1-1-2010

Age and origin of alluvial sediments within and flanking the Mt Lofty Ranges, southern South Australia: a late quaternary archive of climate and environmental change

D Banerjee

N F. Alley
University of Adelaide

R P. Bourman
University of Wollongong, bbourman@uow.edu.au

S Buckman
University of Wollongong, solomon@uow.edu.au

J R. Prescott

Age and origin of alluvial sediments within and flanking the Mt Lofty Ranges, southern South Australia: a late quaternary archive of climate and environmental change

Keywords

within, environmental, flanking, change, mt, lofty, ranges, southern, south, australia, late, quaternary, archive, climate, age, origin, alluvial, sediments

Disciplines

Life Sciences | Physical Sciences and Mathematics | Social and Behavioral Sciences

Publication Details

Bourman, R. P., Prescott, J. R., Banerjee, D., Alley, N. F., & Buckman, S. (2010). Age and origin of alluvial sediments within and flanking the Mt Lofty Ranges, southern South Australia: a late quaternary archive of climate and environmental change. Australian Journal of Earth Sciences: An International Geoscience Journal of the Geological Society of Australia, 57 (2), 175-192.

Australian Journal of Earth Sciences (2010) **57**, (175–192)

Age and origin of alluvial sediments within and flanking the Mt Lofty Ranges, southern South Australia: a Late Quaternary archive of climate and environmental change

R. P. BOURMAN[1]*, J. R. PRESCOTT[2], D. BANERJEE[3], N. F. ALLEY[4] AND S. BUCKMAN[1]

[1]*School of Earth and Environmental Sciences, University of Wollongong, NSW 2522, Australia.*
[2]*Department of Physics and Mathematical Physics, University of Adelaide, SA 5005, Australia.*
[3]*Planetary Sciences and Exploration Group, Physical Research Laboratory, Ahmedabad 380009, India.*
[4]*School of Earth and Environmental Sciences, Geology and Geophysics, University of Adelaide, SA 5005, Australia.*

Quaternary alluvial sediments occur within and on the flanks of the Mt Lofty Ranges of southern South Australia. Within the ranges they occupy colluvium-filled bedrock depressions, alluvial-fan sequences at hill/plain junctions and river terraces that flank major streamlines in both locations. Sediments ranging in age throughout the Quaternary have been identified, but this paper focuses on those deposits of Late Quaternary age. Luminescence dating has verified a Last Interglacial age (132–118 ka) for the most widespread of the alluvial units, the Pooraka Formation. A younger, Marine Isotope Stage 3, alluvial unit, in places containing bones of the extinct marsupial *Diprotodon*, has also been identified. Deposition of the alluvial sediments is associated with relatively warmer and wetter conditions, whereas the valleys that they occupy were eroded under drier climatic conditions. A more widespread occurrence of Stage 3 units is expected to be present but has not yet been verified. Cold, arid environments are inferred from the presence of dunes (~18 ka) deposited during the Last Glacial Maximum when stream valleys were incised. Grey/black mid-Holocene alluvium (Waldeila Formation), forming present-day floodplains and low river terraces, equates with the Holocene Hypsithermal. The sequence of climatic changes revealed by these sediments is correlated with evidence of Late Quaternary climatic change from other Australian locations. The identification of equivalent units in different tectonic settings reveals that sedimentation is largely climatically driven although active tectonism may accelerate the supply of sediments available for transport.

KEY WORDS: **climate change, luminescence dating, megafauna, Mt Lofty Ranges, Pooraka Formation, Quaternary, South Australia, terrestrial sediments.**

INTRODUCTION

Quaternary alluvial sediments forming alluvial fans and river terraces have long been recognised within and on the margins of the Mt Lofty Ranges of southern South Australia. Reasonably reliable stratigraphic relationships between these sediments have been established, but it is only over the past decade or so that luminescence and paleomagnetic dating techniques have been applied to acquire more reliable numerical ages for these sediments.

Sediments ranging throughout the Quaternary have been identified in the study area, but this paper focuses on deposits of Late Quaternary age, specifically those related to and younger than the Last Interglacial (~125 ka BP). The new data reported here depend on luminescence dating. In dealing with alluvial sediments, luminescence dating faces the dilemma of whether water-carried and deposited sediments have been exposed to sunlight for a sufficiently long enough time for the removal of previously stored energy, i.e. whether the luminescence clock has been reset (Wintle & Huntley 1982). However, dating of alluvial sediments has been successfully undertaken, as reviewed in Prescott & Robertson (1997, 2007), Duller (2004) and Lian & Roberts (2006). Furthermore, previous luminescence dating investigations involving Late Pleistocene fluvial sediments in the study area produced results coincident both with stratigraphic relationships and numerical ages derived from amino acid racemisation (AAR) and uranium/thorium dating techniques (Bourman *et al.* 1997). These studies also demonstrated that some radiocarbon analyses, which yielded apparent ages of ~40–30 ka are actually of Last Interglacial age.

AIMS

The aims of this investigation were to: (i) establish a general geochronological framework for the alluvial

*Corresponding author: bbourman@uow.edu.au

ISSN 0812-0099 print/ISSN 1440-0952 online
DOI: 10.1080/08120090903416260

sediments of Late Pleistocene age in southern South Australia; (ii) test the proposition that the Pooraka Formation is of Last Interglacial age, to demonstrate that it is of regional extent and is related to climatic controls; (iii) test the proposition that there is a Marine Isotope Stage 3 Sub-pluvial alluvial deposit in southern South Australia, which may be mistaken for Pooraka Formation sediments; (iv) establish the age of sediments incorporating bones of the extinct *Diprotodon*; and (v) assess geomorphic evidence for environmental changes related to climatic variability during and since the Last Interglacial.

STRATIGRAPHY OF QUATERNARY TERRESTRIAL SEDIMENTS IN SOUTHERN SOUTH AUSTRALIA

A sequence of distinctive terrestrial Quaternary sediments flanking the Mt Lofty Ranges has been described and discussed by Ward (1965, 1966), Firman (1966, 1967, 1969), Twidale *et al.* (1967), Twidale (1968), Williams (1969, 1973), Maud (1972), May & Bourman (1984), Bourman & James (1995), Callen *et al.* (1995), Pillans & Bourman (1996), Sheard & Bowman (1996), Bourman (1968, 2006), Bourman & Pillans (1997) and Bourman *et al.* (1997, 2002).

This research provides a template of the relative ages of the sediments against which numerical ages of the sediments may be assessed. Together, the relative and numerical ages assist in the correlation of equivalent units elsewhere as well as associating them with globally established climatic and sea-level fluctuations. The stratigraphy summarised in Table 1 is dominantly from exposures in the coastal cliffs at Sellicks Beach and in Sellicks Creek but it has been extended over much more extensive areas (Bourman 2006). Paleomagnetic investigations have identified the Brunhes/Matuyama boundary (780 ka) and the uppermost of the Jaramillo Normal Subchron (990 ka) within the Ochre Cove Formation, while the Seaford Formation interfingers with the earliest Pleistocene marine Burnham Limestone (Pillans & Bourman 1996).

This paper is predominantly concerned with the Pooraka Formation and younger units, which are common to many streams and alluvial fans in southern South Australia. High-level river terraces are underlain by red/brown alluvium of the Pooraka Formation, while low-level grey/black terrace/floodplain features are inset in valleys cut into the older red/brown alluvium. Occasionally the grey/black alluvium (Waldeila Formation) spills out of valleys forming levees or aggrading floodplains that completely blanket the red alluvium (Bourman 2006). Following Nanson *et al.* (1992, 2003) alluviation is considered to be a proxy for pluvial events and erosion an indicator of drier episodes.

Pooraka Formation

The Pooraka Formation is a distinctive red/brown sandy clay deposit with occasional gravel lenses and layers. Pedogenic features such as bleached silty sand A horizons and dark-red-brown clay B horizons overlying Bca horizons containing nodules and cylindroids of calcium carbonate are commonly preserved in the Pooraka Formation. Buried red-brown-earth paleosols may also occur in the Pooraka Formation and represent hiatuses in sedimentation. Initially, the red/brown alluvium of the Pooraka Formation was assigned different names by individual workers in restricted locations, but extensive mapping, stratigraphic studies, age relationships and determinations affirm that they are correlatives (Tate 1879; Firman 1966, 1967, 1969; Ward 1966; Bourman 1968; Twidale 1968; Maud 1972; Callen *et al.* 1995; Bourman *et al.* 1997).

Table 1 Series of alluvial/colluvial sediments, their basic characteristics and ages.

Post European Settlement Aggradation (PESA) sediments: Since 1836
Waldeila Formation (Ward 1966): grey/black alluvium of mid-Holocene age, 6–4 ka (MIS 1). Equivalents of Waldeila Formation are the Walkerville Sand (Twidale 1968) in the Torrens River and the Breckan Sand (Bourman 1968) in the Inman and Hindmarsh Rivers.
Colluvium in colluvium-filled bedrock depressions (MIS 2)
Unnamed minor alluvial fill unit, light grey in colour (MIS 3) ~50–40 ka
Pooraka Formation (Firman 1967): red/brown alluvium of Last Interglacial age (~125 ka) (MIS 5e). Equivalents of Pooraka Formation are Christies Beach Formation (Ward 1966), Klemzig Sand (Twidale1968), Adare Clay (Bourman 1968) and Currency Creek Formation (Maud 1972).
Taringa Formation (Ward 1966): columnar, green-grey clay containing angular clasts and calcium carbonate in the upper part of the sequence. In places it may be a mudflow deposit of Late Pleistocene age (probable MIS 6).
Ngaltinga Clay (Ward 1966): green/grey stiff plastic sandy clay with red ferruginous mottles. Firman (1967) regarded it as part of the Hindmarsh Clay. Equivalent of the Ngaltinga Clay is the Keswick Clay (Sheard & Bowman 1987), which they considered to be of Middle Pleistocene age. Some sections comprise cross-bedding and gravel lenses typical of fluvial processes (Phillips & Milnes 1988), other features are indicative of an eolian origin (Ward 1966; Pillans & Bourman 2001) whereas some sections suggest evolution by *in situ* weathering ((Sheard & Bowman 1987).
Ochre Cove Formation (Ward 1966): red and orange iron-mottled sandy sediment. Middle Pleistocene. Contains Brunhes/ Matuyama geomagnetic reversal of 780 ka and Jaramillo Subchron of 990 ka (Pillans & Bourman 1996). Ochre Cove Formation is included in the Hindmarsh Clay of Firman (1967).
Kurrajong Formation (Ward 1966): lithified, resistant breccia that merges with the base of the Ochre Cove Formation in Sellicks Creek (Middle Pleistocene). Kurrajong Formation is included in the Hindmarsh Clay of Firman (1967).
Seaford Formation (Ward 1966): green/grey clayey sand with weak orange mottles. Base interfingers with Burnham Limestone and is of earliest Pleistocene age. Seaford Formation is included in the Hindmarsh Clay of Firman (1967).
Burnham Limestone (Firman 1976): marine fossils present suggest an earliest Pleistocene age.

In the past the Pooraka Formation had been considered to post-date the Last Interglacial marine Glanville Formation (Firman 1969; Callen *et al.* 1995) and was radiocarbon dated as Last Glacial at about 30 ka (Williams 1969, 1973). The 30 ka age represents a minimum age only, but appears to have been taken at face value by Williams. Bourman *et al.* (1989) reported that near Victor Harbor the fluvial Pooraka Formation interfingers with the coastal Glanville Formation suggesting an equivalent Last Interglacial age for the Pooraka Formation. Subsequently, this age was established for the Pooraka Formation alluvium from its type section at Dry Creek (Figure 1) by applying a range of luminescence dating techniques (Bourman *et al.* 1997).

More recently, Quigley *et al.* (2007) reported five optically stimulated luminescence dates from the Pooraka Formation in the Flinders Ranges ranging in age from 71 ± 7 to 29 ± 2 ka. These ages are much younger than the ages we established for the Pooraka Formation in its type section where five analyses returned ages compatible with a Last Interglacial age of 132–118 ka (Chen *et al.* 1991). The younger ages of Quigley *et al.* (2007) may be a result of these sediments being younger interstadial deposits, which overlie the Pooraka Formation, or reworking of the Pooraka Formation sediments due to the considerable fault activity in the Flinders Ranges. Alternatively they may represent contributions from loess (Williams *et al.* 2001; Williams & Adamson 2008).

Holocene Waldeila Formation

A grey/black alluvium that forms low-level terraces and floodplains in many streams has been referred to as the Waldeila Formation (Ward 1965, 1966), the Walkerville Sand (Twidale 1968) and the Breckan Sand (Bourman 1968). Considering the extensive and widespread distribution of the Waldeila Formation in the Noarlunga and Willunga Basins, we recommend that the nomenclature of Ward (1965, 1966) for this unit be followed. The Waldeila Formation is of Holocene age as it interfingers with the marine Holocene St Kilda Formation in various places, including the lower reaches of the Hindmarsh and Onkaparinga Rivers. A mid-Holocene age has also been established for the Waldeila Formation by radiocarbon (Dury 1964; Bourman *et al.* 1997) and amino acid racemisation dating (Kimber & Milnes 1984).

Interstadial unnamed grey alluvial unit

Given the Last Interglacial age of the Pooraka Formation (125 ka) and the mid-Holocene age of the overlying Waldeila Formation, there appears to be a large erosional hiatus of at least 100 ka separating the two units. Belperio *et al.* (1984) reported various interstadial marine sediments, deposited in the interval between 125 and 5 ka now submerged in the northern Spencer Gulf. There is evidence of soil development on and eolian

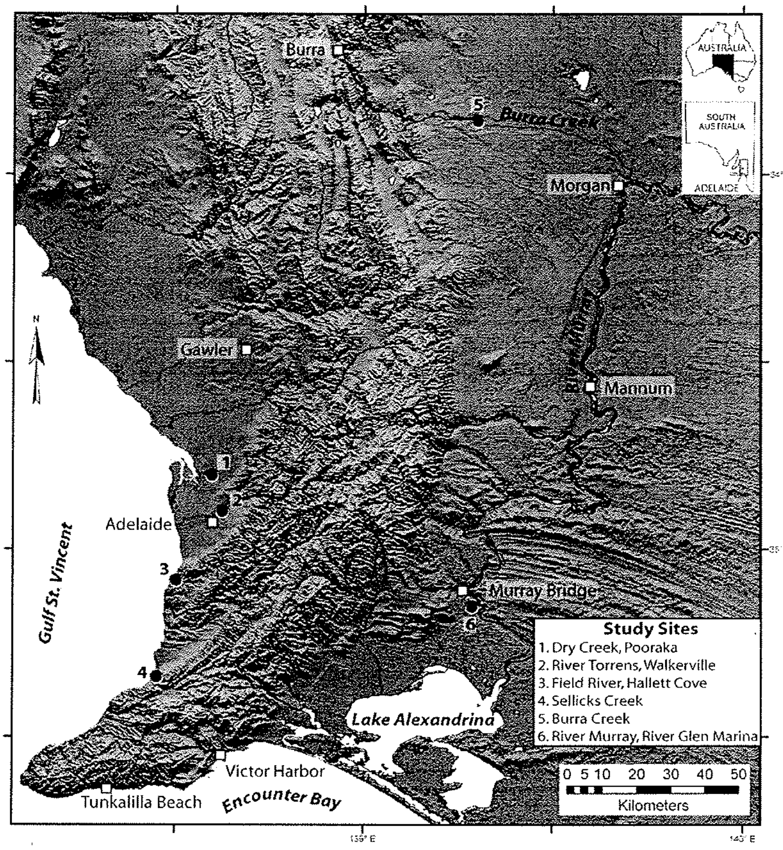

Figure 1 Map showing the locations of the study sites. Source: A. Jarvis, H. I. Reuter, A. Nelson, E. Guevara (2008), Hole-filled seamless SRTM data V4, International Centre for Tropical Agriculture (CIAT), available from <http://srtm.csi.cgiar.org>.

reworking of these units, related to subaerial exposure during lower sea-levels. Williams & Adamson (2008) have reported Late Pleistocene wetland alluvial/colluvial sediments in the Flinders Ranges of South Australia, although to date there has been no formal report of widespread fluvial interstadial deposits in southern South Australia.

The recognition of an unnamed light-buff-grey channel deposit cut into the red/brown Pooraka Formation in Sellicks Creek, which occurs immediately downstream of the Main South Road crossing (Figure 2) (Bourman & James 1995; Bourman & Pillans 1997) suggests an additional phase of aggradation some time between 125 and 6–5 ka. Layers of imbricated pebbles in the Pooraka Formation truncated by erosion clearly mark a disconformable contact with the overlying light-grey alluvial sediments. The buff-grey alluvium occurs on both sides of the present channel as illustrated diagrammatically as unit GA in Figure 2, which also shows the sequence of cut and fill Quaternary alluvial-fan sediments in this locality.

The buff-grey alluvium is of limited distribution, but is also exposed in the lowermost section of Sellicks Creek, where a gully up to 8 m deep was formed following the diversion of water from a farmer's field onto the roadway in 1911 (Howchin 1923 p. 307). The erosion has exposed alternating sediments and paleosols, with the paleosols representing periods of landscape stability and the sediments phases of erosion upstream and sedimentation downstream. The light-grey alluvium occurs above the red Pooraka Formation and below the dark-grey Waldeila Formation (Figure 3) and can be physically traced for some 80 m. The stratigraphic relationships imply an age for the light-grey unit between the Last Interglacial (125 ka) and the mid-Holocene (6–5 ka). The Pooraka Formation, which commonly displays a prominent red-brown clay B horizon and well-developed calcareous rhizomorphs, is easily distinguished from the light-grey alluvium in these respects.

Colluvium-filled bedrock depressions

Quaternary colluvium occurs in the upper reaches of Sellicks Creek and nearby drainage lines. It occupies bedrock valleys and forms colluvium-filled bedrock depressions (Crozier *et al.* 1990) with characteristic smooth and rounded morphologies. Gullies up to 9 m deep, initiated as piping, expose the colluvium, which is dominantly light yellow in colour (Bourman & James 1995). The upper 50 cm of the section contains a dark, humic horizon that represents a former swamp environment, topped by a light-coloured colluvial mantle up to 20 cm thick resulting from Post-European Settlement Aggradation. In the colluvium, both below and above the humic horizon, there is a wide range of locally derived clasts of weathered and fresh bedrock material and quartz fragments.

LUMINESCENCE DATING OF ALLUVIAL AND COLLUVIAL SEDIMENTS

The methods applied for acquiring luminescence ages are described in Appendix 1, where details for individual samples are given. Ages, and the data from which they are directly derived, are given in Table 2.

Adelaide Plains: Dry Creek and Walkerville sites (western side of Mt Lofty Ranges)

Luminescence dating of alluvial sediments in the Adelaide region on the western side of the Mt Lofty Ranges (Bourman *et al.* 1997) established a Last Interglacial age

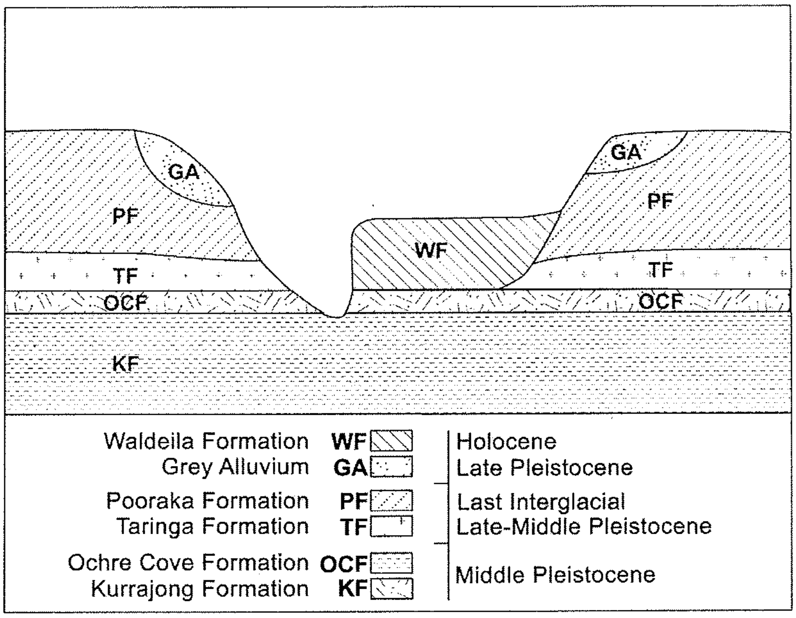

Figure 2 Diagrammatic representation of the stratigraphy of Pleistocene alluvial fan sediments exposed in Sellicks Creek. The Christies Beach Formation is the equivalent of the Last Interglacial Pooraka Formation. The grey alluvial unit is interpreted as Marine Isotope Stage 3 age (modified after Bourman & James 1995).

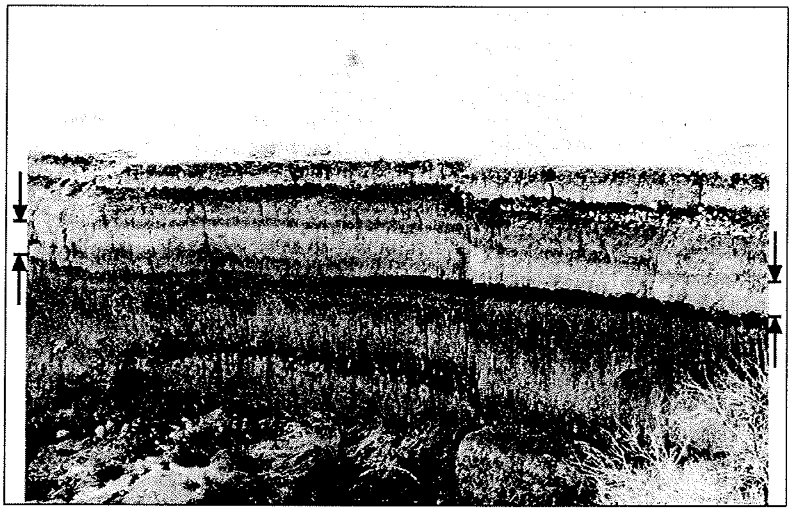

Figure 3 An 8 m section showing an alternating arrangement of sediments and paleosols exposed by accelerated erosion in the lower reaches of Sellicks Creek. The unit equivalent to the grey alluvium shown in Figure 2 is marked by arrows. It overlies a red brown earth developed on sediments of the Pooraka Formation. Locality coordinates: 35°19′45″S, 138°27′10″E.

for the Pooraka Formation. Samples of Pooraka Formation sediments underlying high terraces flanking Dry Creek (Pooraka type section) and the River Torrens (Walkerville) were collected for luminescence dating (Table 2). Of these the youngest of the Dry Creek samples (PK1S/3.5) from a depth of 3.5 m was subjected to a variety of luminescence analyses, returning ages of 126 ± 29 ka (coarse-grained quartz, selective bleach TL), 105 ± 22 ka [coarse-grained quartz, green light stimulated luminescence (GLSL)] and 116 ± 6 ka (fine-grain quartz, GLSL). These have been previously reported (Bourman *et al.* 1997) and are the first three entries of Table 2. All of these results are compatible with a Last Interglacial age

Subsequently, further fine-grain quartz OSL age determinations have been carried out on Pooraka Formation Dry Creek samples: PK2S/4.5 from a depth of 4.5 m (102 ± 16 ka), PK1S/7.5 from a depth of 7.5 m below the base of the Pooraka Formation (164 ± 17 ka) (Table 2). One of the Walkerville samples (River Torrens) (WV1S/4.5) provided an age of 138 ± 18 ka.

These newly acquired data are consistent with the Last Interglacial age of the Pooraka Formation and establish the correlation of the Pooraka Formation sediments between two different river systems on the Adelaide Plains, namely, the River Torrens at Walkerville and Dry Creek at Pooraka (Figure 1). The deepest sample at Dry Creek (PKIS/7.5) returned an expected relatively older result than the youngest PKIS/3.5) (Table 2). The deepest sample, PK1S/7.5 relates to Marine Isotope Stage 6 and was recovered from a depth of 7.5 m below the surface. This is below the level of the Pooraka Formation at Dry Creek and is probably in the older Taringa Formation. Prior to landscaping of the river bluff at this site this unit was visible at a depth below the surface of ~6 m (Bourman *et al.*, 1997).

Burra Creek (eastern side of Mt Lofty Ranges)

In mid-1997 a cluster of bones was found in the Burra Creek north of Adelaide, South Australia, by local landowners (Figure 1). These bones were identified by the South Australian Museum as *Diprotodon.* The bones are grouped together in such a way that suggests fluvial emplacement into a shallow channel. The bones are fragile, having been considerably leached, and the associated teeth were deemed unsuitable for dating by amino acid racemisation. The section of the Burra Creek where the bones are located is shown in Figure 4. Samples of the sediment in which the bones were embedded were collected for OSL dating, in order to acquire an approximate age for the occupation of the area by *Diprotodon.*

The sample site occurs in a river bluff some 10 m high cut into Pleistocene alluvial sediments (Figures 4, 5). The lower 3–4 m part of the section is red-brown in colour and comprises sandy, gravelly clay with a calcareous zone including pedogenic cylindroids and rhizomorphs in its upper section. A disconformity separates this lower unit from an upper unit and this is marked by a 2 mm-thick layer of iron oxides at the contact between the two units. The upper unit is a lighter coloured grey/brown alluvium, which is neither as massive nor as compact as the lower unit. Fluvial laminae and cross-bedded infills occur in the upper unit, throughout which there is some diffuse calcium carbonate. The contact between the two units is an irregular erosional contact with beds and lenses of river gravel that occupy small erosional depressions or scours up to 1–2 m long and ~0.5 m deep. Pronounced ripple-forms occur in places at the contact. A modern analogue of the scour pools occurs close to the location of the *Diprotodon* site in the present stream channel. It has been partially filled with coarse gravels and pebbles.

One paleoerosional scour is occupied not only by pebbles and gravel but also by a cluster of bones of the extinct marsupial *Diprotodon* that include a skull but not a complete skeleton (Figure 6). Apparently washed into a channel depression, the jumbled bones, now in an advanced state of decay, have been preserved by burial, being overlain by at least 8 m of sediment. Superficially the sedimentary succession appears to be of uniform composition, suggesting that the erosional break represents only a minor break in deposition, as a diastem. In order to test this proposition, samples for luminescence

Table 2 Luminescence ages for samples discussed in the text.

Location	Coordinates	Stratigraphic unit	Sample	Method	Lab. identifier	D_e (Gy)	Dose rate (Gy/ka)	Age (ka)	MIS	Source
Dry Creek	34°50′06″S 138°37′19″E	Pooraka Fm	PK1S/3.5	TL	AdTL9601	249 ± 58	1.97 ± 0.03	126 ± 29	5e	Bourman *et al.* 1997
Dry Creek	34°50′06″S 138°37′19″E	Pooraka Fm	PK1S/3.5	OSL	AdGL9611	208 ± 44	1.97 ± 0.03	105 ± 22	5e	Bourman *et al.* 1997
Dry Creek	34°50′06″S 138°37′19″E	Pooraka Fm	PK1S/3.5	FG	AdGL9612	294 ± 15	2.54 ± 0.12	116 ± 6	5e	Bourman *et al.* 1997
Dry Creek	34°50′06″S 138°37′19″E	Taringa Fm?	PK1S/7.5	OSL	AdGL9614	388 ± 26	2.37 ± 0.17	164 ± 17	6	Bourman *et al.* 1997
R. Torrens Walkerville	34°53′48″S 138°37′05″E	Pooraka Fm	WV1S/4.5	OSL	AdGL9616	487 ± 60	3.58 ± 0.14	138 ± 18	5e	This study
Burra Creek	33°51′08″S 139°09′43″E	Pooraka Fm	BK1SJ/10	OSL	AdGL9921	415 ± 27	3.53 ± 0.14	118 ± 9	5e	This study
Burra Creek	33°51′08″S 139°09′43″E	Pooraka Fm	BK1Sb/10	OSL	AdGL9922	417 ± 41	3.43 ± 0.12	122 ± 17	5e	This study
Burra Creek	33°51′08″S 139°09′43″E	Unnamed unit	BK2S/7	OSL	AdGL9923	161 ± 9	3.70 ± 0.13	43 ± 3	3	This study
River Glen Marina	35°11′41″S 139°20′15″E	Unnamed unit	RGM-1	OSL	RGM-1	78.0 ± 3.1	1.51 ± 0.13	51.6 ± 4.8	3	This study
Sellicks Creek	35°20′27″S 138°28′37″E	Waldeila Fm	S6	OSL	S6	15.5 ± 0.3	4.46 ± 0.36	3.5 ± 0.3	1	This study
Sellicks Creek	34°53′48″S 138°28′10″E	Unnamed unit	S9	OSL	S9	75 ± 5	5.07 ± 0.43	14.8 ± 1.7	2	This study

FG, fine-grain quartz optically stimulated luminescence (OSL); TL, thermoluminescence.

dating were collected from above and below the unconformity (Figures 5, 6) in order to establish the ages of the sediments. The age of the upper unit is significant in that it reflects the burial time of the extinct marsupial *Diprotodon* and its probable approximate age.

A sediment sample was collected from site BK1 (Sample BK1Sb/10), near the base of the section 8 m below the surface and a second sample was subsequently collected from the same auger hole (Sample BK1SJ/10) as well as a sample from site BK2 (Sample BK2S/7) ~7.5 m below the surface and judged to be in the same stratigraphic unit as the bones. All the samples were collected by augering 0.6 m horizontally into the river bluff, the operators working beneath an opaque tent. Measurements of dose rates were determined at the limit of each augered hole using a portable gamma spectrometer. These ages are included in Table 2.

The two samples from the lower sedimentary unit in Burra Creek returned ages of 118 ± 9 and 122 ± 17 ka (Marine Isotope Stage 5e) (Table 2), ages compatible with a Last Interglacial age and comparable with the age of the Pooraka Formation in the Adelaide area (Bourman *et al.* 1997). The age derived from a single sample of the material containing the extinct marsupial *Diprotodon* bones from just above the disconformity returned an age of 43 ± 3 ka (Table 2), which correlates with the Late Pleistocene Marine Isotope Stage 3. Thus, the erosional break between the two units is a significant disconformity, a pattern that is repeated in several locations upstream of the extinct marsupial *Diprotodon* site, as well as at Redbanks, east of Burra, and may be marked by the development of red-brown-earth soil profiles. These paleosols indicate that there was sufficient landscape stability to allow pedogenic processes to occur on the Last Interglacial alluvium.

The identification of Stage 3 alluvial sediments provides additional terrestrial information on the period between the Last Interglacial (125 ka BP) and the Holocene Hypsithermal (about 6–4 ka BP), which had been regarded as a long erosional hiatus (Bourman *et al.* 1997). The luminescence age for the Stage 3 sediments is also consistent with the ages of the extinct marsupial *Diprotodon* reported from some other areas in southern South Australia (Pledge *et al.* 2002; Grün *et al.* 2008). It is also possible that the young ages reported for the Pooraka Formation by Quigley *et al.* (2007) are from Stage 3 alluvial sediments.

River Glen Marina in the River Murray Trench (eastern side of Mt Lofty Ranges)

A sequence of alluvial sediments has been exposed in an excavation for a slipway at the River Glen Marina on the western bank of the River Murray, ~10 km downstream from Murray Bridge. The upper surface of the sediments forms a terrace remnant some 4 m above the present river level.

Most of the sediments consist of alternating layers of sand with occasional gravel and silt/clay beds (Figure 7). The clays in places display ferruginous mottles, and the sands and gravels have been cemented with iron oxides, dominantly goethite. These are interpreted as fluvial sediments, deposited either on an aggrading,

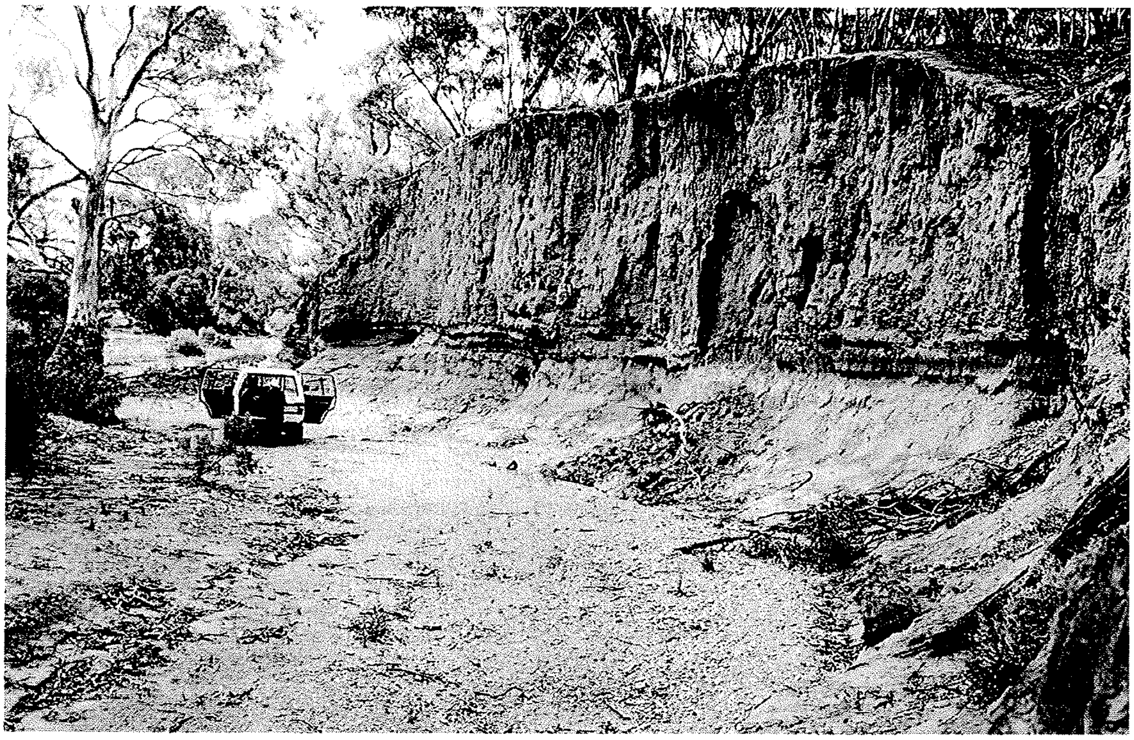

Figure 4 A 10 m-high alluvial bank in Burra Creek. The lower 3 m is the Pooraka Formation and the upper 7 m, which contains bones of the extinct marsupial *Diprotodon* near its base, is a Stage 3 Sub-pluvial unit. Locality coordinates: 33°51′08″S, 139°9′43″E.

braiding channel environment, or within a meandering channel/floodplain, producing fine overbank deposits and coarser channel materials, with the different deposits reflecting former channel positions. These sediments may be correlative with the Blanchetown Clay and occupy a former channel cut into the underlying Tertiary limestone of the region. Attempts to determine the age of these sediments using paleomagnetism were unsuccessful.

A small channel, normal to the main valley of the River Murray, ~4 m deep and ~8 m wide at the surface (Figure 8), cut into the fluvial sediments, has been filled with a fine, light-grey silty clay, containing rounded nodules and pisoliths of calcrete, derived from outcrops of Tertiary limestone situated at higher elevations. A sample of the alluvium was collected from near the base of the channel by digging 30 cm into the sediment from the vertical surface (Table 2).

Other proven and possible Sub-pluvial Marine Isotope Stage 3 alluvial sediments in southern South Australia include those at Hallett Cove, near Redbanks on Kangaroo Island and Sellicks Creek, as discussed above.

Hallett Cove, Field River

Pledge *et al.* (2002) reported the discovery of a bone of the extinct marsupial *Diprotodon* in alluvial sandy sediments sandwiched between gravel lenses at Hallett Cove on the western side of the Mt Lofty Ranges (Figure 1). The bone underlies a river terrace remnant, the surface of which stands about 4 m above the present water level at bank-full stage. The sediment was dated to ~55 ka (Pledge *et al.*, 2002) (Table 2), which falls within the Stage 3 Sub-pluvial time of Nanson *et al.* (1992).

Kangaroo Island, Redbanks

East of Redbanks on the north coast of Kangaroo Island there are possible additional Stage 3 alluvial deposits. This site is undated. A paleovalley cut into weathered Cambrian bedrock is filled with iron-mottled Pleistocene sediments, into which another valley has been cut and filled both with Pooraka Formation and younger sediments resembling the Stage 3 sediments at Burra Creek and the River Glen Marina.

Late Pleistocene colluvium in colluvium-filled bedrock depressions in the Mt Lofty Ranges

A sample for luminescence dating was collected from near the base of a 9 m-deep erosion gully developed in Quaternary colluvium in the upper reaches of Sellicks Creek. As the colluvium sits directly on Precambrian and Cambrian bedrock there is no stratigraphic relationship to provide a clue to its age. The age for this sample determined by luminescence dating was 14.8 ± 1.7 ka (Table 2). This age may be excessive as the colluvium appears to have derived dominantly from the valley sides in a small catchment area, and being

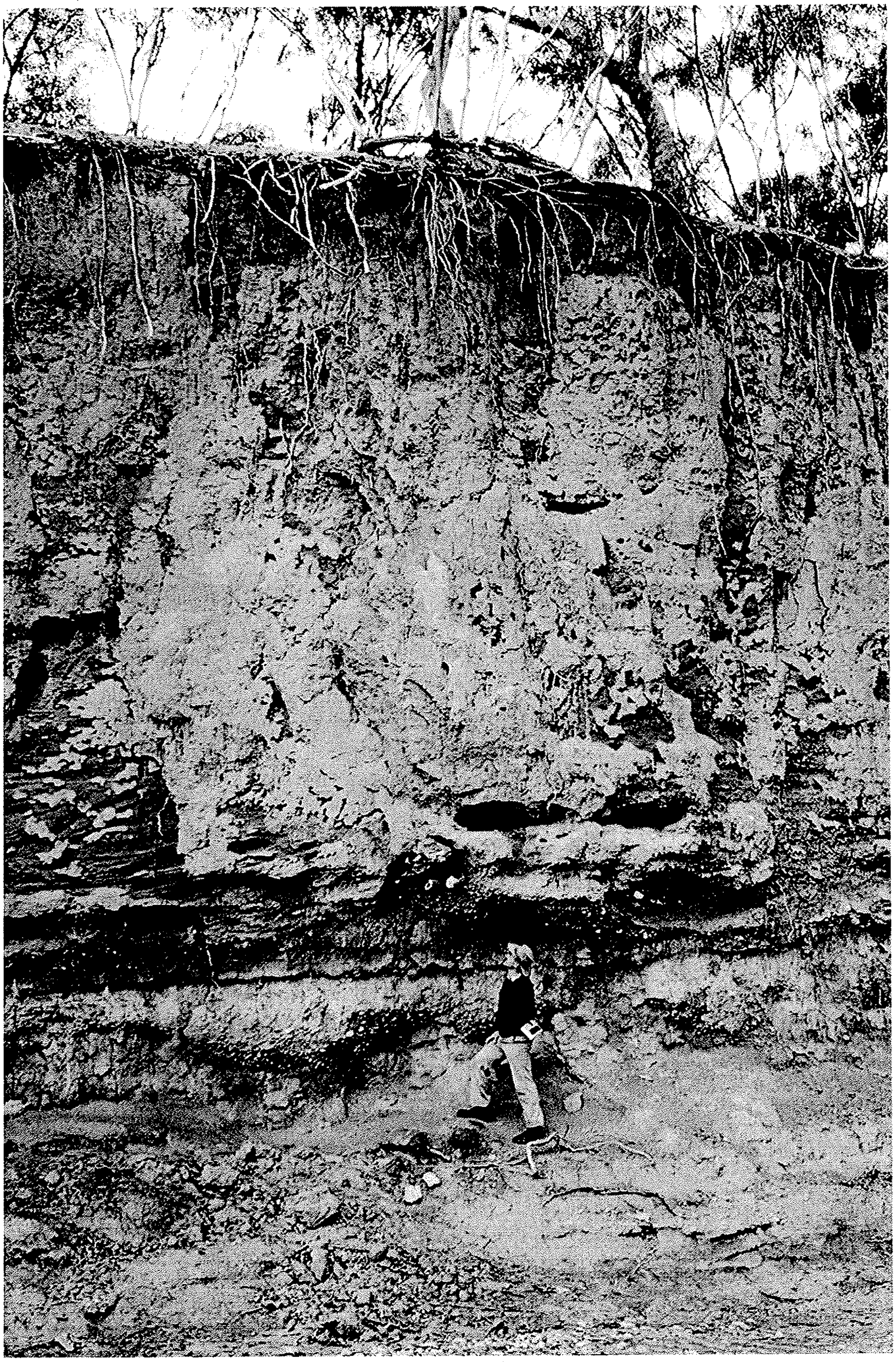

Figure 6 Close-up of the bones of the extinct marsupial *Diprotodon* protruding from Sub-pluvial Stage 3 alluvial deposits. Geological hammer resting on lower bones.

little travelled there may have been insufficient exposure of grains to sunlight for zeroing previously stored energy. Nevertheless the result is reported as luminescence dating of colluvium from this area has not previously been undertaken.

Last-Glacial dunes

A marked phase of relative aridity in the study area is indicated by the widespread presence of fossil yellow/red desert dunes, which extend across large areas of southern South Australia. At Roonka, near Blanchetown, Robertson & Prescott (2006) found luminescence ages that identify a dune built during the Last Glacial Maximum on a base of indurated red sand. In the area of the Murray Lakes dunes have been dated by TL at 16 ka (D. Moyle 1994 pers. comm. *in* Gloster 1998 p. 29; Bourman *et al.* 2000). Gardner *et al.* (1987), who sampled a variety of sites in the Murray Mallee, south and east of Loxton, found TL ages consistent with the dunes having been mainly built during the Last Glacial Maximum. At this time sea-level was some 120 m lower than at present, and conditions were cold, dry and windy. Poor vegetation cover encouraged dune development (Hesse *et al.* 2004) and stream erosion.

Mid-Holocene alluvium

Distinctive grey/black alluvium (Waldeila Formation) occupies the modern valley floors of many streams in southern South Australia, forming low-level terraces and/or floodplains inset within high terraces formed on the red-coloured alluvium of the Pooraka Formation (Bourman 2006). Under some circumstances the terraces converge down-valley sometimes crossing over, with the younger grey-black alluvium forming levees and washing out to completely blanket the older red alluvium.

A sample of Waldeila Formation was collected for luminescence dating from the Waldeila Formation in Sellicks Creek, immediately downstream of the Main South Road at a depth of 2 m below the terrace surface. In some localities the Waldeila Formation exceeds 6 m in thickness. The age returned on this low-level grey-black alluvial fill material was 3.5 ± 0.3 ka, which is compatible with the mid-Holocene age (6–4 ka) derived from radiocarbon and amino acid racemisation techniques (Kimber & Milnes 1984: Gill & Bourman 1972). The Waldella Formation interfingers with fossiliferous marine deposits in paleoestuaries at up to 2 m asl (Bourman 2006). The widespread occurrence of the Waldeila Formation in inland, coastal and upland settings

Figure 5 Extinct marsupial *Diprotodon* bones in Sub-pluvial Stage 3 alluvial sediments. Contact with the underlying Pooraka Formation is near the shoulder of the person. Sample hole in upper unit to right of person. Locality coordinates: 33°51′08″S, 139°9′43″E.

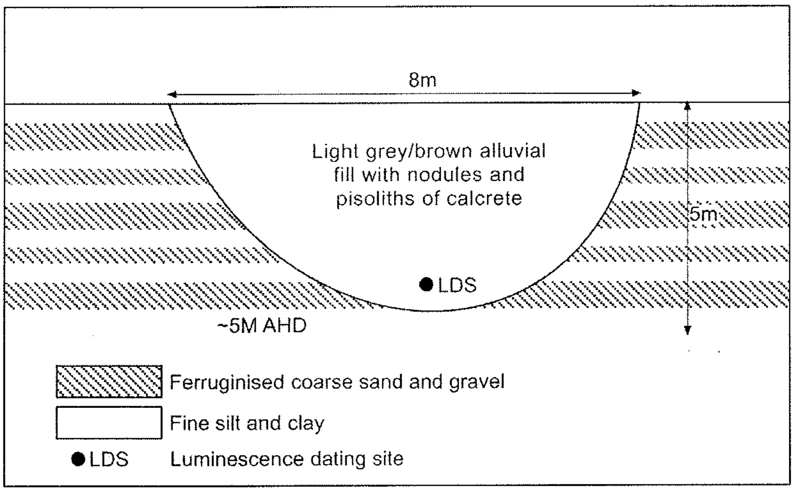

Figure 7 Sketch of the channel section of the Stage 3 Sub-pluvial unit at River Glen Marina in the trench of the River Murray. Locality coordinates: 35°11′41″S, 139°20′15″E.

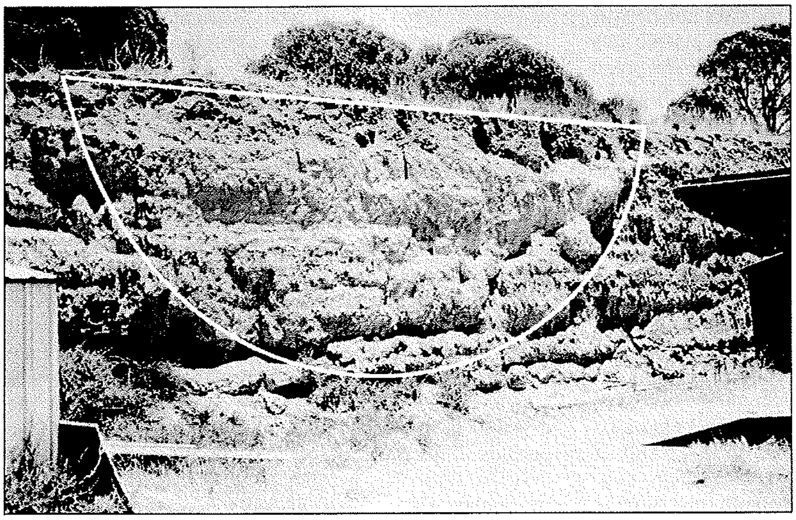

Figure 8 Calcareous alluvial sediments infilling the channel cut into ferruginous sand and clay at the River Glen Marina site, River Murray Trench.

suggests a regional, i.e. climatic, influence associated with its deposition (Bourman 2006). These factors imply that the Waldeila Formation represents a pluvial interval associated with a warmer and wetter mid-Holocene Hypsithermal and a relative sea-level slightly higher than today. The above observations support the view of Nanson *et al.* (1992, 2003), who noted that the mid-Holocene is an interglacial, following a similar pattern to that of the Last Interglacial.

DISCUSSION AND CONCLUSIONS

Luminescence techniques have demonstrated the correlation of alluvial units preserved in fans and river terraces among separate river valleys flanking both sides of the Mt Lofty Ranges. It extends the work of Nanson *et al.* (1992, 2003), Page & Nanson (1996), Page *et al.* (1996) and Hesse *et al.* (2004) in the northern, central and eastern parts of Australia to the south of the continent. In the past, the complexity and variety of river terraces have rendered the correlation of terraces within and between streams uncertain but luminescence dating provides the tools to overcome this problem. Dating provides for causative links to be established between aggradational terraces and cyclic global fluctuations of climate, sea-level oscillations and the marine oxygen isotope record (Shackleton 2006), with the terraces providing evidence of terrestrial environmental changes (Bridgland 2000; Bourman 2006).

The main findings of this study are as follows.

(1) The confirmation of a Last Interglacial age for the widespread alluvial Pooraka Formation (Pluvial Marine Isotope Stage 5e), which has been directly dated in the River Torrens and Dry Creek on the Adelaide Plains as well as on the eastern side of the Mt Lofty Ranges in Burra Creek. Vast volumes of sediment, derived from long-term erosion of the Mt Lofty–Flinders Ranges, were deposited in piedmont zones and flanking streams as alluvial fans and floodplain deposits during the Last Interglacial when the climate was warmer and wetter

than at present, and sea-level stood at least 2 m above its current level (Murray-Wallace & Belperio 1991). The widespread occurrence of the Pooraka Formation suggests that pre-weathering had prepared readily erodible materials prior to the Last Interglacial and/or that earlier Pleistocene fluvial deposits were reworked to form the Pooraka Formation.

(2) The identification of a fluvial unit younger than the Pooraka Formation (Last Interglacial) but older than the Waldeila Formation (mid-Holocene) and filling in a large gap in the sedimentary history between Last Interglacial times ($\sim$125 ka) and the Middle Holocene ($\sim$6–4 ka). This unit has been dated in the Burra Creek and in the trench of the River Murray as a Marine Isotope Stage 3 deposit at $\sim$50–40 ka, which is the equivalent of the Stage 3 Sub-pluvial of Nanson *et al.* (1992) and Page *et al.* (1996). Pledge *et al.* (2002) reported a similar age for alluvial sediments containing bones of the extinct marsupial *Diprotodon* in the Hallett Cove area, revealing the regional character of this pluvial event, as it was synchronous on both sides of the Mt Lofty Ranges. Other occurrences of this Stage 3 Sub-pluvial unit have been noted but they are nowhere as extensive as the deposits of the Pooraka Formation. We suspect, however, that there may be a more widespread distribution of this particular unit. It appears that the Pooraka Formation and younger alluvial sediments may have been lumped together in the past, thus producing a greater age range for the Pooraka Formation than is actually the case (Callen *et al.* 1995). Quigley *et al.* (2007) reported five OSL dates from the Pooraka Formation in the Flinders Ranges ranging in age from 71 ± 7 to 29 ± 2 ka. These ages are much younger than the ages we established for the Pooraka Formation in its type section where five analyses returned ages compatible with a Last Interglacial age of 132–118 ka. The younger ages of Quigley *et al.* (2007) may be a result of these sediments being younger interstadial deposits, ongoing reworking of Pooraka Formation sediments due to the considerable fault activity in the Flinders Ranges, or the result of eolian inputs. We suspect that many dates younger than the Last Interglacial, are probably from the Marine Isotope Stage 3 sediments, which may superficially resemble the Pooraka Formation.

Prior to refereeing we were not aware of the significance of the important work of D. L. G. Williams (1982), which is most informative and in many respects corroborates our findings. At many fossil sites in the Mt Lofty and Flinders Ranges he recognised lower and upper alluvial deposits, with the older lower units containing pedogenic calcareous rhizomorphs and separated from the younger upper units by erosional contacts, as we have described for our Burra Creek site. No reliable radiocarbon dates were achieved from the older units, which we suspect are of Last Interglacial age. Often the younger upper units contained *Diprotodon* and other vertebrate fossil remains. Aquatic and land snails as well as charcoal collected from within these units produced reliable radiocarbon dates, all of which fall in the range of $\sim$40 to 30 ka BP, or MIS 3. He rejected dates on soil carbonates and other contaminated materials as well as dates that provided only minimum ages with little stratigraphic significance. Williams (1982) concluded from his widespread study sites that this phase of deposition was synchronous throughout the region and that climate was the most likely cause of such widespread and uniform alluviation. He recognised that debris flows were largely responsible for fan building and were initiated by climatic changes towards higher rainfall intensity or colder winters. He named this younger unit the Hookina Creek Formation, replacing the term Pooraka Formation for this part of the state. We suspect that the older unit is the equivalent of the Last Interglacial Pooraka Formation and that the upper fossil-bearing unit (his Hookina Creek Formation), which is much less consolidated and without the pronounced calcareous rhizomorphs, may be equated with the MIS 3 unit.

(3) The establishment of an age for the bones of the extinct *Diprotodon*, in the Burra Creek at $\sim 43 \pm 3$ ka. The sampling site for luminescence dating and the bones were adjacent and just above the disconformity with the Pooraka Formation, suggesting contemporaneity of the sediments and the bones. The extinction of the Australian megafauna is a question of current interest (Roberts *et al.* 2001; Wroe & Field 2006). Ages of the Burra Creek (43 ka) and Hallett Cove ($\sim$55 ka) *Diprotodons* fall, locally, in the age range of the Stage 3 Sub-pluvial unit and of dated *Diprotodon* teeth elsewhere in South Australia (Grün *et al.* 2008). However, in the absence of any Aboriginal associations, nothing can be concluded about extinction, one way or the other, from our work.

(4) Extension of evidence of wetting and drying of Australia during the Late Quaternary. By and large our data support the findings of Nanson *et al.* (1992, 2003) who reported on TL dating of eolian and fluvial deposits over an extensive region of central and eastern Australia that revealed an alternating pattern of fluvial and arid episodes. These were broadly coincident with Late Quaternary climatic changes associated with interglacial and glacial times. Nanson *et al.* (1992) used the deposition of widespread alluvium as a proxy for periods of greater rainfall and runoff, while increased dune activity was associated with greater aridity. In particular, they noted increasing aridity and dune-building peaking during the last glacial (30–10 ka). They proposed Australian Pluvial Stages 7 and 5 equivalent to the Penultimate Interglacial (Marine Isotope Stage 7) and the Last Interglacial (Marine Isotope Stage 5), respectively, and a Stage 3 Sub-pluvial at Marine Isotope Stage 3. To date no Pluvial Stage 7 alluvium has been precisely identified in our present study area but it is likely to be present, especially in the piedmont zone of the Mt Lofty–Flinders Ranges. For example, Murray-Wallace *et al.* (1988) reported 'Older Pleistocene marine beds' (Marine Isotope Stage 7) in the upper Spencer Gulf area, interfingering with alluvium derived from the Flinders Ranges. There is one age determination on material immediately underlying the Pooraka Formation at Dry Creek, PK1S/7.5 with an age of 164 ± 17 ka, (Marine Isotope Stage 6), which is probably related to the Taringa Formation, a possible mudflow deposit. Ward (1966) mapped the Taringa Formation in several places in Sellicks Creek, consistently underlying the Pooraka Formation (his Christies Beach Formation) as well as forming a terrace tread in the lower Onkaparinga Valley higher than the terrace formed on the

Pooraka Formation. The Taringa Formation has also been recognised underlying the Pooraka Formation at Tunkalilla Beach (Bourman *et al.* 1997).

(5) Pluvial Stage 5 is widespread as the Last Interglacial Pooraka Formation, but there is no indication of a time lag of some 15 ka between sea-level and temperature maxima and the onset of alluviation, as reported by Nanson *et al.* (1992). In contrast, the great majority of luminescence ages for the Pooraka Formation fall within Last Interglacial (MIS 5e) times, which range from 132 to 118 ka (Zhu *et al.* 1993). Furthermore, the ages determined for the Pooraka Formation do not support a coastward trend of the Pluvial Stage 5 event reported by Nanson *et al.* (1992), who suggested that the Stage 5 Pluvial persisted in a time-transgressive fashion coast-wards, with alluvial reworking leading to the preservation of more recent deposits in three different regions (e.g. ~110 ka at Lake Eyre, 90 ka in the Riverine Plain and ~80 ka on the Nepean River). The number of samples reported here may be insufficient to detect the suggested trends, but they serve to extend the record further to the south.

(6) Data presented in this paper suggest that in southern South Australia, there is no time lag between the acquisition of temperature and sea-level peaks, and alluviation for either the Last Interglacial or the mid-Holocene. Furthermore, the ages determined for the Pooraka Formation do not support a coastward trend of the Pluvial Stage 5 event. However, there do appear to be decreasing volumes of sediment deposited from the Last Interglacial to the Holocene, with valleys cut into the Last Interglacial Pooraka Formation during drier phases becoming partially infilled during the Stage 3 Sub-pluvial and the pluvial of the mid-Holocene.

(7) The Last Interglacial provides a geological analogue for the present as suggested by Nanson *et al.* (1992), who noted that the Holocene appears to be following the pattern of the Last Interglacial. They argued that there is as yet no sign of a pluvial alluviation equivalent to those of the Stage 5 Pluvial or Stage 3 Sub-pluvial, despite a maximum peak in temperature at ~9 ka and a sea-level peak at ~7.5–6.0 ka, suggesting that the renewed wetting of Australia could lag other indicators by up to 15 ka. However, in our study area, the Last Interglacial was characterised by warm and wet conditions as attested to by the vast amounts of alluvium that were washed down from the ranges to form alluvial deposits and river sediments, in places graded to a regionally higher sea-level 2 m above present sea-level. Furthermore, the present Interglacial, particularly the mid-Holocene, is also characterised by a high regional sea-level and alluviation of the Waldeila Formation in valleys. More recent work by Nanson *et al.* (2003) also suggests a period in the mid-Holocene that in eastern coastal Australia was significantly wetter than today, but not as fluvially active as the Stage 5 Pluvial or Stage 3 Sub-pluvial.

ACKNOWLEDGEMENTS

We are grateful to the owners of the property containing the *Diprotodon* bones, Mr and Mrs Clarke, for drawing them to our attention and for facilitating access. Neville Pledge is thanked for identifying the bones, and G. Robinson, L. Waldron and P. Martinaitis for field assistance. PIRSA provided support funding the luminescence dating of the Burra Creek samples. The luminescence dating was also assisted by grants 96/080 and 98/P008 from the Australian Institute of Nuclear Science and Engineering and the Archaeometry Special Fund of the Physics Department, University of Adelaide. We are grateful to Gerald Nanson for providing useful feedback on an early version of the paper. Philip Roetman is thanked for preparing the illustrations. Funding for dating of the Sellicks Creek samples was provided by the University of South Australia. We appreciate the critical reviews of the paper by Colin Murray-Wallace and Nick Harvey. We thank the referees Paul Hesse and Wolfgang Preiss for their insightful improvements to the paper: we are particularly indebted for having our attention drawn to the most important and informative work of the late D. L. G. Williams.

REFERENCES

AITKEN M. J. 1985. *Thermoluminescence dating.* Academic Press, London.

AITKEN M. J. 1998. *An introduction to optical dating.* Oxford University Press, Oxford.

ADAMIEC G. & AITKEN M. J. 1998. Dose-rate conversion factors: new data. *Ancient TL* **16**, 37–50.

BELPERIO A. P., SMITH B. W., POLACH H. A., NITTROUER C. A., DEMASTER D. J., PRESCOTT J. R., HAILS J. R. & GOSTIN V. A. 1984. Chronological studies of the Quaternary marine sediments of the Northern Spencer Gulf, South Australia. *Marine Geology* **61**, 265–296.

BOURMAN R. P. 1968. Terraces of the Inman and Hindmarsh Rivers. *Taminga* **6**,17–21.

BOURMAN R. P. 2006. River terraces of the Fleurieu Peninsula, South Australia. *South Australian Geographical Journal* **105**, 1–24.

BOURMAN R. P., ALLEY N. F. & JAMES K. F. 2002. European-induced environmental change in the Adelaide area, South Australia: evidence from Dry Creek at Mawson Lakes. *Transactions of the Royal Society of South Australia* **126**, 29–38.

BOURMAN R. P. & JAMES K., 1995. Gully evolution and management: a case study of the Sellicks Creek drainage basin. *South Australian Geographical Journal* **94**, 81–105.

BOURMAN R. P., MARTINAITIS P., PRESCOTT J. R. & BELPERIO A. P. 1997. The age of the Pooraka Formation and its implications, with some preliminary results from luminescence dating. *Transactions of the Royal Society of South Australia* **121**, 83–94.

BOURMAN R. P., MURRAY-WALLACE C. V., BELPERIO A. P. & HARVEY N. 2000. Rapid coastal geomorphic change in the River Murray Estuary of Australia. *Marine Geology* **170**, 141–168.

BOURMAN R. P. & PILLANS B. J. 1997. The use of the geomagnetic polarity time scale in elucidating Pleistocene landscape evolution: an example from South Australia. *The South African Geographical Journal* **79**, 75–82.

BOURMAN R. P., SCOBIE D. & TSCHARKE M. T. 1989. Origin and development of Police Point Spit, Victor Harbor, South Australia. *South Australian Geographical Journal* **89**, 25–45.

BØTTER-JENSEN L., BULUR E., DULLER G. A. T. & MURRAY A. S. 2000. Advances in luminescence instrument systems. *Radiation Measurements* **32**, 523–528.

BRIDGLAND D. R. 2000. River terrace systems in northwest Europe: an archive of environmental change, uplift and early human occupation. *Quaternary Science Reviews* **19**, 1293–1303.

CALLEN R. A., SHEARD M. J., BENBOW M. C. & BELPERIO A. P. 1995. Alluvial fans and piedmont slope deposits. *In*: Drexel J. F. & Preiss W. V. eds. *The geology of South Australia volume 2, The Phanerozoic*, pp. 241–243. Geological Survey of South Australia Bulletin **54**.

CHEN J. H., CURRAN H. A., WHITE B. & WASSERBURG G. J. 1991. Precise chronology of the last interglacial period: ^{234}U–^{230}Th data from fossil coral reefs in the Bahamas. *Geological Society of America Bulletin* **103**, 82–97.

CROZIER M. J., VAUGHAN E. E. & TIPPETT J. M. 1990. Relative instability of colluvium-filled bedrock depressions. *Earth Surface Processes and Landforms* 15, 329–339.

DULLER G. A. T. 2004. Luminescence dating of Quaternary sediments: recent advances. *Journal of Quaternary Science* **19**, 183–192.

DURY G. H. 1964. Australian geochronology: checklist 1. *Australian Journal of Science* **278**,103–109.

FIRMAN J. B. 1966. Stratigraphic units of late Cainozoic age in the St Vincent Basin. *Geological Survey of South Australia Quarterly Geological Notes* 17, 6–8.

FIRMAN J. B. 1967. Stratigraphy of late Cainozoic deposits in South Australia. *Transactions of the Royal Society of South Australia* **91**, 165–180.

FIRMAN J. B. 1969. Stratigraphic analysis of soils near Adelaide. *Transactions of the Royal Society of South Australia* **93**, 39–54.

FIRMAN J. B. 1976. Limestone at the base of the Pleistocene sequence in South Australia. *Geological Survey of South Australia Quarterly Geological Notes* **58**, 2–5.

GALBRAITH R. F., ROBERTS R. G., LASLETT G. M., YOSHIDA H. & OLLEY J. M. 1999. Optical dating of single and multiple grains of quartz from Jinmium rock shelter, northern Australia. Part I, Experimental design and statistical models. *Archaeometry* **41**, 339–364.

GARDNER G. J., MORTLOCK A. J., PRICE D. M., READHEAD M. L. & WASSON R. J. 1987. Thermo-luminescence and radiocarbon dating of Australian desert dunes. *Australian Journal of Earth Sciences* 34, 343–357.

GILL E. D. & BOURMAN R. P. 1972. Research on Quaternary Shorelines in Australia and New Zealand—a summary report of the ANZAAS Quaternary Shorelines Committee report for South Australia. *Search* 3, 103–104.

GLOSTER A. 1998. The Late Pleistocene and Holocene sedimentary history of Lake Albert, South Australia. MSc thesis, Flinders University of South Australia, Adelaide (unpubl.).

GRÜN R., WELLS R., EGGINS S., SPOONER N., AUBERT M., BROWN L. & RHODES E. 2008. Electron spin resonance dating of South Australian megafauna sites. *In*: De Laeter J. R., Gleadow A. J. W. & McDougall I. eds. *Geochronology in Australia*, pp. 917–936. Australian Journal of Earth Sciences **55**.

HESSE P. P., MAGEE J. W. & VAN DER KAARS S. 2004. Late Quaternary climates of the Australian arid zone: a review. *Quaternary International* **118/119**, 87–102.

HOWCHIN W. 1923. A geological sketch section of the sea cliffs on the eastern side of Gulf St Vincent from Brighton to Sellicks Hill, with descriptions. *Transactions of the Royal Society of South Australia* **47**, 279–315.

KIMBER R. W. L. & MILNES A. R. 1984. The extent of racemisation of amino acids in Holocene and Pleistocene marine molluscs in Southern South Australia: preliminary data on a time-framework for calcrete formation. *Australian Journal of Earth Sciences* 31, 279–286.

LIAN O. B. & ROBERTS R. G. 2006. Dating the Quaternary: progress in luminescence dating of sediments. *Quaternary Science Reviews* **25**, 2449–2468.

MAUD R. R. 1972. Geology, geomorphology and soils of Central County Hindmarsh (Mount Compass–Milang), South Australia. *CSIRO Soil Publication* **29**.

MAY R. I. & BOURMAN R. P. 1984. Coastal landslumping in Pleistocene sediments at Sellicks Beach, South Australia. *Transactions of the Royal Society of South Australia* **108**, 85–94.

MEJDAHL V. 1979. Thermoluminescence dating: beta-dose attenuation in quartz grains. *Archaeometry* **21**, 61–72.

MURRAY A. S., MARTEN R., JOHNSON A. & MARTIN P. 1987. Analysis for naturally occurring radionuclides at environmental concentrations by gamma spectrometry. *Radioanalytical and Nuclear Chemistry Articles* **115**, 263–288.

MURRAY A. S. & WINTLE A. G. 2000. Luminescence dating of quartz using an improved single aliquot regenerative-dose protocol. *Radiation Measurements* **32**, 57–73.

MURRAY A. S. & WINTLE A. G. 2003. The single aliquot regenerative dose protocol: potential for improvements in reliability. *Radiation Measurements* **37**, 377–381.

MURRAY-WALLACE C. V. & BELPERIO A. P. 1991. The Last Interglacial shoreline in Australia—a review. *Quaternary Science Reviews* **10**, 441–461.

MURRAY-WALLACE C. V., KIMBER R. W. L., GOSTIN V. A. & BELPERIO A. P. 1988. Amino acid racemisation dating of the 'Older Pleistocene marine beds,' Redcliff, northern Spencer Gulf, South Australia. *Transactions of the Royal Society of South Australia* **112**, 51–56.

NANSON G. C., COHEN T. J., DOYLE C. J. & PRICE D. M. 2003. Alluvial evidence of major Late Quaternary climate and flow-regime changes on the coastal rivers of New South Wales, Australia. *In*: Gregory K. J. & Benito G. eds. *Palaeohydrology: understanding global change*, pp. 233–258. Wiley, Chichester.

NANSON G. C., PRICE D. M. & SHORT S. A. 1992. Wetting and drying of Australia over the past 300 ka. *Geology* **20**, 791–794.

OLLEY J. M., PIETSCH T. & ROBERTS R. G. 2004. Optical dating of Holocene sediments from a variety of geomorphic settings using single grains of quartz. *Geomorphology* **60**, 337–358.

PAGE K. & NANSON G. C. 1996. Stratigraphic architecture resulting from Late Quaternary evolution of the Riverine Plain, southeastern Australia. *Sedimentology* **43**, 927–945.

PAGE K., NANSON G. C. & PRICE D. 1996. Chronology of Murrumbidgee River palaeochannels on the Riverine Plain, southeastern Australia. *Journal of Quaternary Science* 11, 311–326.

PHILLIPS S. E. & MILNES A. R. 1988. The Pleistocene terrestrial carbonate mantle on the south-eastern margin of the St Vincent Basin, South Australia. *Australian Journal of Earth Sciences* **35**, 463–481.

PILLANS B. J. & BOURMAN R. P. 1996. The Brunhes/Matuyama Polarity transition (0.78 Ma) as a chronostratigraphic marker in Australian regolith studies. *AGSO Journal of Australian Geology & Geophysics* **16**, 289–294.

PILLANS B. J. & BOURMAN R. P. 2001. Mid Pleistocene arid shift in southern Australia, dated by magnetostratigraphy. *Australian Journal of Soil Research* **39**, 89–98.

PLEDGE N. S., PRESCOTT J. R. & HUTTON J. T. 2002. A Late Pleistocene occurrence of *Diprotodon* at Hallett Cove, South Australia. *Transactions of the Royal Society of South Australia* **26**, 39–44.

PRESCOTT J. R. & HUTTON J. T. 1994. Cosmic ray contributions to dose rates for luminescence and ESR dating: large depths and long term variations. *Radiation Measurements* **23**, 497–500.

PRESCOTT J. R., HUNTLEY D. J. & HUTTON J. T. 1993. Estimation of equivalent dose in thermoluminescence dating—the 'Australian slide' method. *Ancient TL* **11**, 1–5.

PRESCOTT J. R. & ROBERTSON G. B. 1997. Sediment dating by luminescence: a review. *Radiation Measurements* **27**, 893–922.

PRESCOTT J. R. & ROBERTSON G. B. 2007. Luminescence dating: an Australian perspective. *In*: De Laeter J. R., Gleadow A. J. W. & McDougall I. eds. *Geochronology in Australia*, pp. 997–1007. Australian Journal of Earth Sciences **55**.

QUIGLEY M. C., SANDIFORD M. & CUPPER M. L. 2007. Distinguishing tectonic from climatic controls on range-front sedimentation. *Basin Research* **19**, 491–505.

ROBERTS R. G., FLANNERY T. F., AYLIFFE L. K., YOSHIDA H., OLLEY J. M., PRIDEAUX G. J., LASLETT G. M., BAYNES A., SMITH M. A., JONES R. & SMITH B. L. 2001. New ages for the last Australian megafauna: continent-wide extinction about 46,000 years ago. *Science* **292**, 1888–1892.

ROBERTSON G. B. & PRESCOTT J. R. 2006. Luminescence dating at the archaeological and human burial site at Roonka, South Australia. *Quaternary Science Reviews* **25**, 2586–2593.

SHACKLETON N. J. 2006. Formal Quaternary stratigraphy—what do we expect and need? *Quaternary Science Reviews* **25**, 3458–3462.

SHEARD M. J. & BOWMAN G. M. 1987. Definition of the Keswick Clay, Adelaide/Golden Grove Embayment, Para and Eden Blocks, South Australia. *Geological Survey of South Australia Quarterly Geological Notes* **103**, 4–9.

SHEARD M. J. & BOWMAN G. M. 1996. Soils, stratigraphy and engineering geology of near surface materials of the Adelaide Plains. *Mines and Energy South Australia Report Book* **94/9**.

STOKES S., INGRAM S., AITKEN M. J., SIROCKO F., ANDERSON R. & LEUSCHNER D. 2003. Alternative chronologies for Late Quaternary (Last Interglacial–Holocene) deep sea sediments via optical dating of silt-sized quartz. *Quaternary Science Reviews* **22**, 925–941.

TATE R. 1879. The Anniversary Address of the President. *Transactions of the Royal Society of South Australia* **2**, xxxix–lxxv.

TWIDALE C. R. 1968. *Geomorphology: with special reference to Australia*. Nelson, Melbourne.

TWIDALE C. R., DAILY B. & FIRMAN J. B. 1967. Eustatic and climatic history of the Adelaide area, South Australia: a discussion. *Journal of Geology* 75, 237–242.

YOSHIDA H., ROBERTS R. G., OLLEY J. M., LASLETT G. M. & GALBRAITH R. F. 2000. Extending the age range of optical dating using single 'supergrains' of quartz. *Radiation Measurements* 32, 439–446.

WARD W. T. 1965. Eustatic and climatic history of the Adelaide area, South Australia. *Journal of Geology* 73, 592–602.

WARD W. T. 1966. Geology, geomorphology and soils of the south-western part of County Adelaide, South Australia. *CSIRO Soil Publication* 23.

WILLIAMS D. L. G. 1982. Late Pleistocene vertebrates and palaeo-environments of the Flinders and Mount Lofty Ranges, South Australia. PhD thesis, Flinders University, Adelaide (unpubl.).

WILLIAMS G. E. 1969. Glacial age of the piedmont alluvial deposits in the Adelaide area, South Australia. *Australian Journal of Science* 32, 257.

WILLIAMS G. E. 1973. Late Quaternary piedmont sedimentation, soil formation and palaeoclimates in arid South Australia. *Zeitschrift für Geomorphologie* 17, 102–125.

WILLIAMS M., PRESCOTT J. R., CHAPPELL J., ADAMSON D., COCK B., WALKER K. & GELL P. 2001. The enigma of a late Pleistocene wetland in the Flinders Ranges, South Australia. *Quaternary International* 83/85, 129–144.

WILLIAMS M. A. J & ADAMSON D. A. 2008. A biophysical model for the formation of late Pleistocene valley-fills in the arid Flinders Ranges of South Australia. *South Australian Geographical Journal* 107, 1–14.

WINTLE A. G. & HUNTLEY D. J. 1982. Thermoluminescence dating of sediments. *Quaternary Science Reviews* 1, 31–53.

WROE S. & FIELD J. 2006. A review of the evidence for a human role in the extinction of Australian Megafauna and an alternative explanation. *Quaternary Science Reviews* 25, 2692–2703.

ZHU Z. R., WYROLL K-H., COLLINS L. B., CHEN J. H., WASSERBURG G. J. & EISENHAUER A. 1993. High-precision U-series dating of Last Interglacial events by mass spectrometry: Houtman Abrolhos Islands, Western Australia. *Earth and Planetary Science and Letters* 118, 281–293.

Received 24 May 2009; accepted 13 October 2009

APPENDIX 1: METHODOLOGY OF LUMINESCENCE DATING

Although carried out at different times and in different places, laboratory and field measurements were essentially the same (Aitken 1985, 1998).

The actual laboratory process of luminescence dating involves a four-step measurement: (i) suitable minerals, e.g. pure quartz, are extracted from a sample by chemical and/or physical means; (ii) energy trapped by crystal impurities as a result of exposure to environmental ionising radiation is measured by heating or optical stimulation, while recording the light emitted in the process; this measurement gives what is known as the equivalent dose, D_e; (iii) the sensitivity to ionising radiation is determined with a calibrated radiation source; and (iv) the dose rates to the sample from radioactivity in the sample itself and from the environment are found. The age then follows from the age equation:

$$\text{Age (years)} = \frac{\text{lumin escence output}}{\text{luminescence per unit dose} \times \text{dose per year}}$$

The natural dose rate is due to potassium, uranium and thorium in the sample and surroundings, and cosmic rays.

In the present case U, Th and K were measured by at least two independent methods: (i) scintillometry, whereby U, Th and K concentrations and gamma-ray doses are measured in the field at the time of sampling; (ii) in the laboratory, delayed neutron analysis (DNA) is used to determine U, neutron activation analysis (NAA) to find Th, and X-ray fluorescence spectrometry (XRS) or atomic absorption spectrometry (AAS) to determine K; and (iii) thick source alpha-counting is used to determine U and Th (Aitken 1985). Not all methods were used for all samples. Cosmic-ray dose rates were determined from Prescott & Hutton (1994).

The ages of the samples were calculated using the age equation, incorporating conversion factors from Adamiec & Aitken (1998). The allowance for water content was based on the measured contemporary level. The estimated age would increase by $\sim 1\%$ for every 1% increase in water content: the history of the water content of the site is allowed for, when known, in assessing the age. Beta values close to 0.05 were measured for all samples. The method of preparation of the samples was substantially the same in all cases. After sieving, the requisite grainsize fraction was treated with hydrochloric acid and hydrogen peroxide to remove carbonates and organic materials, respectively. It was then etched in 40% HF for 40 min to remove possible feldspar contamination and to remove the outer alpha-irradiated layer of the grains, followed by a treatment with hydrochloric acid to remove acid-soluble fluorides. The purity of the quartz extract was checked using infrared stimulated luminescence. All coarse-grain aliquots were mounted on to 9.7 mm stainless steel discs using silicone oil spray. Fine grains were deposited directly on to 9.7 mm discs by Stokes settling from N/100 NaOH.

Adelaide Plains: Dry Creek and Walkerville sites

Samples were from Pooraka Formation sediments underlying high terraces flanking Dry Creek (Pooraka) and the River Torrens (Walkerville). For evaluation purposes, the youngest of the Dry Creek samples (PK1S/3.5), from a depth of 3.5 m, was analysed by four methods, all using quartz: (i) 100 μm grains—selective bleach thermoluminescence (TL); (ii) 100 μm grains—green light optically stimulated luminescence (OSL); (iii) fine-grain 4–11 μm quartz—green light OSL; and (iv) fine-grain quartz—infrared stimulated luminescence, which failed to return an age. The results for PK1S/3.5 were reported in Bourman *et al.* (1997) and are repeated in the first three lines of Table 2. Comparison of these lines shows that all methods are compatible but that fine-grain quartz OSL gives the most precise determination. On the basis of this experience, ages for the Pooraka formation at depths of 4.5 m (PK2S/4.5) and 7.5 m (PK 1S/7.5), and for Walkerville at a depth of 4.5 m

(WV1S/4.5) were found using fine-grain quartz OSL. The equivalent dose was determined using the multiple aliquot 'Australian slide' method (Prescott *et al.* 1993). Normalisation among aliquots was by a preliminary 0.5 s 'short shine.' For OSL a preheat of 300 s at 220°C was used, and the shine-down was for 250 s; the light emitted in the interval 4–13 s of the shine-down was used to define the equivalent dose, corrected for background by subtracting counts in 9 s at the end of the shine-down. To find dose rates, the methods mentioned above were used, in most cases giving multiple determinations (Table 3). Dose rates found by independent methods were statistically identical and the weighted average dose rate was used in finding the age.

For each sample two sets of 20–30 aliquots were prepared. One set of aliquots (natural samples) was given doses of artificial radiation ranging from zero to about three times the approximate equivalent dose determined by a pilot study (additive set). The other set (bleached samples) was bleached in the sun for 3–4 h in order to remove all naturally acquired luminescence and then irradiated in the same way as the natural set (regenerated set). Both sets of samples were then preheated for 300 s at 220°C in order to remove low-temperature luminescence, and then illuminated for 250 s by green light and the emitted luminescence measured. This luminescence can be displayed graphically as a 'shine-down curve.' Each group of administered doses makes a so-called growth curve. The growth curves of natural and bleached sample sets were compared with the computer. This determines the lateral shift required to superimpose one curve upon the other. This lateral shift is equivalent to the equivalent dose. The data for these sites are shown in Tables 2 and 3.

Burra Creek

Sediment sample site BK1Sb/10 was collected from near the base of the section and a second sample (BK1SJ/10) was subsequently collected from the same auger hole. Sample BK2S/7 was judged to be in the same stratigraphic unit as the bones. The scintillometer measurements were made in the same hole that the samples came from.

The laboratory methods used were the same as those described above for Pooraka/Walkerville. Equivalent doses were found by green-light OSL using the fine-grain, 4–11 μm fraction. A set of shine-down curves for sample BK2S/7 is shown in Figure 9. (The shine-down curves for samples BK1SJ/10 and BK1Sb/10 are similar to this but are more closely grouped, indicating that these samples are close to saturation, i.e. almost all available luminescence centres have been filled due to natural radiation over a long period of time.)

Superimposed growth curves for each for each of the three Burra Creek samples are shown in Figure 10. The data for the three Burra Creek samples are shown

Table 3 Th, U, K and water analyses for samples discussed in the text.

Sample	TSAC	U ppm DNA	SCIN	TSAC	Th ppm NAA	SCIN	K% XRS	K% SCIN	Water% dry wt
PK1S/3.5	1.5 ± 0.6	1.5 ± 0.1	1.74 ± 0.17	7.0 ± 2.0	7.2 ± 0.5	7.12 ± 0.29	1.08 ± 0.03	0.86 ± 0.02	6.8 ± 0.07
PK1S/7.5	1.2 ± 0.6	1.22 ± 0.1	1.75 ± 0.17	7.1 ± 2.0	6.9 ± 0.4	9.7 ± 0.3	1.20 ± 0.04	1.13 ± 0/03	12 ± 0.07
PK2S/4.5	1.1 ± 0.5	1.26 ± 0.11	1.74 ± 0.17	7.8 ± 1.0	7.3 ± 0.4	7.7 ± 0.3	0.89 ± 0.03	0,82 ± 0.02	3.7 ± 0.06
WV1S/4.5	1.8 ± 0.3	1.81 ± 0.12	1.89 ± 0.24	12.0 ± 1.0	11.7 ± 0.5	12.5 ± 0.5	1.85 ± 0.06	1.60 ± 0.04	8.8 ± 0.07
BK1SJ/10	2.45 ± 0.11	1.94 ± 0.14	2.04 ± 0.18	11.2 ± 0.5	13.0 ± 0.7	9.72 ± 0.31	1.72 ± 0.04	1.52 ± 0.05	8.0 ± 0.5
BK1Sb/10	1.72 ± 0.54	1.79 ± 0.13	2.04 ± 0.18	11.6 ± 0.4	11.3 ± 0.6	9.72 ± 0.31	1.76 ± 0.05	1.52 ± 0.05	8.0 ± 0.5
BK2S/7	2.2 ± 0.6	1.89 ± 0.13	1.98 ± 0.21	12.0 ± 0.7	12.9 ± 0.7	11.0 ± 0.4	1.99 ± 0.04	1.70 ± 0.05	10 ± 0.5
RGM-1	1.9 ± 0.1	–	–	6.4 ± 0.2	–	–	0.75 ± 0.05	<AAS	20 ± 10

AAS, atomic absorption spectrometry, potassium; DNA, delayed neutron analysis, uranium; NAA, neutron activation analysis, thorium; SCIN, *in situ* scintillation counting; TSAC, thick source alpha particle counting; XRS, X-ray spectrometry, potassium.

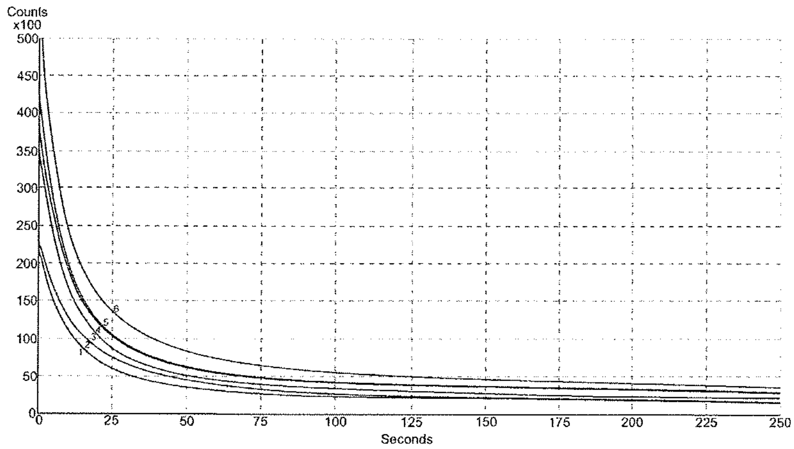

Figure 9 Shine-down curve for selected natural aliquots of sample BK2S/7. Aliquots 1, 2, 3, 4, 5 and 6 received artificial radiation doses of 0, 262.8, 394.1, 525.6, 656.9 and 1182.5 Gy, respectively.

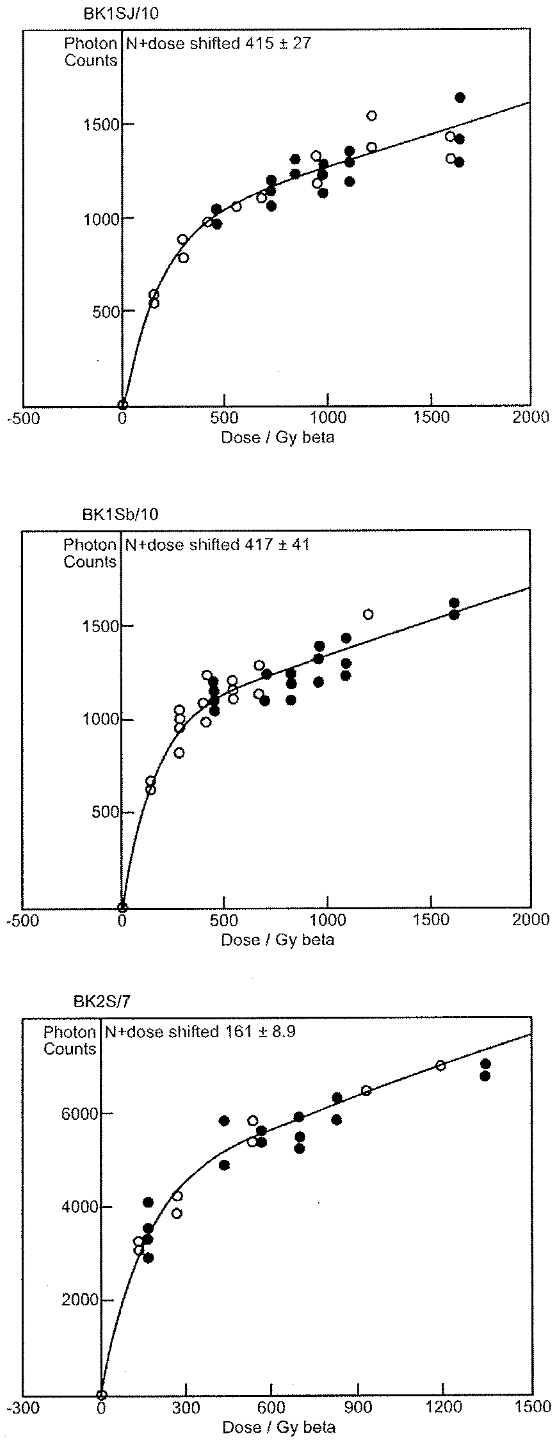

Figure 10 Fitted growth curves for samples BK1SJ/10, BK1Sb/10 and BK2S/7. The natural + dose rate data (closed circles) have been shifted along the dose axis and brought into coincidence with the bleach and dose data (open circles): an exponential + linear fit was found to be most suitable for all three samples.

in Tables 2 and 3. The results obtained for BK1Sb/10 and BK1SJ/10, which were obtained from the same hole, but on two different occasions, are in excellent agreement and are a good indicator of reproducibility. These results indicate that the extinct marsupial *Diprotodon* bones are about 40 000 years old.

River Glen Marina (RGM-1) (Murray Valley)

The sample was collected from near the base of a channel by digging 30 cm into the sediment from the vertical surface, and hammering in a 15 cm-long piece of 2.5 cm-diameter galvanised pipe, capped on the outer end. Once filled, the pipe was extracted and capped, to exclude all light. The laboratory work was carried out at the University of Wollongong on a Risø TL/OSL reader (Bøtter-Jensen *et al.* 2000) fitted with a blue stimulation source (470 ± 30 nm) and three U-340 detection filters (290–370 nm). Coarse (63–106 μm) quartz grains were extracted for luminescence analyses. The equivalent dose was estimated using a modified version of the single-aliquot regenerative-dose (SAR) protocol (Murray & Wintle 2000, 2003). In this protocol, a natural aliquot is preheated, typically at 250°C, for 10 s, followed by shine-down, 40 s at 125°C, to measure the natural OSL. The signal used for equivalent dose estimation is the background-corrected 0–1.6 s of shine-down. A test dose is then applied and the OSL signal from the test dose is measured. To determine the equivalent dose, the 'natural' OSL signal is compared with the OSL signals from a series of known regeneration doses. To allow for changes in sensitivity, each regeneration cycle includes a test dose, which is used to correct for such a change. A fifth regeneration dose (equal to the first regeneration dose) is included to confirm reproducibility of the measurements.

The dose rate was estimated using thick-source alpha-counting for U and Th, and AAS for K. The water content was assumed to be $20 \pm 10\%$. The dose-rate components were estimated from the alpha count-rates and the potassium concentration using the conversion data given by Adamiec & Aitken (1998).

A typical sensitivity-corrected OSL growth curve for the sample RGM-1 was constructed. The ratio of the fifth to first sensitivity-corrected regeneration dose OSL signal is an acceptable 1.07. A single saturating exponential was used to fit the data points. The mean equivalent dose estimate for the sample is 78.0 ± 3.1 Gy (11 aliquots). This is much less than the estimated saturation dose of about 500 Gy. The dose-rate estimate is 1.51 Gy/ka. The data are given in Tables 2 and 3.

Sellicks Creek

Analysis of samples from Sellicks Creek was undertaken by T. Pietsch of CSIRO Land and Water. Quartz grains from each of the samples were obtained and prepared in the standard manner (Aitken 1998). Sodium polymetaphosphate was used to remove clays, followed by wet then dry sieving to obtain the 180–212 μm fraction. This was then treated with hydrochloric acid and hydrogen peroxide to remove carbonates and organics. Hydrofluoric acid (40%) etches of 40 and

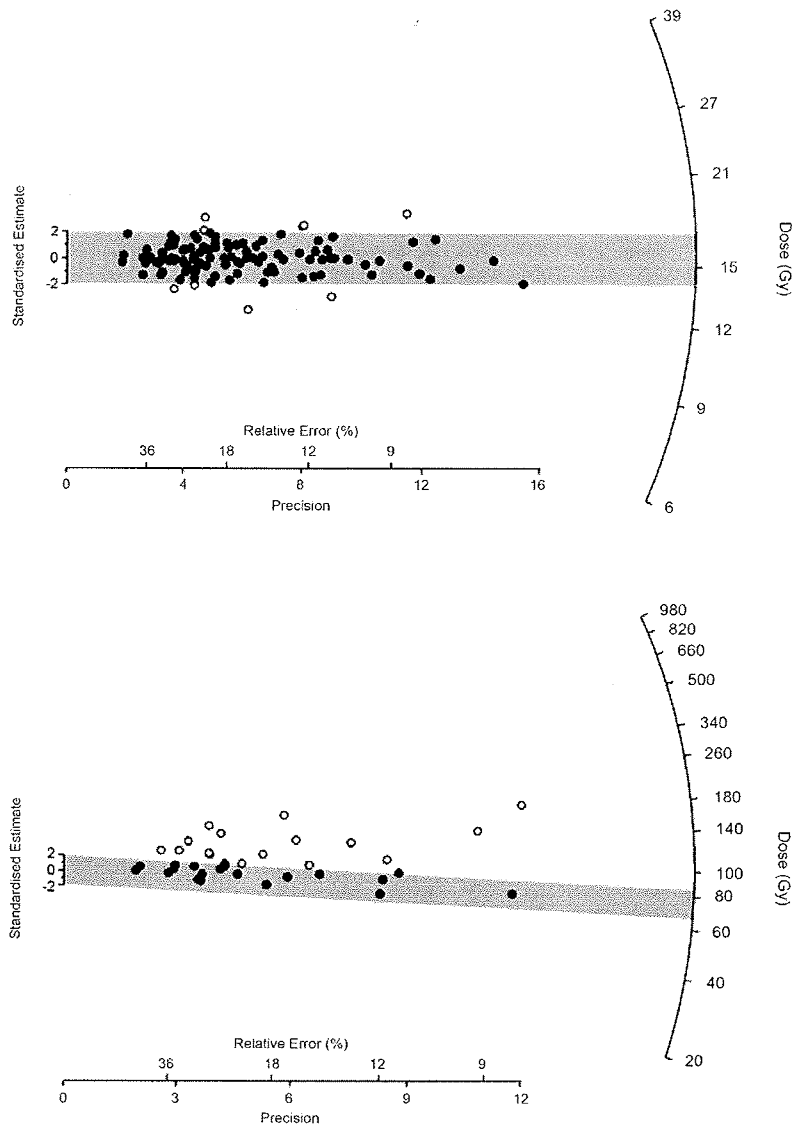

Figure 11 Radial plots of single grain D_e distributions for Sellicks Creek samples.

5 min were then undertaken to remove the majority of feldspars and to etch the outer ~10 μm alpha-irradiated rind of each grain, followed by a further wash in hydrochloric acid to remove acid-soluble fluorides. Two density separations using sodium polytungstate solutions with specific gravities of 2.72 and 2.62 were then used to ensure mineralogical purity. Finally, the samples were wet sieved through a 180 μm sieve to remove any grains fractured during the etching process.

Burial doses were determined from measurement of the OSL signals emitted by single grains of quartz. The etched quartz grains were loaded on to custom-made aluminium discs drilled with a 10 × 10 array of chambers, each of 300 μm depth and 300 μm diameter (Bøtter-Jensen *et al.* 2000). The OSL measurements were made on a Risø TL/OSL DA-15 reader using a green (532 nm) laser for optical stimulation, and the ultraviolet emissions were detected by an Electron Tubes Ltd. 9235QA photomultiplier tube fitted with 7.5 mm of Hoya U-340 filter. Laboratory irradiations were conducted using a calibrated $^{90}Sr/^{90}Y$ beta source mounted on the reader.

Equivalent doses (D_e) were determined using a modified SAR protocol (Olley *et al.* 2004). A dose-response curve was constructed for each grain. The OSL signals were measured for 1 s at 125°C (laser at 90% power), using a pre-heat of 240°C (held for 10 s) for the 'natural' and regenerative doses, and a pre-heat of 160°C (held for 10 s) for the test doses (0.5 Gy). The OSL signal was determined from the initial 0.1 s of data, using the final 0.2 s to estimate the background count rate. Each disc was exposed to infrared (IR) radiation for 40 s at 125°C prior to measurement of the OSL signal to bleach any IR-sensitive signal.

Grains were rejected if they did not produce a measurable OSL signal in response to the 2 Gy test dose, had OSL decay curves that did not reach background after 1 s of laser stimulation, or produced natural OSL signals that did not intercept the regenerated dose-response curves (Class 3 grains of Yoshida *et al.* 2000). For the sample with an apparently single dose population (S6), as determined by visual inspection of radial plots and probability density plots, burial doses (the radiation dose received by all grains since the most recent transport event) were calculated using the central age model of Galbraith *et al.* (1999). For the over dispersed sample (S9) the burial dose was calculated using an approximation of the minimum age model of Galbraith *et al.* (1999), whereby the lowest dose subpopulation of grains is identified by inspection of the radial plot, with the minimum age D_e defined as the centre of the 2σ uncertainty band (shaded grey in radial plots of Figure 11) encompassing the lowest dose grain. This approach assumes that the single-grain dose dispersion is due solely to partial bleaching prior to deposition. The calculated age will be erroneous if the cause of the over-dispersion is otherwise (e.g. grain migration due to bioturbation).

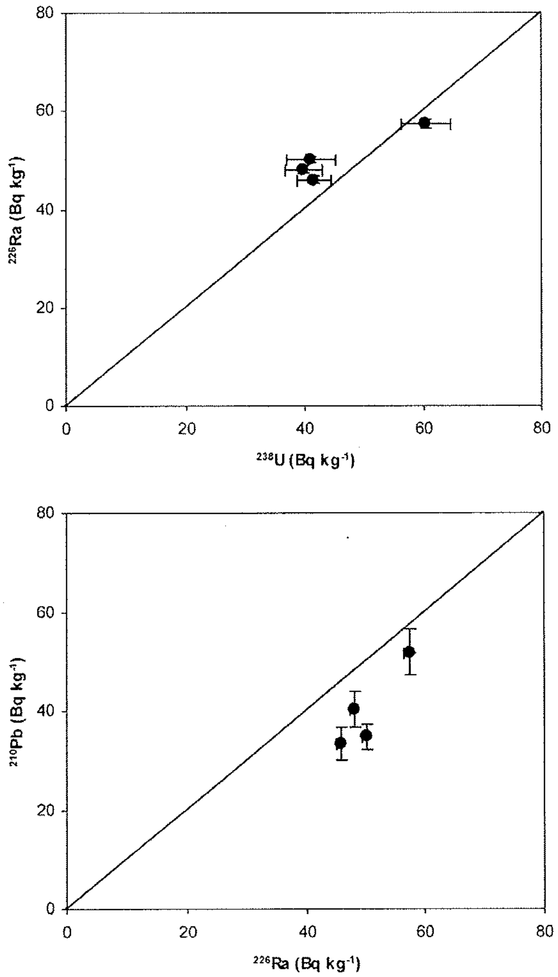

Figure 12 Activity concentrations of ^{226}Ra *vs* ^{238}U and ^{210}Pb *vs* ^{226}Ra for Sellicks Creek samples.

Radial plots of D_e populations are shown in Figure 11. For the radial plots, the measured D_e (in Gy) for a grain can be read by tracing a line from the y-axis origin through the point until the line intersects the radial axis (log scale) on the right-hand side. The corresponding standard error for this estimate can be read by extending a line vertically to intersect the x-axis. The x-axis has two scales: one plots the relative standard error of the D_e estimate (in %) and the other ('Precision') plots the reciprocal standard error. Therefore, values with the highest precisions and the smallest relative errors plot closest to the radial axis on the right of the diagram, and the least precise estimates plot furthest to the left. The shaded regions indicate those D_e values that, at the 2σ confidence interval, are consistent with a single estimated burial dose.

Lithogenic radionuclide activity concentrations (Figure 12; Table 4) were determined using high-resolution gamma spectrometry (Murray *et al.* 1987), with dose rates calculated using the conversion factors of Stokes *et al.* (2003). β-attenuation factors were taken from Mejdahl (1979). Cosmic-dose rates were calculated from Prescott & Hutton (1994). For all samples, dose rates have been calculated using the as-measured radionuclide contents.

Table 4 Data for Sellicks Creek samples.

Sample	^{238}U	^{226}Ra	^{210}Pb	^{232}Th	^{40}K	D.R. (Gy/ka)	De (Gy)	Age (ka)
S6	41 ± 4	50 ± 1	35 ± 3	76 ± 2	801 ± 18	4.46 ± 0.36	15.5 ± 0.3	3.5 ± 0
S9	60 ± 4	57 ± 1	52 ± 5	90 ± 3	815 ± 20	5.07 ± 0.43	75 ± 5	14.8 ± 1

All radionuclide values are in Bq/kg. Values <10 (and their uncertainties) reported to two decimal places. Values between 10 and 30 (and their uncertainties) rounded to one decimal place. Values above 30 (and their uncertainties) rounded to the nearest integer.