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ESR and U-series analyses of faunal material from Cuddie Springs, NSW, Australia: implications for the timing of the extinction of the Australian megafauna

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ABSTRACT

The timing and cause of late Pleistocene faunal extinctions in Australia are subjects of a debate that has become polarised by two vigorously defended views. One contends that the late Pleistocene extinction was a short event caused by humans colonising the Australian continent, whereas the other promotes a gradual demise of the fauna, over a period of at least 10–20 ka, due to a combination of climatic changes and ecological pressures by humans. Cuddie Springs is central to this debate as it is the only site known in continental Australia where archaeological and megafauna remains co-occur.

We have analysed more than 60 bones and teeth from the site by laser ablation ICP-MS to determine U, and Th concentrations and distributions, and those with sufficiently high U concentrations were analysed for U-series isotopes. Twenty-nine teeth were analysed by ESR. These new results, as well as previously published geochronological data, contradict the hypothesis that the clastic sediments of Stratigraphic Unit 6 (SU6) are in primary context with the faunal, archaeological and other materials found in SU6, and that all have ages consistent with the optically stimulated luminescence (OSL) estimates of 30–36 ka. These young OSL results were used to argue for a relatively recent age of the extinct fauna. Our results imply that SU6 is either significantly older than the OSL results, or that a large fraction of the faunal material and the charcoal found in SU6 was derived from older, lateral deposits.

Our U and Th laser ablation ICPMS results as well as the REE profiles reported by Trueman et al. [2008. Comparing rates of recrystallisation and the potential for preservation of biomolecules from the distribution of trace elements in fossil bones. *C.R. Palevol. General Paleontology (Taphonomy and Fossilization)* 7, 145–158] contradict the interpretation of previously reported rare earth element compositions of bones, and the argument based thereon for the primary context of faunal material and clastic sediments in SU6 layers.

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1. Introduction

The timing and cause of late Pleistocene faunal extinctions in Australia are the subjects of ongoing debate (Flannery, 1990, 1994; Field et al., 2008; Gillespie, 2008). Around 70 species, many much larger than today's fauna, existed throughout the Quaternary, but disappeared sometime during the late Pleistocene. This extinct faunal assemblage is often summarily referred to as 'megafauna'. The debate is highly polarised with some researchers arguing for a rapid, human mediated, extinction event around or shortly after the

human colonisation of the continent (Miller et al., 1999, 2005; Roberts et al., 2001a; Johnson, 2005; Brook et al., 2007; Gillespie, 2008; Turney et al., 2008). Others suggested that the available evidence is too sparse to pinpoint either humans or climatic change as the primary cause of extinction (Wroe and Field, 2006) and argued that the megafauna died out gradually, over a period of 10–20 ka or more (e.g. Field and Boles, 1998; Wroe et al., 2002; Trueman et al., 2005; Field, 2006; Wroe and Field, 2007; Field et al., 2008).

Much of this debate has become centred on Cuddie Springs because it is the only site known in continental Australia where archaeological and megafauna remains co-occur (Dodson et al., 1993; Field and Dodson, 1999). Some studies at the site concluded that there was an overlap of megafauna and humans in this part of the continent for up to 15,000 years (Field et al., 2001, 2008;

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Trueman et al., 2005). Such an extended temporal overlap and association of humans and megafauna counters the notion of human overkill being the sole cause for the demise of the megafauna (Field et al., 2008). However, other studies have proposed that the association of megafauna and cultural material is the result of site disturbance (Roberts et al., 2001b; Gillespie and Brook, 2006). Direct dating of the fauna remains may provide further insights into the age of the site as well as site formation processes. The aim of this paper is to present the results of electron spin resonance (ESR) and U-series analyses as well as U and Th distributions determined by laser ablation ICPMS on faunal remains from Cuddie Springs and to compare the results with previous interpretations regarding stratigraphy, nature of the sediments, and age of the remains.

1.1. Location and stratigraphy

Cuddie Springs is located in the Riverine Plains of northern New South Wales, about 85 km ESE of Walgett at 147°20'36"E, 30°20'55"S. It is a low point in the landscape that is not directly connected to a river system and the site of an ephemeral lake that fills during local rains that may take several months to dry out. The stratigraphic sequence was described in Dodson et al. (1993), Field and Dodson (1999) and Field et al. (2001, 2002). In brief, Stratigraphic Units (SU) 1–4 comprise undifferentiated clays with various degrees of disturbance from European activities. SU5–SU12 represent the underlying Pleistocene sequence. Archaeological and megafauna remains overlap in SU6. The stratigraphic sequence at Cuddie Springs is subdivided as follows:

SU1 (0–25 cm): lacustrine clays and sands, disturbed by cattle trampling. The bones and archaeology found in this unit are most likely derived from the spoil heaps of the 1933 excavations by the Australian Museum (Anderson and Fletcher, 1934).

SU2 (25–47 cm): well sorted coarse gravels. The layer is disturbed and discontinuous, probably the excavation spoil from well digging operations in the 1950s. It contains numerous teeth from extant and extinct faunas as well as some archaeological material which is not in primary context.

SU3 (47–50 cm): laminated fine silts. The surface of this level contains hoof marks from European cattle and probably represents the base of post European colonisation deposits.

SU4 (50–100 cm): undifferentiated lacustrine clays. A canine tooth, glass flakes, complete cow skeletons and other historic material at its base indicate disturbance, most likely from trampling by large modern herbivores (Field et al., 2001). Field and Dodson (1999) labelled this unit "Archaeological Level 5" (AL5).

SU5 (100–105 cm): a lag deposit consisting of flaked and ground stone (silcrete cobbles). This unit contained megafauna remains. It caps the Pleistocene deposits where megafaunal remains and archaeology co-occur. No modern (or European) material was recovered from within this unit or the underlying levels. In Field and Dodson (1999), the unit was also labelled AL4.

SU6 (105–172 cm): lacustrine clays and silts with a minor component of fine sand, but does not contain coarse sand or gravels (Field et al., 2002). Based on archaeological, faunal, sedimentological, geochemical and palynological evidence, the unit was divided into two sub-units.

SU6A (105–135 cm): intercalating silts and clays indicate intermittent flooding. Stone artefacts, bone and charcoal are common, ochre was also found. In Field and Dodson (1999),

SU6A was further subdivided into AL3 (105–115 cm) and AL2 (115–135 cm).

SU6B (135–172 cm): intercalating silts and clays associated with peds, structured clays and plant roots indicate marshy conditions. Stone artefacts and bones of extinct and extant fauna co-occur throughout the unit. Flaked stone artefacts were found in close association with extinct faunal remains (see Field and Dodson, 1999: their Fig. 5, Field et al., 2008, their Fig. 3). At the interface with SU7, limited mixing was identified through the occurrence of some small, rounded bone fragments (Fillios et al., in press) and geochemical alterations (Trueman et al., 2005). No archaeology has been identified below SU6. In Field and Dodson (1999), SU6B was also labelled AL1.

SU7 (172–183 cm): consolidated lag deposits (SU7A) overlying a band of ferruginised, well sorted coarse sand and some gravel (SU7B), containing a very high density of heavily mineralised bones. SU7A contained well sorted bone, mostly rounded and abraded, and non-artefactual stones in varying degrees of preservation (Fillios et al., in press).

SU8 (183–195 cm): lacustrine clays and silts, containing a low concentration of scattered bones. This unit is not present in parts of the excavation.

SU9 (195–210 cm): lacustrine clays and silts, containing dense bone accumulations, some bones are articulated. This horizon was formed on a surface sloping towards the claypan centre. The bone is well preserved and shows no abrasion or weathering, suggesting relatively rapid burial.

SU10 (210–250 cm): lacustrine clays, containing a low density of scattered bones.

SU11 (250–300 cm): lacustrine clays and silts, may represent lake full conditions. A few scattered bones.

SU12 (300–700 cm, sampled by auger): fine, clean aeolian sands with some occurrences of dense bone accumulations.

SU13 (>700 cm, sampled by auger): coarse gravels, waterlogged clay with abundant complete and fragmented bone.

1.2. Previous dating results

A suite of radiocarbon results obtained on charcoal from the site are summarised in Field et al. (2008) (their Table 1). Three samples from SU4 yielded highly scattered radiocarbon ages in the range 5600–29,000 BP, and a single sample from the SU5 lag-layer an age of $28,770 \pm 300$ BP. Extensive sampling from SU6 has provided ages ranging between $28,310 \pm 200$ and $33,660 \pm 530$ BP, but without any distinct difference between layers SU6A ($n = 7$) and SU6B ($n = 8$). Ages obtained for SU6 using the refined ABOX sample pretreatment technique and AMS by Fifield et al. (2001) lie in a range from 28.6 to 32.0 ka BP consistent with earlier classical radiocarbon results. Gillespie and Brook (2006) analysed these published radiocarbon data with extensive Monte Carlo simulations. They confirmed that the results for SU6A and SU6B (as well as SU5) were statistically indistinguishable and that there was no sensible age-depth relationship for the charcoal. However, rather than simply assuming the units were deposited within a time frame that could not be resolved with radiocarbon dating strategies, they proposed that the charcoal was a secondary deposition from an unknown source via unknown mechanisms. Gillespie and Brook (2006) pointed out that none of the bones found in SU6 and below contained any collagen, thus precluding direct radiocarbon dating of faunal material. Using the calibration of Fairbanks et al. (2005), calibrated radiocarbon ages range between $33,690 \pm 260$ and $39,040 \pm 540$ cal BP.

Table 1
Description of faunal remains analysed (T: tooth; B: bone, LA: laser ablation; TIMS: thermal ionisation mass spectrometry; US: U-series analysis; Th&U: elemental Th and U scans).

Lab No.	Field No	Species	Depth (cm b.D.)	SU	Analyses
1436	F10–S20	T: <i>Pallimnarchus</i>	115–135	6A	LA-US
2008	F11 base 84	B: macropus	>300	12	LA-Th&U
2009	F11 base 82	B: mammal	>300	12	LA-Th&U
2010	F11 base 86	B: macropus	>300	12	LA-Th&U
2011	F11 1 D2	B: mammal	172–175	7A	LA-Th&U
2012	F11 base 87	B: mammal	>300	12	LA-Th&U
2013	F11 base 85	B: macropus	>300	12	LA-Th&U
2014	F11 1 D4	B: mammal	172–175	7A	LA-Th&U
2015	F11 2 A24	B:	175–180	7B	LA-Th&U
2016	E10 6 A20	B: macropus	135–172	6B	LA-Th&U
2017	F11 1 D3	B:	175–180	7B	LA-Th&U
2018	E10 15 B1	B: protemnodon	172–175	6B	LA-Th&U
2019	F10 25 D1	B: <i>M. giganteus</i>	135–172	6B	LA-Th&U
2020	F10 29 D36	B: <i>Genyornis</i>	135–172	6B	LA-Th&U
2021	G11 AL1D	B: diprotodont	135–172	6B	LA-Th&U
2022	F10 30 C13	B: chelidae	135–172	6B	LA-Th&U
2023	F10 D 41	B: chelidae	135–172	6B	LA-Th&U
2024	F10 28 D40	B: <i>Genyornis</i>	135–172	6B	LA-Th&U, TIMS-US
2025	F10 29 C38	B: <i>Genyornis</i>	135–172	6B	LA-Th&U
2026	F11 base 83	B: mammal	>300	12	LA-Th&U
2027	G11 AL 1C	B: sthenurus	135–172	6B	LA-Th&U
2028	F11–6 D16	T: macropus	190–195	8b	LA-Th&U, ESR
2029	G11 AL 1E	T: diprotodont	135–172	6B	ESR
2030	F10 29 C37	B: sthenurus	135–172	6B	
2031	E11 2 A15	B: sthenurus	105–115	6A	LA-Th&U, LA-US
2032	E10–3	T: macropus	115–135	6A	LA-Th&U, ESR
2033	E10–15 D19	T: wombat?	172–175	7A	LA-Th&U, ESR
2034	G10 27 B1	T: titan	135–172	6B	LA-Th&U, LA-US
2035	E10–4 D159	T: sthenurus	115–135	6A	LA-Th&U, LA-US, ESR
2036	H10–2 A3	T: diprotodont	105–115	6A	LA-Th&U, ESR
2037	H10–3 A59	T: <i>M. asphranter</i>	105–115	6A	LA-Th&U, LA-US, ESR
2038	E10–15	T: protemnodon	135–172	6B	LA-Th&U, LA-US
2039	H10–2FB B16	T: m. rufus	105–115	6A	LA-Th&U, ESR
2040	E10 5 A60	T: macropus	115–136	6A	LA-Th&U, LA-US, ESR
2041	F11 2 D168	T: diprotodont	175–183	7B	LA-Th&U, ESR
2042	F11 2 D161	T: macropus	175–183	7B	LA-Th&U, ESR
2043	F11 2 D170	B: diprotodont	175–183	7B	LA-Th&U
2044	F11 2 B10	T: diprotodont	175–183	7B	LA-Th&U, ESR
2045	F11 2 D51	T: diprotodont	175–183	7B	LA-Th&U
2046	F11 2 D160	B: diprotodont	175–183	7B	LA-Th&U
2047	F11 3 B100	T: <i>Pallimnarchus</i>	175–183	7B	LA-Th&U
2048	F11 3 D93	T: macropus	175–183	7B	LA-Th&U, ESR
2049	F11 3 D15	T: macropus	175–183	7B	LA-Th&U, ESR
2050	F11 3 D96	T: macropus?	175–183	7B	LA-Th&U
2051	F11 3 D73	T: macropus	175–183	7B	LA-Th&U, ESR
2052	F11 4 D108	T: mammal	175–183	7B	LA-Th&U, ESR
2053	F11 4 D105	T: mammal	175–183	7B	LA-Th&U, ESR
2054	F11 4 D110	T: mammal	175–183	7B	LA-Th&U, ESR
2055	F11 6 D16	T: macropus	190–195	8B	LA-Th&U, ESR
2056	F11 5 D1	T: <i>Pallimnarchus</i>	175–183	7B	LA-Th&U
2057	F11 5 B26	T: mammal	175–183	7B	LA-Th&U, ESR
2058	F11 6 D1	T: wombat	190–195	8B	LA-Th&U, ESR
2059	F11 6 D17	T: mammal	190–195	8B	LA-Th&U, ESR
2060	F11 8 D12	T: diprotodont	190–195	8B	ESR
2061	F11 8 D1	T: <i>Pallimnarchus</i>	190–195	8B	LA-Th&U
2062	F11B base 15	T: diprotodont	>300	12	LA-Th&U, ESR
2063	F11 base 5	T: ferragus	>300	12	LA-Th&U, ESR
2064	F11 base 4	T: diprotodont	>300	12	LA-Th&U, ESR
2065	F11 base 2	T: titan	>300	12	LA-Th&U, ESR
2066	F11 base 14	T: titan	>300	12	LA-Th&U, ESR
2067	F11 base 1	T: ferragus	>300	12	LA-Th&U
2068	F11 base 6	T: ferragus	>300	12	LA-Th&U

Field et al. (2001) reported an OSL result from SU6A of 35.4 ± 2.8 ka. Field and Dodson (1999) mention two thermoluminescence results of >76.1 and >78.6 ka from a drill core, some 30 m distant from the excavation and an estimated depth equivalent to SU8. Samples from Cuddie Springs were also included in the single grain OSL dating study of Roberts et al. (2001a) that established an

extinction event for the Australian Megafauna at between 39.8 and 51.2 ka. The Cuddie Springs results were reported as maximum ages because sediment disturbance seemed evident from the dose distributions obtained. The oldest dose populations of each sample were associated with ages of 16.7 ± 1.2 ka for SU4, 26.6 ± 1.9 ka (SU5), 30.3 ± 2.3 ka (SU6A) and 36.5 ± 2.9 ka (SU6B). All samples

contained significant amounts of much younger material, indicating significant sediment disturbance (more detailed results are given in [Fillios et al., in press](#)). These authors also reported an independent OSL result from SU6B of 35.4 ± 2.8 ka (ANU_{OD}118a). These results have caused controversy because they were excluded from the interpretation of the extinction event ([Roberts et al., 2001a](#)), based on the postulate that the megafauna in SU6 was redeposited from older units. This ignited a debate over selective sampling, the effective sample size and the exclusion of sites that did not contain articulated skeletal remains (e.g. [Field and Fullagar, 2001; Wroe and Field, 2001a,b](#)). It was suggested that the controversy surrounding Cuddie Springs and similar sites could be resolved by directly dating the megafauna fossils themselves ([Roberts et al., 2001b,c](#)).

A study of the rare earth element (REE) compositions of bones by [Trueman et al. \(2005\)](#) purports to show that the deposition of the bones, including those of the megafauna, in SU9, SU6A and SU6B was autochthonous or at least para-autochthonous. This conclusion is based on a large scatter of REE ratios in bones from SU7 and the interface between SU7 and SU6, as compared to the more tightly clustered compositions of bones from SU9, SU6A and SU6B. These observations have been used to support the reliability of the radiocarbon and luminescence results data for SU6A and SU6B and interpretations that there was a temporal overlap of humans and megafauna of perhaps 15 ka in Australia ([Trueman et al., 2005](#)).

2. Samples

The faunal material analysed in this study consists of 62 bones and teeth provided by Judith Field (sample details are summarised in [Table 1](#)). They derive from excavations carried out between 1991 and 2001. The samples were not accompanied with specific depths. In the diagrams, the plotted sample sequence does not reflect relative or absolute depth within a stratigraphic unit but was only used to separate the results of the different samples. Their depth allocation followed the older stratigraphic scheme of [Field and Dodson \(1999, see above\)](#) which made a further subdivision within SU6A into AL2 and AL3 (see above). However, the excavators insist this to be an artificial subdivision of SU6A that is not corroborated by detailed sedimentological analysis.

Two teeth were of particular interest. Sample 2029 is a tooth from the diprotodon mandible, under which a silcrete stone tool was found (see [Fig. 5](#) in [Field and Dodson, 1999](#)), and sample 1436 is a *Pallimnarchus* tooth, a giant crocodile thought to be extinct since the middle Pleistocene ([Willis and Molnar, 1997](#)). The latter was found in SU6A.

3. Experimental

3.1. Sediment analysis

For an anticipated OSL study, NS collected 31 sediment samples from all exposed units. Water content was measured by heating; U, Th, and K by neutron activation analysis. Several gamma spectrometric measurements were carried out *in situ* with a portable 3" × 3" NaI detector. Small sediment samples attached to teeth used for ESR dating were analysed by ICP-MS. The results are listed in [Table 2](#) and shown in [Fig. 1](#). Generally, there is good agreement between the results obtained from the same stratigraphic unit by the different techniques.

The U, Th, and K compositions were converted into gamma and beta dose rates in [Fig. 1](#). This was necessary as some teeth did not have any sediment attached, and averaged values were used for age assessment. The *in situ* gamma dose rate measurements are very

Table 2

Sediment analysis and gamma spectrometry results.

Depth	Unit	U	Th	K	Water	$\gamma\text{-}\dot{D}$	$\beta\text{-}\dot{D}$
(cm)		(ppm)	(ppm)	(%)	(wet/dry)	($\mu\text{Gy a}^{-1}$)	($\mu\text{Gy a}^{-1}$)
<i>Neutron activation analysis</i>							
12	1	1.3	8.9	1.3	4	855	1390
33	2	0.95	4.2	0.3	0.7	387	510
43	3	0.56	11	1.7	10	909	1544
69	4	0.87	12	1.6	12	904	1450
94	4	1	11	1.4	11	879	1360
102	5	1.1	5.7	0.72	7.8	525	804
112	6A	1.8	6.5	0.83	10	629	952
120	6A	0.98	9.4	1.5	15	768	1299
126	6A	1.5	8.8	1.3	14	760	1227
132	6A	1.9	9.7	1.5	13	893	1476
140	6B	1.4	9.7	1.5	15	822	1369
148	6B	1.6	10	1.6	17	856	1408
155	6B	1.7	11	1.9	19	930	1584
162	6B	1.2	11	1.5	18	815	1297
157	6B	1.1	11	1.6	14	848	1405
169	6B	1.4	9.6	1.3	18	737	1153
184	7B	0.65	2.8	0.37	1.8	292	454
192	8B	1.6	9.3	1.1	13	774	1179
200	9	1.2	7.3	0.97	9.3	644	1009
207	10	1.2	9.4	1.2	7.9	796	1234
216	10	1.5	8.1	1.2	14	712	1137
223	10	1.7	8.9	1.1	17	726	1111
231	10	1.4	11	1.7	18	884	1454
239	10	1.6	9.1	1.5	18	788	1332
247	11	1.9	9.7	0.9	9.2	802	1109
255	11	2.2	13	1.1	7.1	1063	1438
264	11	2.3	12	0.8	9.2	924	1148
274	11	1.7	11	1.1	20	768	1103
284	11	1.9	12	1	21	796	1183
294	12	1	5.3	0.52	0.7	490	689
302	12	0.93	3.4	0.45	0.3	376	576
<i>Gamma spectrometry</i>							
123	6A	1.6	6.7	0.93		726	1140
143	6B	1.5	7.3	1.1		784	1272
196	8b	1.6	7.2	1.1		788	1274
241	10	1.8	7.7	0.9		792	1174
287	11	1.4	5.9	0.66		596	873
337	12	1.6	6	0.54		604	823
<i>Average dose rates (20 ± 10% water)</i>							
105–115	6A	1.2 ± 0.3	6.7 ± 1.4	1.1 ± 0.5		564 ± 106	955 ± 371
115–135	6A	1.5 ± 0.1	9.2 ± 0.5	1.3 ± 0.4		720 ± 134	1171 ± 336
	6B	1.5 ± 0.2	9.9 ± 1.5	1.3 ± 0.3		752 ± 133	1189 ± 279
	7b	1.4 ± 0.6	6.2 ± 3.2	0.9 ± 0.3		531 ± 163	854 ± 353
	8b	1.6 ± 0.6	9.8 ± 2.5	1.2 ± 0.3		745 ± 161	1148 ± 347
	12	1.4 ± 0.7	8.4 ± 4.4	1.1 ± 0.2		638 ± 200	987 ± 318

close to the averages calculated from the sediment samples in the respective unit. Given the consistency in the results between the origin of the sediment (i.e. collected at the site and from the faunal collection) and analytical method (NAA, ICP-MS, gamma spectrometry), the averaged values for the various units given in [Table 2](#) should provide reasonable assessments of the radioactivity of the respective layers.

3.2. U and Th concentrations and distributions in bone and teeth

Most faunal samples had their U and Th concentrations profiled using the ANU laser ablation ICPMS system (for details see [Eggins et al., 2003](#)). [Fig. 2](#) shows three examples of U and Th profiles in bones. [Fig. 2A](#) shows the development of a U-shaped concentration profile for U, and similarly for Th but at a concentration level about two orders of magnitude lower than U (the average concentrations of U and Th in sample 2012 are 0.504 and 0.013 ppm, respectively). [Fig. 2B](#) is a typical profile obtained for many bone samples, which shows elevated U and particularly Th concentrations where the

Fig. 1. Results of the U, Th, and K sediment analyses of samples from the profile, analysed by neutron activation analysis, sediments attached to the submitted teeth (ICP-MS analysis). Water could only be measured on samples collected at the site. Sediment radioactivity was converted into gamma and beta dose rates and the former compared with *in situ* gamma spectrometry.

laser scanned across pores. In many pores, the Th concentration is actually higher than the U-concentration. Two samples covered with black (Mn-rich) coatings were also scanned. These coatings also have Th concentrations that are significantly higher than U concentrations (Fig. 2C). Average U and Th concentrations for all

samples were evaluated after first eliminating anomalous compositions associated with pores. The resulting average concentrations are listed in Table 3, along with measured minimum and maximum concentration values. Large differences between the latter are indicative of U-shaped concentration profiles.

Fig. 2. Three exemplary U and Th concentration profiles (the ^{31}P scan is used for normalisation). A: Sample 12 shows typical U-shaped U and Th concentration profiles, the average U concentration about 50 times higher than Th. B: Sample 2008 shows generally similar profiles, but greatly enhanced Th concentration when the laser passes pores. C: laser scan of sample 2058 coated in a thin black precipitate. Note that the phosphate scan is hardly influenced by the coating. Th concentrations are 10 times higher than U, very similar to the ratios found in the sediments (Table 2).

Table 3

Laser ablation U and Th results (all analytical results are in ppm).

Sample	Layer	Th-av	Th-min	Th-max	U-av	U-min	U-max	U/Th
2031	6A	0.090 ± 0.017	0.049	0.135	24.61 ± 5.55	19.6	36.7	275
2036	6A	0.020 ± 0.013	0.002	0.069	0.187 ± 0.046	0.104	0.274	9.35
2037	6A	0.415 ± 0.266	0.114	1.88	11.14 ± 3.36	7.16	28.67	26.9
2037	6A	0.182 ± 0.078	0.049	0.344	12.38 ± 1.58	10.06	15.91	68.1
2039	6A	0.008 ± 0.007	0	0.036	0.205 ± 0.166	0.010	0.679	27.3
2032	6A	0.039 ± 0.030	0.002	0.129	0.572 ± 0.160	0.160	1.07	14.6
2035	6A	0.049 ± 0.015	0.021	0.100	8.544 ± 0.958	6.49	10.66	174
2040	6A	0.164 ± 0.105	0.017	0.408	11.28 ± 1.55	9.32	18.2	68.8
2016	6B	0.059 ± 0.118	0	1.33	6.60 ± 6.32	1.22	49.9	112
2018	6B	0.084 ± 0.027	0.047	0.186	10.52 ± 1.65	7.98	13.7	125
2019	6B	0.115 ± 0.062	0.024	0.375	8.37 ± 1.23	5.97	11.3	72.5
2020	6B	0.056 ± 0.019	0.028	0.142	1.036 ± 0.217	0.648	1.50	18.4
2021	6B	0.055 ± 0.035	0.008	0.209	1.95 ± 0.406	1.08	3.36	35.7
2022	6B	0.010 ± 0.005	0.001	0.028	1.333 ± 0.419	0.634	2.79	140
2023	6B	1.91 ± 3.58	0	17.1	40.6 ± 8.97	23.4	84.2	21.2
2024	6B	0.052 ± 0.092	0	0.787	5.18 ± 1.87	3.01	11.5	99.4
2025	6B	0.028 ± 0.040	0	0.315	2.733 ± 0.495	1.84	4.97	99.0
2027	6B	0.032 ± 0.016	0.003	0.101	3.559 ± 0.812	1.80	6.18	111
2038	6B	0.202 ± 0.137	0.056	0.781	8.62 ± 1.560	6.23	13.2	42.7
2011	7A	0.048 ± 0.091	0	1.03	1.24 ± 1.02	0.383	3.80	25.8
2014	7A	0.087 ± 0.262	0	2.66	1.235 ± 0.524	0.574	2.72	14.2
2033	7A	0.025 ± 0.027	0	0.167	0.802 ± 0.709	0	4.50	31.7
2033	7A	0.060 ± 0.046	0.005	0.245	0.081 ± 0.021	0.013	0.156	1.35
2015	7B	0.068 ± 0.010	0	0.064	0.578 ± 0.246	0.190	1.636	8.50
2017	7B	0.072 ± 0.056	0.015	0.399	16.7 ± 2.13	12.9	24.4	234
2041	7B	0.014 ± 0.009	0	0.056	0.225 ± 0.035	0.134	0.313	15.9
2042	7B	0.015 ± 0.013	0	0.052	0.146 ± 0.034	0.080	0.252	10.0
2043	7B	0.025 ± 0.023	0	0.139	0.390 ± 0.088	0.209	0.677	15.7
2044	7B	0.008 ± 0.006	0	0.033	0.472 ± 0.087	0.298	0.718	58.9
2045	7B	0.003 ± 0.005	0	0.035	0.468 ± 0.109	0.277	0.715	146
2046	7B	0.000 ± 0.001	0	0.0058	0.001 ± 0.002	0	0.009	
2047	7B	0.015 ± 0.005	0.003	0.028	0.195 ± 0.051	0.099	0.323	13.3
2048	7B	0.023 ± 0.011	0.007	0.063	0.169 ± 0.113	0.044	0.540	7.25
2049	7B	0.013 ± 0.008	0.001	0.040	0.129 ± 0.039	0.065	0.260	10.3
2051	7B	0.006 ± 0.005	0	0.024	0.016 ± 0.007	0.003	0.044	2.66
2052	7B	0.029 ± 0.018	0.005	0.078	0.735 ± 0.297	0.395	1.35	25.0
2053	7B	0.057 ± 0.021	0.021	0.116	0.895 ± 0.099	0.735	1.10	15.8
2054	7B	0.663 ± 0.799	0.015	3.59	0.055 ± 0.039	0.005	0.219	0.082
2056	7B	0.113 ± 0.076	0	0.724	0.551 ± 0.135	0	0.867	4.87
2057	7B	0.001 ± 0.003	0	0.016	1.210 ± 0.308	0.679	1.98	864
2028	8B	0.045 ± 0.024	0.009	0.150	0.938 ± 0.131	0.626	1.31	20.7
2058	8B	35.2 ± 16.0	7.59	76.2	1.240 ± 0.196	0.893	1.79	0.035
2059	8B	0.919 ± 0.621	0.175	2.66	2.823 ± 0.421	1.85	3.49	3.07
2061	8B	0.202 ± 0.131	0.033	0.566	0.643 ± 0.136	0.432	0.968	3.18
2008	12	0.030 ± 0.058	0	0.394	0.198 ± 0.375	0.006	2.89	6.56
2009	12	0.012 ± 0.018	0	0.139	0.199 ± 0.200	0.054	1.12	16.9
2010	12	0.015 ± 0.023	0	0.187	0.111 ± 0.056	0.041	0.314	7.25
2012	12	0.013 ± 0.020	0	0.259	0.504 ± 0.230	0.109	2.87	37.7
2013	12	0.014 ± 0.024	0	0.242	0.407 ± 0.375	0.082	1.64	29.3
2026	12	0.015 ± 0.021	0	0.206	0.247 ± 0.277	0.050	1.43	17.0
2062	12	0.097 ± 0.088	0.002	0.479	0.097 ± 0.023	0.050	0.180	1.00
2063	12	0.022 ± 0.019	0	0.103	0.498 ± 0.212	0.144	1.03	22.7
2064	12	0.006 ± 0.010	0	0.058	0.024 ± 0.032	0	0.330	3.86
2065	12	0.002 ± 0.004	0	0.015	0.028 ± 0.012	0.005	0.059	14.8
2067	12	0.004 ± 0.005	0	0.047	9.52 ± 5.11	4.34	39.1	2720
2066	12	0.052 ± 0.019	0.018	0.102	1.183 ± 0.158	0.853	1.64	22.8
2068	12	0.010 ± 0.006	0.001	0.027	0.021 ± 0.006	0.006	0.036	2.03

3.3. U-series analysis

U-series analysis was carried out by laser ablation MC-ICPMS in samples with sufficiently high U contents (for details see [Eggins et al., 2005](#); [Grün et al., 2006, 2008a](#)). The results are shown in [Table 4](#). Of particular interest was the *Pallimnarchus* tooth (#1436), of which four separate analyses were made. The laser ablation MC-ICPMS profiles show intensity peaks that are associated with small pores and cracks (see [Fig. 3A](#)). If these regions are removed ([Fig. 3B](#)), the mean count rates for isotopes across the profile drop by between 25 and 80%. However, the $^{234}\text{U}/^{238}\text{U}$ and the $^{230}\text{Th}/^{234}\text{U}$ activity ratios change by less than 0.5%. The results of the four scans of #1436 are

shown in [Table 4](#), along with those obtained on other teeth with sufficiently high U-concentrations in the dentine. None of the analysed bone samples showed signs of U-leaching, which would manifest as decreasing U-concentrations close to the surface of the bone ([Pike et al., 2002](#)). For dentine, which is protected by surrounding enamel, U-leaching is less likely than in the surface layers of bones. Moreover, closed-system U-series results represent minimum age estimates because of generally delayed uranium migration into dental tissue ([Pike et al., 2002](#); [Grün et al., 2008a](#)). One *Genyornis* bone from SU6B was analysed by thermal ionisation mass spectrometry (TIMS) for calculation of an open system diffusion-adsorption U-series age (for analytical details, see [Pike et al.,](#)

Table 4
U-series results (1-sigma errors).

Sample	Position (mm)	U (ppm)	$^{234}\text{U}/^{238}\text{U}$	$^{230}\text{Th}/^{234}\text{U}$	Age (ka)
<i>Laser ablation</i>					
1436-1	Cross section	31.9	1.0507 ± 0.0021	1.0315 ± 0.0257	>451
1436-2	Cross section	29.6	1.0364 ± 0.0021	1.0856 ± 0.0265	∞
1436-3	Cross section	38.8	1.0501 ± 0.0012	1.0589 ± 0.0259	∞
1436-4	Cross section	34.1	1.0638 ± 0.0031	1.0329 ± 0.0259	>466
2031	Cross section	24.6	1.4670 ± 0.0103	0.3468 ± 0.0117	45.3 ± 1.9
2034	Cross section	12.9	1.3980 ± 0.0127	0.2487 ± 0.0184	30.7 ± 2.6
2035	Cross section	8.5	1.5008 ± 0.0196	0.1173 ± 0.0308	13.5 ± 3.8
2037	Cross section	11.1	1.4213 ± 0.0099	0.3468 ± 0.0118	45.3 ± 1.9
2038	Cross section	8.7	1.4654 ± 0.0210	0.2842 ± 0.0305	35.7 ± 4.5
2040	Cross section	11.2	1.4653 ± 0.0180	<0.044	<4.9
<i>TIMS</i>					
2024a	-0.86 ± 0.13	5.64 ± 0.02	1.4824 ± 0.0067	0.2217 ± 0.0011	26.9 ± 0.21
2024b	-0.57 ± 0.15	4.19 ± 0.04	1.4435 ± 0.0067	0.1093 ± 0.0012	12.5 ± 0.14
2024c	0.06 ± 0.59	2.73 ± 0.08	1.4552 ± 0.0070	0.0862 ± 0.0014	9.8 ± 0.16
2024d	0.68 ± 0.31	4.00 ± 0.15	1.4478 ± 0.0087	0.0479 ± 0.0042	5.3 ± 0.49

2002). Unfortunately, the data do not conform to the D-A model and an open system U-series age could not be established. These results are also listed in Table 4.

3.4. ESR analysis

The ESR dating procedures applied to the teeth samples followed those routinely used in the ANU ESR dating laboratory (e.g., Grün et al., 2001). For ESR dose analysis, the enamel was powdered and aliquots were successively irradiated in 18 steps to 3786 Gy. Radiation doses were monitored with alanine dosimeters and evaluated against a calibrated dosimeter set (A. Wieser, Messtechnik, München). Dose values were determined by partial spectrum fitting (Grün, 2002).

To assess the environmental dose rate, sediment samples were collected in the immediate vicinity of the tooth and analysed by solution ICP-MS analysis. These were used for the calculation of the beta dose rate. To avoid potential bias introduced by the small size of the sediment samples attached to the teeth, 50% of the gamma dose rate was derived from the composition of these samples and 50% from the average composition of the respective stratigraphic unit (Table 2). Where nearby *in situ* gamma spectrometric measurements were carried out, these were combined with the

sediment data. The sediments were assumed to have an average water content of $20 \pm 10\%$ (Table 2). This value may be too low as measured *in situ* values for SU6 were in the range 10–19%, even though the sediment had been drained for a considerable time by the excavation. The cosmic dose rate was calculated from the present sample depth (after Prescott and Hutton 1988, 1994), and ranged between $180 \mu\text{Gy/a}$ (SU6) and $130 \mu\text{Gy/a}$ (SU12). Given evidence for repeated deflation events, it is difficult to construct a model for the time-dependent sediment build-up and associated changes in the cosmic dose rate. However, any such model would not affect the cosmic dose rate by more than $30 \mu\text{Gy/a}$, causing an overall error of less than 4%.

For the calculation of the internal dose rate values, beta attenuation values of Marsh (1999) and an alpha efficiency of 0.13 ± 0.02 (Grün and Katzenberger-Apel, 1994) were used. Only a few U-series evaluations could be carried out, so that for most teeth it was only possible to calculate ESR ages according to parametric early and linear U-uptake models. Because it is not possible to constrain the U-uptake history without U-series data, only the EU-ESR data are shown in Table 5, which provide minimum age estimates. The U-series data in Table 4 were used to calculate open-system combined U-series-ESR ages (Grün et al., 1988; Grün, 2009a). These are also shown in Table 5.

Fig. 3. U-series scan 3 of the *Palimnarchus* tooth 1426. All isotopes increase in distinct peaks (A). Eliminating these (B), reduces the ^{232}Th by significant amounts (between 25 and 80%). However, the $^{230}\text{Th}/^{234}\text{U}$ and $^{234}\text{U}/^{238}\text{U}$ ratios are little affected because the elemental U/Th ratios are already >700 in the non-corrected scans.

Table 5
Results of chemical analysis and ESR age estimates for samples from Cuddie Springs.

Sample No.	Unit	D _e (Gy)	U (EN) (ppm)	U (DE) (ppm)	TT (μm)	Sediment				Early U-uptake				US-ESR						
						U (ppm)	Th (ppm)	K (%)	γ-D (μGy/a)	β-D (μGy/a)	int-D (μGy/a)	DE-D (μGy/a)	total D (μGy/a)	Age (ka)	int/DE-D (μGy/a)	total D (μGy/a)	p-value	AGE (ka)		
2036a	6A	520 ± 22	0.02	0.28	1400	1.3	5.5	0.80	725 ± 92	65 ± 11	7	3	800 ± 92	650 ± 78						
2036b		532 ± 6	0.01	0.28	1450	1.3	5.5	0.80	725 ± 92	63 ± 11	5	3	796 ± 92	668 ± 77						
2037	6A	42.7 ± 1.6	0.11	9	1400	1.5	7.8	0.92	760 ± 100	78 ± 15	24	70	932 ± 101	45 ± 5		24	70	932 ± 101	−1	45 ± 5
2039a	6A	44.0 ± 1.9	0.04	1.8	1500	1.2	8.5	1.06	773 ± 103	77 ± 14	10	13	873 ± 103	50 ± 6						
2039b		42.6 ± 2.1	0.03	1.8	1250	1.2	8.5	1.06	773 ± 103	93 ± 17	6	15	887 ± 104	48 ± 6						
2032a	6A	687 ± 27	0.13	1.3	1400	1.5	8.8	0.98	860 ± 114	83 ± 15	63	19	1025 ± 115	672 ± 79						
2032b		659 ± 30	0.19	1.3	1300	1.5	8.8	0.98	860 ± 114	89 ± 16	91	20	1059 ± 115	622 ± 73						
2035a	6A	80.6 ± 2.2	0.16	7	910	1.5	9.2	1.3	898 ± 125	152 ± 42	42	91	1183 ± 133	68 ± 7		5	12	1067 ± 132	3.3 ± 1.7	75 ± 12
2035b		74.9 ± 2.7	0.16	7	860	1.5	9.2	1.3	898 ± 125	160 ± 45	41	92	1191 ± 134	63 ± 7		6	14	1078 ± 133	2.9 ± 1.7	69 ± 8
2040a	6A	43.7 ± 1.9	0.85	11	930	1.5	9.2	1.3	898 ± 125	149 ± 41	167	113	1327 ± 134	32 ± 3		<15	<11	1073 ± 131	>6.2	40 ± 4
2040b		43.4 ± 2	0.48	11	1030	1.5	9.2	1.3	898 ± 125	135 ± 37	97	105	1235 ± 132	35 ± 4		<8	<10	1051 ± 130	>6.3	41 ± 5
2029a	6B	54.6 ± 1.8	0.20	0.75	1500	1.5	9.9	1.3	917 ± 130	94 ± 21	47	6	1064 ± 132	51 ± 6						
2029b		52.1 ± 1.6	0.13	0.75	2200	1.5	9.9	1.3	917 ± 130	64 ± 14	31	4	1016 ± 131	51 ± 6						
2029c		51.4 ± 1.2	0.09	0.75	2100	1.5	9.9	1.3	917 ± 130	67 ± 15	21	4	1009 ± 131	50 ± 6						
2038a	6B	65.0 ± 2.0	0.17	7.3	450	1.5	9.9	1.3	917 ± 130	262 ± 61	37	133	1349 ± 144	48 ± 5		26	94	1300 ± 146	−0.65 ± 0.24	50 ± 3
2038b		63.2 ± 2.1	0.35	7.3	700	1.5	9.9	1.3	917 ± 130	192 ± 44	80	104	1293 ± 138	48 ± 5		55	72	1237 ± 139	−0.62 ± 0.25	51 ± 8
2033a	7A	560 ± 17	0.06	0.64	800	1.5	11	1.5	993 ± 117	195 ± 38	24	14	1226 ± 123	456 ± 47						
2033b		472 ± 25	0.22	0.64	920	1.5	11	1.5	993 ± 117	172 ± 32	97	12	1274 ± 122	370 ± 37						
2041a	7B	111 ± 3	0.06	0.37	2000	1.4	6.2	0.90	689 ± 158	51 ± 15	20	3	763 ± 159	145 ± 30						
2041b		116 ± 3	0.07	0.37	1800	1.4	6.2	0.90	689 ± 158	56 ± 16	25	3	773 ± 159	150 ± 31						
2042a	7B	108 ± 4	0.01	0.58	930	1.4	6.2	0.90	689 ± 158	108 ± 33	4	8	809 ± 162	133 ± 27						
2042b		107 ± 4	0.01	0.58	1000	1.4	6.2	0.90	689 ± 158	101 ± 31	4	8	802 ± 161	133 ± 27						
2044a	7B	201 ± 5	0.01	0.08	1800	1.4	6.2	0.90	689 ± 158	56 ± 16	5	0	750 ± 159	268 ± 57						
2044b		197 ± 6	0.01	0.08	2100	1.4	6.2	0.90	689 ± 158	49 ± 14	5	0	743 ± 159	265 ± 57						
2044c		201 ± 5	0.04	0.08	2050	1.4	6.2	0.90	689 ± 158	50 ± 14	15	0	754 ± 159	266 ± 56						
2048a	7B	492 ± 18	0.02	0.25	900	1.7	3.2	0.58	618 ± 98	82 ± 16	11	5	716 ± 99	687 ± 98						
2048b		478 ± 9	0.03	0.25	1300	1.7	3.2	0.58	618 ± 98	58 ± 11	12	3	691 ± 99	691 ± 99						
2049a	7B	555 ± 35	0.02	0.13	1100	1.4	6.2	0.90	689 ± 158	92 ± 27	11	2	794 ± 161	698 ± 148						
2051a	7B	104 ± 3	0.01	0.36	1000	1.4	6.2	0.90	689 ± 158	101 ± 31	2	5	797 ± 161	130 ± 26						
2051b		102 ± 4	0.01	0.36	1000	1.4	6.2	0.90	689 ± 158	101 ± 31	2	5	797 ± 161	127 ± 26						
2052a	7B	421 ± 15	0.01	0.73	1700	2.0	6.6	0.98	733 ± 118	69 ± 12	4	8	814 ± 118	517 ± 76						
2052b		429 ± 9	0.04	0.73	1900	2.0	6.6	0.98	733 ± 118	62 ± 11	19	8	822 ± 118	521 ± 75						
2053a	7B	496 ± 29	0.04	1.3	2200	1.4	6.2	0.90	689 ± 158	46 ± 14	19	12	766 ± 159	647 ± 139						
2053b		490 ± 26	0.04	1.3	2550	1.4	6.2	0.90	689 ± 158	40 ± 11	19	10	758 ± 159	646 ± 139						
2054a	7B	695 ± 36	0.17	1.6	1300	1.5	8	1.06	743 ± 120	91 ± 16	82	25	941 ± 121	738 ± 102						
2054b		664 ± 41	0.06	1.6	1000	1.5	8	1.06	743 ± 120	118 ± 22	28	31	920 ± 122	721 ± 105						
2057a	7B	544 ± 25	0.04	0.93	880	1.4	6.2	0.90	689 ± 158	114 ± 34	18	20	841 ± 162	646 ± 127						
2057b		524 ± 22	0.04	0.93	850	1.4	6.2	0.90	689 ± 158	117 ± 36	18	20	844 ± 162	620 ± 121						
2055a	8B	406 ± 12	0.01	0.35	780	1.4	7	0.88	808 ± 111	127 ± 25	4	7	946 ± 115	429 ± 53						
2055b		437 ± 13	0.02	0.35	760	1.4	7	0.88	808 ± 111	130 ± 26	7	8	953 ± 115	458 ± 56						
2028a	8B	644 ± 12	0.34	1.3	1200	1.6	9.8	1.2	895 ± 147	113 ± 22	161	21	1190 ± 150	541 ± 68						
2028b		663 ± 18	0.25	1.3	1200	1.6	9.8	1.2	895 ± 147	182 ± 37	13	10	1100 ± 152	445 ± 64						
2058a	8B	490 ± 22	0.03	0.43	710	1.6	10	1.2	896 ± 131	177 ± 35	13	10	1096 ± 135	447 ± 55						
2058b		474 ± 15	0.02	0.43	720	1.6	10	1.2	896 ± 131	175 ± 35	8	10	1089 ± 135	435 ± 55						

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Table 5 (continued)

Sample No.	Unit	D _e (Gy)	U (EN) (ppm)	U (DE) (ppm)	TT (μm)	Sediment				Early U-uptake			US-ESR				
						U (ppm)	Th (ppm)	K (%)	γ-D (μGy/a)	β-D (μGy/a)	int.D (μGy/a)	DE-D (μGy/a)	total D (μGy/a)	Age (ka)	int/DE-D (μGy/a)	total D (μGy/a)	p-value
2059a	8B	341 ± 13	0.04	1.4	2500	1.6	9.8	1.2	895 ± 157	54 ± 12	18	11	978 ± 158	348 ± 57			
2059b		345 ± 9	0.08	1.4	2500	1.6	9.8	1.2	895 ± 157	54 ± 12	34	11	994 ± 158	347 ± 55			
2060a	8B	652 ± 20	0.02	0.65	1500	2.5	13	1.3	1014 ± 158	112 ± 19	10	8	1144 ± 159	569 ± 80			
2060b		582 ± 19	0.01	0.65	1500	2.5	13	1.3	1014 ± 158	112 ± 19	6	8	1140 ± 159	510 ± 72			
2062a	12	647 ± 31	0.02	0.57	1800	1.7	8.8	1.1	787 ± 138	69 ± 12	7	6	869 ± 138	744 ± 123			
2062b		701 ± 15	0.01	0.28	1900	1.7	8.8	1.1	787 ± 138	65 ± 11	4	3	859 ± 138	816 ± 131			
2063a	12	676 ± 42	0.00	0.4	1350	1.8	7.3	1.4	792 ± 139	106 ± 19	1	6	905 ± 140	746 ± 124			
2063b		733 ± 12	0.00	0.4	1550	1.8	7.3	1.4	792 ± 139	93 ± 17	1	5	891 ± 140	822 ± 129			
2064a	12	651 ± 22	0.00	0.03	1600	1.7	9.5	1.2	814 ± 144	85 ± 14	1	0	900 ± 145	723 ± 118			
2064b		649 ± 46	0.01	0.03	1900	1.7	9.5	1.2	814 ± 144	72 ± 13	3	0	889 ± 144	730 ± 128			
2065a	12	763 ± 26	0.01	0.17	1100	1.4	8.4	1.1	776 ± 200	110 ± 27	3	3	892 ± 202	855 ± 195			
2065b		767 ± 48	0.00	0.17	1600	1.4	8.4	1.1	776 ± 200	76 ± 18	1	2	855 ± 201	897 ± 217			
2066a	12	709 ± 27	0.01	0.53	1100	2.3	16	0.89	934 ± 170	126 ± 23	4	9	1073 ± 171	660 ± 107			
2066b		770 ± 39	0.02	0.53	950	2.3	16	0.89	934 ± 170	145 ± 27	10	10	1099 ± 171	700 ± 114			

Sample numbers in italics were submitted without sediment. Average sediment values from Table 2 were used. EN = enamel; DE = dentine; TT = total enamel thickness; S1/S2 = surface layer removed from each side of the enamel samples. Error in D_E after Grün and Brumby (1994); dose rates after Adamiec and Aitken (1998); beta dose attenuation after Marsh (1999); alpha efficiency: 0.13 ± 0.02 (Grün and Katzenberger-Apel, 1994); initial $^{234}\text{U}/^{238}\text{U} = 1.2 \pm 0.2$ in enamel and dentine; water in sediment 20 ± 10 ; ICP-MS errors (U, Th): 5% (relative); K: 0.05% (absolute). Sediment gamma dose rates averaged from analytical data from a given unit and *in situ* measurements where available (see Table 2), includes cosmic dose rate calculated from sediment thickness.

4. Dating results

With respect to the ESR analysis, we will only discuss the EU-ESR and the combined U-series-ESR results. The EU-ESR results provide minimum age estimates for the ESR system, and any delay of U-uptake would result in older age estimates (Grün, 2009b). Samples 2035 and 2040 were analysed by both ESR and U-series analyses. Their calculated *p*-values indicate delayed U-uptake (Table 5, see Grün, 2007, 2009b). Nevertheless, their combined U-series/ESR age estimates are only 6–8 ka older than the EU-ESR values. The other samples, for which both ESR and U-series data were obtained, indicate even earlier U-uptake. As result, their combined ESR-U-series age calculations are only between 0 and 3 ka older than the EU age calculations, and well within error ranges. All other samples contained significantly less uranium, and hence the mode of U-uptake has an insignificant influence on the determined ESR age. The ESR results obtained for each stratigraphic unit, from the base up, are described below (see also Table 5 and Fig. 4).

SU12: all mean age results fall within a range from 660 to 897 ka, and overlap within their 1- σ errors with no indication of mixing of samples with different ages. It is impossible to discern from the data whether the unit was deposited over a longer time range or represents a short period of deposition. For calculation of a weighted mean age for SU12, the separate results obtained for each tooth were first averaged and the standard deviation added to the average error of the individual measurements (to avoid correlated errors). The resulting age estimate for Unit 12 is 746 ± 69 ka.

No samples were analysed from SU11 to SU9.

SU8B: like SU12, the samples show no particular trends or age groupings. Because the relative depths of the samples are unknown it is also not possible to work out whether the results represent a single age population or accumulation over a longer time range. The weighted mean of SU8B is 423 ± 33 ka.

SU7B: the results obtained from this unit are very scattered. This matches the notion that SU7B, which is only 5 cm thick, represents a deflation lag deposit or possibly a higher energy environment that led to the re-deposition of older material. Because these bones are likely to have started their burial history in other sediments, any ESR age calculations can only result in apparent ages. The youngest age estimates, at around 130 ka, will be closest to the age of the event leading to the deposition of this layer.

SU7A: only one sample was analysed, and falls within the age range of samples from SU7B.

SU6B: the two samples from SU6B have closely similar results, with a weighted mean of 50.6 ± 4.3 ka. At the 2- σ uncertainty level, samples 2038 (extinct protomodon) and 2029 (extinct diprotodon in association with a stone tool) agree with the oldest radiocarbon ages. The results imply a considerable time-gap between the youngest samples in SU7 and the older samples in SU6.

SU6A: all ESR mean values are older than the range of calibrated radiocarbon ages between 33.4 and 39.6 ka cal BP. Only two samples, 2040 (extant macropus) and 2037 (extant m. osphranter), agree within error with the radiocarbon results. The other samples are older, two of them significantly. Samples 2036 (extinct diprotodon) and 2032 (extant macropus) have ages consistent with significantly older layers (SU7 or below). The dose values in the range 520– to 690 Gy which cannot be reconciled with any other samples from SU6A which all have dose values of less than about 80 Gy. The tooth of the long extinct *Pallimnarchus* (sample 1436) from layer SU6A has a U-series age >451 ka. At the 2- σ uncertainty level, sample 2039 (extant m. rufus) agrees with the oldest radiocarbon ages. Sample 2035 (extinct sthenurus) yielded significantly older ESR results. In addition, the apparent (closed system) U-series results of samples 2037 and 2031 (extinct sthenurus), are also significantly ($>2\text{-}\sigma$) older than the radiocarbon age range (Table 4, Fig. 5).

Fig. 4. EU-ESR age results, for the whole site (A) and expanded between 0 and 80 ka (B). The solid and the two dotted lines indicate the proposed extinction window by Roberts et al. (2001a).

In summary, the six megafauna samples analysed from Unit 6, all have mean ages older than calibrated radiocarbon range; two (1436, 2036) are several hundreds of thousands years older, two are significantly older ($>2\sigma$: 2031, 2035) and two just agree within the 2σ range (2029, 2038). The ESR results for the three teeth from extant fauna agree better with the radiocarbon range of SU6.

Fig. 5. U-series age results, over the whole age range (A) and expanded between 0 and 80 ka (B). The solid and the two dotted lines indicate the proposed extinction window by Roberts et al. (2001a). Data points with arrows indicate either minimum or maximum age estimates.

If a case is to be made that a megafauna tooth is younger than the proposed extinction event between 39.8 and 51.2 ka (Roberts et al., 2001a), the mean age of this sample should be at least 1σ younger than the low end of this extinction range (39.8 ka). The two megafauna samples with the youngest ESR age estimates were submitted without any associated sediment. For these samples to be younger than 39.8 ka, the combined external beta and gamma dose rate used in their age calculation would need to be more than 50% higher. No sediment sample collected anywhere at the site could produce such a high dose rate. Water contents were more likely higher than lower in the past than used in the calculations, which would also lead to older age results. Finally, any large bone accumulations in the vicinity of a tooth would mute the external gamma dose rate rather than enhance it, because of the relatively low U-levels in bones (see Table 3) and associated small time averaged $^{230}\text{Th}/^{234}\text{U}$ activity ratios. This is the case for sample 2029 which was part of the diprotodon mandible. This mandible would provide gamma shielding from the sediment gamma dose in the order of 20% (Nathan and Grün, 2003), and the gamma self-dose would be very small, as the specimen does not contain much uranium. Therefore, it is unlikely that these two samples could be younger than the postulated extinction event of Roberts et al. (2001a).

5. Discussion

In the context of this study, it is unimportant whether the SU5 pavement covering SU6A was protecting the lower sediments from trampling and other disturbances (see discussions in Gillespie and Brook, 2006; Field, 2006). The younger OSL age populations present in SU6 indicate the incorporation of grains that were bleached much later than the deposition of sedimentary units below this pavement. These grains may have migrated via narrow root canals, without necessitating the incorporation of larger items such as

bones or stone tools (Field 2006). The important question is what happened prior to the deposition of SU5?

Field et al. (2008) and Fillios et al. (in press) have made the case that SU6 and its contents are largely in primary context, based on:

- a thorough understanding of the site formation processes;
- none of the charcoal samples showing signs of abrasion or rounding;
- Fourier transform infra-red spectroscopy analyses indicating that the charcoal was largely uncontaminated and clean (personal communication of J. Head to J. Field);
- extensive studies of bone preservation that point to *in situ* deposition (Fillios et al., in press);
- the REE compositions of bones excluding their incorporation and intermingling from other stratigraphic units (Trueman et al., 2005);
- the oldest grain populations of the OSL single grain analysis being in stratigraphical order (Fillios et al., in press);
- possible limited incorporation of older materials at the base of SU6B, perhaps being due to well-digging by ancient people, explaining the occurrence of the *Pallimnarchus* tooth.

5.1. The chronology of SU6 based on published age results

The most likely ages of SU6A and SU6B, using the published age estimates, are based on the following reasoning:

For SU6A, the OSL age of 30.3 ± 2.3 ka has been widely promoted for this unit in discussions supporting a long temporal overlap between the first human colonisation of the Australian continent and the final extinction of the megafauna. However, this OSL age is contradicted by the calibrated radiocarbon ages for charcoal which fall between $33,690 \pm 490$ and $39,700 \pm 540$ cal BP. The spread of radiocarbon ages suggests that deposition occurred over an extended period lasting at least 5–6 ka, or alternatively, if the unit was deposited in a shorter timeframe, the radiocarbon age spread could be the result of variable contamination with groundwater derived carbon. In the latter case, the age for the unit will be best constrained by the oldest radiocarbon result (e.g. Turney et al., 2001), and should be around 40 ka. The radiocarbon results of Fifield et al. (2001), using significantly more rigorous ABOX pretreatment procedures and AMS measurement, corroborate the earlier radiocarbon dating results and may be taken as evidence that the charcoal samples have not been contaminated. Consequently, SU6A could have been deposited over a longer time range, perhaps between 30 ka (OSL) and nearly 40 ka (radiocarbon). Since the stratigraphic relationships within SU6A of the individual samples are not known, we are unable to assess these competing possibilities whether SU6A was rapidly or slowly deposited. The result is that one is left with the least precise age assessment, namely that the layer was deposited between about 40 and 28 ka (upper error of oldest age estimate and lower error of youngest age estimate). Any choice of a more specific date within this range cannot be justified without ignoring the other available geochronologic evidence.

For SU6B, OSL yielded two age estimates of 35.4 ± 2.8 and 36 ± 3 ka and the calibrated radiocarbon results fall within the range $34,180 \pm 490$ to $38,690 \pm 540$ cal BP. If no mixing has taken place between SU6A and SU6B, then any non-contaminated radiocarbon sample from SU6B should return an age >39.2 ka cal BP (the lower error of sample Beta 81379 in SU6A). It follows that any younger age estimate in SU6B reflects groundwater carbon contamination (with up to 1% modern carbon equivalent, pMC). If SU6B is obviously affected by carbon contamination, the same most likely applies for the overlying SU6A. Consequently, SU6A is older

than 33.7 ka cal BP and commenced deposition as early as 39.2 ka cal BP. SU6B is older than 39.2 ka cal BP. These radiocarbon results need to be regarded as minimum age estimates as the age range for SU6A does not account for any contamination, and because only a small number of charcoal samples were analysed, less contaminated samples may well exist. In this regard we note that the oldest sample was located somewhere in the middle of SU6A! The offset between radiocarbon and OSL could perhaps be explained through erroneous water content assumptions. The sediments show signs of compaction (Fillios et al., in press), the water content during the deposition of SU6 may have been considerably higher than the present day measured pore volume.

If, on the other hand, it is assumed that the OSL results are reliable, the absence of older, saturated grains indicates that the deposition of the sedimentological layers of SU6 was a reasonably slow process. The sedimentation allowed full bleaching of all sand sized grains, any postdepositional incorporation of older grains from lower levels did not occur (e.g., through bioturbation). Since the dose distribution of SU6A did not contain SU6B grains, intermixing from SU6B into SU6A is not supported, at least in the vicinity of the OSL samples. If the OSL results do constrain the timing of deposition of SU6A and SU6B, then the older radiocarbon samples (some of which have ages that are more than 4- σ older than the OSL results) must have been reworked from older sediments (see also Gillespie and Brook, 2006). Charcoal of the type found in SU6 does not occur in the units where megafauna is found in high density (SU7 and below), and thus could not have moved up the sedimentary column through trampling or any other process. Furthermore, the complete lack of older grains in the OSL samples excludes large scale intermixing of charcoal between SU6B and SU6A. Any older charcoal would thus need to come from lateral deposits. That the charcoal samples were clean (based on FTIR spectrometry) and did not show any signs of abrasion, would have no relevance to the argument that charcoal and clastic sediments were in primary position.

Two scenarios emerge from previous dating at Cuddie Springs:

- If the sediments and their contents are in their primary context, then the radiocarbon dating results are most relevant for assessing the age of the SU6 layers. If there is no intermixing between SU6A and SU6B, the radiocarbon samples from SU6B must be compromised by diagenetic carbon contamination, and this would also likely affect overlying charcoal samples from SU6A. The agreement between classical and ABOX AMS cannot be taken as proof that the samples were not contaminated. The radiocarbon results indicate deposition of SU6B before 39.2 ka cal BP and SU6A between 33.7 and 39.2 ka cal BP. The true age of SU6A and SU6B would likely be older than these estimates. Consequently, the OSL results must systematically underestimate the age of the layers.
- If the OSL results correctly estimate the age of the deposition of SU6A and SU6B, then the majority of the radiocarbon samples must be allochthonous. The lack of older grains in the OSL analysis excludes charcoal movement up through the sedimentary column, incorporation from lateral deposits is thus the only explanation.

For us, it is impossible to create a sedimentological history where the clastic sediments, the charcoal pieces and faunal remains of SU6A and SU6B are in primary context and their ages are represented by the OSL dating results.

5.2. The chronology of SU6 incorporating the results of this study

How can the results reported here be reconciled with the view that the sedimentological layers of SU6 and their contents

are autochthonous or paraautochthonous? In the first instance one could perhaps defend a null hypothesis, namely that geochronological methods have created a haze over the deposits that could be explained sample by sample given some of the many problems associated with the different dating techniques (see, for example, Grün, 2006), and ESR in particular (Grün et al., 2008b).

There is no doubt, however, that the directly dated faunal samples 1436, 2032 and 2036 are many hundreds of thousands years older than the deposition of SU6. In the case of 1436, it has been established that *Pallimnarchus* went extinct in the middle Pleistocene (Willis and Molnar, 1997), and our U-series results confirm the antiquity of this specimen. The three samples could derive from SU7, or below. This would incur vertical displacements of at least 40 cm (from the top of SU7 to the base of SU6A), and perhaps up to 80 cm (from the base SU7 to the top of SU6A) or more (if the sample came from a layer below SU7). However, at least in the vicinity of the OSL samples, any incorporation of grains from lower layers did not take place, i.e. there is no sign of mixing upwards while there is clear evidence for the incorporation of younger grains down the sedimentary column. The alternative is that these three teeth were redeposited. While the *Pallimnarchus* sample was specifically selected for analysis because of its suspected much older age, the other samples were chosen at random. Our results suggest that a reasonably large fraction, at least two of eight teeth in SU6, have originated elsewhere. This possibility may also apply to other samples, closer in age to the SU6 deposits. Well-digging by prehistoric people may have been responsible for the incorporation of older teeth in SU6 (e.g. Field et al., 2008), but it must have been a frequent exercise without leaving older grains in the vicinity of the OSL sampling sites. Alternatively, the samples were incorporated into SU6 by lateral movement.

All other teeth from SU6 had dose values inconsistent with those found in underlying units, SU7 and below (see Fig. 6 and Table 5). Some of the ESR and U-series ages are also significantly

older than the calibrated radiocarbon age range. The U-series results on samples 2031 and 2037 suggest a minimum age for SU6A of around 45 ka. This is supported by the ESR results on samples 2037 and 2040. SU6B returned ESR age estimates of around 50 ka. Sample 2035 is older than the other samples from SU6, around 70 ka, and may have originated from a similar source as the much older samples 1436, 2032 and 2036. Ages around the range 45–50 ka for SU6 would well fall within the accepted range of early colonisation of Australia (e.g. Roberts et al., 1990, 1994a,b; Turney et al., 2001; Bowler et al., 2003), without the necessity of referring to the more controversial Lake Mungo 3 results (Thorne et al., 1999; Bowler and Magee, 2000; Gillespie and Roberts, 2000; Grün et al., 2000).

The ESR and the older U-series age estimates indicate that SU6 is either older than the minimum radiocarbon age ranges (as discussed above), or that samples were also reworked from other layers. The argument that the present day land surface has a very low relief is not particularly convincing (Fillios et al., in press), because the landscape surface at the onset of the sedimentation of SU6 may have been quite different. What we do know is that the surface at the centre of the site was around 185 cm lower than today. If the surrounding surfaces were anywhere near where they are today, this lower base level would add a considerable gradient for slow mass transport. Indeed, section profiles and a contour map of the SU5 deflation pavement provided in previous studies (see Figs. 2 and 3 in Fillios et al., in press) indicate surface slopes into the Cuddie Springs claypan of 5° for SU5 and reaching up to 15° at the base of SU7. These slopes are more than sufficient to allow mass movement. The question is, where does the clastic material in SU6, and above, actually come from? Unfortunately it is not in the scope of the present paper to provide any primary sedimentological data to address this question.

While lateral redeposition has already been suggested by others (Roberts et al., 2001a; Gillespie and Brook, 2006), it is in stark contradiction to the findings of Trueman et al. (2005) who concluded from the REE compositions of bulk bone samples from SU6 that the bones found in this layer were *in situ* and at least paraautochthonous.

5.3. Implications of U and Th scans on bones and teeth for the previous REE study

There are, however, very substantial problems with the assumptions and interpretations of Trueman et al. (2005). Their study was predicated on assumed rapid uptake and adsorption of REE from porewaters by bone, which are then locked into and preserved by the bone as it recrystallizes during early diagenesis. In this way, bones inherit REE signatures determined by the porewater chemistry of their original depositional units, and any postdepositional mixing of bones may be evidenced from compositional variability within and between bones assemblages from different strata. In the case of Cuddie Springs, Trueman et al. (2005) state that laser ablation profiles of the bones “typically show steep, U-shaped concentration profiles consistent with single-event introduction of REE occurring over a time scale on the order of 1 ka and controlled by the diffusion-adsorption mechanism” citing Pike et al. (2002). Such fast uptake is an essential for the interpretation of their results. We can confirm that nearly all the bones we have analysed from Cuddie Springs have U-shaped Th and U concentration profiles (see Fig. 2). However, these U-shaped profiles actually reflect diffusion over much longer time-scales. This is demonstrated, for example, through the closed-system apparent U-series ages obtained on sample 2024 (Table 4), which record age differences between 2024A and 2024D and hence the continuation of U-uptake over a period exceeding 20,000 years.

Fig. 6. ESR dose values.

The interpretations made by Trueman et al. (2005) are compromised further by their methodology which involved removing the outer 1 mm of each bone sample prior to analysis. Diffusion-adsorption process modelling in bone indicates that the sub-cortical bone interiors analysed by Trueman et al. (2005) are subject to delayed REE uptake and obtain their REE signatures potentially tens of thousands of years after their original deposition. The young closed-system apparent U-series ages in Table 4 indicate very recent U-uptake and by inference also REE-uptake by samples in SU6. Thus, rather than giving evidence of a uniform origin of the samples, the REE data most likely present a more or less uniform response of bones to a much more recent geochemical environment in SU6.

When and how the bones in SU6 acquired the REE compositions reported by Trueman et al. (2005) is actually even more problematic than predicted from consideration of diffusion-adsorption processes and U-series constraints on the time-scales involved. The U and Th data reported by Trueman et al. (2005) point to a fundamental problem with their approach. Many of their bone samples are reported to have elemental U/Th ratios of <1 (see supplementary material to Trueman et al., 2006 on the PNAS web-site). In our extensive work on bones and dental tissues, we have never encountered such low U/Th ratios, except in very young or unaltered samples where both U and Th concentrations are close to the detection limit, <5 ppb. The insolubility of Th compared to U in porewater, generally leads to bones become enriched in U over time, but acquiring little or no Th. This is consistent with our laser ablation results which reveal elemental U/Th ratios that are typically $\gg 1$ and often >100 . When the peaks in the laser ablation profiles associated with cracks and large pores in the bone samples from Cuddie Springs are removed, all bone samples show U/Th ratios of ≥ 10 , except those with very low U-concentrations. The only materials with U/Th ratios <1 , apart from sediments, are the black Mn/Fe-oxy-hydroxide coating present on some bones (see Fig. 2C). Based on our U–Th laser ablation profiles we believe that the bulk sub-cortical bone U/Th compositions reported by Trueman et al. (2005) are dominated by surface coatings and/or detrital material contained in cracks and pores. The effect of this is shown in Fig. 7. The U/Th ratios of the bulk bone samples (from Trueman et al., 2005) are significantly lower than our laser ablation results (from Table 3), and clearly biased towards the sediment compositions (taken from Table 2, see Fig. 7A). Because of the relatively low U-concentrations in the sediment and the black coatings (see Fig. 2C), the U-concentration results of the bulk bone samples and laser ablation analyses are reasonably similar (Fig. 7B). However, because of the much higher Th concentrations in the sediment and black coatings (cf bone), the bulk compositions are strongly biased to much higher Th concentrations (Fig. 7C).

The bulk REE compositions in sub-cortical bone are also likely to be dominated by sediment and surface coatings rather than REE taken up from porewater. Indeed, this is demonstrated by laser ablation ICPMS REE profiles of bones from Cuddie Springs reported by Trueman et al. (2008). In this more recent study of Cuddie Springs bones, Trueman et al. (2008) showed that the uptake of lanthanum (a light REE) by bone tissue is consistent with diffusion processes, typically limited to <0.5 mm but insignificant beyond a distance of 1 mm. It follows that the high REE concentrations and REE signatures reported by Trueman et al. (2005) for bulk sub-cortical bone samples from which the outer 1mm was removed, are not the result of REE uptake from porewater by diffusion. Rather they reflect the REE concentrations and signatures of coatings and detrital sediments within pore spaces and cracks. The reality is that the study of Trueman et al. (2005) focussed on bone domains in the bones that experienced strongly

Fig. 7. Comparison of bulk (Trueman et al., 2005) and laser ablation (from Table 3) analysis on bones with sediment data (from Table 2). U/Th ratios (A), U concentration (B) and Th concentration (C). Compared to laser ablation analysis (after the removal of concentrations peaks in pores and cracks) the bulk analysis data have a bias towards the sediment data.

delayed if any uptake of REE, and which are subject to strong compositional masking by REE-rich diagenetic surface coatings and detrital material. Unless it can be demonstrated that these coatings and detrital components were formed early in a bone's history, the conclusions drawn by Trueman et al. (2005) must be disregarded. The study of Trueman et al. (2005) may provide some insight into the geochemical homogeneity of sediments and diagenetic processes within SU6 and of bone contamination by these materials. It has, however, little or no bearing on the question whether bones and teeth in this unit were allochthonous or autochthonous.

6. Conclusions

The geochemical and geochronological data from Cuddie Springs do not allow for a scenario where the clastic sediments, artefacts, bones and teeth of SU6A and SU6B were all in primary context and deposited around 36 ka (SU6B) and 30 ka (SU6A), based on the OSL results of SU6. If the samples are in primary context, the radiocarbon and closed system U-series samples would provide the minimum age estimates for SU6, indicating an initial deposition of SU6A around at least 45 ka and SU6B around 50 ka. Some of the teeth were clearly incorporated from older sediments, perhaps by well digging of ancient people. If there was overlap between humans and megafauna, it was considerably earlier than deduced from the OSL results. This scenario would entail significant systematic errors in the OSL age assessments.

Alternatively, the deposition of SU6 took place by slow lateral movement of sediments allowing for the complete bleaching of the quartz grains, and was accompanied by incorporation of older bones and charcoal pieces. Episodic human presence at the waterhole contributed artifacts to this deposit.

The REE compositions of sub-cortical bone sample reported by Trueman et al. (2005) from SU6 have no relevance to the demonstration that the bones found in SU6 were deposited in primary context. Rather these compositions reflect or are strongly biased towards the compositions of detrital sediments and secondary diagenetic surface precipitates in larger pore spaces within the bones. The REE compositions reported by Trueman et al. (2005) are unlikely to preserve geochemical evidence of the early diagenetic history of these samples.

Whether or not humans had a temporal overlap with the megafauna at Cuddie Springs can neither be demonstrated nor refuted.

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