are incised into the uppermost Etadunna Formation and overlain by the Pliocene Tirari Formation. The Tirari Formation is unconformably overlain by the Pleistocene Kutjitara Formation and Katipiri Sands (Tedford et al. 1986; Woodburne et al. 1993).

Etadunna Formation pollen species, including samples from Mammalon Hill, are also known from the marine, early-middle Miocene Geera Clay of the Murray Basin (Johns & Ludbrook 1963; Truswell & Harris 1982), but magnetostratigraphic and biostratigraphic correlations suggest that the Etadunna Formation is late Oligocene (Woodburne et al. 1983). Pollen (Alley & Pledge 2000) and megafossil plants (Greenwood et al. 1990) from the upper Etadunna Formation, like those of the correlative and nearby upper Namba Formation (Martin 1994), lack humid forest elements such as Nothofagus and podocarps, found in the lower Etadunna Formation and Eyre Formation. The foraminifer Buliminoides chattonensis at ~30 m in the Etadunna Formation in Palankarrina-2 core (Lindsay 1967) has a well calibrated age range within the marine Duntroonian Stage (25.2–27.3 Ma) of New Zealand (Cooper 2004). Illite of the lower Etadunna Formation at Moralina Station, equivalent to the ~26.5 m level in the Palankarinna-2 core (Callen & Plane 1986), has a Rb-Sr age of 25 Ma (Norrish & Pickering 1983). These foraminiferal and radiometric constraints provide lower tie-points for the age-model used this study, based on the best correlation (highest $R^2$) between stratigraphic levels of magnetic reversals in the Etadunna Formation and the known geological age of reversals (Figure 6) from late Oligocene to middle Miocene (Ogg and Smith 2004), not available at the time of the original paleomagnetic work (Woodburne et al. 1993).

The best-fit age-model (Table 1) for the Etadunna Formation paleomagnetic data gives geological age ($A$ in Ma) for stratigraphic levels in BMR Palankarinna-2 core ($L$ in m).

![Figure 3 Field photograph of Mammalon Hill (left) from the east (A), with paleosols observed in Palankarinna-2 core (B–D), including Kaldri pedotype at 8.1 m (B), Maralji pedotype at 4.3 m (C) and Chindina pedotype at 2.4 m (D).](image-url)
famous mammal faunas of the Riversleigh cave deposits (Archer et al. 1991; Travouillon et al. 2009). The Wipajiri Formation does not extend as far south as Lake Palankarinna, but fills paleochannels incised into the top of the Etadunna Formation at the same stratigraphic level as the Maralji paleosol at Mammalon Hill. The Maralji paleosol is paleomagnetically normal (Woodburne et al. 1993), but because there are many short-lived middle Miocene normals (Ogg & Smith 2004) the age of the Maralji paleosol is paleomagnetically unconstrained.

Incised into the Maralji paleosol are paleochannels of the Mampuwordu Sands containing the Palankarinna local fauna (Stirton et al. 1961, 1967) and capped by the Dantu pedotype paleosol. The Palankarinna local fauna in Lawson’s quarry 100 m south of Mammalon Hill has *Zygomaturus* more primitive than Pleistocene, but more derived than late Miocene (such as at Alcoota), and

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**Figure 4** Measured section of paleosols in outcrop at Mammalon Hill, northeast Lake Palankarinna, South Australia. Location of paleosols is indicated by black boxes whose width corresponds to degree of development inferred by pedogenic destruction of bedding according to a scale devised by Retallack (1997). Calcareousness is from degree of reaction with dilute hydrochloric acid and hue from a Munsell Chart.

**Figure 5** Measured section of paleosols in BMR Palankarinna-2 core, South Australia. Location of paleosols is indicated by black boxes whose width corresponds to degree of development inferred by pedogenic destruction of bedding according to a scale devised by Retallack (1997). Calcareousness is from degree of reaction with dilute hydrochloric acid and hue from a Munsell Chart.
Prionotemnus with the Kanunka fauna, so the Mampuwordu Sands have been considered a member of the basal Tirari Formation (Stirton et al. 1961; Rich et al. 1991). Thus, the Tirari Formation is probably Pliocene (4–2.5 Ma). In the upper Tirari Formation, the Kanunka fauna is within the magnetically reversed Matuyama chron (Tedford et al. 1986), just above the Gauss chron and so late Pliocene (~2.59 Ma; Ogg & Smith 2004). The Kanunka fauna predates late Pleistocene (~45 Ka) megafaunal extinctions (Hope 1978; Prideaux et al. 2007).

### PALEOSOLS

At Mammalon Hill, eight distinctly different kinds of paleosols (pedotypes) within ten meters of exposed section were described, sampled, and logged (Figure 4). Each pedotype is based on a type profile, sampled in more detail for chemical and petrographic analysis. The same eight pedotypes were found in the drill core, where a total of 35 m of section was described and logged, extending down to additional new pedotypes in the Eyre Formation, beyond the scope of this study (Figure 5).

Table 1: Transfer functions used for interpretation of Lake Palankarinna paleosols.

<table>
<thead>
<tr>
<th>No.</th>
<th>Independent variable</th>
<th>Dependent variable</th>
<th>Equation</th>
<th>$R^2$</th>
<th>Standard error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Geological age ($A$ in Ma)</td>
<td>Stratigraphic level in Palankarinna core ($L$ in m)</td>
<td>$A = 0.1168L + 23.023$</td>
<td>0.98</td>
<td>± 0.35 Ma</td>
<td>Herein</td>
</tr>
<tr>
<td>2</td>
<td>Mean annual precipitation ($P$ in mm)</td>
<td>Depth to salts ($D_s$ in cm)</td>
<td>$P = 58.53e^{0.0277D_s}$</td>
<td>0.99</td>
<td>± 14 mm</td>
<td>Dan &amp; Yaalon (1982)</td>
</tr>
<tr>
<td>3</td>
<td>Radiocarbon age ($K$ in ka)</td>
<td>Calcareous nodule diameter ($M$ in cm)</td>
<td>$K = 1.79M^{0.34}$</td>
<td>0.57</td>
<td>± 1.8 ka</td>
<td>Retallack (2005)</td>
</tr>
<tr>
<td>4</td>
<td>Mean annual precipitation ($P$ in mm)</td>
<td>Depth to Bk horizon ($D_k$ in cm)</td>
<td>$P = 137.24 + 6.45D_k + 0.013D_k^2$</td>
<td>0.52</td>
<td>± 147 mm</td>
<td>Retallack (2005)</td>
</tr>
<tr>
<td>5</td>
<td>Mean annual range of precipitation = difference between wettest and driest month precipitation ($S$ in mm)</td>
<td>Thickness ($H$ in cm) of calcareous nodular horizon (Bk)</td>
<td>$S = 0.79H + 13.7$</td>
<td>0.58</td>
<td>± 22 mm</td>
<td>Retallack (2005)</td>
</tr>
</tbody>
</table>

Table 2: Stratigraphic formations and their geological ages near Lake Palankarinna.

<table>
<thead>
<tr>
<th>Formation</th>
<th>Description</th>
<th>Mammal local faunas</th>
<th>Geological age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Katapiri Sands</td>
<td>Cross-bedded white quartz sand</td>
<td>Malkuni, Madigan Gulf,</td>
<td>Late Pleistocene</td>
</tr>
<tr>
<td>Kutjitara Formation</td>
<td>Red gypsiferous claystones and sandstones</td>
<td>Price Peninsula, Kalamurina</td>
<td>Early Pleistocene</td>
</tr>
<tr>
<td>Tirari Formation</td>
<td>Red sandstones and claystones with gypsum beds</td>
<td>Kanunka, Toolapinna</td>
<td>Late Pliocene</td>
</tr>
<tr>
<td>Mampuwordu Sands</td>
<td>Cross-bedded white to red quartz sand</td>
<td>Palankarinna</td>
<td>Early Pliocene</td>
</tr>
<tr>
<td>Wipajiri Formation</td>
<td>White quartz sand and gray shale</td>
<td>Kutjamarpu</td>
<td>Middle Miocene</td>
</tr>
<tr>
<td>Etadunna Formation</td>
<td>Gray dolomitic marls and shales</td>
<td>Ngama, Ngapakaldi, Dijimanka</td>
<td>Late Oligocene</td>
</tr>
<tr>
<td>Eyre Formation</td>
<td>Red claystones and silicretized sandstones</td>
<td></td>
<td>Paleocene</td>
</tr>
</tbody>
</table>

After Tedford et al. (1986), Woodburne et al. (1993).
found throughout this portion of the Etadunna Formation, but the principal fossil quarry is in the Kobera pedotype at 2.8 m (Figure 4). The Kaldri pedotype is the most common pedotype found in outcrop and core of the Etadunna Formation (Figures 4, 5). Kaldri soils are weakly developed, with small root traces and gypsic horizons, with little variation down profile in molecular weathering ratios within the pedotype section, but elevated Na2O/K2O ratios. The Kobera pedotype is distinguished by its brown A horizon and red B horizon with significant gypsum accumulation at depth. The Junduru pedotype is a weakly developed, silty-sandy paleosol with relict bedding and ripple marks.

The unconformable contact of the Etadunna with the overlying Tirari Formation is marked by a distinctive bright red paleosol landscape surface, the Maralji pedotype (Figure 9) with a red surface (A) horizon, and a subsurface calcic (Bk) horizon above a gypsic (By) horizon. The Maralji pedotype has deep, thick root traces, and is at the same stratigraphic level as the Kutjamarpu fauna and a small assemblage of fossil leaves at Lake Ngapakaldi, 60 km to the north (Tedford et al. 1986; Rich & van Tets 1982).

The Mampuwordu Sands of the basal Tirari Formation are incised into this Maralji landsurface and contain the Palankarinna local mammal fauna (Stirton et al. 1961; Tedford et al. 1986). The Dantu (Figure 10) pedotype found within the upper Mampuwordu Sands is red in colour and has stout root traces (Figure 2B), but is less strongly developed, with fewer clay skins and more relict bedding (Bw horizon) than in the better developed Maralji pedotype.

Paleosols within the overlying Tirari Formation, with its associated Kanunka fauna (Callen & Plane 1986), are weakly to moderately developed, mostly of the Chindina (Figure 11) pedotype. Chindina paleosols are red in colour, with shallow gypsum (By) horizons and few root traces. The Maru pedotype also has a gypsic (By) horizon, in addition to prominent black nodules and mangans (manganese-coated cutans) deep in the profile. Interbedded with Chindina paleosols, the Juldru pedotype is thin with abundant relict bedding, like the Junduru pedotype of the Etadunna Formation, but redder and of coarser grainsize.

### PALEOENVIRONMENTAL RECONSTRUCTIONS

#### Late Oligocene

The lower Etadunna Formation (16.8–34.3 m in Palankarinna-2 core) contains foraminifera and is mainly lacustrine clayey dolostones. The entire Etadunna Formation was previously interpreted as lacustrine, with minor fluvial deposits, due to the presence of foraminifera, freshwater gastropods, ostracods, fish, crocodiles, turtles (Gaffney 1981), frogs (Tyler 1976), and birds such as pelicans, flamingos, ducks, cranes, gulls, rails, song birds, and pigeons (Miller 1963, 1966a, b; Rich & van Tets 1982).

Different paleosol pedotypes named here represent different parts of the landscape that can be inferred from sedimentary facies and evidence of former water-tables. For example, Kaldri and Kobera pedotypes are interbedded within stratified lacustrine deposits of the upper Etadunna Formation, and would have formed along shores of ephemeral lakes (Figure 12). Both pedotypes are interpreted as Salids (Soil Survey Staff 2000) or

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### Table 3 Lake Palankarinna pedotypes and classification.

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<thead>
<tr>
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<tbody>
<tr>
<td>Kaldri (salty)</td>
<td>Grey (5Y 6/1) thin clayey surface (A) over shallow gypsum (By &lt; 25 cm depth)</td>
<td>Gleyic Solonchak</td>
<td>Salid</td>
<td>Grey clay</td>
<td>Salic Hydrosol</td>
</tr>
<tr>
<td>Kobera (root)</td>
<td>Brown (7.5YR 5/6) surface (A) over shallow gypsum (By &lt; 34 cm)</td>
<td>Mollic Solonchak</td>
<td>Salid</td>
<td>Brown clay</td>
<td>Salic Hydrosol</td>
</tr>
<tr>
<td>Junduru (clay)</td>
<td>Dark olive grey (5Y 3/2) laminated clay (A) over sand (C)</td>
<td>Eutric Fluvisol</td>
<td>Fluvent</td>
<td>Alluvial soil</td>
<td>Stratric Rudosol</td>
</tr>
<tr>
<td>Maralji (red)</td>
<td>Reddish brown (5YR 5/4) clayey surface (A) over caliche (Bk at 66 cm depth) and gypsum (By at 82 cm)</td>
<td>Calcic Xerosol</td>
<td>Calcid</td>
<td>Calcareous red earth</td>
<td>Calcic Calcarosol</td>
</tr>
<tr>
<td>Dantu (soft)</td>
<td>Reddish brown (5YR 5/6) A over clayey Bw</td>
<td>Calcic Cambisol</td>
<td>Ochrept</td>
<td>Red earth</td>
<td>Orthic Tenosol</td>
</tr>
<tr>
<td>Chindina (soft)</td>
<td>Yellowish red (5Y 4/6) clayey surface (A) over gypsum (By at 12 to 29 cm depth)</td>
<td>Orthic Solonchak</td>
<td>Salid</td>
<td>Red clay</td>
<td>Red Dermosol</td>
</tr>
<tr>
<td>Maru (black)</td>
<td>Yellowish red (5Y 4/6) clayey surface over gypsum (By at 31 cm depth) with black Fe–Mn nodules and stains</td>
<td>Gleyic Solonchak</td>
<td>Salid</td>
<td>Grey clay</td>
<td>Red Dermosol</td>
</tr>
<tr>
<td>Juldru (narrow)</td>
<td>Laminated red (2.5YR 5/6) clay (A) over sand (C)</td>
<td>Eutric Fluvisol</td>
<td>Fluvent</td>
<td>Alluvial soil</td>
<td>Stratric Rudosol</td>
</tr>
</tbody>
</table>
Solonchaks (of Food & Agriculture Organization 1974). Their well-developed but shallow gypsic horizons indicate a mean annual precipitation declining from 137 to 85 mm up-section, as estimated from the known relationship between mean annual precipitation ($P$ in mm) and the depth to salts ($D_y$ in cm) in Holocene desert soils of sandy alluvial terraces in southern Israel (equation 2 of Table 1). These calculations can be compromised by burial compaction of paleosols (Sheldon & Retallack 2001), but compaction is not significant in the very thin sequence at Lake Palankarinna, which has never been deeply buried (Callen & Plane 1986).

The most productive quarry for mammal fossils in the upper Etadunna Formation was the Ngama fauna in a Kobera paleosol, which included lungfish ($\text{Neoceratodus} \text{sp. indet.}$), catfish ($\text{Siluriformes}$), perch ($\text{Perciformes}$), turtles (cf. $\text{Emydura}$), horned tortoise ($\text{Meiolania} \text{sp. indet.}$), crocodile ($\text{Crocodilia}$), skink (cf. $\text{Egernia}$), boa ($\text{Boidae}$), cassowary ($\text{Casuariidae}$), eagle ($\text{Accipitridae}$), rail ($\text{Rallidae}$), thick-knee ($\text{Burhinidae}$), flamingo ($\text{Phoenicopteridae}$), pigeon ($\text{Columbiformes}$), platypus ($\text{Obdurodon} \text{sp.}$), marsupial cat ($\text{Dasylurinja kokuminola}$), perameloid ($\text{Perameloidae}$), koala ($\text{Litokoala kanunkensis}$), diprotodon ($\text{Neohe-}$

\begin{table}[h]
\centering
\begin{tabular}{|l|l|l|l|l|l|
\hline
\textbf{Pedotype} & \textbf{Climate} & \textbf{Vegetation} & \textbf{Animals} & \textbf{Time to form (ka)}
\hline
Kaldri (salty) & Arid (65–107 ± 14 mm MAP), cool temperate & Halophytic shrubs & Uncertain & ~2
\hline
Kobera (root) & Arid (89–108 ± 14 mm MAP), cool temperate & Halophytic shrubs & Uncertain & ~2
\hline
Junduru (clay) & Not diagnostic & Early successional wetland & Dry woodland (high mallee) & ~2
\hline
Maralji (red) & Subhumid (506 ± 147 mm MAP), warm temperate, weak seasonality & Dry woodland (low mallee) & Similar to mulga and bluebrush scrub & ~2.3
\hline
Dantu (soft) & Arid (56 ± 14 mm MAP), warm temperate & Well-drained fluvial levee & Early successional riparian & ~2.6
\hline
Chindina (soft) & Arid (65–107 ± 14 mm MAP), cool temperate & Early successional wetland & Similar to mulga and bluebrush scrub & ~2
\hline
Maru (black) & Arid (12 ± 14 mm MAP), warm temperate & Well-drained floodplain & Early successional riparian & ~2
\hline
Juldru (narrow) & Not diagnostic & Uncertain & Dry well-drained floodplain & ~2
\hline
\end{tabular}
\end{table}

Figure 7 Field, petrographic and geochemical data for the late Oligocene Kaldri pedotype of the upper Etadunna Formation in outcrop near Mammalon Hill, Lake Palankarinna (2.0 m in Figure 3).

Figure 8 Field, petrographic and geochemical data for the late Oligocene Kobera and Junduru pedotypes of the upper Etadunna Formation in outcrop near Mammalon Hill, Lake Palankarinna (2.8 and 3.2 m respectively in Figure 3).
magnus, Marlu sp. cf. M. kutjamarpensis) and possum (Petauridae) (Rich et al. 1991; Woodburne et al. 1993). Standing water is needed for many of these species, such as platypuses, pelicans, ducks and cranes, but flamingos thrive around saline playa lakes, such as Lake Nakuru in Kenya (Owino et al. 2001). The marsupials are all extinct species smaller than modern related species, and are comparable in diversity with faunas of dry or riparian woodlands, similar to nearby Cooper Creek (Woodburne et al. 1993). Mammal assemblages of the comparable and coeval faunal zone A of the Riversleigh fossil localities of Queensland have the uneven size distribution of open habitats (Travouillon et al. 2009). Fossil pollen (Alley & Pledge 2000) and megafossil plants (Greenwood et al. 1990) of the upper Etadunna and nearby Namba Formations (Martin 1994) lack humid forest taxa known lower in these formations, and include evidence of *Acacia*, *Banksia*, *Casuarina*, cypress (*Cupressaceae*), grass (*Gramineae*) and desert shrubs (*Chenopodiaceae*). Evidence from paleosols confirms these indications of dry conditions.

Fine root traces in Kaldri and Kobera paleosols are comparable with those of glassworts such as *Sclerostegia arbuscula* common on the dry pan of Lake Palankarinna today (Costermans 1981), and such vegetation would be expected considering the gypsiferous and laminated clayey parent materials of these paleosols, similar to margins of present Lake Palankarinna. The Junduru pedotype experienced more energetic influxes of sediments, as evidenced by thin ripple-marked sandy units. The drab colour and thick root traces of the Junduru paleosol are evidence of waterlogged conditions under riparian woodland, comparable with red gum (*Eucalyptus camaldulensis*) riparian vegetation of the Australian outback today (McKenzie et al. 2004).

In the Food & Agriculture Organization (1974) classification, the Kaldri-Kobera-Junduru assemblage...
of soils can be interpreted as Gleyic Solonchaks (Zg, Kaldri), Mollic Solonchaks (Zm, Kobera) and Eutric Fluvisols (Je, Junduru). As a group these are like the modern soilscape around Lake Amadeus, north of Uluru (Ayers Rock), Northern Territory (map unit Zo 36-2a of Food & Agriculture Organization 1978). The modern climate of Yulari airstrip (25°11.4'S 130°58.2'E), north of Uluru is 266 mm mean annual precipitation and 22°C mean annual temperature (<http://www.bom.gov.au> accessed 4 November 2009). Lake Palankarinna was further south (34°10.8'S 117°42'E estimated using Plate-tracker program of Scotese (1997)) during the Oligocene, close to the present latitude of Balladonia, on the western margin of the Nullarbor Plain, Western Australia, where comparable saline lakes and soils (Food & Agriculture Organization 1978) have a mean annual temperature of 16.8°C and mean annual precipitation of 262 mm (<http://www.bom.gov.au> accessed 4 November 2009). This modern analogue is a reasonable estimate for Oligocene paleoclimate at Lake Palankarinna, especially considering the occurrence of frost intolerant ectothermal crocodiles and tortoises (Rich et al. 1991). The minimum mean annual temperature tolerated by crocodilians today is about 14.2°C (Markwick 1990). Marine temperatures estimated from isotopic composition of late Oligocene marine rocks of Southern Australia were 10–15°C (McGowran et al. 2004).

Middle Miocene

The top of the Etadunnna Formation in outcrop at Mamallon Hill is an erosional land surface on which the Maralji paleosol formed (Figure 13). The Maralji paleosol has calcareous nodules 2 cm in diameter, a size (M in cm) consistent with radiocarbon-age (K in ka) of nodules formed in soils of New Mexico desert alluvial fans formed over some 2.3 ± 1.8 ka (using equation 3 of Table 1). Also suggestive of moderate development for the Maralji paleosol is blocky pedal structure obscuring original bedding and a differentiated subsurface horizon of gypsic horizon (By). A shorter duration of pedogenesis is represented by the Juldru paleosol, which is sandy with prominent relict bedding, a facies comparable with the Juldru paleosol, which is sandy with prominent relict bedding, a facies comparable with that of the Juldru paleosol. Such an equable non-monsoonal rainfall pattern would be expected this far south at ca 16 Ma (32°30'S 123°12'7.2'E following Scotese 1997).

Stout woody root traces in the Maralji paleosol are evidence of a vegetation of trees. These were probably Eucalyptus and Acacia, because fossils of these genera dominate a small collection of fossil leaves, including also aquatic dicots and reeds, at the same stratigraphic level in the Wipajiri Formation some 60 km to the north at Lake Ngapakaldi (Rich et al. 1991; Stirton et al. 1961). The leaf locality has also yielded the Kutjamarpu local fauna, including lungfish (Neoceratodus gregoryi, N. djelleh, N. eyrensis, N. spp.), bony fish (Teleostei), turtle (Emydura sp. indet.), horned tortoise (Meiolania sp. indet.), skinks (Egernia sp. indet., Tiliqua sp. indet.), lizard (Agamidae), cassowary (Dromaius gudju), dromornithid (Dromornithidae), pelican (Pelecanus tirarensis), duck (Anatidae), plover (Charadriiformes), marsupial cat (Wakamatha tasseli, Ankoratiranga spp., Keeuna sp. indet., Dasyuridae sp. indet.), peramelid (Perameloidae), koala (Litokoala kutjamarpensis), diprotodont (Neohelos tirarensis, Diprotodontidae sp. indet.), wombat (Rhizophascolonus croucrofti), marsupial lion (Wakaleo oldfieldi), possum (Phalangeridae), ektopodont (Ektopodon serratus), potoroo (Wakiewakie lawsoni, Bulungamaya sp. indet.), kangaroo (Balbaroo spp., Macropodinae spp. indet.), burramyid (Burramyidae),

Maralji paleosol was 26 ± 22 mm, a small difference considering mean annual precipitation inferred for this paleosol. Such an equable non-monsoonal rainfall pattern would be expected this far south at ca 16 Ma (32°30'S 123°12'7.2'E following Scotese 1997).
and ringtail possum (*Pildra tertius, Palijara tirarentae*; Rich et al. 1991). This mammal assemblage is similar to that in modern Australian woodland and mallee, with both arboreal and open country mammals (Bennett et al. 1989, 2006).

The Maralji paleosol is most like low woodland or high mallee soils (Blackburn & Wright 1989), which are solonised brown soils (of Stace et al. 1968), Calcarosols (of Isbell 1998), Calcids (of Soil Survey Staff 2000) and Calcic Xerosols (of Food & Agriculture Organization 1974). Comparable soils can be found today in the central Riverina region of New South Wales (map unit Xk 40-1/2b of Food and Agriculture Organization 1978). Within this region, Balranald currently has a mean annual rainfall of 320 mm, a mean annual range of precipitation of 9.8 mm, and mean annual temperature of 17.1°C (<http://www.bom.gov.au> accessed 4 November 2009). The current range of mallee soils, plants, and animals is restricted to Mediterranean climatic regions of South Australia, Victoria and New South Wales (Carnahan & Bullen 1990). Marine temperatures estimated from isotopic composition of middle Miocene marine rocks of southern Australia were 15–20°C (McGowran et al. 2004).

The Maralji paleosol is evidence that during the middle Miocene, mallee vegetation and mallee soils were present much further north than currently in South Australia (Figure 2). Scattered small trees of round-leaf mallee (*Eucalyptus orbifolia*) are widespread in central Australia (Hill 1989). Scattered trees alone would not give the profile depth and differentiation seen in the Maralji paleosol, but it is difficult to determine whether range extension of mallee was due to northward expansion of biomes as in postglacial North America (Williams et al. 2004), or due to climatically induced woody thickening from existing seed stocks as currently documented in Queensland (Krull et al. 2004). Mammal faunas of the Kutjamarpu local fauna are evidence of continued diversification of lineages from the older Etadunna Formation (Rich et al. 1991), thus supporting the idea of woody thickening of the vegetative community rather than biome migration.

## Early Pliocene

The Mampuwordu Sands (Figure 14) form a large paleochannel, and represent a large stream that drained southwest into the Lake Eyre Basin (Callen & Plane 1988). The Dantu pedotype, although not as well developed as the Maralji and lacking a nodular Bk horizon, does however contain a zone of calcareous mottles as a precursor of the Bk horizon, formed over a shorter duration of pedogenesis (ca 1 kyr) than estimated above for the Maralji paleosol (using equation 3 of Table 1). These calcareous mottles are at a depth of 55 cm, as in modern soils receiving 453 ± 147 mm mean annual precipitation (using equation 4 of Table 1) and the 23 cm thickness of this horizon is evidence of precipitation seasonality of 32 ± 22 mm (using equation 5 of Table 1).

This shallower depth and the smaller size of root traces than in the Maralji paleosol, are evidence that the Dantu paleosol supported low mallee vegetation (<5 m tall), as described by Carnahan & Bullen (1990). Such an ecosystem is also compatible with the Palankarinna local fauna collected from Lawson’s quarry, where the Dantu paleosol was sampled for this project. The fauna includes crab (Decapoda), lungfish (*Neoceratodus* sp. indet.), bony fish (Teleostei), crocodile (*Crocodylia*), cassowary (*Dromaius occypus*), dromornithid (*Dromornithidae*), bandicoot (*Ischodon australis*), large diprotodont (*Zygomaturus keanei, Meniscolophus maesoni*), and kangaroo (*Prionotemmnus palankarinnicus, Sthenurinae* sp. indet.) (Rich et al. 1991).

The Dantu paleosol is also similar to mallee soils, specifically solonised brown soils (of Stace et al. 1968), Orthic Tenosols (of Isbell 1998), Ochrepts (of Soil Survey Staff 2000) and Calcic Cambisols (of Food & Agriculture Organization 1974). With more time for soil formation, the Dantu paleosol would have developed nodules comparable with the Maralji paleosol, but its carbonate formed at a shallower level than for the Maralji paleosol. Comparable soils can be found today from the western Riverina region of New South Wales, around the head of South Australia’s Spencer Gulf, west toward the Nullarbor Plain (map unit Xk 40-1/2b of Food & Agriculture Organization 1978). Mildura, for example, has a mean annual rainfall of 266 mm, a mean annual range of precipitation of 13.6 mm, and mean annual temperature of 17.4°C (<http://www.bom.gov.au> accessed 4 November 2009).
Late Pliocene

Within the Tirari Formation, the Chindina, Maru, and Juldru pedotypes are red and oxidised, indicating landscapes with good free drainage and a low water-table (Figure 15). However, iron-manganese nodules and coatings (mangans) like those of the Maru pedotype are common in soils with slow drainage, especially when groundwater is perched by hardpans or in rice paddies (Rahmatullah et al. 1990).

The very shallow gypsic (By) horizons in Chindina and Maru paleosols are similar in depth to soils within Israel receiving 81–119 mm mean annual precipitation (estimated using equation 2 of Table 1). The surface soil at the top of the measured section near Mammalon Hill is similar in profile form to the Chindina pedotype, implying a dry climate like that today around Lake Palankarinna: nearby Marree has mean annual precipitation of 160 mm and mean annual temperature of 22 °C (http://www.bom.gov.au accessed 4 November 2009).

The Kanunka fauna of the upper Tirari Formation, largely from localities north of Lake Palankarinna, includes the following: crabs (Decapoda), lungfish (Ceratodontidae), bony fish (Teleostei), cassowary (Casuariiformes), duck (Anatidae), eagle (Accipitridae), crane (Grus sp. indet.), rail (Rallidae), bustard (Otididae), plover (Charadriiformes), flamingo (Ocyptimus prooetus, cf. Phoenicopterus ruber, Xenorhynchus minor), marsupial cat (Dasyuridae), diprotodont (Diprotodon sp. indet., Megalopisma sp. indet.), wombat (Phascolonus sp. indet., Vombatus/Lasiorhinus), potaroo (Betongia sp. indet.), kangaroo (Lagorcheses sp. indet., Dendrolagus sp. indet., Jurra sp. indet., cf Prionotemnus sp. indet., Tropodon lentii, T. sp. cf. T. minor, Proteomodon sp. cf. P. devisi, P. sp. indet., Osphranter sp. cf. O. woodsii, Macropus (Fissidens) pearsoni, M. (Notocaprops) sp. indet., Sthenurinae sp. indet.), and mouse (Muridae) (Rich et al. 1991). This diversity includes a variety of large mammals that were victims of late Pleistocene megafaunal extinctions (Hope 1978), as well as riparian communities from Cooper Creek and its antecedents to the north (Tedford et al. 1986).

Root traces within paleosols of the Tirari formation are stout, and represent woody vegetation with sparse ground cover. There is no indication of the fine crumb pedds associated with grassland cover (Retallack 2004). Such gypsic soils probably supported vegetation like that of well-drained clayey interfluves in this region today, such as saltbush (Atriplex nummularia), with scattered bushes of mulga (Acacia aneura) and gum (Eucalyptus intertexta) (Carnahan & Bullen 1990).

The Chindina-Maru-Juldru pedotype assemblage of the Tirari Formation can be classified as Orthic Solonchak (Zo, Chindina), Gleyic Solonchak (Zg) and minor Eutric Fluvisols (Je, Juldru) (Food & Agriculture Organization 1978). Although Orthic Solonchaks cover parts of the plateau west of Lake Palankarinna, the principal soil map units of this area today are Dystric Regosols (Rd 1ab, sand dunes) and Orthic Fluvisols (Je, Juldru) (Food & Agriculture Organization 1974). For the Upper Etadunna Formation, a comparable modern soilscape is Lake Amadeus, north of Uluru (Ayers Rock), Northern Territory (map unit Zo 36-2a of Food & Agriculture Organization 1978). The modern climate of Yulari airstrip (S25.19°E130.97°) , north of Uluru is 266 mm mean annual precipitation and 22 °C mean annual temperature (<http://www.bom.gov.au> accessed 4 November 2009). Although Orthic Solonchaks cover parts of the plateau west of Lake Palankarinna, the principal soil map units of this area today are Dystric Regosols (Rd 1ab, sand dunes) and Orthic Solonetz (So 14-1ab, duplex soils under gibber) (Food & Agriculture Organization 1978). These may reflect episodes of landscape instability during Pleistocene erosion of the Tirari Formation (Callen & Plane 1986).

ARID OR HUMID MIOCENE OUTBACK?

A long running controversy in interpreting Cenozoic mammal communities of outback Australia has concerned whether they lived in humid rain forest (Archer et al. 1991; Travouillon et al. 2009) or in semiarid to subhumid woodlands and shrublands (Megirian et al. 1996, 2004; Murray & Vickers-Rich 2004). Fossil plants and pollen of the lower Namba and Etadunna Formations include humid forest taxa such as southern beech (Nothofagus) and podocarps, but the upper portions of these formations studied here have arid land taxa such as wattle (Acacia), belah (Casuarina), desert shrubs (Chenopodiaceae) and grasses (Graminaceae) (Greenwood et al. 1990; Martin 1990; Alley and Pledge 2000). The interpretation of such records is complex.
because many Australian plants that evolved in rain forests have adapted to deserts: notably the vine, Sturt’s desert pea (*Swainsonia formosa*), which now spreads over bare sand (Murray & Vickers-Rich 2004). Thus, ‘indicator taxa’ of fossil plants and snails found with mammal assemblages at Riversleigh and Kangaroo Well have been disputed as evidence of woodland or rain forest (Megirian et al. 2004; Travoullion et al. 2009). Use of cenograms (plots of ranked body weights of mammal taxa) of Riversleigh mammals to address the question of habitat (Travoullion et al. 2009), may instead reflect sample size, as found in comparable cenograms of open habitat (not rain forest) mammals in the middle Miocene of Fort Ternan, Kenya (Retallack et al. 1992; Dugas & Retallack 1993) and Pasalar, Turkey (Andrews 1990).

Problems of individual ‘indicator taxa’ and potential redeposition are avoided in this work by considering paleosols, which are by definition in the place they formed and are laterally extensive. Furthermore, the fragmentary mammal fossils within the paleosols, stained similar colours to the most altered parts of the paleosols, are evidence that mammals were parts of these soil communities. Paleosols of the Mammalon Hill section are, for the most part, rich in pedogenic gypsum found in both outcrop and in the core section. Concentrations range from sparse fine-grained dispersal to individual nodules to laterally extensive gypcrete layers, representing different stages of pedogenic development seen in Quaternary desert soils (Dan & Yaalon 1982). Soil features (roots, peds) cut and overprint gypsum of paleosols in both outcrop and core, suggesting that although there is also significant coarse secondary diagenetic gypsum precipitation in outcrop, much gypsum is pedogenic in origin. Depth to gypsum and to carbonate in a soil profiles is known to be related to mean annual precipitation (equations 2 and 3 in Table 1), and these relationships can be applied to paleosols of Lake Palankarinna, Kangaroo Well, Alcoota, and Mungo Lake to create a preliminary time series of Neogene precipitation in outback Australia (Figure 16). The middle Miocene Maralji paleosol, with the deepest gypsic (By) and calcic (Bk) horizons, formed under the most humid conditions of the past 25 Ma. Our paleoprecipitation estimates all fall well short of the 1186 mm mean annual precipitation required for Ultisols and 1270 mm for Oxisols and rain forest in Australia (Retallack 2008b). Oxisols typical of rain forest have been found at Maroomba (Pickett 2003) and other parts of the greater Sydney area (Faniran 1971). Middle Miocene kaolin deposits in the Gulgong-Dubbo region, New South Wales, also suggest similarly warm, wet climate during this time period (Dulhunty 1971; McMinn 1981). Microflora from the Home Rule clay pit (McMinn 1981) near Gulgong have two fossil pollen assemblages attributed to the *Triporopollenites bellus* zone of Stover and Partridge (1973) suggesting an age of late Early Miocene to Pliocene (17.5 to 8.0 Ma). Also found in the Home Rule assemblage is *Elaeocarpus*, a tropical evergreen (Dettmann & Clifford 2000). Extensive middle Miocene brown coals are found throughout Latrobe Valley and in the Gippsland Basin in Victoria, and represent widespread humid swamp and heath (Shuiter et al. 1995). Rainforests and wetlands in eastern and southeastern Australia were more extensive during the middle Miocene than before or since, but our study shows that such vegetation did not extend to inland Australia. Because Miocene mammal faunas of Riversleigh are so similar to those from Lake Palankarinna (Megirian et al. 2004), it is unlikely that they lived in a middle Miocene rain forest there. Further work on clay mineralogy, paleosols and paleobotany at Riversleigh is needed to settle the issue.

**CONCLUSIONS**

Paleosols of Lake Palankarinna from before and after the middle Miocene thermal maximum reflect climatic and vegetative regimes similar to those found at the modern salina lake. A middle Miocene paleosol (Maralji
pedotype) reflects warmer and wetter climate than before or after, and is most like soils of mallee vegetation of southern South Australia and Victoria (Blackburn & Wright 1989). Because documented middle Miocene CO₂ and climate change (Retallack 2009) is comparable with changes predicted due to global warming by 2100 (Alley et al. 2007), mallee vegetation may expand into the Tirari Desert as it did during the middle Miocene. There are no rain forest paleosols (Oxisols, Ultisols) yet recorded in Miocene sequences of central Australia, in support of paleoenvironmental interpretations of Megirian et al. (2004). Neither middle Miocene nor future global change is likely to have been, or to be, so extreme.

Paleosols are a widespread and little exploited paleoclimatic record of inland Australia (Firman 1994). Existing records still show significant temporal gaps (Figure 16) compared with time series now available from paleosols of North America (Retallack 2007a, 2008a) and Kenya (Retallack 2007b). The approaches to their study outlined here could productively be applied more widely.

ACKNOWLEDGEMENTS

This research was supported by the National Science Foundation East Asia Pacific Summer Institute and the Australian Academy of Science. Work was done under permit from Kate Wood of the South Australian Department of Environment and Heritage, and aboriginal cultural issues were approved by Reg Dodd, coordinator for the Lake Eyre region. Helpful advice in Australia was provided by Neville Pledge, Ian Percival, Rod Wells and Erick Bestland.

REFERENCES


SUPPLEMENTARY PAPERS

APPENDIX 1: THE PALEOSOL RECORD OF NEOGENE CLIMATE CHANGE IN THE AUSTRALIAN OUTBACK

Data Table 1. Chemical analyses of Miocene paleosols.
Data Table 2. Point count data on grainsize and minerals of Miocene paleosols.
Data Table 3. Depth to Bk and By in Miocene paleosols of Australia.
<http://www.uoregon.edu/~dogsci/directory/faculty/greg/about>