

Research paper

# A cautionary tale from down under: Dating the BlackCreek Swamp megafauna site on Kangaroo Island, South Australia

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## Abstract

The extinction of the Australian megafauna is presently one of the most hotly contested debates in Australian Quaternary sciences. [Roberts et al., 2001. U-series and ESR analyses of bones and teeth relating to the human burials from Skhul. *Journal of Human Evolution*. 49, 316–334.] proposed contentiously that the megafauna went extinct within a short time period somewhere in the range of 39,000–52,000 years ago. Being tucked away at the continental fringe, Kangaroo Island offers an ideal refuge for the megafauna for survival. Initial radiocarbon analyses of soil organic matter, ESR of teeth and OSL of quartz provided consistent age assessments, which strongly suggested that the site could be as young as 20,000 years. However, it turned out that the sediments contained extreme disequilibria in the U-decay chain, with  $^{230}\text{Th}/^{238}\text{U}$  ratios in the range of 0.3 and  $^{210}\text{Pb}/^{238}\text{U}$  ratios around 0.1. Furthermore, *in situ* laser ablation analysis revealed that uranium migrated into the teeth at a very late stage during the Holocene. Contrary to expectations, insoluble organic matter was considerably younger than the soluble fraction. After combining all analytical results, a complex geochemical history can be reconstructed, implying that organic matter and large amounts of uranium were injected into the megafauna-bearing layers around the Last Glacial Maximum. When combined U-series/ESR dates are calculated, they all turn out older than the proposed extinction window. This was confirmed by a subsequent OSL study.

The Black Creek Swamp site is another example that the parametric early (EU) and linear U-uptake (LU) ESR age models, particularly when applied to teeth with high-U concentrations, may provide completely unreliable age results.

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## 1. Introduction

Megafauna was a suite of large animals that disappeared towards the close of the Pleistocene and include the hippopotamus-sized *Diprotodon* and *Zygomaturus*, the giant kangaroo *Procoptodon*, the marsupial lion *Thylacoleo*, and the large flightless bird *Genyornis*. Flannery (1994)

speculated that their extinctions were the result of a ‘blitzkrieg’: overhunting by early human colonisers combined with fire-stick farming practices. This changed the ecology of the continent so dramatically, that many larger marsupial species were driven to extinction. The blitzkrieg model was fortified by the dating of the extinction of *Genyornis* to about 45,000 years ago in central Australia (Miller et al., 1999), although it was claimed that *Genyornis* survived until later in other locations (Field and Boles, 1998). More recently, Roberts et al. (2001) presented optical dates on sediment layers at a series of sites, which contained articulated megafauna remains. They argued that the megafauna went extinct within a short time period

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somewhere in the range of 39,000–52,000 years ago. Johnson et al. (1999) and Miller et al. (2005) observed a severe change in vegetation (strong depletion of C<sub>4</sub> grasses) as reconstructed from <sup>13</sup>C measurements in emu eggshells when *Genyornis* vanished. At that time there were no significant world-wide climatic shifts that could explain any large-scale vegetational change in Australia. Consequently, Miller et al. (2005) speculated that human firing of the landscapes had converted drought-adapted vegetation to fire-adapted desert scrub. Animals that could not adapt became extinct.

Being tucked away at the continental fringe, Kangaroo Island (KI, see Fig. 1) offers an ideal refuge for the megafauna for survival, in a manner that some of the European, glacial megafauna (giant deer and mammoth) survived the last glaciation for many thousands of years in Siberia (Stuart et al., 2004). KI is situated 16 km off the southern coast of South Australia is up to 155 km long, up to 55 km wide, covering an area of 4500 km<sup>2</sup>. Although it was unpopulated at the time of first European contact in 1802, several archaeological sites document earlier human presence.

The Black Creek Swamp site, adjacent to Rocky River, is within the bounds of the Flinders Chase National Park (Fig. 1). It consists of three major layers: a light-brown mottled calcified clay-rich base layer, a black clayey layer, about 60 cm thick (containing the fossil beds), a lighter clay-rich layer (fossil free) of about 40 cm with the present day soil developed in the upper 10 cm (see Figs. 2 and 7, below). It has been investigated on a number of occasions, each attempt yielding megafaunal remains (Hope et al., 1977) Gröcke (1996) collected faunal material from a small



Fig. 1. Location of the Black Creek Swamp site on Kangaroo Island.

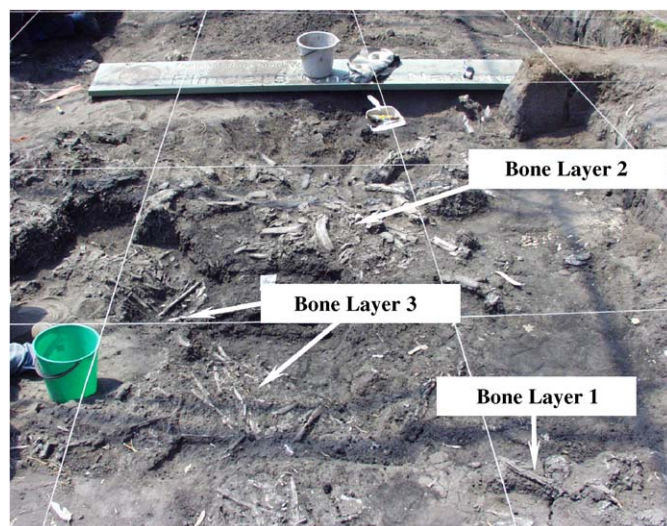


Fig. 2. Photograph during the 2004 excavation showing three distinct bone layers. Layer 1 contains sparse fauna, but includes the marsupial lion, *Thylacoleo carnifex*, Layer 2 contains a series of diprotodons and other megafauna elements, whereas Layer 3 mainly contains extant macropod remains.

1 m<sup>2</sup> test pit. At a depth of about 40 cm below surface, he collected an entirely new taxon, a dwarf version of the extinct megafaunal diprotodontid, *Zygomaturus trilobus*. Further excavations were carried out during 1996/97, which revealed the full extent of the fossil site covering an area of 0.5 hectares (Wells et al., 1997; 2001) New excavations commenced in 2003 (the datum is located at S 35° 56.972', E 136° 44.115') and have been summarised by Wells et al. (in press).

Hope et al. (1977) reported <sup>14</sup>C dates of around 18–19 ka BP for the megafauna layers. Gill (1996) obtained U-series age estimates of about 3 ka on bones from Gröcke's excavation. Forbes et al. (2004) reported <sup>14</sup>C dates on soluble soil organic carbon (the sediment samples contain about 8% of organic carbon). The uppermost sample at the base of the modern soil had an age of 5589 ± 259 BP and three samples from the organic-rich fossil layer located 45–75 cm below the current surface yielded in stratigraphic sequence: 15,687 ± 110, 16,326 ± 385 and 17,618 ± 447 BP. This would suggest that the megafauna deposits were between 15 and 19 ka old, similar to the findings of Hope et al. (1977), but at odds with the U-series results of Gill (1996).

If the <sup>14</sup>C dates could be substantiated, the Black Creek Swamp site would be the youngest megafauna site in Australia and challenge the conclusions of Roberts et al. (2001), that all megafauna had vanished by 39 ka. Furthermore, weight would be added to the notion that the vanished Aboriginal inhabitants of Kangaroo Island were indeed contemporaneous with megafauna. The extinct dwarf species may indicate long isolation and resource depletion, perhaps contributing to the demise of the human population.

## 2. Samples

Samples were collected at different times. Nine teeth (2119–2127) were selected from the 1996/7 excavation for ESR dating. One sample (2119) was collected at the nearby WFPC site, all other samples came from Pit 2, six of which (2120, 2123–2127) were found close to a large diprotodon. Three samples were of extinct megafauna: *Diprotodon* (2119), *Stenurus* (2120) and *Protemnodon* (2121), the other six samples of extant *Macropus*. Sediment adherent to each tooth was used for the calculation of the external beta dose rate. Six *in situ* gamma spectrometric measurements were carried out and sediment samples in their immediate vicinity were collected for elemental and water analysis. At that time it was thought that the bones were contained in a single layer at about 60 cm depth. One sample for OSL was collected from the re-opened excavation site in 2001 at the approximate depth of this bone-bearing layer. However, the new excavations showed that the site consists of at least three distinct bone-bearing layers (Fig. 2). In 2004, more gamma spectrometric measurements were carried out, and three more samples were collected for OSL dating with a clear relationship to the bone-bearing layers (see Fig. 7). Further ESR samples were collected from the three layers, but their analysis has not yet been finished.

## 3. Experimental

*In situ* gamma spectrometry was carried out with a calibrated TSA multi-channel gamma spectrometer and a 3 × 3 in NaI detector. The first OSL sample was measured by a multi-aliquot protocol using the Australian slide technique (Prescott et al., 1993), the second set was analysed using a single-aliquot regenerative-dose (SAR) protocol (Murray and Wintle, 2000), incorporating an IRSL measurement before each OSL measurement. SAR OSL measurements were performed at 125 °C, with a 10 s, 260 °C preheat before the natural- and regenerative-dose measurements, and a heating of 10 s at 220 °C before sensitivity checks. A few aliquots had much smaller dose values than the bulk, these were discarded in the calculation of the average dose value. ESR and elemental analyses of the teeth were carried out with the procedures routinely applied in the ANU ESR laboratory (Grün et al., 2005), laser ablation U-series analysis followed Eggins et al. (2003, 2005). U-disequilibrium of the sediments was measured for at least two weeks with a high-resolution Ge-detector system (Simpson and Grün, 1998). <sup>238</sup>U, <sup>230</sup>Th and <sup>210</sup>Pb were assessed via the low energy peaks at 63, 67 and 46 keV, <sup>226</sup>Ra at 186 keV (corrected for the <sup>235</sup>U contribution), the short-living <sup>222</sup>Rn daughters <sup>214</sup>Bi at 609 keV and <sup>214</sup>Pb at 295 and 353 keV.

Some samples had unexpected ESR features (Fig. 3). Sample 2122 (Fig. 3A) shows a typical tooth enamel spectrum, the central part dominated by the CO<sub>2</sub><sup>-</sup> radical (Callens et al., 1987). In contrast, the spectrum of sample 2119 (Fig. 3B) is dominated by a signal, which has so far

not been reported in fossil teeth. The natural spectrum seems to contain a small component of the CO<sub>2</sub><sup>-</sup> radical. When this is removed (by subtracting a fraction of the natural 2122 spectrum so that the dip at  $g = 2.0071$  disappears), a symmetric, non-Gaussian line remains with a width of about 0.33 mT and a  $g$ -value of 2.0025 (Fig. 3C). We do not know, which radical or paramagnetic centre causes this line. Most other samples contain a peak at the low magnetic field shoulder of the CO<sub>2</sub><sup>-</sup> centre (2121 in Fig. 3D). The application of the same subtraction process yields a peak with a width of about 0.65 mT and a  $g$ -value of 2.0045 (Fig. 3E). Such lines have been observed in relatively modern tooth enamel and attributed to unspecified organic radicals (Wieser et al., 2000). Similar radicals, attributed to humic acids, occur in spring-deposited travertines (DeCanniere et al., 1985). Sample 2119 yielded nonsensical dose values ( $D_e$  estimations in the same enamel layer varied by factors of more than three without any apparent cause). The shoulder at  $g = 2.0062$  would lead to erroneous dose values, if peak-to-peak estimations were used (the dip of the wide signal interferes with the top of the CO<sub>2</sub><sup>-</sup> peak). This was overcome by using spectrum fitting within an appropriately wide range, where symmetrical interferences have little influence on the estimation of the signal intensity (Grün, 2002).

## 4. Results and discussion

In the context of this study, it is educational to report the results in the temporal sequence as they were obtained (because of the page restriction in this paper, the analytical data are not tabulated). It can be seen (Fig. 4A) that the U concentrations in enamel and dentine are very high, reaching more than 700 ppm in the dentine of sample 2123 (which virtually corresponds to mining-grade U ore). Even in enamel, U concentration of more than 10 ppm were obtained. One would usually expect that such high values to be associated with particularly old samples. Initial ESR results were based on the application of early (EU) and linear U-uptake (LU) models (for more details of U-uptake models see Grün et al. (1988) and Grün (2000)) and the elemental analysis of the surrounding sediments. Surprisingly, the resulting ages are quite young (Fig. 4B), within a range of 9–30 ka (EU) and 14–35 ka (LU). In spite of the very high U concentrations in the constituents of the teeth, the differences between the EU and LU models are moderate, because of the small iteratively calculated <sup>230</sup>Th/<sup>234</sup>U ratios (between about 0.1 and 0.24) and the high-U concentrations in the surrounding sediment (20–40 ppm U, about 13 ppm Th and 0.9% K, 53–59% water/dry). At the same time, a preliminary OSL result of about 20 ka was obtained and the preliminary radio-carbon results (of between 15 and 18 ka BP; see above) were communicated. At this stage we were certain, that the Black Creek Swamp site could be nothing else than a refuge for megafauna, which had survived the so-called ‘blitzkrieg’ for many millenia.

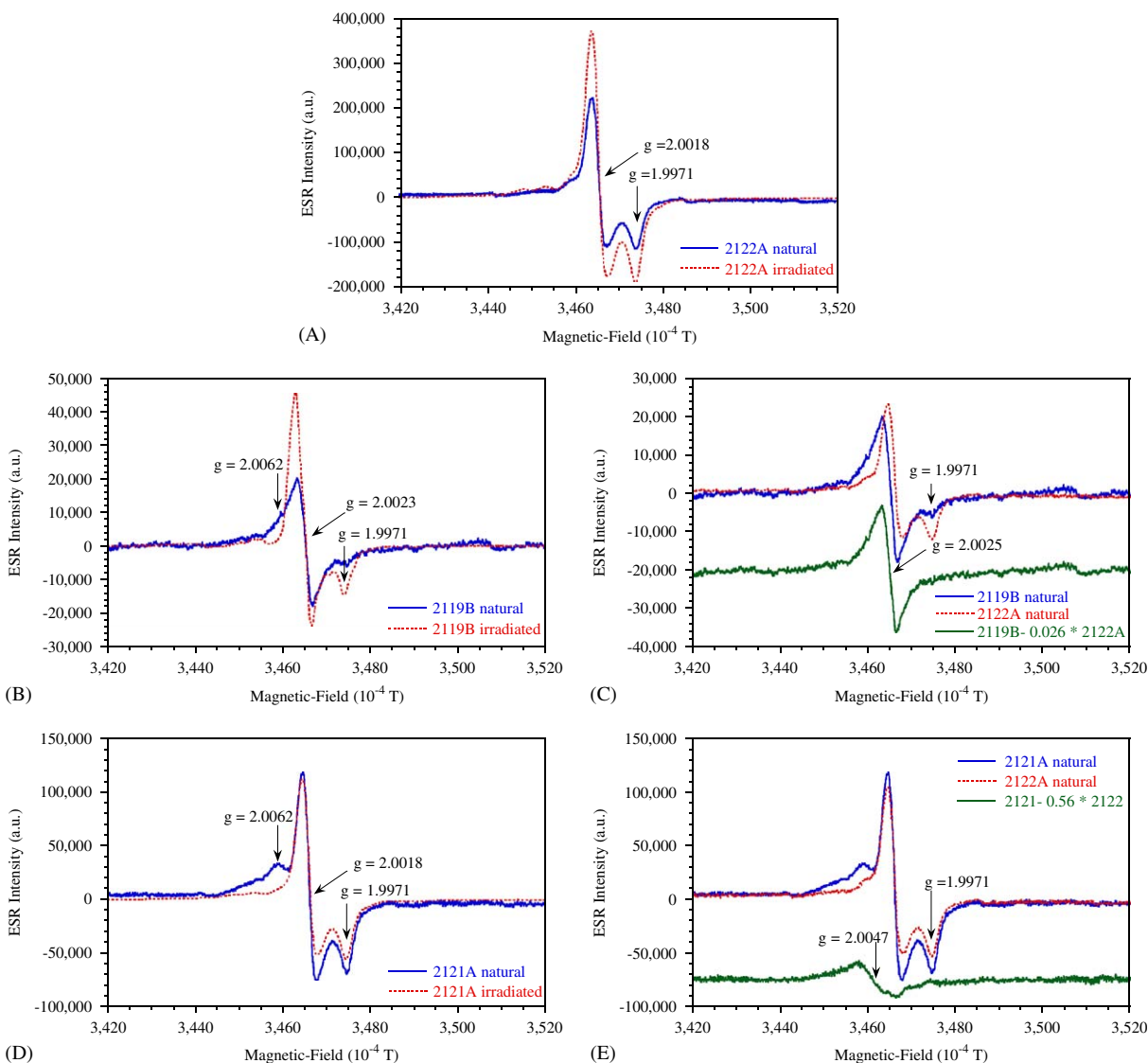


Fig. 3. ESR spectra of a range of samples. A: Sample 2122 contains a typical ESR spectrum of tooth enamel, which is dominated by the  $\text{CO}_2^-$  radical. B and C: Spectra of sample 2119. The spectrum is dominated by a signal at slightly lower fields than the  $\text{CO}_2^-$  radical shown in A. It contains a small proportion of the  $\text{CO}_2^-$  radical as evidenced by the dip at  $g = 1.9971$ . When subtracting a proportion of the natural spectrum of sample 2122 from the natural spectrum of 2119 (C), so that the dip at 1.9971 disappears, the remaining spectrum (offset for clarity) is a symmetrical, non-Gaussian line, centred around  $g = 2.0025$  with a line width of about 0.33 mT. The origin of this line is unknown. D and E: Spectra of sample 2121. This sample is again dominated by the  $\text{CO}_2^-$  radical, but has a low-field shoulder with a peak at  $g = 2.0062$ . Note that this line is absent in sample 2119 (B and C). When using a similar subtraction strategy as for sample 2119, a near-symmetrical line centred around a  $g$ -value of 2.0047 and a width of 0.66 mT remains (E). This line could either be attributed to organic radicals in the enamel (Wieser et al., 2000) or incorporation of humic substances (DeCanniere et al., 1985).

It was obvious, however, that in the sediments, the U-decay chain was in disequilibrium. This was evidenced by discrepancies between the gamma spectrometric measurements and the neutron activation results. The former technique is based on measuring end members of the  $^{238}\text{U}$  decay chain (mainly  $^{214}\text{Pb}$  and  $^{214}\text{Bi}$ ), whereas the latter measures the parent isotope. Fig. 4C shows the results of five samples which were measured with high resolution gamma ray spectrometry (for details see Simpson and Grün (1998)). Fig. 4C shows that all samples exhibit disequilibrium in the U-decay chain. The  $^{230}\text{Th}/^{238}\text{U}$  ratios (all U-series isotopic ratios are given as activity ratios) vary between 0.3 and 0.4. These U-series results correspond to

apparent U-series ages of about 25–34 ka (using a  $^{234}\text{U}/^{238}\text{U}$  of 1.46, see below), indicate a relatively recent injection of uranium. The samples around the bone layer at 65 cm depth show a slight depletion of  $^{226}\text{Ra}$  ( $^{226}\text{Ra}/^{238}\text{U}$  ratios in the range of about 0.2–0.4) and a further depletion of the Rn daughters  $^{214}\text{Bi}$  and  $^{214}\text{Pb}$  (parent-normalised ratios of about 0.15–0.25). The  $^{210}\text{Pb}/^{238}\text{U}$  ratios of 0.12–0.18 show that the suspected Rn loss has been a longer-term process for at least a few tens of years, as  $^{210}\text{Pb}$  is the longest living daughter of  $^{222}\text{Rn}$  with a half-life of about 22.3 years. Indeed, the somewhat lower  $^{210}\text{Pb}/^{238}\text{U}$  ratios (compared to  $^{214}\text{Bi}/^{238}\text{U}$  and  $^{214}\text{Pb}/^{238}\text{U}$ ), may indicate that Rn loss was even stronger in the past. Using

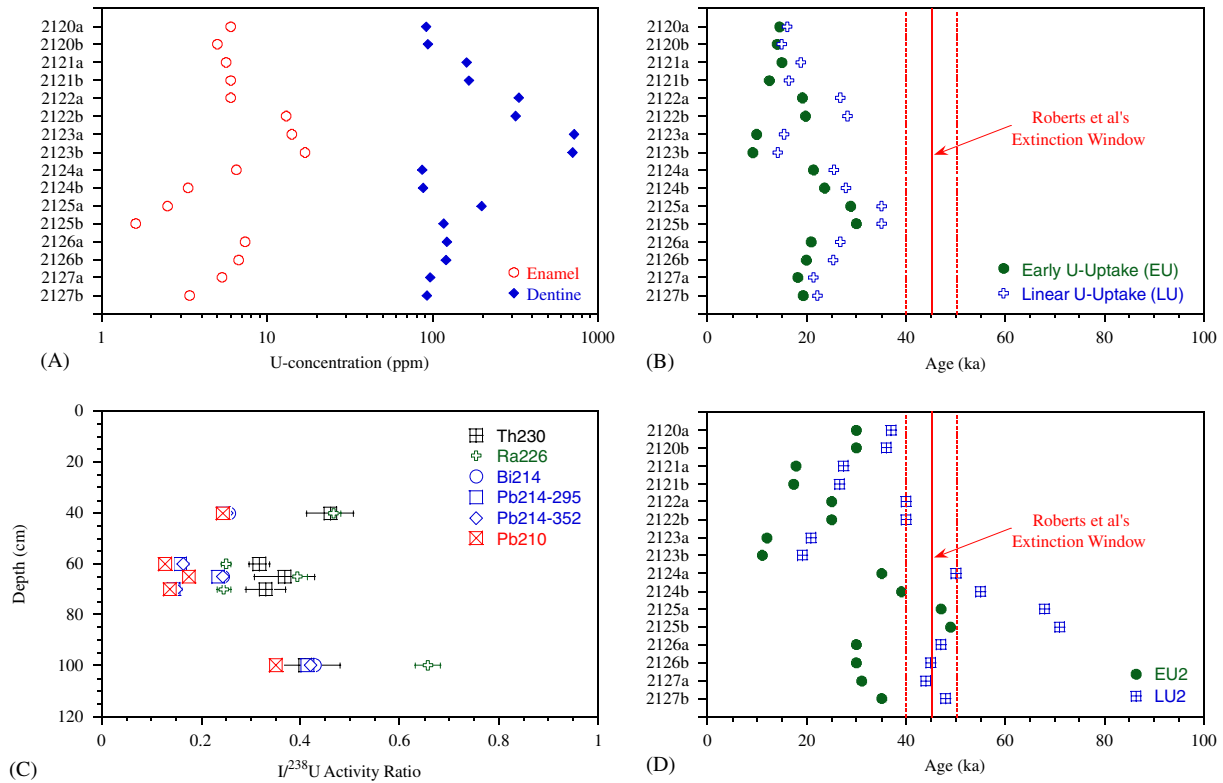


Fig. 4. A: U concentrations in enamel and dentine. B: ESR age estimations using the elemental concentrations of enamel, dentine and sediment applying the parametric early linear U-uptake models. All ages are significantly younger than the proposed extinction window of about 39–52 ka (Roberts et al., 2001). C: U disequilibrium in the sediment samples normalised on the parent isotope  $^{238}\text{U}$ . All samples show  $^{230}\text{Th}/^{238}\text{U}$  ratios significantly smaller than 1. For the fossil-bearing black layer (upper four samples), there is a slight Ra depletion and a stronger depletion of Rn. The most recent Rn loss is shown by the short-lived isotopes  $^{214}\text{Bi}$  and  $^{214}\text{Pb}$ . The somewhat longer trend (over tens of years) is shown by the  $^{210}\text{Pb}$  data, indicating that Rn loss was even stronger than most recently. D: The ESR results, considering the U disequilibria in the sediment, yield ages that are older than shown in Fig. 4B, but the megafauna teeth (2120 and 2121) are still younger than the proposed extinction window.

the present day disequilibrium values for the calculation of the external dose rate, EU ages in the range of 11–50 ka and LU ages of 20–70 ka are obtained (Fig. 4D). Most importantly, sample 2121, that of an extinct *Stenurus*, was younger than 30 ka. Because of the unusually high U concentration in dentine and, particularly, enamel, we assumed that it must have taken a considerable amount of time for the uranium to enrich to the high values that were measured (Fig. 4A). However, the only way for the ESR age estimates to become significantly older than the LU age estimates would be that the uranium migrated into the teeth very recently, corresponding to apparent U-series ages significantly younger than the EU model ages.

It is worthwhile to note that radiocarbon and trapped charge dating methods are completely independent, and the methodological overlap between OSL and ESR mainly relates to the external gamma and beta dose rates. Under normal circumstances, say 5 years ago, the study would have been written up at this stage with the clear implication that all dating results indicated ages for the megafauna of less than 40 ka.

With the advent of laser ablation analysis, it has become possible to carry out in situ analysis of the fossil teeth for U, Th as well as U-series isotopes (i.e.  $^{238}\text{U}$ ,  $^{234}\text{U}$ , and

$^{230}\text{Th}$ ; see Eggins et al. (2003, 2005)). The technique is particularly well suited for material with high-U concentrations. Fig. 5 shows the laser ablation scans of two samples. Each measurement contained between 200 and 600 data points for each tooth (sample 2128 was used up for the ESR analysis). As can be seen, each data point on the dentine could be converted into an individual U-series age estimate. For the calculation of combined U-series/ESR (US-ESR) age estimates (Grün et al., 1988; Grün, 2000), the U-series data were binned over the constituents of the teeth. The  $^{234}\text{U}/^{238}\text{U}$  ratios were all within a narrow range, with an average of  $1.464 \pm 0.023$  for all tissues. The apparent (closed system) U-series ages varied between 2 and 11 ka for dentine and 3–9 ka for enamel, except sample 2124 which yielded 11 ka for the dentine and 26 ka for enamel (Figs. 5C and D). Our U-series data agree well with those found on bones (Gill, 1996). The combined ESR/U-series results are all older than the ‘extinction window’ (Fig. 6). Unfortunately, the age estimates now scatter significantly more than the first age calculations. It seems that there could be three distinct populations: 45–50 ka (2120 and 2121), 60–80 ka (2123, 2124, 2126) and one around 100 ka (2122 and 2125). The  $p$ -values are all  $> 5$ , except for 2124 ( $p \sim 0$ ).

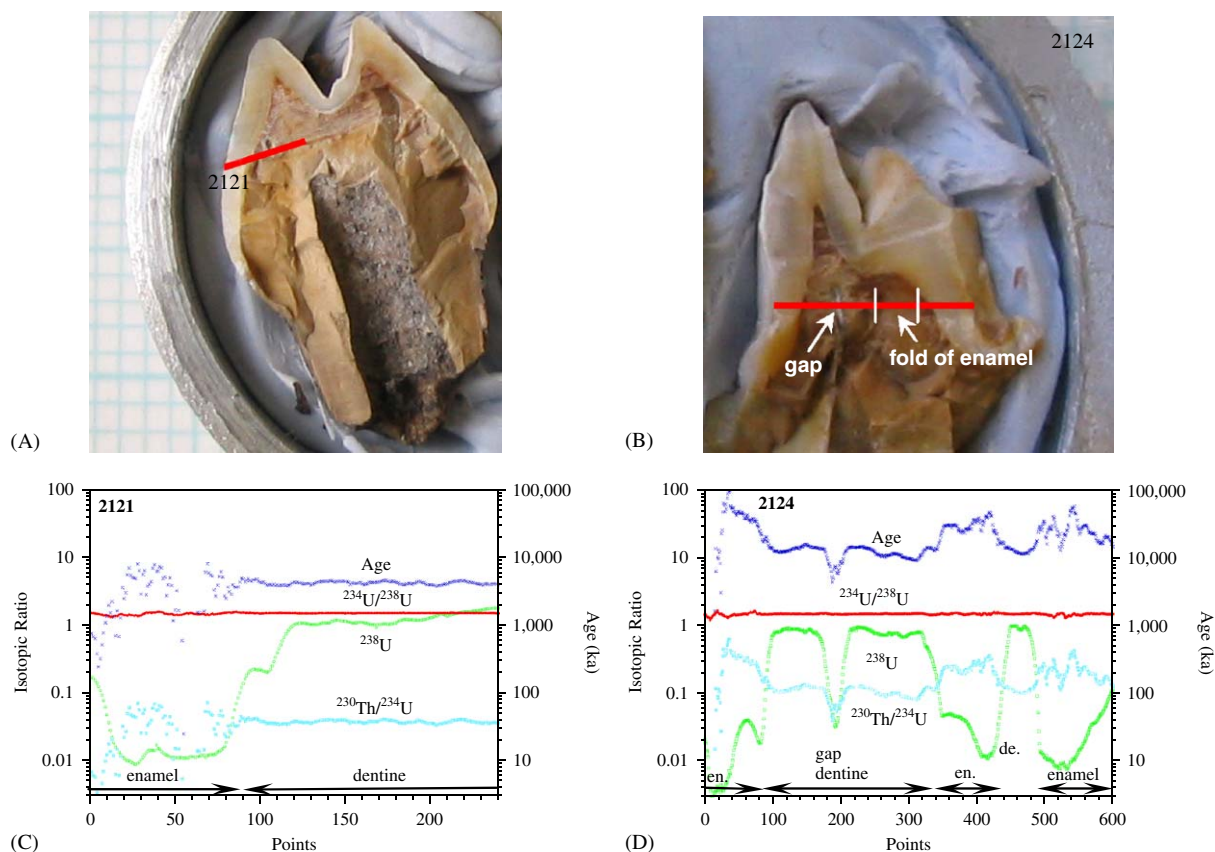


Fig. 5. Laser ablation results on some of the teeth (the lines in the photos indicate the track position). The U concentrations are so high that each data point in the dentine can be converted into an individual U-series age estimate. The apparent U-series ages are surprisingly young, around 4 ka for sample 2121 (A and B). Sample 2124 (C and D) shows significantly older apparent U-series ages in the centre of the enamel. This clearly demonstrates at least two phases of U uptake, one earlier phase leading to apparent U-series ages of 50 ka in the centre of the enamel, and a later one which coincides with the U uptake in the other teeth.

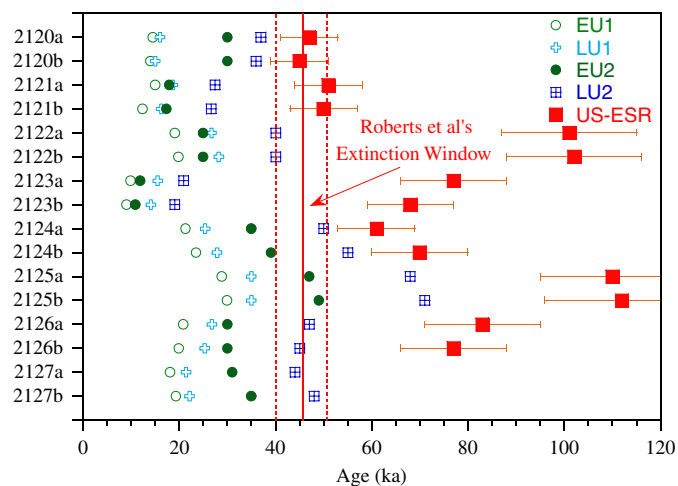


Fig. 6. Combined U-series/ESR age estimates, in comparison with the earlier EU and LU calculations (Figs. 4B and D). All ages are now older than the proposed extinction window. The age scatter is due to the fact that the samples are not provenanced. They may belong to different sedimentological layers or be the result of reworking.

The U-series data on the sediment as well as the teeth show that fossil-bearing sediments of the sites have received one or several injections of uranium. The average

timing of this injection must have been later than the apparent U-series age of the sediment (around 35 ka). If we assume that the original sediment contained about 5 ppm U (as measured in a nearby deposit where the  $^{230}\text{Th}/^{238}\text{U}$  is in equilibrium), i.e. about 12% of the present day U concentration, a single event U injection would have taken place around 20 ka ago (i.e. slightly after the last glacial maximum, LGM).

The laser ablation scans of sample 2124 show that the enamel experienced at least two U-uptake phases. The U-series data at the outside of the tooth enamel are significantly younger than on the inside. This is only possible if there is a second, later U-uptake phase with much higher-U concentration in the groundwater. In the centre of the enamel, the apparent U-series ages reach up to about 50 ka. This has to be regarded as a minimum age for the sample, and clearly indicates that this specimen is significantly older than the extinction window. We also observe that the centre of the enamel of sample 2121 (Fig. 5B) yields older apparent U-series ages than the volume near the surface.

In order to check the ESR chronology, new OSL samples were collected in 2001. One sample was taken just above the bone-bearing layer, one below and one further down

into the sedimentary layers underlying the black swamp sediments (Fig. 7). Using the disequilibrium values found by gamma spectrometry for the respective layers, we calculate OSL ages of around 153 ka for the basal layer, 145 ka for the black sediments underlying the bone beds and  $28.2 \pm 2.7$  ka for the overlying black sediment layer. Because of the large diameter sampling tube (see Fig. 7) and the inferred slow deposition rate of the fossil-bearing layers, this age is an average of perhaps 10–20 ka deposition. Nevertheless, the OSL results clearly indicate that there is most likely a long time span (in the range of 100–120 ka) involved in the deposition of the lower layers. This is, not surprisingly, mirrored in the wide apparent scatter of the CSUS-ESR age estimates. As the teeth are unprovenanced with respect to the three fossil-bearing layers (Fig. 2), it is not possible to decide whether the three age groups present the ages of the fossil layers or whether the fossils were re-worked over a short distance, as some sedimentary observations indicate.

Subsequent radiocarbon analysis was carried out on two additional samples. These were base treated to remove soluble organic matter (humic and fulvic acids);

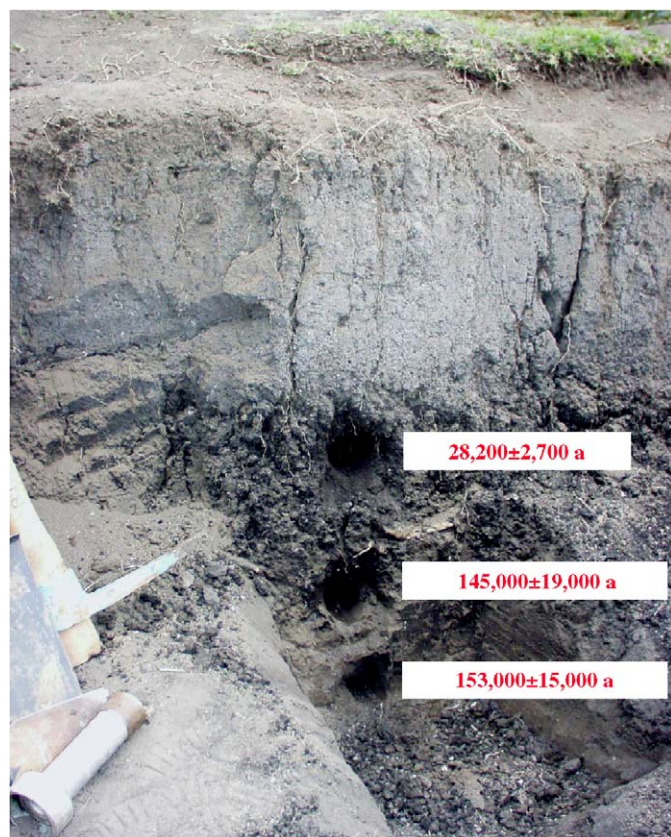


Fig. 7. OSL age estimates (considering all dosimetric factors and U-series disequilibria). The bottom of the black layer was deposited shortly after the deposition of the basal layer. The black layer itself has a very slow average deposition rate (in the range of 6 mm/1000 yr). The bone beds are located between the two upper samples (one bone is visible between the holes that were made for OSL sampling).

the very small fraction of insoluble residue (less than 1% of bulk) provided ages of  $1938 \pm 35$  and  $4227 \pm 45$  BP. Our preliminary model based on these dates as well as the composition and context of the fossil layer is that the organic matter accumulated from the precipitation of soluble organic matter during the LGM (~20 ka BP) probably in a subsurface soil (e.g.  $B_h$ ) horizon. Such subsurface accumulations of precipitated organic matter are common in Podzols (e.g., Buurman and Jongmans (2005)), which occur elsewhere on Kangaroo Island (Northcote, 2002). It is possible that some of the humic material migrated into the tooth enamel of some of the samples, as perhaps indicated by the interfering line at  $g = 2.0047$  (see Fig. 3E). The young insoluble residue represents minor accumulation of organic matter (probably charcoal) originating from the soil surface which infiltrated down-profile through cracks and macropores.

The relatively young age of the original OSL sample (20 ka) could be explained by either incorporation of younger quartz grains into the sample (similar to the contamination of the radiocarbon samples and evidenced in some of the SAR aliquots), the sediments develop large cracks during drying of the sediments (see Fig. 7), or the fact that the surface of the bone-bearing layers is somewhat undulated. The sample could have originated from a layer slightly above those analysed in the second OSL set.

## 5. Reconstruction of the history of the site

From the analyses outlined above, it is possible to reconstruct some of the environmental history of the Black Creek Swamp Site. The underlying mottled light-brown, calcified sediment was deposited before about 145 ka. The lowermost layers of the black sediment were deposited from this time onwards, with a relatively slow average deposition rate (about 6 mm/ka). Fossils were deposited at the site between about 100–40 ka (this corresponds to the approximate spacing of the fossil layers of about 30 cm). Around, or shortly after, the LGM there was an accumulation of organic and U-rich fluids. Such conditions are usually associated with a reducing environment, where uranium becomes insoluble. It is envisioned that during the LGM, cool and moist conditions in the Black Creek Swamp area led to the nearby calcareous dunes being stabilized which would have caused a decrease in the flux of carbonate aeolian detritus. This led in turn to a lowering of the pH in the Black Creek Swamp soil system and to the development of Podzol soil conditions and the widespread precipitation of soluble soil organic matter in the Black Creek Swamp. After the decomposition of much of the organic matter, during the early to mid Holocene, U became more soluble and migrated into the bones and teeth along with some humic substances (see Figs. 3D and E). In a more recent drying-out phase, a small proportion of

insoluble organic matter, and perhaps windblown quartz grains, migrated downwards, along cracks developing in the black sediments.

## 6. Conclusions

Our study demonstrates that radiocarbon analysis on soluble organic matter may lead to significant age underestimations, when used for the age assessment of the deposition of sedimentary layers in which the organics are found. The sediments of the site show discrepancies between elemental and *in situ* gamma spectrometric analysis. These have to be investigated if reliable ESR and OSL chronologies are to be established (Olley et al., 1996). The Black Creek Swamp site is another example showing that the parametric EU and LU models, particularly when applied to teeth with high-U concentrations, may provide completely unreliable age results. The study also highlights the necessity for the detailed sedimentological and taphonomical analysis of Quaternary sites to be dated. If the samples are not correctly provenanced, it is impossible to decide whether the age scatter in the samples relates to the ages of the distinct fossil layers, whether the samples were re-deposited or the dating approach is inherently noisy. Nevertheless, rather than representing a site that provided a refuge for the megafauna, the Black Creek Swamp site has now joined a number of other sites, which contain megafauna just before the proposed extinction event. Whether other sites, such as Cuddie Springs or Lancefield, contain a younger megafauna is subject to ongoing research.

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