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Criteria for assessing the quality of Middle Pleistocene to Holocene vertebrate fossil ages

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Abstract

Confidence in fossil ages is a recognized constraint for understanding changes in archaeological and palaeontological records. Poor estimates of age can lead to erroneous inferences-such as timing of species arrival, range expansions and extinctions-preventing robust hypothesis testing of the causes and consequences of past events. Therefore, age reliability must be demonstrated before patterns and mechanisms are inferred. Here we present a generalized quality-rating scheme based on a two-stage set of objective criteria: first, our method assesses the reliability of an age regarding the dating procedure, and second, if the age is based on association, it assesses the confidence in its association with the target vertebrate fossil. We developed this quality rating specifically for Australian applications, but it could be applied to other regions and to longer timescales with some modification. Our method ranks ages in four categories of reliability (A* and A are reliable; B and C are unreliable). In our case study of the late Pleistocene megafauna of Sahul, accounting for reliability (i.e., accepting only reliable ages) reduced the number of useful records within chronologies by 70%; for most species, this greatly affects any inferences regarding the timing and possible drivers of extinction. Our method provides a simple, replicable and general tool for assessing the age quality of dated fossils, as well as provides a guide for selecting useful protocols and samples for dating.

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Criteria for assessing the quality of Middle Pleistocene to Holocene vertebrate fossil ages

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Abstract

Confidence in fossil ages is a recognized constraint for understanding changes in archaeological and palaeontological records. Poor estimates of age can lead to erroneous inferences—such as timing of species arrival, range expansions and extinctions—preventing robust hypothesis testing of the causes and consequences of past events. Therefore, age reliability must be demonstrated before patterns and mechanisms are inferred. Here we present a generalized quality-rating scheme based on a two-stage set of objective criteria: first, our method assesses the reliability of an age regarding the dating procedure, and second, if the age is based on association, it assesses the confidence in its association with the target vertebrate fossil. We developed this quality rating specifically for Australian applications, but it could be applied to other regions and to longer timescales with some modification. Our method ranks ages in four categories of reliability (A* and A are reliable; B and C are unreliable). In our case study of the late Pleistocene megafauna of Sahul, accounting for reliability (i.e., accepting only reliable ages) reduced the number of useful records within chronologies by 70 %; for most species, this greatly affects any inferences regarding the timing and possible drivers of extinction. Our method provides a simple, replicable and general tool for assessing the age quality of dated fossils, as well as provides a guide for selecting useful protocols and samples for dating.

Key words: Age reliability, quality control, dating techniques, fossil deposits, geochronology, archaeology, palaeontology, Quaternary

Introduction

Reliable dating of fossil remains is essential for resolving questions related to the timing of past events, and the construction of chronologies through different dating methods remains a research priority in palaeoecology (Seddon et al., 2014) and many other branches of Quaternary research. Dating techniques, and the laboratory and field protocols supporting them, have been refined over time (Ludwig and Renne, 2000; Wagner, 1998; Walker and Walker, 2005), so the veracity of age/event estimates are subject to continual reassessment (e.g., Gillespie and Polach, 1979; Schoene et al., 2006). Unfortunately, the uncritical use of unreliable ages has partially fuelled long-standing debates that compromise our understanding of fundamental issues such as the global spread of modern humans (e.g., Lima-Ribeiro and Diniz-Filho, 2013) or the disappearance of the Late Pleistocene megafauna (Brook et al., 2013; Sandom et al., 2014). Consequently, the evaluation of the quality of fossil ages should be a mandatory pre-requisite for any subsequent modelling, inference and interpretation of records of past life and human impacts.

Archaeologists and palaeontologists have proposed a range of quality-assessment methods, mainly tailored to the evaluation of radiocarbon ages across multiple sites (e.g., Barnosky and Lindsey, 2010; Graf, 2009; Mead and Meltzer, 1984; Pettitt et al., 2003; Spriggs, 1989; Waterbolk, 1971). However, none of these methods has been widely adopted, probably because of their restriction to radiocarbon dating or because the criteria were strongly dependent on particular studies, regions or time periods. In fact, all attempts to apply Pettitt and colleagues' (2003) or Graf's (2009) methods required their modification to fit the data available in a particular area of study (Seitsonen et al., 2012), because the approaches of those studies were highly specific (Seong, 2011). In the absence of a general system therefore, many researchers have developed *ad hoc* or tailor-made criteria based on, for example, percentage of gelatin collagen, C:N ratios of collagen, and percent nitrogen of

whole bone (Brock et al., 2010b; Mena et al., 2003), the specific chemical fraction dated from bone (Stafford et al., 1991), pre-treatment protocols and comparison with ages from other material (Petchey, 2000), and many other criteria (e.g., Perry et al., 2014).

In this paper we develop a quality-rating approach that was designed for application in Sahul (the combined landmass of Australia and New Guinea, including the areas of continental shelf exposed at lower sea levels) to interrogate the timing and potential environmental associations of the extinction of Australian megafauna. Consequently, we focus on five dating techniques applicable to ages from Middle Pleistocene (Ionian stage, ~ 781 to 126 thousand years before present, ka), Late Pleistocene (Tarantian stage, 126 to 11.7 ka) and Holocene epoch (11.7 ka to Recent) in Sahul. While our proposed criteria are not intended as a comprehensive assessment of all dating techniques and time periods, our system is sufficiently flexible that it can be applied to other geochronological settings or regions, making our method a generalized tool. Our aim is to provide users with a simple and replicable method for assessing the reliability of vertebrate fossil ages, thus allowing causative models of archaeological and environmental change to be tested openly and robustly.

Quality-rating criteria

Definitions necessary for understanding and applying our quality-rating scheme are provided in Table 1. The quality rating includes two sequential steps to classify the quality of an age in one of four final categories of reliability (A*, A, B or C). To illustrate the approach, we provide a decision tree (Figure 1). In the first step, the quality of the age is assessed depending on the dating procedure, placing the age into one of the four preliminary categories (m*, m, B or C); only indirect ages considered as reliable in the first step (m* and m categories) pass to the second step where the association of the dated remains with the

remains of the target vertebrate species is assessed. For assessing the quality of the dating, we categorized the different dating techniques and their protocols relative to our quality categories: m*, m, B and C (Tables 2–6). For assessing association, we describe different types and levels of association and the difficulties in determining if an age has close or unambiguous association with the fossil (*yes* in the decision tree), does not have such an association (*no* in the decision tree), or if the association is uncertain (*uncertain* in the decision tree) (see below).

Category A* is assigned to the most reliable ages. This category includes direct age estimates (i.e., on the fossil material itself) using the most appropriate, up-to-date dating protocols. **Category A** includes reliable indirect ages obtained using the most appropriate or just appropriate dating protocols on material that is not the fossil, but has a close or unambiguous association with it. This category also includes reliable direct ages where the quality of the dating technique is appropriate, but not ideal (i.e., lower compared to m*, see *Dating* section). **Category B** refers to direct ages that are unreliable due to sub-optimal dating protocols, or indirect ages dated with appropriate methods but with uncertain association. **Category C** ages are unreliable because of out-dated protocols or material unsuited to the dating technique used, or indirect ages with appropriate dating, but with no association.

All of our quality-rating criteria depend on the information published along with the fossil ages. Factors to consider include the description of depositional processes and reporting of error and inconsistencies. We caution that when a study that published reliable ages according to our criteria is followed by a more detailed study of the same depositional context within the same deposit, two or more reliable ages for the same sample or target species might persist in the literature. In such situations, the age published with the more reliable category and more detailed information should prevail.

Below we describe the application of our quality rating according to the two criteria: (1) dating procedure and (2) association with the fossil.

Dating

Radiocarbon (^{14}C) dating (Table 2)

Radiocarbon dating can provide reliable ages up to ~ 55 ka (Bird et al., 1999; Fairbanks et al., 2005; Turney et al., 2001) using both beta-counting and accelerator mass spectrometry (AMS) measurement techniques, alongside careful sample preparation. Beta-counting relies on the rate of radioactive decay of ^{14}C measured using a gas-liquid-scintillation counter, whereas AMS measures the number of ^{14}C atoms without having to wait for them to decay, and can date smaller samples than is practical using beta-counting. Both techniques have equivalent reliability (Hogg et al., 2006), so our quality-rating method for radiocarbon ages does not assign a better performance to one over the other.

Contaminants acquired after deposition affect materials used for dating, resulting in older or younger ages than the material's true age. Therefore, one must assess radiocarbon ages based on the type of '**pre-treatment**' used to remove those potential contaminants. Physical pre-treatment removes visible foreign substances and chemical pre-treatments remove extraneous materials according to their differential solubility in acids, alkalis, organic solvents and other reagents. The latter is arguably the most important aspect for ^{14}C dating and has been highly refined over time for most materials (Bird et al., 2014; Higham et al., 2006b; Ramsey et al., 2004; Wood et al., 2012).

We assigned an m* category to all ages of bone and dentin collagen processed using ultrafiltration, ninhydrin or XAD-2 protocols because they provide the most rigorous pre-treatment for contaminant removal on collagen samples (e.g., Higham et al., 2006a; Nelson, 1991; Stafford et al., 1988). We also assigned an m* to ages on individual amino acids

because they are well-defined chemical compounds that can be purified and characterized (Gillespie et al., 1984; Stafford et al., 1991). Collagen degradation or contamination can be checked through quantitative amino acids analysis and/or from the carbon nitrogen ratio (C:N) and percent nitrogen (% N) in comparison to reference values (Brock et al., 2010b; Stafford et al., 1991; Van Klinken, 1999). Where decalcified bone or tooth was dated and no information about collagen presence was provided in the publication, or when problems in collagen purification and isolation were reported, we assigned the ages to category B. Tooth enamel is not routinely dated by radiocarbon due to difficulties in extracting unaltered chemical components and, in common with apatite, its tendency to exchange carbon with secondary carbonates (Hedges et al., 1995).

By definition, we gave no higher than an m category to ages of ‘assorted remains’, because such ages can only be indirect ages for the target species. To be ranked m, charcoal had to be pre-treated to remove chemical contamination using strong oxidation reagents, such as acid chlorate (Gillespie, 1997) and acid dichromate (ABOX, Bird et al., 1999). These pre-treatments effectively remove contamination from charcoal samples when compared with other protocols, such as acid-base-acid (called ABA or AAA) or acid-wash only (Higham et al., 2009). Where only ABA or acid-wash was used, a B category was assigned. Alpha-cellulose is the most reliable material for dating plant remains because it does not exchange carbon with the environment following its formation (Ramsey, 2008). Thus, we assigned ages of cellulose isolated from wood, seeds or macrofossils an m category, while we gave m* to radiocarbon age estimates on purified cellulose isolated from gut contents or coprolites (e.g., Gillespie et al., 2008). All bulk soil organic samples were assigned to the C category because the composition of this material is unknown and contamination by younger or older carbonaceous material is common (e.g., Brock et al., 2010a; Gillespie et al., 2006).

We classified ages on biogenic carbonates (e.g., corals, shells) as B due to issues related to recrystallization and carbonate exchange (Chappell and Polach, 1972), but applied an m category if the carbonate fraction was dated or if recrystallization was assessed as insignificant through X-ray diffraction (e.g., Douka et al., 2010; Gillespie and Temple, 1977). Eggshell carbonate, such as from *Dromaius* (emu) or *Genyornis*, was assigned (like shell carbonate) to the B category, or to m* where stringent removal of secondary carbonate was done; we assigned the organic fraction to C because the low concentrations of primary organic molecules have proven difficult to isolate from traces of non-indigenous carbon-bearing molecules (Bird et al., 2003). We assigned all ^{14}C dating of inorganic calcite formations (e.g., speleothem, soil carbonates) to category C because of active chemical exchange of carbon with the environment (Hercman and Goslar, 2002), specially within the carbonate powder used, and the difficulties in calculating the dead-carbon fraction of these materials (Hua et al., 2012). We assigned all bulk soil organics to C because the carbon source and composition are unknown.

Amino acid racemization (AAR) dating (Table 3)

Racemization is the process by which chiral amino acids invert to their stereoisomer configuration after biological constraints are removed, usually with the death of an organism. The measurement of enantiomers of D-amino to L-amino acids (D:L ratio) in biogenic mineral provides a measure of relative age (Bada and Protsch, 1973) up to a maximum of 1 million years (Ma). As in most chemical reactions, the reaction rate depends on temperature. For fossils, the integrated history of temperature surrounding the remains since death, often referred to as the effective diagenetic temperature (EDT), defines the racemization rate for amino acids within the fossil. The time range over which the method is useful depends on EDT and the specific amino acid measured. For Australia, equilibrium of the slower

racemizing amino acids is reached in 150 to 300 ka, offering relative age indices for the entire Late Quaternary. The D:L ratio can be compared directly between fossils across limited geographic ranges over which the EDT is unlikely to differ by more than 1 °C. Independently reconstructing the integrated thermal history of a fossil is difficult, so conversion from D:L to age results in greater uncertainties. Most conversions rely on calibrations using other well-established dating techniques and models describing racemization kinetics (Clarke and Murray-Wallace, 2006; Miller et al., 1999). Consequently, relative ages based on D:L ratios were assigned a maximum category of m if: (*i*) multiple analyses were replicated within reasonable uncertainties, (*ii*) the dated remain behaved as chemically '**closed systems'** (i.e., no uptake or loss of amino acids substances, following the burial of the remains), and (*iii*) it was used to date directly (e.g., eggshell of target species). AAR ages were assigned an m* category if they met the above criteria and also (*iv*) had reliable calibration to independent dates obtained from independent dating techniques (e.g., Clarke et al., 2007; Miller et al., 1999).

AAR ages on burnt materials, or ages for which the thermal history was unknown or that had no local calibration were assigned to C. We assigned AAR ages from tooth and bone materials to B because their 'open system' behaviour can result in accumulation or leaching of amino acids (e.g., Grün, 2006).

Uranium-series dating (Table 4)

Ages of up to 500 ka can be estimated using the abundance of isotopes in the uranium decay chain. Dating of bone and tooth remains with U-series techniques has generally been avoided because of their 'open system' behaviour. However, recent developments have improved the reliability of using thorium to uranium (^{230}Th:^{234}U) ratios to determine age for teeth and, to a lesser extent, bone (e.g., Eggins et al., 2005; Grün et al., 2014; Grün et al., 2006; Pike et al.,

2002; Sambridge et al., 2012). Such novel approaches quantify these ratios across sections of bone or tooth, and compare U-profiles through the sections with models of uranium diffusion and adsorption. Therefore, to rank bone and tooth ages in the m category, U-series profiling and modelling is required, based on continuous profiles or spot sampling using laser-ablation inductively coupled plasma-mass spectrometry (ICP-MS) or thermal ionization mass spectrometry (TIMS).

Alternatively, ‘closed-system’ behaviour can be supported by the concordance between ^{230}Th and ^{231}Pa (protactinium) ages (the latter being a radioisotope in the ^{235}U chain) or through a comparison of ^{230}Th:^{234}U and ^{231}Pa:^{235}U age diagrams (e.g., Cheng et al., 1998). Note that U-series dating is based on the uptake of uranium by the fossil remains post-mortem, so neither ^{230}Th nor ^{231}Pa disequilibrium dating provide ‘direct’ ages for the fossil remains. We assigned an m category to U-series ages of demonstrated closed-system teeth of target species or teeth with profiling and modelling, whereas all bulk bone or tooth assays, including alpha and gamma spectrometry measurements, were assigned a C because their materials are subject to uncertainties in the absorption/diffusion of uranium and their ‘true’ isotope ratios can be masked by contaminants. For teeth, an m* can be assigned if U-series dating is combined with ESR dating, which provides additional constraints on the likely uranium uptake history of the dental tissues.

A range of other materials can also be dated with U-series dating. Thus, ages on eggshell with good integrity measured using TIMS were assigned an m* due to their demonstrably closed-system behaviour (Miller et al., 1999), and we assigned an m category to other closed-system materials, such as speleothems, gypsum and halite crusts, when assessed via ICP-MS or TIMS and corrected for detrital thorium contamination (Kaufman, 1993).

Electron spin resonance (ESR) dating (Table 5)

This technique, like luminescence dating (see next section), is based on the observation that the radiation energy trapped in mineral crystals increases with time. The technique can estimate ages for tooth enamel of up to 1 Ma. There are some potential complications with ESR dating that can alter the quality of an age. Uncertainties in the determination of the amount of environmental radioactivity experienced by the remains (the dose rate) are potentially the most serious because the effects of radioactivity on materials can be complex, and in many situations the dose rate cannot be determined easily (e.g., Grün et al., 2006; Rink, 1997). Ideally, the dated material and surrounding deposits should form a geochemically closed system with regard to the relevant radioisotopes. But teeth are prone to the uptake of uranium after burial, and the history of uranium uptake (and sometimes later uranium loss) commonly cannot be reconstructed easily or in its entirety. Two main models have been suggested as possible age constraints for ESR dating of teeth: the early U-uptake (EU) model assumes that uranium accumulates shortly after burial of the tooth, whereas the linear U-uptake (LU) model is based on the premise that uranium steadily accumulates throughout the period of tooth burial (Ikeya, 1982). It is often assumed that the ages of most samples lie somewhere between EU and LU estimates, although this might rarely be true in practice (Grün, 2006). To deal with this problem, Grün et al. (1988) proposed an innovative coupled U-series/ESR model (US-ESR), involving a combination of ESR and U-series ($^{230}Th/^{234}U$) dating that allows for model constraints to be placed on the history of post-mortem U-uptake. Hence, we assigned an m category to EU and LU ages modelled using a specific U-uptake parameter (*p*-value) derived from U-series estimates (Grün et al., 1988). Such ages are considered the youngest possible ages for tooth enamel, provided there was no later loss of uranium (Grün, 2006). When U-leaching is the dominant process, *p*-values cannot be calculated, so Grün (2000) also developed the closed-system U-series/ESR model

(CSUS-ESR) for tooth enamel. This model makes the assumption that all of the uranium migrated into the tooth sample at the time indicated by the closed-system U-series age and, thus, provides the oldest possible age for the tooth (Grün, 2006). We assigned CSUS-ESR ages an m* category and US-ESR an m because the latter is prone to any U-leaching that is particularly likely in teeth.

If there is no uranium in the dentine or enamel, we assigned an m* category to the ESR tooth ages if the internal dose rate accounts for < 10% of the total dose rate and the gamma dose rate was measured *in situ*. Alternatively, we assigned an m category if the internal dose rate is < 10% of the total and the external dose rate was measured in the laboratory, because in the laboratory it is not possible to measure the inhomogeneous radioactivity and water content present in the environment, and the gamma dose rate is usually reconstructed from sediment attached to the tooth, which generates large errors (Grün, 2006). Samples with internal dose rates > 10% were assigned to category B.

Luminescence dating (Table 6)

Luminescence dating is a term that embraces several related methods, including optically stimulated luminescence (OSL) and thermoluminescence (TL), that can be applied to time periods of up to 1 Ma in favourable circumstances, but more commonly to the last 250 ka. Quartz and potassium-rich feldspar grains are the minerals usually chosen for luminescence dating, being ubiquitous in a range of sedimentary settings (Aitken, 1998; Lian, 2013; Ludwig and Renne, 2000; Wintle, 2014). The depositional history of the sediment also needs to be considered because in some contexts (see below) it is desirable to measure individual grains of quartz, rather than single aliquots containing several tens to thousands of grains, to determine the equivalent dose for the dated material (e.g., Duller, 2008; Jacobs and Roberts, 2007; Roberts et al., 2015).

OSL measurements on single grains are particularly useful in depositional contexts where disturbance is a possibility or where there is inhomogeneous bleaching of the material at the time of deposition, because these two factors can skew the luminescence ages if their presence is not identified prior to calculating an age (e.g., pitfall trap sites; Prideaux et al., 2010). The potential influence of these factors varies among sites and samples, so each sample should be assessed individually. In cases where single-grain dating is not necessary or is not feasible, and where stratigraphic integrity can be assured and sediment mixing discounted, then single-aliquot OSL or multiple-aliquot TL dating can provide accurate ages. Therefore, we assigned an m category to ages on sediment that were based on (*i*) single-grain OSL, single-aliquot OSL or multi-aliquot TL dating of sediments that can be inferred to be well-bleached (e.g., from radial plots of D_e values), or where the context would support the high likelihood of the sediments being fully bleached at deposition (e.g., aeolian dunes), or (*ii*) single-grain OSL ages that can be modelled to obtain a robust estimate of equivalent dose for other samples. Single-aliquot OSL or multi-aliquot TL ages on mixed or partially bleached sediments, and single-grain OSL ages that cannot be modelled, were assigned a C category.

Association

Once an age has been assigned to one of the four categories of reliability according to the dating technique and protocols used, those ‘indirect ages’ categorized as reliable (m* and m) pass to the next step to check their association with the target species. ‘Direct ages’ do not need to be assessed by association because they are the result of directly dating the remains of the target species. Some processes acting on fossils and sediments can nullify the association: (*i*) reworking of fossils and other materials and (*ii*) lack of stratigraphic integrity (Table 1).

Also, such processes have associated uncertainties and exceptions that can make controlling for association difficult.

When indirect ages are from 'body remains', the most certain association is when both the dated remains and the remains of the target species are articulated skeletons, because this indicates a lack of reworking (*yes* in the decision tree; Figure 1)—in the best case, with element articulation. When some dated remains in the context have articulation or associated elements but the remains of the target species are disarticulated elements, or vice versa, there is a need to consider the possibility of reworking. If the disarticulated elements have been reworked, then there can be no confirmed association (*no* in the decision tree; Figure 1). The most undesirable association is when dated and target remains are disarticulated elements, because both could have experienced reworking.

When indirect ages are from 'assorted remains', the most certain association comes from dating the sediment that forms the depositional context of articulated remains of the target species. Assorted remains do not have articulation so that status can only give reworking information for the target species' remains. However, some assorted remains can show greater evidence of perturbation than others. For example, a layer of hearth charcoal is better than an isolated fragment of charcoal because the first suggests a lack of reworking and stratigraphic integrity, whereas the latter might have been dispersed.

There is no association when there is no stratigraphic control or any lack of stratigraphic integrity that affects the depositional context of the target species (then, *no* in the decision tree; Figure 1). When there is no information related to the remains and the depositional context, or no association decision can be made from the available information, we default to an uncertain association (*uncertain* in the decision tree; Figure 1).

Our quality criteria include three sub-categories that are independent of the categories indicating age reliability. The sub-categories specify the context of any reliable indirect age

and are particularly important when dated remains are placed in a different depositional context than the target fossils. They are also useful in providing age constraints (bracketing ages for target species' fossils) and complementing chronological information of a deposit.

Sub-category 'a' ('after or above') corresponds to indirect ages where the dated remains were deposited after the remains of the target species; these are frequently obtained from materials excavated from a depositional context overlying the target species, and should thus be treated as an upper bound or minimum age. **Sub-category 'b'** ('before or below') includes indirect ages in which dated remains were deposited before the remains of target species accumulated or, ages from a depositional context underlying the target species; these should be treated as a lower bound or maximum age. **Sub-category 'w'** ('within layer') indicates indirect ages where the dated remains were deposited in the same depositional context as the remains of the target species. Ages within sub-categories 'a' and 'b', although reliable and providing some useful information, cannot date the target species precisely because these ages are older or younger than the evidence of the target species. Depending on the statistical method selected for calculating the dates of an environmental event (e.g., inferring the extinction time), these ages should be omitted from or included in the time-window analysis or modelling because they only provide one bound of the uncertainty window. For instance, Bayesian chronology models (Parnell et al., 2011) require stratigraphic information such that upper- and/or lower-bound ages can be included as deposition limits to the prior distributions (Macken et al., 2013). On the other hand, frequentist Signor-Lipps-correction methods require only the estimated date limits for a focal species' time series, with the interval between records being one the most influential parameters dictating model performance (Saltré et al., 2015). Hence, including an indirect age or one from the same stratigraphic context will have major implications for estimating extinction time.

Minimum and maximum ages

Many dating techniques can yield minimum or maximum ages. For radiocarbon dating, minimum ages usually apply to samples that lie beyond the time range of the technique or when samples are too small [e.g., > 17,600 BP (ANU-145A) "because of a small amount of carbonized wood capable of being hand-picked from sample" (Polach et al., 1969)]. For U-series dating, minimum ages apply when the ^{230}Th:^{234}U ratio in a sample reaches equilibrium, and coupled U-series/ESR ages are regarded as minimum ages to allow for the possible delay in U-uptake by teeth after burial. Many of these ages are reliable, but a minimum or maximum age is of modest value compared to a finite age when estimating extinction times. Such ages, as well as those rated with 'a' and 'b' sub-categories, should be treated with caution and, depending of the requirement of the statistical techniques applied to them, can be used or not for timing inferences. They can provide upper or lower age constraints on datasets, thereby complementing chronologies built primarily on finite age estimates.

Fossil ages and megafauna extinctions in Sahul

Debate continues on the relative role of humans (through habitat alteration and/or hunting) and climate (e.g., increased aridity) in the global extinctions of Late Pleistocene megafauna (Parnell et al., 2011) and this is particularly the case in Sahul because the times of arrival of humans and extinction of the megafauna took place earlier than in other continents (> 40 ka BP). Direct evidence for the co-existence of humans and megafauna can be obtained mostly from the co-occurrence of bones and implements (ideally with evidence of interactions, such as cut marks or marrow extraction), but interpretation is challenging even where such data are abundant (e.g., the Clovis occupation of North America) (Grayson and Meltzer, 2002) . In Sahul, such co-occurrence has been suggested for only a few sites (Field et al., 2008) and, it has been argued that the number and quality of available chronologies is too sparse and

individually problematic for unravelling extinction mechanisms (e.g., Brook et al., 2013; Gillespie and Brook, 2006; Gillespie et al., 2006). We addressed such expectations by calculating the frequency of our four categories in the set of ages cited in case studies advocating climate or humans as the main driver of Sahul megafauna extinctions in publications up to and including 2013, and by re-constructing the time series of Tasmanian devils (genus *Sarcophilus*) and Pleistocene kangaroos (of the genus *Simosthenurus*) using all available published records.

Six studies over two decades have concluded that the main driver of megafauna extinctions was climate variability (Dortch, 2004; Field and Dodson, 1999; Horton, 1980; Lundelius, 1983; Price et al., 2011; Wroe et al., 2013), using 164 megafauna ages to support this claim. Seven studies over the same period have advocated humans as the main driver (Gillespie, 2008; Gillespie et al., 2006; Johnson, 2005; Miller et al., 2005; Miller et al., 1999; Prideaux et al., 2010; Turney et al., 2008), taking into account 802 ages. The proportions of reliable ages (A* and A) in papers advocating the primary role of climate or humans in megafauna extinctions were 11 and 76 %, respectively (Figure 2).

As to chronological reconstructions, only 36 of the 138 (26 %) *Sarcophilus* ages (Table S1.) and 38 of the 98 (39 %) *Simosthenurus* ages (Table S2) were assigned to the two reliable categories A* or A (Figure 3). Of particular importance was the observation that application of the quality-rating scheme to all dates shifted the youngest (reliable) fossil age from 420 years to 25.5 ka for *Sarcophilus*, and from 11.5 ka to 44.9 ka years for *Simosthenurus*. The latter chronology had two reliable ages younger than 44.9 ka (33.6 and 35.4 ka), but both were indirect ages from sediments deposited after (overlying) the *Simosthenurus* fossils. These ages, therefore, fall into sub-category ‘a’, meaning that a *Simosthenurus* individual buried some (unknown) time before the dated sediments were deposited, and so as indicated above, such ages should be treated with caution depending on the statistical model applied.

The number of reliable ages increased sharply prior to ~ 40.5 ka for *Sarcophilus* and ~ 55 ka for *Simosthenurus*, and they were mainly estimated by OSL and U-series techniques. Most of the rejected younger ages were from materials dated by radiocarbon using inappropriate pre-treatment protocols, unsuitable dated materials and/or a lack of collagen (Table S1 and S2).

Discussion

We have presented a generally applicable and easily used, two-step quality-rating system for Middle Pleistocene and later vertebrate fossil ages that resolves into four categories of reliability. Using our criteria, a researcher can evaluate the quality of any vertebrate fossil ages (including humans) from a wide range of types of remains (e.g., bones, artefacts, sediments), dated materials (e.g., collagen, quartz, cellulose), deposits (e.g., lacustrine, caves), depositional contexts (bone-bed, eroded or perturbed, multi-layer), laboratories (e.g., ANU, SUA or OxA) and sources (reports, peer-review publication), tailored to the current generation of dating techniques (radiocarbon, amino acid racemization, luminescence, ESR and U-series). Our approach also constitutes a template that, with modification and elaboration, could be used to develop analogous methodologies for deeper-time chronologies and to regions other than Sahul.

The two highest-quality categories (A* and A) comprise direct ages on fossils of the target species and ages obtained from other materials that can be associated confidently with the fossils – ideally based on association with articulated skeletons. Such ages are estimated using state-of-the-art protocols and measurement techniques. Ages rated in categories B and C are unreliable because they are estimated using inaccurate or obsolete dating protocols and/or from remains in dubious association with the target species; we therefore recommend not using such ages in modelling and inference. Our additional three sub-categories of

association highlight ages that, although reliable, should be treated with caution in terms of inclusion or omission in temporal modelling, as should minimum and maximum ages. In the absence of body remains, archaeologists can infer the presence of *Homo* spp. using indirect signs such as artefacts, hearth charcoal, shell middens, rock art, and bone cut marks (Williams et al., 2014), just as palaeontologists can infer the presence of predators based on teeth marks on bone (Sobbe, 1990). The criteria presented here can therefore also be used to determine the quality rating of ages where no fossils are present, although a greater effort in assessing association is required.

Our approach is not meant to be rigid, but should instead be considered as open to refinement as dating technology progresses and researchers test existing and improved protocols and incorporate these into new or updated age datasets. To improve our method, we encourage future research comparing our quality rating and those developed by others and addressing how interpretations change by the use of our rating, including revisiting chronologies of controversial sites and competing hypotheses, and independent applications of the scheme on the same dataset to check for consistency of application and thereby highlight ambiguities. It is also clear that full details on sampling of dated remains, their association with the target species' remains and the protocols used in the estimation of ages need to be published more consistently than is currently typical. In addition, researchers making inferences based on fossil ages should include statements of the age quality and, when using a quality-rating scheme, providing a description of their application. Failure to do so can hinder progress on topics such as the long-standing debate on the drivers of megafauna extinctions. For Sahul, we show that the chronology emerging from the compilation of published ages of *Sarcophilus* and *Simosthenurus* fossils is strongly biased towards the recent by the disproportionate number of unreliable young ages, with major implications for accurately inferring their extinction times (Bradshaw et al., 2012; Saltré et al., 2015). Further,

we showed that the relative frequency of reliable ages is notably higher in studies that have postulated humans as the key factor in the extinctions of Late Pleistocene megafauna in Sahul than in studies arguing for climate. Much of the debate has therefore been focussed on studies that have lacked control for data quality, in turn stressing the need to revisit the strength of evidence for such scenarios of extinction.

With the recent emergence of the field of conservation palaeobiology, fossil-based chronologies also provide a crucial source of baseline information needed to assess the vulnerability of extant species and ecosystems (Dietl and Flessa, 2011) in the Anthropocene (Steffen et al., 2011). The quality rating we propose constitutes a potentially important tool not only for studying past events but also for contextualizing the relevance of those events for present and future conservation management and restoration.

A crucial aspect of our criteria is the acknowledgement that some dating protocols are consistently more reliable than others. Dating fossils can often be expensive and require lengthy methodological protocols, forcing researchers to make decisions on the choice of dating method(s) and protocol(s) to ensure the timely and cost-effective progress of their projects. We hope our criteria will guide researchers to allocate their resources efficiently, while sponsors and funding agencies can likewise gauge the feasibility of different options with regard to proposed dating protocols as one of the aspects to support funding.

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Table 1. Definitions for the reliability criteria

Term	*Definition*
Age (estimate)	Estimated value of age along with the error bounds that result from dating (e.g., 10 ± 1 ka). Age is sometime termed 'date'.
Body remains (fossil)	Part of a vertebrate body (e.g., bones, teeth, hair, skin, otoliths) or its internally-derived products (e.g., gut contents, coprolites, eggshells).
Assorted remains	Remains different from vertebrate body parts, such as artefacts, charcoal, wood, corals, halite crusts, footprints, shells, seeds, speleothems and other minerals (e.g., quartz, feldspar, gypsum).
Target species	Vertebrate taxon that owns the age under assessment.
Direct ages	Ages on body remains of the target species.
Indirect ages	Ages not on remains of the target species but can potentially be used to date the target species based on association.
Association	Physical (e.g., stratigraphic) relationship between the fossil of a target species and the dated remain based on the premise that, if there is no evidence of disturbance, remains buried at the same time have the same age.
Depositional context	Physical setting within which fossils are located.
Reworking	Displacement of remains from their original depositional context. Reworking can be caused by natural processes or human activities, and might be immediately *post mortem* or due to later erosion and transport.
Stratigraphic integrity	Persistence of sedimentary layers and their contents in the sequence in which they were originally deposited, without subsequent disturbance.
Articulation	Degree to which skeletal elements maintain a close approximation of the joint articulations an organism possessed while alive. We differentiate three degrees of articulation:

i)	'*element articulation*': skeletal remains that are still joined, and all remains can be identified as elements of the skeleton. Although uncommon, this state of fossil preservation provides compelling evidence that the specimen is in its final resting place and the remains are not reworked.
ii)	'*separated articulation*', or '*associated elements*' refer to skeletons or partial skeletons where elements within a stratigraphic layer are no longer articulated, but are found close together and can be identified as belonging to an individual.
iii)	'*disarticulated elements*' are isolated body-fossil elements that maintain no proximate trace of the rest of the body within a stratigraphic layer. This situation entails more uncertainties about the original depositional context of a specimen, and alternative taphonomic or chemical evidence is required to eliminate the possibility of reworking.

Table 2. Application of dating criteria for **radiocarbon** ages of vertebrate fossils.

Dating technique	Dated remain/material	m*	m	B	C
radiocarbon (**^{14}C**) **detection limit = 55 ka**	bone collagen dentin collagen	- collagen preservation checked with C:N ratio and % N and using ultrafiltration, XAD-2, ninhydrin pre-treatments - dating on individual amino acids and using ultrafiltration, XAD-2, ninhydrin pre-treatments		- ABA, AAA or acid-wash pre-treatments - decalcification but no info about collagen presence on bone or dentine - collagen purification difficulties reported	- mixture of multiple bones or teeth
	wood seeds		- dating of alpha-cellulose isolated from plant remains		
	gut contents coprolites	- dating of alpha-cellulose isolated from digestive remains			

	corals, shells		- dating of carbonate fraction if outer surfaces removed with mechanical grinding and acid wash, and if X-ray diffraction shows that recrystallization is insignificant	- dating without treatment and x-ray diffraction analysis	
	eggshells	- dating of carbonate fraction with stringent removal of secondary carbonate with grinding and acid etching		- dating without treatment	- organic fraction
	charcoal		- ABOX and chlorate oxidation pre-treatments	- ABA, AAA or acid-wash pre-treatments	
	Inorganic calcite (speleothem, soil carbonate) bulk soil organics	not acceptable	not acceptable	not acceptable	not acceptable

Table 3. Application of dating criteria for **amino acid racemization** ages of vertebrate fossils.

Dating technique	Dated remain/material	m*	m	B	C
amino acid racemization (AAR) **detection limit = 1Ma**	eggshell otolith	- direct date on the target species - absolute age requires demonstrated closed-system behaviour and multiple analyses replicated within low uncertainties and calibration using independent dating techniques and models describing racemization kinetics	- direct date on the target species - relative age on demonstrated closed-system material and multiple analyses are replicated within low uncertainties within a limited geographic region (mean annual temperature range < ± 1 °C)		- unknown thermal history - burnt materials - no local calibration
	bone tooth	not acceptable	not acceptable	not acceptable	not acceptable

Table 4. Application of dating criteria for **uranium-series** ages of vertebrate fossils.

Dating technique	**Dated remain/material**	**m***	**m**	**B**	**C**
Uranium-series **detection limit = 500 ka**	tooth	- combined with ESR dating (see Table 5)	- demonstrated closed-system continuous profiles through tooth with laser-ablation ICP-MS, combined with U-uptake modelling - demonstrated closed-system spot sampling with ICP-MS or TIMS, combined with modelling	- ICP-MS or TIMS without modelling	
	bone		- continuous profiles through bone with laser-ablation ICP-MS, combined with uptake modelling - spot sampling with ICP-MS or TIMS, combined with modelling	- ICP-MS or TIMS without modelling	

	eggshell	- eggshell with stringent removal of secondary carbonate, acid wash, and ICP-MS or TIMS			
	closed-system of no body remains (e.g., speleothems, corals		- ICP-MS or TIMS with a detrital correction		

Table 5. Application of dating criteria for **electron spin resonance** ages of vertebrate fossils.

Dating technique	Dated remain/material	m*	m	B	C
electron spin resonance (ESR) **detection limit = 1 Ma**	tooth enamel	- direct age, combined ESR and closed-system U-series modelling (CSUS-ESR) - ESR ages with low U content in dentine and enamel (model independent); internal dose rate < 10% of total dose rate; gamma dose rate measured *in situ*	- direct age, EU and LU ages that are model dependent with a *p*-value derived from a U-series estimate (US-ESR) - ESR ages with low U content in dentine and enamel (model independent); internal dose rate < 10% of total dose rate; gamma dose rate assumed from sediment attached to tooth	- early U-uptake model (EU) and linear U-uptake model (LU), with no U-series constraint on the possible history of U-uptake - ESR ages with low U content in dentine and enamel (model independent); internal dose rate > 10% of total dose rate	

Table 6. Application of dating criteria for **luminescence** ages of vertebrate fossils.

Dating technique	Dated remain/material	m*	m	B	C
Luminescence **detection limit = 1 Ma**	sediment		- single-grain OSL ages for well-bleached or partially bleached sediments that can be modelled - single-grain OSL, single-aliquot OSL or multi-aliquot TL ages on demonstrated well-bleached sediments or sediments with high likelihood of being fully bleached at deposition. Resetting of the luminescence signal needs to be demonstrated explicitly		- single-grain OSL ages that cannot be modelled - single-aliquot OSL or multi-aliquot TL ages for mixed or partially-bleached sediments
	organic material (e.g., bone)	not acceptable	not acceptable	not acceptable	not acceptable

Figure legends

Figure 1. Quality-rating decision tree representing the two sequential steps for allocating an estimated age to four categories of reliability. In the first step, age reliability is assessed based on dating techniques and protocols resulting in one of four categories (m*, m, B, C). In the second step, only reliable (m* and m) indirect ages are assessed for association, which has three outcomes (*yes* = A, *uncertain* = B, and *no* = C) so indirect ages with appropriate dating and association can be assigned an A at best. Only direct ages can receive an A* category of reliability.

Figure 2. Percentage of fossil ages (*y*-axis) assigned to each of the quality-rating categories (A*, A, B and C, from high to low reliability) in the literature advocating or dismissing climate or humans as the key driver of Sahul megafauna extinctions during the Middle Pleistocene to Holocene (*x*-axis).

Figure 3. Time-series of all published ages of Tasmanian devil genus *Sarcophilus* (left) and short-faced kangaroo genus *Simosthenurus* (right) fossils from Sahul (Tables S1 and S2), showing the temporal sequence of fossils from youngest to oldest ages (*y*-axis) against logarithmic ages (ka) ± 1 standard deviation (*x*-axes). High-reliability categories (A* and A) are in dark grey and low-reliability categories (B and C) are in light grey. Arrows point to the most recent reliable ages for both genera. Published, uncalibrated radiocarbon ages were calibrated using the SHcal13 curve in Oxcal 4.1 (Ramsey, 2010).

Figure 1

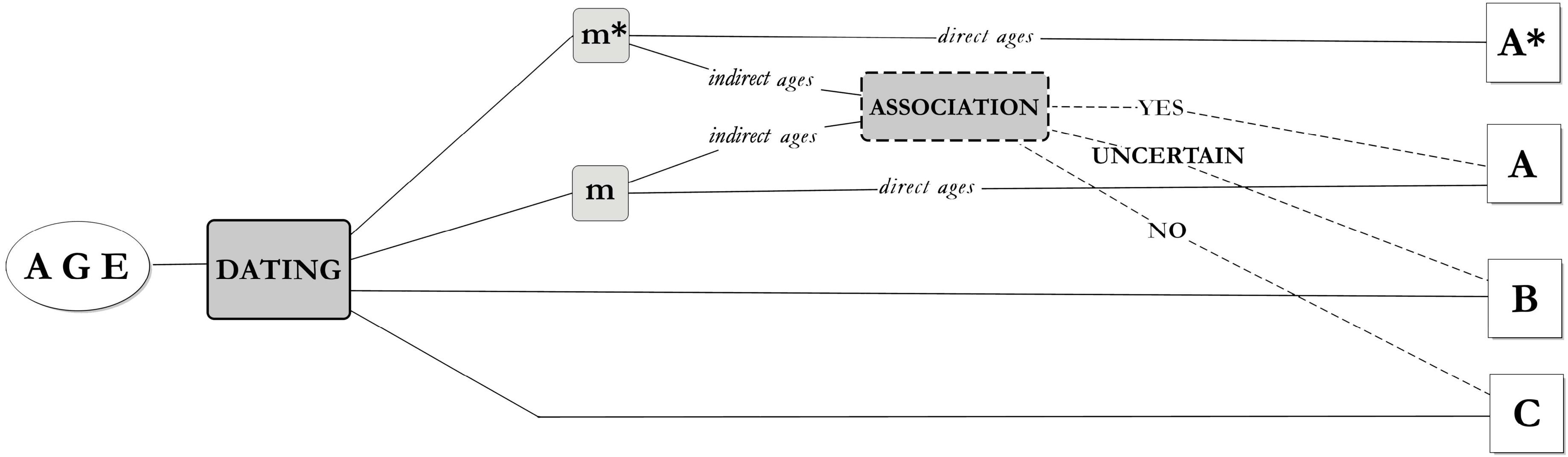

A G E
DATING
m*
m
direct ages
indirect ages
indirect ages
direct ages
ASSOCIATION
YES
UNCERTAIN
NO
A*
A
B
C

Figure 2

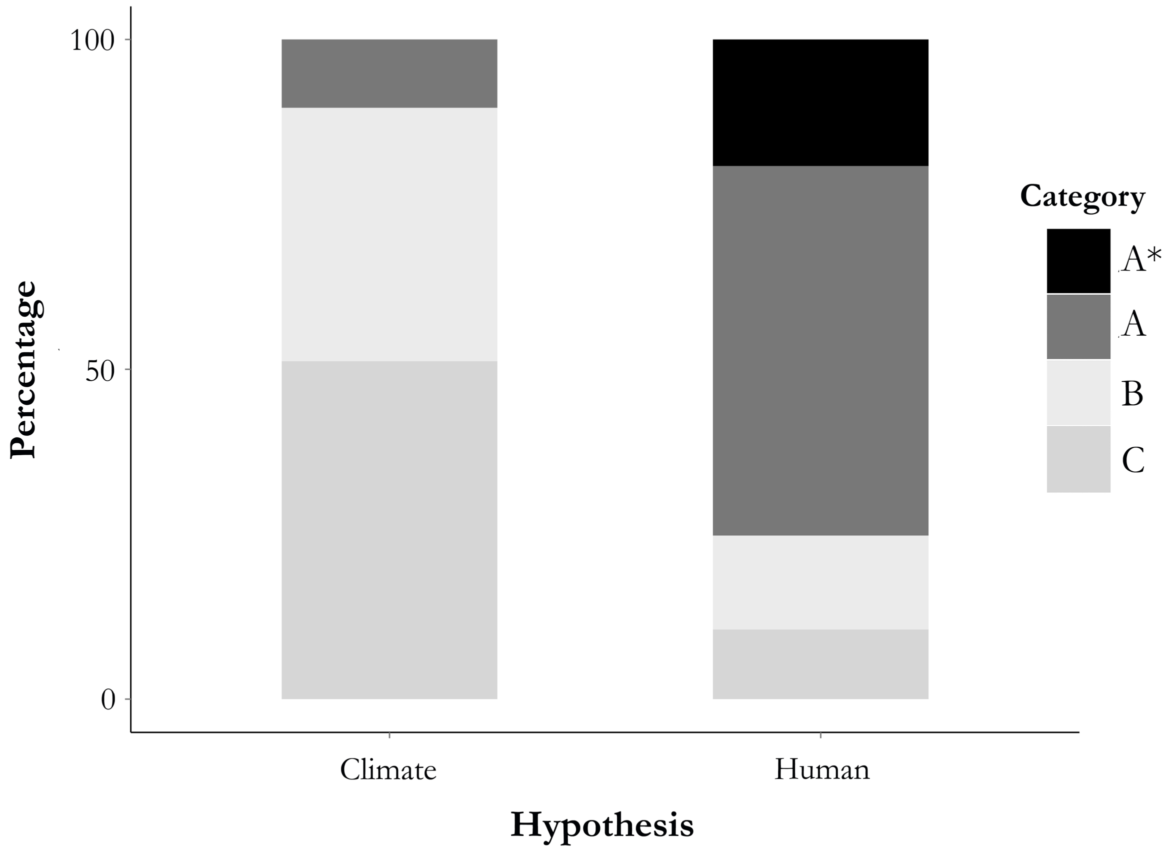
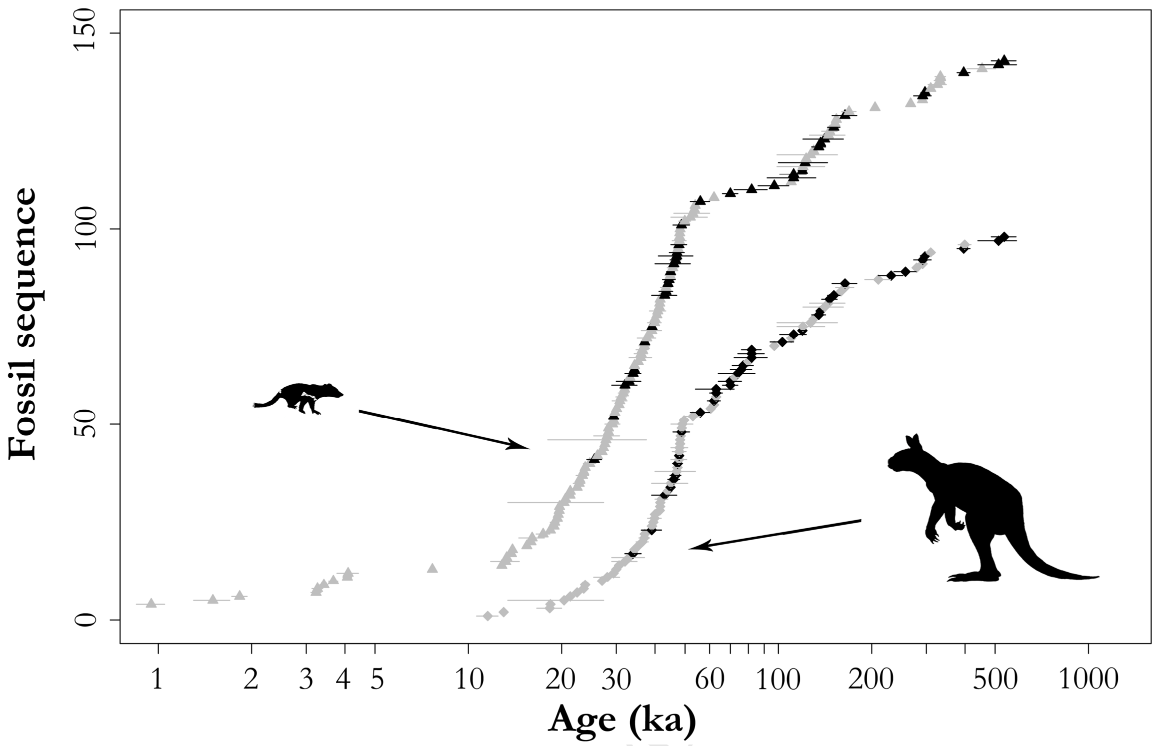

100
50
0
Percentage
Climate
Human
Hypothesis
Category
A*
A
B
C

Figure 3


Fossil sequence
0
50
100
150
1
2
3
4
5
10
20
30
60
100
200
500
1000
Age (ka)

Highlights

- Reliability of ageing fossil material is a major constraint in the correct interpretation of palaeontological and archaeological events
- We present a quality-rating guide for assessing the age reliability of vertebrate fossils
- Dates are assigned one of four categories of reliability (A* & A are reliable ages, while B & C are unreliable)
- Our method can be easily applied to other regions and geochronological settings

Genus	AgeID	Dated remain/material	Dating technique	Age	Estimate Type	Precision	Quality Category	Quality Sub-category	Refence
Sarcophilus	AG-27	Bone	AAR (Asparctic acid)	40.000	=	na	C	*null*	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary b
Sarcophilus	AG18	Bone	AAR (Asparctic acid)	110.000	=	na	C	*null*	Murray, P.F., Goede, A., Bada, J.L., 1980. Pleistocene human occupation at
Sarcophilus	AG14	Bone	AAR (Asparctic acid)	130.000	=	na	C	*null*	Murray, P.F., Goede, A., Bada, J.L., 1980. Pleistocene human occupation at
Sarcophilus	ANUA-10313	Sediment Charcoal	AMS radiocarbon	24.300	=	0.30	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	OZG-540	Sediment Shell (*Velesunio ambiguus*)	AMS radiocarbon	30.300	=	0.50	B	*null*	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	SUA-885b	Eggshell	AMS radiocarbon	35.900	=	2.17	B	*null*	Williams, D.L.G., 1981. Genyornis eggshell (Dromornithidae; Aves) from th
Sarcophilus	OZG-548	Sediment Shell (*Velesunio ambiguus*)	AMS radiocarbon	44.300	>	2.20	B	*null*	Price, G.J., Sobbe, I.H., 2005. Pleistocene palaeoecology and environmental
Sarcophilus	OZD-538	Sediment Charcoal	AMS radiocarbon	45.200	=	1.80	B	w	Pate, F.D., McDowell, M.C., Wells, R.T., Smith, A.M., 2002. Last recorded e
Sarcophilus	OZG-547	Sediment Shell (*Velesunio ambiguus*)	AMS radiocarbon	49.900	>	2.20	B	*null*	Price, G.J., Sobbe, I.H., 2005. Pleistocene palaeoecology and environmental
Sarcophilus	OZD-323	Sediment Charcoal	AMS radiocarbon (ABA)	12.950	=	0.11	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-322	Sediment Charcoal	AMS radiocarbon (ABA)	13.300	=	0.12	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-325	Sediment Charcoal	AMS radiocarbon (ABA)	21.850	=	0.21	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-324	Sediment Charcoal	AMS radiocarbon (ABA)	23.050	=	0.25	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-326	Sediment Charcoal	AMS radiocarbon (ABA)	25.900	=	0.30	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-327	Sediment Charcoal	AMS radiocarbon (ABA)	38.800	=	1.75	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-330	Sediment Charcoal	AMS radiocarbon (ABA)	40.500	=	1.75	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	OZD-329	Sediment Charcoal	AMS radiocarbon (ABA)	41.500	=	2.00	B	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	Z-3370	Bone	ESR	27.000	=	na	C	*null*	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary b
Sarcophilus	B-2	Bone	ESR	310.000	=	na	C	*null*	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary b
Sarcophilus	MC1-k1	Sediment Quartz	OSL	1.500	=	0.20	C	*null*	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	MC1-k2	Sediment Quartz	OSL	13.200	=	1.40	C	*null*	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	DL-4	Sediment Quartz	OSL	25.500	=	1.40	A	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	TEC-H	Sediment Quartz	OSL	32.000	=	*3.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	na	Sediment Quartz	OSL	33.000	=	*3.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	TEC07–5	Sediment Quartz	OSL	34.000	=	*2.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	MC1-k3	Sediment Quartz	OSL	36.000	=	3.00	C	*null*	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	DL-8	Sediment Quartz	OSL	43.400	=	2.20	A	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	DL-7	Sediment Quartz	OSL	44.400	=	2.10	A	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	1	Sediment Quartz (90-125 microns)	OSL	46.000	=	6.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	1	Sediment Quartz (180-212 microns)	OSL	47.000	=	6.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	DL-19	Sediment Quartz	OSL	47.100	=	2.60	A	w	Turney, C.S.M., Bird, M.I., Fifield, L.K., Roberts, R.G., Smith, M., Dortch, C
Sarcophilus	14	Sediment Sediment (180-212 microns)	OSL	48.000	=	6.00	C	*null*	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	14	Sediment Quartz (90-125 microns)	OSL	52.000	=	7.00	C	*null*	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	14	Sediment Quartz (180-212 microns)	OSL	53.000	=	7.00	C	*null*	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	ST-1	Sediment Quartz	OSL	56.000	=	4.00	A	w	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	TEC–F	Sediment Quartz	OSL	70.000	=	*4.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	16	Sediment Quartz (180-212 microns)	OSL	82.000	=	10.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	11	Sediment Quartz (90-125 microns)	OSL	97.000	=	11.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	TEC-F	Sediment Calcite	OSL	112.000	=	*11.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	MU-206	Sediment Quartz	OSL	120.000	>	21.00	C	*null*	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	Risø-060702	Sediment Quartz	OSL	122.000	=	22.00	A	w	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	MU-203-205	Sediment Quartz	OSL	127.000	>	28.00	C	*null*	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Highar
Sarcophilus	TEC07–1	Sediment Quartz	OSL	135.000	=	*7.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	26	Sediment Quartz (90-125 microns)	OSL	141.000	=	21.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	?	Sediment Quartz	OSL	145.000	<	19.00	C	*null*	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.
Sarcophilus	19	Sediment Quartz (90-125 microns & 180-212 n	OSL	164.000	=	15.00	A	w (averaged)	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideau
Sarcophilus	NC4	Sediment Quartz	OSL	292.000	=	19.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.
Sarcophilus	NC5	Sediment Quartz	OSL	513.000	=	73.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.
Sarcophilus	NC6	Sediment Quartz	OSL	535.000	=	49.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.
Sarcophilus	GaK-2949	Sarcophilus Hair	Radiocarbon	0.430	=	0.16	C	*null*	Archer, M., Baynes, A., 1972. Prehistoric mammal faunas from two small ca
Sarcophilus	na	Sediment Charcoal	Radiocarbon	1.086	<	0.09	C	*null*	Mulvaney, D.J., Lawton, G.H., Twidale, C.R., Macintosh, N.W.G., Mahoney
Sarcophilus	na	Sediment Charcoal	Radiocarbon	1.931	<	0.09	B	w	Mulvaney, D.J., Lawton, G.H., Twidale, C.R., Macintosh, N.W.G., Mahoney
Sarcophilus	ANU-716	Sediment Charcoal	Radiocarbon	3.090	=	0.09	B	w	Archer, M., 1974. New information about the Quaternary distribution of the
Sarcophilus	NZ-1225	Bone (Femur) Collagen	Radiocarbon	6.820	=	0.20	B	*null*	Brown, P., 1987. Pleistocene homogeneity and Holocene size reduction: The
Sarcophilus	SUA-539	Sediment Charcoal	Radiocarbon	27.700	=	0.70	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	Not given	Sediment Charcoal	Radiocarbon	0.538	=	0.20	C	*null*	Gill, E.D., 1955. Aboriginal midden sites in Western Victoria dated by radio
Sarcophilus	GaK-3477	na	Radiocarbon	0.620	=	0.09	B	*null*	Gale, S.J., 2009. Event chronostratigraphy: A high-resolution tool for dating
Sarcophilus	ANU-17	Sediment Charcoal	Radiocarbon	3.120	=	0.10	B	w	Calaby, J.H., White, C., 1967. The Tasmanian devil (Sarcophilus harrisii) in r
Sarcophilus	na	na	Radiocarbon	3.240	=	0.08	B	w	Gale, S.J., 2009. Event chronostratigraphy: A high-resolution tool for dating
Sarcophilus	ANU-807	Sediment Charcoal	Radiocarbon	3.450	=	0.10	B	*null*	Milham, P., Thompson, P., 1976. Relative antiquity of human occupation an
Sarcophilus	na	na	Radiocarbon	3.750	=	0.24	B	w	Gale, S.J., 2009. Event chronostratigraphy: A high-resolution tool for dating
Sarcophilus	na	na	Radiocarbon	3.756	=	0.09	B	w	Gale, S.J., 2009. Event chronostratigraphy: A high-resolution tool for dating
Sarcophilus	ANU-925	Sediment Charcoal	Radiocarbon	10.940	=	0.16	B	w	Hope, J.H., Lampert, R.J., Edmondson, E., Smith, M.J., Tets, G.F.v., 1977. I
Sarcophilus	ANU-3013	Sediment Shellfish	Radiocarbon	11.500	>	0.09	B	*null*	Balme, J., 1990. A Pleistocene tradition: aboriginal fishery on the Lower Dar
Sarcophilus	SUA-102	Sediment Charcoal	Radiocarbon	11.960	=	0.14	B	w	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA-103	Sediment Charcoal	Radiocarbon	12.050	=	0.14	B	w	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA- 2215	Fireplace Charcoal	Radiocarbon	13.300	=	1.10	B	*null*	Brown, P., 1987. Pleistocene homogeneity and Holocene size reduction: The
Sarcophilus	GaK-6875	Sediment Charcoal	Radiocarbon	14.130	=	2.97	C	*null*	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary b
Sarcophilus	Wk-1366	Sediment Charcoal	Radiocarbon	14.400	=	0.69	C	*null*	O'Connor, S., 1989. New radiocarbon dates from Koolan Island, West Kiml
Sarcophilus	GaK-509	Bone Mixed mammal bones	Radiocarbon	15.200	=	0.32	C	*null*	Hope, J.H., Wilkinson, H.E., 1982. Warendja wakefieldi, a new genus of wor
Sarcophilus	ANU-2783	Fireplace Charcoal	Radiocarbon	15.670	=	0.53	B	w	Garvey, J.M., 2006. Preliminary zooarchaeological interpretations from Kuti
Sarcophilus	Wk-11487	Sediment Bulk soil organic matter	Radiocarbon	15.687	=	0.11	C	*null*	Forbes, M.S., Bestland, E.A., Wells, R.T., 2004. Preliminary 14C dates on bu
Sarcophilus	ANU-1221	Sediment Charcoal	Radiocarbon	16.110	=	0.10	B	w	Hope, J.H., Lampert, R.J., Edmondson, E., Smith, M.J., Tets, G.F.v., 1977. I
Sarcophilus	Wk-1367	Sediment Bulk soil	Radiocarbon	16.300	=	0.09	C	*null*	O'Connor, S., 1989. New radiocarbon dates from Koolan Island, West Kiml
Sarcophilus	Wk-11488	Sediment Bulk soil organic matter	Radiocarbon	16.326	=	0.39	C	*null*	Forbes, M.S., Bestland, E.A., Wells, R.T., 2004. Preliminary 14C dates on bu
Sarcophilus	na	Sediment Shellfish	Radiocarbon	17.000	=	5.00	B	*null*	Balme, J., 1990. A Pleistocene tradition: aboriginal fishery on the Lower Dar
Sarcophilus	ANU-2520	Sediment Shellfish	Radiocarbon	17.050	<	1.47	B	*null*	Balme, J., 1990. A Pleistocene tradition: aboriginal fishery on the Lower Dar
Sarcophilus	Wk-11489	Sediment Bulk soil organic matter	Radiocarbon	17.618	=	0.45	C	*null*	Forbes, M.S., Bestland, E.A., Wells, R.T., 2004. Preliminary 14C dates on bu
Sarcophilus	Pta-2506	Flowstone (overlaying) Calcite	Radiocarbon	17.670	=	0.18	C	*null*	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary b
Sarcophilus	na	Sediment Carbonaceous pellet	Radiocarbon	18.600	>	0.30	C	*null*	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.
Sarcophilus	GaK-335	Fireplace Charcoal	Radiocarbon	18.800	=	0.80	B	*null*	Tedford, R.H., 1955. Report on the extinct mammalian remains at Lake Mer
Sarcophilus	SUA-101	Sediment Charcoal	Radiocarbon	19.000	=	0.25	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA-33	Sediment Charcoal	Radiocarbon	19.250	=	0.90	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	na	Sediment Carbonaceous pellet	Radiocarbon	19.600	>	0.31	C	*null*	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.
Sarcophilus	Teledyne I-11018	Plant remains Leaf, seed and stem fragments	Radiocarbon	19.800	=	0.40	C	*null*	Flannery, T.F., Gott, B., 1984. The Spring Creek locality, southwestern Victo
Sarcophilus	SUA-32	Sediment Charcoal	Radiocarbon	20.400	=	1.00	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	ANU-1220	Sediment Charcoal	Radiocarbon	22.980	=	2.00	B	*null*	Flood, J., 1974. Pleistocene man at Cloggs Cave: his took kit and environme
Sarcophilus	SUA-31	Sediment Charcoal	Radiocarbon	24.600	=	1.50	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA-685	Sediment Charcoal	Radiocarbon	25.200	=	0.80	B	*null*	Gillespie, R., Horton, D.R., Ladd, P., Macumber, P.G., Rich, T.H., Thorne,
Sarcophilus	LJ-204	Fireplace Charcoal	Radiocarbon	26.300	=	1.50	B	*null*	Tedford, R.H., 1955. Report on the extinct mammalian remains at Lake Mer
Sarcophilus	SUA-538	Sediment Charcoal	Radiocarbon	26.600	=	0.65	B	*null*	Gillespie, R., Horton, D.R., Ladd, P., Macumber, P.G., Rich, T.H., Thorne,
Sarcophilus	Wk-1365	Sediment Marine shell	Radiocarbon	26.850	=	1.10	B	*null*	O'Connor, S., 1989. New radiocarbon dates from Koolan Island, West Kiml
Sarcophilus	Wk-1365	Sediment Marine shell	Radiocarbon	27.300	=	1.10	B	*null*	O'Connor, S., 1989. New radiocarbon dates from Koolan Island, West Kiml
Sarcophilus	SUA-457	Sediment Charcoal	Radiocarbon	31.400	=	1.50	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	Tx-31	Sediment Charcoal	Radiocarbon	31.500	>	0.00	C	*null*	Merrilees, D., 1979. The prehistoric environment in Western Australia. Journ
Sarcophilus	SUA-546	Sediment Charcoal	Radiocarbon	31.800	na	1.40	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA-585	Sediment Charcoal	Radiocarbon	32.480	=	1.25	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	ANU-5328	Sediment Charcoal	Radiocarbon	32.500	=	2.10	B	*null*	Dawson, L., Augee, M.L., 1997. The late Quaternary sediments and fossil ve
Sarcophilus	ANU-5327	Sediment Charcoal	Radiocarbon	33.800	=	0.20	B	*null*	Dawson, L., Augee, M.L., 1997. The late Quaternary sediments and fossil ve
Sarcophilus	SUA-234	Sediment Charcoal	Radiocarbon	33.800	=	*2.40*	B	w	Pledge, N.S., 1990. The upper fossil fauna of the Henschke fossil cave, Nara
Sarcophilus	SUA-586	Sediment Charcoal	Radiocarbon	35.160	=	1.80	B	*null*	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remain
Sarcophilus	SUA-885a	Eggshell	Radiocarbon	35.900	=	2.98	C	*null*	Williams, D.L.G., 1981. Genyornis eggshell (Dromornithidae; Aves) from th
Sarcophilus	OZG-852	Sediment Charcoal	Radiocarbon	36.000	=	1.20	C	*null*	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	O-657	Sediment Charcoal	Radiocarbon	37.000	>	0.00	C	*null*	Merrilees, D., 1979. The prehistoric environment in Western Australia. Journ
Sarcophilus	OZM-084	Bone (right femur) Collagen	Radiocarbon	40.510	=	0.38	A*	*null*	Gillespie, R., Camens, A.B., Worthy, T.H., Rawlence, N.J., Reid, C., Bertuch
Sarcophilus	OZG-539	Sediment Shell (V*elesunio ambiguus*)	Radiocarbon (ABOX-SC)	24.300	=	0.34	B	*null*	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	ANUA-10312	Sediment Charcoal	Radiocarbon (ABOX-SC)	23.400	=	0.30	C	*null*	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	ANUA-10311	Sediment Charcoal	Radiocarbon (ABOX-SC)	25.300	=	0.40	C	*null*	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	ANUA-10412	Sediment Charcoal	Radiocarbon (ABOX-SC)	30.300	=	0.40	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	ANUA-10324	Sediment Charcoal	Radiocarbon (ABOX-SC)	32.800	=	0.80	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	ANUA-13410	Sediment Charcoal	Radiocarbon (ABOX-SC)	43.000	=	2.70	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	OZG-539	Sediment Shell (*Velesunio ambiguus*)	U-series Th/U	19.500	=	0.30	B	*null*	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	OZG-540	Sediment Shell (*Velesunio ambiguus*)	U-series Th/U	29.700	=	0.40	B	*null*	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	TEC-F (WAM 07.6.147)	Sediment Calcite	U-series Th/U	44.900	=	*1.30*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	TEC-F (unit G lower)	Sediment Calcite	U-series Th/U	48.700	=	3.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	Risø-060703	Sediment Quartz	U-series Th/U	112.000	=	20.00	A	w	Price, G.J., Webb, G.E., Zhao, J.-X., Feng, Y.-X., Murray, A.S., Cooke, B.N.
Sarcophilus	TEC-K-D2	Sediment Calcite	U-series Th/U	146.300	<	*8.40*	C	*null*	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	TEC-97	Sediment Calcite	U-series Th/U	151.000	=	*7.00*	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R.
Sarcophilus	NCF1-2 top	Flowstone	U-series Th/U	289.000	=	10.00	A	a	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.
Sarcophilus	NCF1-3 mid	Flowstone Calcite	U-series Th/U	297.000	=	9.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.

Sarcophilus	NCF1-1 base	Flowstone Calcite	U-series Th/U	396.000	=	19.00	A	b	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C.
Sarcophilus	TEXAS-01	Post-depositional formation Calcite	U-series Th/U (TIMS)	41.300	>	0.30	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages f
Sarcophilus	GORE-01	Tooth	U-series Th/U (TIMS)	53.600	>	0.20	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages f
Sarcophilus	GORE-05	Tooth	U-series Th/U (TIMS)	53.900	>	0.30	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages f
Sarcophilus	ROK-13	Tooth from breccia	U-series Th/U (TIMS)	122.900	>	0.70	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New records of F
Sarcophilus	ROK-12	Calcite within tooth	U-series Th/U (TIMS)	152.300	>	1.30	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New records of F
Sarcophilus	ROK-12	Tooth	U-series Th/U (TIMS)	153.800	>	1.30	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New records of F
Sarcophilus	ROK-27 bone	Bone Macropod bone	U-series Th/U (TIMS)	267.000	=	5.00	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New records of F
Sarcophilus	TEXAS-05	Post-depositional formation Calcite	U-series Th/U (TIMS)	291.600	>	7.20	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages f
Sarcophilus	ROK-04/04	Flowstone Calcite	U-series Th/U (TIMS)	326.000	<	22.00	C	*null*	Hocknull, S.A., Zhao, J.-X., Feng, Y.-X., Webb, G.E., 2007. Responses of Q
Sarcophilus	ROK-27cal	Calcite filling in bone	U-series Th/U (TIMS)	332.000	>	14.00	C	*null*	Hocknull, S.A., Zhao, J.-X., Feng, Y.-X., Webb, G.E., 2007. Responses of Q
Sarcophilus	ROK-27 cal	Calcite filling in bone	U-series Th/U (TIMS)	333.000	=	13.00	C	*null*	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New records of F
Sarcophilus	ROK-20-4cal	Calcite filling in bone	U-series Th/U (TIMS)	454.000	>	48.00	C	*null*	Cramb, J., Hocknull, S., Webb, G.E., 2009. High diversity Pleistocene rainfo
Sarcophilus	TE-FS-16a	Flowstone Calcite	U-series Th/U (TIMS) (corrected for	47.800	=	2.80	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	TE-FS-21a	Flowstone Calcite	U-series Th/U (TIMS) (corrected for	119.500	=	3.70	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	TE-FS-UG	Flowstone Calcite	U-series Th/U (TIMS) (corrected for	136.800	=	2.60	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A
Sarcophilus	QML-1312	Snail shell/Broken straw	U-series Th/U (TIMS) (corrected for	169.000	>	9.00	C	*null*	Cramb, J., Hocknull, S., Webb, G.E., 2009. High diversity Pleistocene rainfo
Sarcophilus	QML-1312-6	Flowstone (broken straw) Calcite	U-series Th/U (TIMS) (corrected for	205.000	<	4.00	C	*null*	Hocknull, S.A., Zhao, J.-X., Feng, Y.-X., Webb, G.E., 2007. Responses of Q

Genus	AgeID	Dated remain/material	Dating technique	Age	Estimate Type	Precision	Quality Category	Quality Sub-category	Refence
Simosthenurus	AG-26	Bone	AAR (Asparctic)	13.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	AG-28	Bone	AAR (Asparctic)	30.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	AG-27	Bone	AAR (Asparctic)	40.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	AG18	Bone	AAR (Asparctic)	110.000	=	na	C	null	Murray, P.F., Goede, A., Bada, J.L., 1980. Pleistocene human occupation at Begin
Simosthenurus	AG14	Bone	AAR (Asparctic)	130.000	=	na	C	null	Murray, P.F., Goede, A., Bada, J.L., 1980. Pleistocene human occupation at Begin
Simosthenurus	AG-19	Bone	AAR (Asparctic)	80.000	=	na	C	null	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	JF155/Roof	Bone (rib)	AMS radiocarbon	44.700	=	3.30	B	w	Cosgrove, R., Field, J., Garvey, J., Brenner-Coltrain, J., Goede, A., Charles, B., W
Simosthenurus	JF1S4/1	Bone (occipital bone) occipital bone	AMS radiocarbon	45.400	>	na	C	null	Cosgrove, R., Field, J., Garvey, J., Brenner-Coltrain, J., Goede, A., Charles, B., W
Simosthenurus	JF155/2	Bone (Femur) Collagen	AMS radiocarbon	46.200	>	0.00	C	null	Cosgrove, R., Field, J., Garvey, J., Brenner-Coltrain, J., Goede, A., Charles, B., W
Simosthenurus	2739	Tooth (molar M3)	ESR	53.000	=	3.00	C	null	Cosgrove, R., Field, J., Garvey, J., Brenner-Coltrain, J., Goede, A., Charles, B., W
Simosthenurus	B-10	Bone	ESR	13.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	Z-3370	Bone	ESR	27.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	B-19	Bone	ESR	97.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	B-2	Bone	ESR	310.000	=	na	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	JF-79	Bone	ESR	63.000	=	na	C	null	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	1533	Tooth Enamel	EU-ESR	49.000	=	4.00	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	1531a	Tooth Enamel	LU/ESR	164.000	=	11.00	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	GH09-2	Sediment Quartz	OSL	70.000	=	6.00	A	w	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH09-5	Sediment Quartz	OSL	76.000	=	6.00	A	w	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH09-4	Sediment Quartz	OSL	77.000	=	6.00	A	w	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH09-1	Sediment Quartz	OSL	82.000	=	6.00	A	w	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH09-3	Sediment Quartz	OSL	82.000	=	8.00	A	w	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	NC2	Sediment Quartz	OSL	231.000	=	21.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NC3	Sediment Quartz	OSL	257.000	=	21.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NC4	Sediment Quartz	OSL	292.000	=	19.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NC5	Sediment Quartz	OSL	513.000	=	73.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NC6	Sediment Quartz	OSL	535.000	=	49.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	TEC-H	Sediment Quartz	OSL	32.000	=	3.00	C	null	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC07–5	Sediment Quartz	OSL	34.000	=	2.00	C	null	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC–F	Sediment Quartz	OSL	70.000	=	4.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC07–1	Sediment Quartz	OSL	135.000	=	7.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	26	Sediment Quartz (90-125 microns)	OSL	33.000	=	4.00	C	null	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	23	Flowstones Calcite	OSL	35.400	=	1.00	A	a	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	22	Sediment Quartz (90-125 microns)	OSL	42.000	=	2.00	B	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	26	Sediment Quartz (90-125 microns)	OSL	45.000	=	6.00	C	null	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	23	Sediment Quartz (125-250 microns)	OSL	46.000	=	6.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	22	Sediment Quartz (90-125 microns)	OSL	47.000	=	7.00	B	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	22	Sediment Sediment (90-125 microns)	OSL	48.000	=	3.00	B	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	24	Sediment Quartz (90-125 microns)	OSL	55.000	=	9.00	A	a	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	24	Sediment Quartz (90-125 microns)	OSL	63.000	=	9.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	24	Sediment Sediment (90-125 microns)	OSL	74.000	=	10.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	16	Sediment Quartz (180-212 microns)	OSL	82.000	=	10.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	26	Sediment Quartz (90-125 microns)	OSL	141.000	=	21.00	C	null	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	19	Sediment Quartz (90-125 microns & 180-212 n	OSL	164.000	=	15.00	A	w (average)	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	ST-1	Sediment Quartz	OSL	56.000	=	4.00	A	w	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	JF-155	Sediment Quartz	OSL	103.000	=	9.00	A	w	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	MU-206	Sediment Quartz	OSL	120.000	>	21.00	C	null	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	MU-203-205	Sediment Quartz	OSL	127.000	>	28.00	C	null	Turney, C.S.M., Flannery, T.F., Roberts, R.G., Reid, C., Fifield, L.K., Higham, T.
Simosthenurus	?	Sediment Quartz	OSL	145.000	<	19.00	C	null	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.A., R
Simosthenurus	SUA-546	Sediment Charcoal	Radiocarbon	31.800	na	1.40	B	w	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remains spa
Simosthenurus	SUA-585	Sediment Charcoal	Radiocarbon	32.480	=	1.25	B	w	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remains spa
Simosthenurus	SUA-586	Sediment Charcoal	Radiocarbon	35.160	=	1.80	B	w	Balme, J., Merrilees, D., Porter, J.K., 1978. Late Quaternary mammal remains spa
Simosthenurus	Teledyne I-11018	Plant remains Leaf, seed and stem fragments	Radiocarbon	19.800	=	0.40	C	null	Flannery, T.F., Gott, B., 1984. The Spring Creek locality, southwestern Victoria: a
Simosthenurus	ANU-1220	Sediment Charcoal	Radiocarbon	22.980	=	2.00	C	null	Flood, J., 1974. Pleistocene man at Cloggs Cave: his took kit and environment. M
Simosthenurus	OxA-17143	Tooth upper I1 fragment	Radiocarbon	44.500	=	1.00	A*	w	Gillespie, R., Camens, A.B., Worthy, T.H., Rawlence, N.J., Reid, C., Bertuch, F., I
Simosthenurus	SUA-685	Sediment Charcoal	Radiocarbon	25.200	=	0.80	B	null	Gillespie, R., Horton, D.R., Ladd, P., Macumber, P.G., Rich, T.H., Thorne, R., W
Simosthenurus	SUA-538	Sediment Charcoal	Radiocarbon	26.600	=	0.65	B	null	Gillespie, R., Horton, D.R., Ladd, P., Macumber, P.G., Rich, T.H., Thorne, R., W
Simosthenurus	GaK-6875	Sediment Charcoal	Radiocarbon	14.130	=	2.97	B	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	Pta-2506	Flowstone (overlaying) Calcite	Radiocarbon	17.670	=	0.18	C	null	Goede, A., Bada, J.L., 1985. Electron spin resonance dating of Quaternary bone r
Simosthenurus	GaK-509	Bone Mixed mammal bones	Radiocarbon	15.200	=	0.32	C	null	Hope, J.H., Wilkinson, H.E., 1982. Warendja wakefieldi, a new genus of wombat
Simosthenurus	Tx-31	Sediment Charcoal	Radiocarbon	31.500	>	0.00	C	null	Merrilees, D., 1979. The prehistoric environment in Western Australia. Journal of
Simosthenurus	O-657	Sediment Charcoal	Radiocarbon	37.000	>	0.00	C	null	Merrilees, D., 1979. The prehistoric environment in Western Australia. Journal of
Simosthenurus	R-50001/2	Bone Collagen	Radiocarbon	10.000	>	0.70	B	null	Murray, P., 1978. A Pleistocene spiny anteater from Tasmania (Monotremata: Ta
Simosthenurus	SUA-234	Sediment Charcoal	Radiocarbon	33.800	=	2.40	B	null	Pledge, N.S., 1990. The upper fossil fauna of the Henschke fossil cave, Naracoor
Simosthenurus	SUA-140	Sediment Charcoal	Radiocarbon	35.000	>	0.00	B	null	Pledge, N.S., 1990. The upper fossil fauna of the Henschke fossil cave, Naracoor
Simosthenurus	Wk-2565	Sediment Charcoal	Radiocarbon	14.950	=	1.24	B	null	Van Huet, S., 1999. The taphonomy of the Lancefield swamp megafaunal accum
Simosthenurus	?	Sediment Carbonaceous pellet	Radiocarbon	18.600	>	0.30	C	null	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.A., R
Simosthenurus	?	Sediment Carbonaceous pellet	Radiocarbon	19.600	>	0.31	C	null	Wells, R.T., Grün, R., Sullivan, J.O., Forbes, M.S., Dalgairns, S., Bestland, E.A., R
Simosthenurus	ANUA-10412	Sediment Charcoal	Radiocarbon (ABOX)	30.300	=	0.40	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-10324	Sediment Charcoal	Radiocarbon (ABOX)	32.800	=	0.80	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-11703	Sediment Charcoal	Radiocarbon (ABOX)	40.100	=	1.05	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-13410	Sediment Charcoal	Radiocarbon (ABOX)	43.000	=	2.70	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-11702	Sediment Charcoal	Radiocarbon (ABOX)	45.200	=	1.50	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-10314	Sediment Charcoal	Radiocarbon (ABOX)	45.200	=	0.95	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	ANUA-11701	Sediment Charcoal	Radiocarbon (ABOX)	46.800	=	1.55	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	CC FC FS-2	Speleothem Speleothem	U-series Th/U	159.200	>	2.20	C	null	Brown, S.P., Wells, R.T., 2000. A middle Pleistocene vertebrate fossil assemblage
Simosthenurus	CC FC FS-3	Flowstone Flowstone	U-series Th/U	279.200	=	7.20	C	null	Brown, S.P., Wells, R.T., 2000. A middle Pleistocene vertebrate fossil assemblage
Simosthenurus	CC FC St-1	Flowstone Flowstone	U-series Th/U	399.000	<	19.00	C	null	Brown, S.P., Wells, R.T., 2000. A middle Pleistocene vertebrate fossil assemblage
Simosthenurus	G_H-En4	Tooth Dentine	U-series Th/U	67.200	=	2.20	C	null	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH-En9	Tooth Dentine	U-series Th/U	60.500	=	1.40	C	null	Macken, A.C., Prideaux, G.J., Reed, E.H., 2012. Variation and pattern in the resp
Simosthenurus	GH-En3	Tooth Dentine	U-series Th/U	72.300	=	2.20	C	null	Macken, A.C., Jankowski, N.R., Price, G.J., Bestland, E.A., Reed, E.H., Prideaux,
Simosthenurus	NCF1-2 top	Flowstone	U-series Th/U	289.000	=	10.00	A	a	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NCF1-3 mid	Flowstone Calcite	U-series Th/U	297.000	=	9.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	NCF1-1 base	Flowstone Calcite	U-series Th/U	396.000	=	19.00	A	w	Prideaux, G.J., Roberts, R.G., Megirian, D., Westaway, K.E., Hellstrom, J.C., Oll
Simosthenurus	TEC-F (WAM 07.6.147)	Sediment Calcite	U-series Th/U	44.900	=	1.30	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC-F (unit G lower)	Sediment Calcite	U-series Th/U	48.700	=	3.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC-F	Sediment Calcite	U-series Th/U	112.000	=	11.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC-K-D2	Sediment Calcite	U-series Th/U	146.300	<	8.40	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	TEC-97	Sediment Calcite	U-series Th/U	151.000	=	7.00	A	w	Prideaux, G.J., Gully, G.A., Couzens, A.M.C., Ayliffe, L.K., Jankowski, N.R., Jaco
Simosthenurus	VC SC S-1(a)	Speleothem Speleothem	U-series Th/U	210.000	>	20.00	C	null	Reed, E.H., Bourne, S.J., 2000. Pleistocene fossil vertebrate sites of the South Ea
Simosthenurus	23	Flowstones Calcite	U-series Th/U (corrected for detrital :	33.600	=	1.60	A	a	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	23	Sediment Quartz (90-125 microns)	U-series Th/U (corrected for detrital :	46.000	=	2.00	A	w	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	24	Flowstones Calcite	U-series Th/U (corrected for detrital :	55.200	=	2.20	A	a	Roberts, R.G., Flannery, T.F., Ayliffe, L.K., Yoshida, H., Olley, J.M., Prideaux, G
Simosthenurus	TE-FS-16a	Flowstone Calcite	U-series Th/U (TIMS)	47.800	=	2.80	C	null	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	TE-FS-21a	Flowstone Calcite	U-series Th/U (TIMS)	119.500	=	3.70	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	TE-FS-UG	Flowstone Calcite	U-series Th/U (TIMS)	136.800	=	2.60	A	w	Ayliffe, L.K., Prideaux, G.J., Bird, M.I., Grün, R., Roberts, R.G., Gully, G.A., Jon
Simosthenurus	TEXAS-01	Post-depositional formation Calcite	U-series Th/U (TIMS)	41.300	>	0.30	C	null	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages for Pl
Simosthenurus	TEXAS-05	Post-depositional formation Calcite	U-series Th/U (TIMS)	291.600	>	7.20	C	null	Price, G.J., Zhao, J.-X., Feng, Y.-X., Hocknull, S.A., 2009. New U/Th ages for Pl

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