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Late survival of megafauna refuted for Cloggs Cave, SE Australia: Implications for the Australian Late Pleistocene megafauna extinction debate

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A B S T R A C T

Understanding of Late Pleistocene megafaunal extinctions in Australia and New Guinea (Sahul) suffers from a paucity of reliably dated bone deposits. Researchers are divided as to when, and why, large-bodied species became extinct. Critical to these interpretations are so-called 'late survivors', megafauna that are thought to have persisted for tens of thousands of years after the arrival of people. While the original dating of most sites with purported late survivors has been shown to have been erroneous or problematic, one site continues to feature: Cloggs Cave. Here we report new results that show that Cloggs Cave's youngest megafauna were deposited in sediments that date to 44,500–54,160 years ago, more than 10,000 years older than previously thought, bringing them into chronological alignment with the emerging continental pattern of megafaunal extinctions. Our results indicate that the youngest megafauna specimens excavated from Cloggs Cave datedate to well before the Last Glacial Maximum (LGM), and their demise could not have been driven by climate change leading into the LGM, the peak of the last Ice Age.

1. Introduction

The debate over Australia and New Guinea's (Sahul) Late Pleistocene megafaunal[1] extinctions is divided into two major camps, mirroring arguments first iterated in the late 1800s (Horton, 1980). One group argues that while most megafauna became extinct prior to the arrival of Australia's first people, several genera, such as *Diprotodon*, *Phascolonus*, *Thylacoleo*, *Procoptodon*, *Protemnodon* and *Simosthenurus*, persisted until c. 39,800–51,200 years ago (probability ranges are given at 95%), although this age range is often referred to by its mean of c. 46,400 years (Gillespie et al., 2006; Grellet-Tinner et al., 2016; Hocknull et al., 2020;

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[1] Throughout this paper, 'megafauna' are defined as species weighing ≥45 kg (after Martin and Klein, 1984).

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Miller et al., 2005; Roberts and Brook, 2010; Roberts et al., 2001; Turney et al., 2008). This postdates the arrival of people on the continent, variably accepted to date between 48,000 and 50,000 (O'Connell et al., 2018) and 59,300–72,700 years ago (Clarkson et al., 2017). This scenario would indicate an overlap of a few thousand up to 30,000 years between megafauna and people, with the shorter periods of overlap (<10,000 years) selected from the tail of the uncertainty ranges. Shorter overlap ages are usually used to argue that people played a significant role in the megafauna's disappearance. People allegedly overhunted megafauna, causing population collapse (Brook and Johnson, 2006; Flannery, 1994), or exerted pressure via habitat modification such as increased landscape burning (Bird et al., 2013).

A second group have instead argued for the 'late survival' of megafauna, suggesting that up to 13 species coexisted with people for many thousands of years up to the Last Glacial Maximum (LGM). In this view, the late-surviving megafauna became extinct as late as 16,000 to 23,000 years ago (Field, 2006; Field et al., 2008; Fillios et al., 2010; Wroe and Field, 2007; Wroe et al., 2013; see also Field et al., 2013), more than 25,000 and perhaps as much as c. 50,000 years after the arrival of people on the continent. A prolonged coexistence of megafauna and people, combined with peak Late Pleistocene climate change, would suggest that people were not the primary cause of megafaunal extinctions.

Most recently, an intermediary view has been advanced of sustained habitat change involving a combination of hydroclimate deterioration resulting in competition between people and large animals for water resources (potentially positioning species within the immediate purview of human hunting; Saltré et al., 2019), reduction of forest cover and heightened fire frequency, together indicating increased drying of the landscape beginning c. 50,000 years ago, and especially after c. 40,000 years ago. This view was proposed as a result of newly discovered 40,100 $\pm$ 1700-year-old (1σ uncertainty) megafauna remains in north Queensland (Hocknull et al., 2020).

A key site used in support of the late survival argument is Cloggs Cave, in southeast Australia (Field et al., 2013; Wroe et al., 2013). Here, a radiocarbon (^{14}C) age on charcoal of 23,360–33,920 cal BP (22,980 $\pm$ 2000 BP, ANU-1220; all ^{14}C ages are calibrated against SHCal20), measured in the 1970s, has been argued by Flood (1973a, 1974, 1980, 2007) and supporters of late survival (e.g. Field et al., 2008; Wroe and Field, 2007) to reliably represent the time of extinction of some species of Australia's megafauna. Prior to the present study, the evidence from Cloggs Cave, along with contested evidence from the Cuddie Springs, Nombe and Seton archaeological sites (see below and Supplementary Information 1), suggested that megafauna had survived in Sahul until 20,500 to 31,000 years ago (Field et al., 2008).

It is important to note that there are major methodological problems with the ways ages have been acquired for megafaunal deposits across Sahul prior to the turn of the 21st Century. Many of the relevant chronometric determinations are ^{14}C ages on charcoal from associated sedimentary matrices rather than direct ages on the megafauna remains. Radiocarbon samples are extremely sensitive to young contaminants. If just 1% of the carbon in a 50,000-year-old sample is a modern contaminant, the age will be underestimated by more than 10,000 ^{14}C years. While the potential impact of such contamination has been known since the early days of the ^{14}C dating method (Anderson et al., 1951), the prevalence of the problem was not realized in the Australian context until much later (Jones, 1982; Roberts et al., 1994), and methods to effectively clean the most contaminated samples and assess decontamination were not developed until the late 1990s (e.g. Bird et al., 1999; Rebollo et al., 2011). Preservation of charcoal is a closely aligned problem, with degradation being particularly rapid in hot, wet and/or alkaline sediments (Ascough et al., 2011; Braadbaart et al., 2009). Where charcoal is poorly preserved, any method used to clean it can also dissolve the charcoal, concentrating sedimentary inclusions that may contain carbon of a very different age (Rebollo et al., 2011). Many of the indicators of charcoal preservation and contamination used today, such as %C or δ^{13}C, were not measured and/or recorded in the past (Higham et al., 2012). We therefore cannot assess whether samples that lack such information were contaminated.

Issues of contamination are compounded where conventional ^{14}C measurement methods such as those initially applied at Cloggs Cave were used. These methods require very large samples, and it was common practice to aggregate multiple small fragments of charcoal (sometimes with ash), in some cases collected over several excavation levels spanning relatively broad and widespread depths to generate single age estimates. In the best-case scenario, this gave an average age for a large volume of sediment, which may not represent the age of any of the charcoal fragments present, let alone any of the faunal remains from a particular depth. If just one of those fragments was intrusive from a higher level through post-depositional mixing or excavation error, the ^{14}C age is most likely to have been underestimated. In some cases, the paucity of charcoal has meant that accelerator mass spectrometry (AMS) determinations were also undertaken on combined fragments (e.g. Nombe), with potentially the same problems as described for conventional methods.

While it is possible that ^{14}C ages generated on charcoal in the 1970s are accurate, the problems outlined here mean they should usually be regarded as minimum age estimates until their accuracy is tested using modern methods. Therefore, there is an important need to re-examine existing ^{14}C chronologies at purportedly late surviving megafauna sites using more rigorous and up-to-date ^{14}C methodologies, as well as complementary dating techniques that do not suffer the same types of methodological biases (e.g. OSL and uranium-series [U-series] dating).

In this context, we present new and conclusive evidence for the significantly older age of Cloggs Cave's youngest extinct megafauna remains, this being the sole remaining uncontested site mustered in support of the late survival argument (for a summary of recent re-assessments of the Cuddie Springs, Nombe and Seton sites, see Supplementary Information 1).

2. Study area: Cloggs Cave

Cloggs Cave is a small limestone cave located 72.3 m above sea level. It is found in GunaiKurnai Aboriginal Country (East Gippsland, southeast Australia), in the foothills of the Australian Alps (Figs. 1 and 2). It was first studied by archaeologist Josephine Flood in 1971–1972, who excavated a 2.4 m-deep pit inside the cave. Four juxtaposed 1 $\times$ 1 m squares were excavated. The stratigraphy was complex and not well understood: the deepest layers contained bones and teeth of the extinct megafauna species *Sthenurus orientalis* (now synonymised with *Simosthenurus occidentalis*) and *Macropus giganteus titan*, as well as of smaller, regionally extinct (e.g. *Thylacinus* sp., *Sarcophilus* sp.) and extant fauna (e.g. *Wallabia bicolor,* Dasyuridae, Peramelidae, Macropodidae, Potoridae, Burramyidae, Muridae and Squamata) (Flood, 1973a, 1974, 1980; Hope, 1973). The accumulation of extant large-bodied mammals continued after specimens of extinct megafauna stopped accumulating, demonstrating taphonomic changes were not responsible for the cessation of extinct megafauna accumulation (Hope 1973: table xiv). Little *in situ* charcoal could be found in the megafauna layers during the original excavations, so multiple pieces spanning numerous c. 10 cm-thick excavation 'spits' across a broad area were aggregated to obtain a single conventional ^{14}C age of

Fig. 1. Location of Cloggs Cave, southeast Australia. Artwork by CartoGIS Services, College of Asia and the Pacific, Australian National University.

23,260–33,920 cal BP (22,980 ± 2000 BP, ANU-1220) for the megafauna layer. Three other ^{14}C ages were obtained during the 1971–1972 excavation, two from a subsidence crater's fill to the south (and to the side) of the megafauna layers (see below), and one from near the top of the excavation. Comminuted charcoal and ash were combined (Flood, 1973a, 1974) to obtain poorly provenanced and potentially contaminated ^{14}C ages. Clarification of the stratigraphic sequence, and of the antiquity of the megafauna, requires a more detailed examination of the evolution of the cave and an inter-disciplinary approach that systematically crosses the geological, archaeological, geomorphological, geochronological and megafaunal evidence (Delannoy et al., 2020).

In 2019–2020, Cloggs Cave was re-excavated from the exposed walls of the 1971–1972 pit that had remained open during the intervening 47 years (Fig. 2C). Two juxtaposed 50 × 50 cm squares (P34 and P35) were excavated down Flood's southeast wall, exposing a subsidence crater that transected the deeper layers with megafauna remains and had subsequently become rapidly infilled with surrounding sediments during the Mid-Holocene (Delannoy et al., 2020). This catastrophic collapse feature was not known at the time of the 1971–1972 excavations. The Late Pleistocene layers of the northeast corner of Square S, which contained most of the

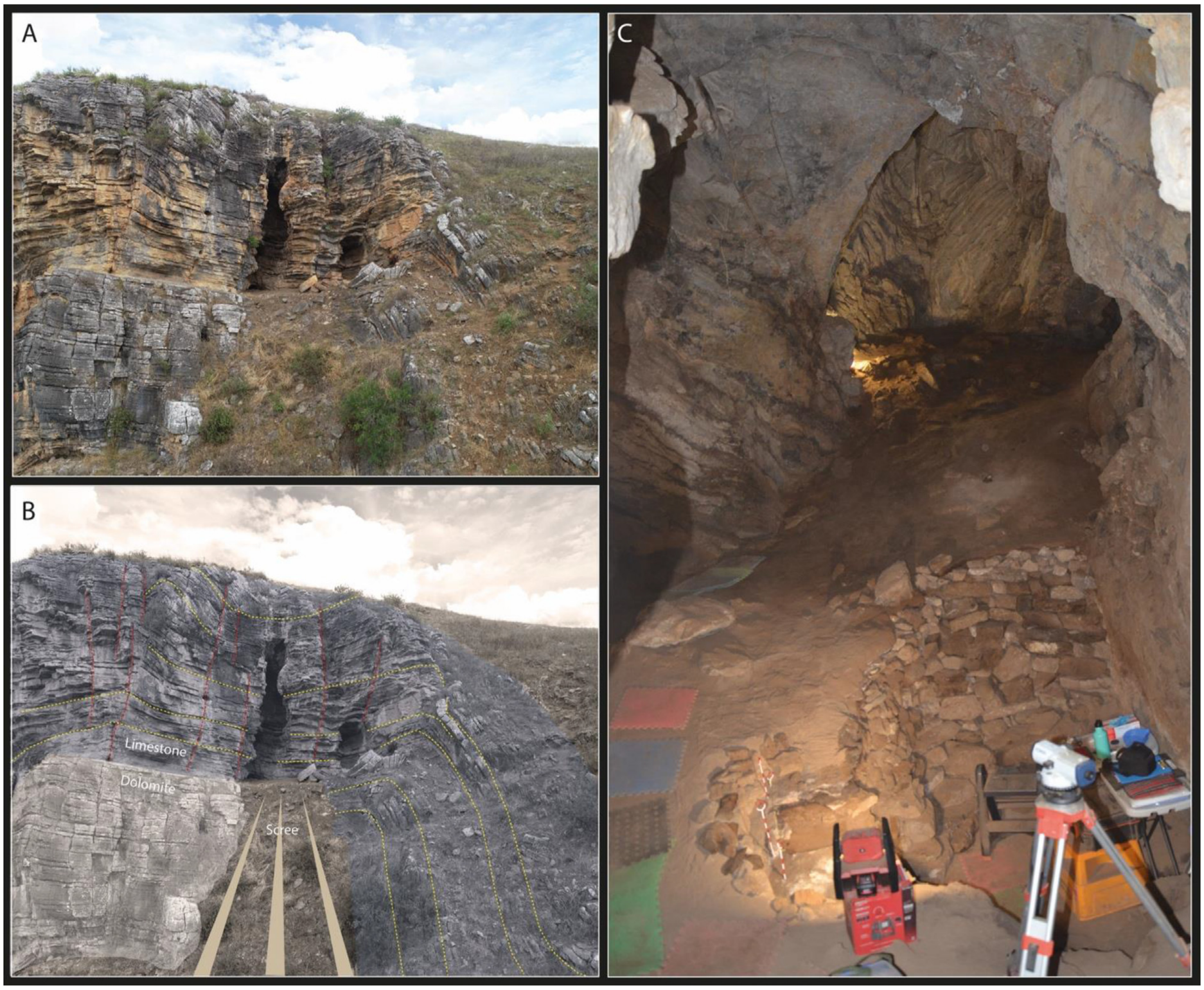

Fig. 2. Cloggs Cave. A, B keyhole walk-through entrance. **C** Inside Cloggs Cave, Square R31 (left-hand side extension to the pit) excavations in progress, 3 February 2020. The dry-stone wall was built by the GunaiKurnai Land and Waters Aboriginal Corporation in 2019, to protect the walls of the pit from collapsing.

excavated megafauna bones and teeth, remained intact. Yet the sub-vertical disconformity caused by the subsidence crater immediately to the south was poorly defined, and the 1971–1972 archaeological excavation did not clearly distinguish the disconformity's mixed interface from the intact deposits.

A further 50 × 50 cm square (R31) was excavated 1.4 m to the north of the megafauna remains in 2020, from the cleaned northeast wall of the 1971–1972 pit. Unlike the southeast wall of the pit, here the entire length of the wall was well stratified, from the surface down to the megafauna layers: this part of the deposit had not been affected by the subsidence crater further to the south. Square R31 was excavated in mean 2.3 cm-thick arbitrary excavation units (XUs) following the stratigraphy.

The Square R31 stratigraphic sequence begins with stratigraphic unit (SU) 5B at its base, being the silty layer where, 1.4 m to the south, the uppermost now-dated megafauna bones were found in 1971–1972. Only the top of SU5B was excavated in Square R31. SU5B is capped by SU5A, a c. 30 cm-thick silty layer which, in Square R31, contains numerous small limestone blocks. The interface between SU5B and SU5A is diffuse, as is the interface between SU5A and SU4V higher up. SU5A is superimposed by 22 distinct layers of SU4, most of which show excellent chronostratigraphic resolution and shallow interfaces of typically 1–2 cm thickness (see below). The exception is the contiguous SU4U–SU4V, where a number of limestone blocks, the largest c. 30 cm long, fell from the ceiling. Here the sediments, including the charcoal within them, show slight reversals over a depth of c. 20 cm. SU4 is capped by SU2, being a 15 cm-thick sequence of hearths. Only the very base of SU1 is present in Square R31, because most of it had been removed during the 1971–1972 excavations (a protective thick plastic sheet had been laid over the base of SU1 and covered by 20 cm of soft sediment in 1972) (Figs. 3 and 4).

2.1. Methods

During the 2019–2020 excavations, we collected samples for dating from Squares P34 and P35 and from the southeast wall of the 1971–1972 pit. Forty AMS ^{14}C ages were obtained on individual pieces of charcoal, possum scats and a leaf, along with eight single-grain OSL ages, and 13 U-series ages on a broken and redeposited stalagmite and a stalactite that had fallen from the roof and incorporated into the assemblage. While collecting the samples we were careful to stay away from (i.e. to the south of) the mixed interface of the subsidence crater's fill and megafauna layers (David et al., in press; Delannoy et al., 2020). A further 69 AMS ^{14}C ages were obtained from individual pieces of charcoal, bark, wood, plant fibre and possum scats from Square R31 on the pit's northeast wall. Two additional single-grain OSL ages were obtained 1.4 m to the

Fig. 3. Cloggs Cave, Square R31 after completion of excavation. The excavated deposit is 1.33 m thick, from the top of the ash layers (top of photo) to the base of the excavation (bottom of photo).

south of excavation square R31, from the cleaned-up, well stratified northeast wall of Flood's original pit corresponding with two key areas of deposit: 1) the precise location of the uppermost indeterminate *Simosthenurus* sp. bone (a humerus) in SU5B, chronostratigraphically located at an equivalent depth to a *Simosthenurus occidentalis* mandible 45 cm to the southwest (Flood, 1973a, 1973b), representing the youngest known megafauna remains from the site; and 2) the base of SU5A, the stratigraphic layer immediately above that which contained the megafauna bones (SU5B), 45 cm above the *Simosthenurus* humerus (Fig. 5).

2.1.1. ^{14}C dating methods

The ^{14}C dating methods for samples dated at the Accelerator Mass Spectrometry ^{14}C facility at the University of Waikato (laboratory code Wk-) have been fully detailed in Stephenson et al. (2000) and are thus not repeated here. All ^{14}C ages were calibrated using OxCal v4.4.2 (Bronk Ramsey, 1995) with the SHCal20 curve (Hogg et al., 2020) and are reported at 95% probability.

2.1.2. Single-grain OSL dating methods

Ten OSL dating samples were collected from SU2, SU3 and SU5 to provide estimates of when these infill deposits were last exposed to light prior to burial (e.g. Supplementary Fig. 1). These samples were obtained from cleaned exposure faces using metal or opaque PVC tubes, and were immediately sealed with light-proof plastic upon extraction. Approximately 500 g of additional bulk sediment was collected from material directly surrounding each sample for dosimetry and water content assessments. Single-grain OSL dating of quartz was routinely applied to all ten samples, and was preferred over standard multiple-grain OSL dating in this cave setting because of its ability to identify insufficiently bleached grain populations (Arnold et al., 2007, 2008, 2009), contaminant grains associated with syn- or post-depositional mixing (Arnold et al., 2011, 2013, 2019), and aberrant grains displaying inherently unsuitable luminescence properties (Demuro et al., 2008, 2013).

Quartz grains were processed under safe light conditions (dim red LEDs) at the University of Adelaide using standard preparation procedures (Aitken, 1998), including a 48% hydrofluoric acid etch (40 min) to remove the alpha-irradiated outer layers of the quartz extracts, a subsequent 30% hydrochloric acid wash to remove any precipitated fluorides, and a repeated sieving cycle at the end of the preparation procedure (using a 90 μm sieve) to eliminate any disaggregated grains.

OSL measurements were made using experimental apparatus, single-aliquot regenerative-dose (SAR) procedures, and quality assurance criteria published previously (Arnold et al., 2013, 2016), which are further detailed in Supplementary Information 2. Purified quartz grains with a diameter of 212–250 μm were manually loaded onto aluminium discs drilled with an array of 300 × 300 μm holes to ensure true single-grain resolution during equivalent dose (D_e) evaluation (Arnold et al., 2012a). Individual D_e values were determined using the SAR procedure (Murray and Wintle, 2000) shown in Supplementary Table 1. Between 800 and 1100 single-grain D_e measurements were made for each sample (Supplementary Table 2). Sensitivity-corrected dose-response curves were constructed using the first 0.08 s of each OSL stimulation after subtracting a mean background count obtained from the last 0.25 s of the signal.

The SAR procedure used for single-grain D_e determination includes a preheat of 260 °C for 10 s prior to measurement of the natural (L_n) and regenerative dose (L_x) OSL signals, and a preheat of 200 °C for 10 s prior to measurement of the test-dose (T_n and T_x) OSL signals. These preheating conditions yielded an accurate recovered-to-given dose ratio of 1.01 ± 0.02, and overdispersion values of 11 ± 2% to 17 ± 2% for dose recovery tests performed on individual grains of samples CLO19-1 and CLO19-7 (Supplementary Fig. 2).

Full discussions of the single-grain D_e distributions and statistical age models used to derive representative burial dose estimates for each sample are provided in Supplementary Information 2. Individual and sample-averaged D_e estimates are presented with their 1σ uncertainties, which are derived from three sources of uncertainty: 1) a random uncertainty term arising from photon counting statistics for each OSL measurement, calculated using Eq. 3 of Galbraith (2002); 2) an empirically determined instrument reproducibility uncertainty of 1.9% for each single-grain measurement (calculated specifically for the Risø reader used in this study; Jacobs et al., 2006a); and 3) a dose-response curve fitting uncertainty determined using 1000 iterations of the Monte Carlo method and implemented in Analyst v4 (Duller, 2007).

Dose rate evaluations have been undertaken using a combination of *in situ* gamma-ray spectrometry and low-level beta counting of dried and homogenised, bulk sediments collected directly from the OSL sampling positions (Table 1). Gamma dose rates were

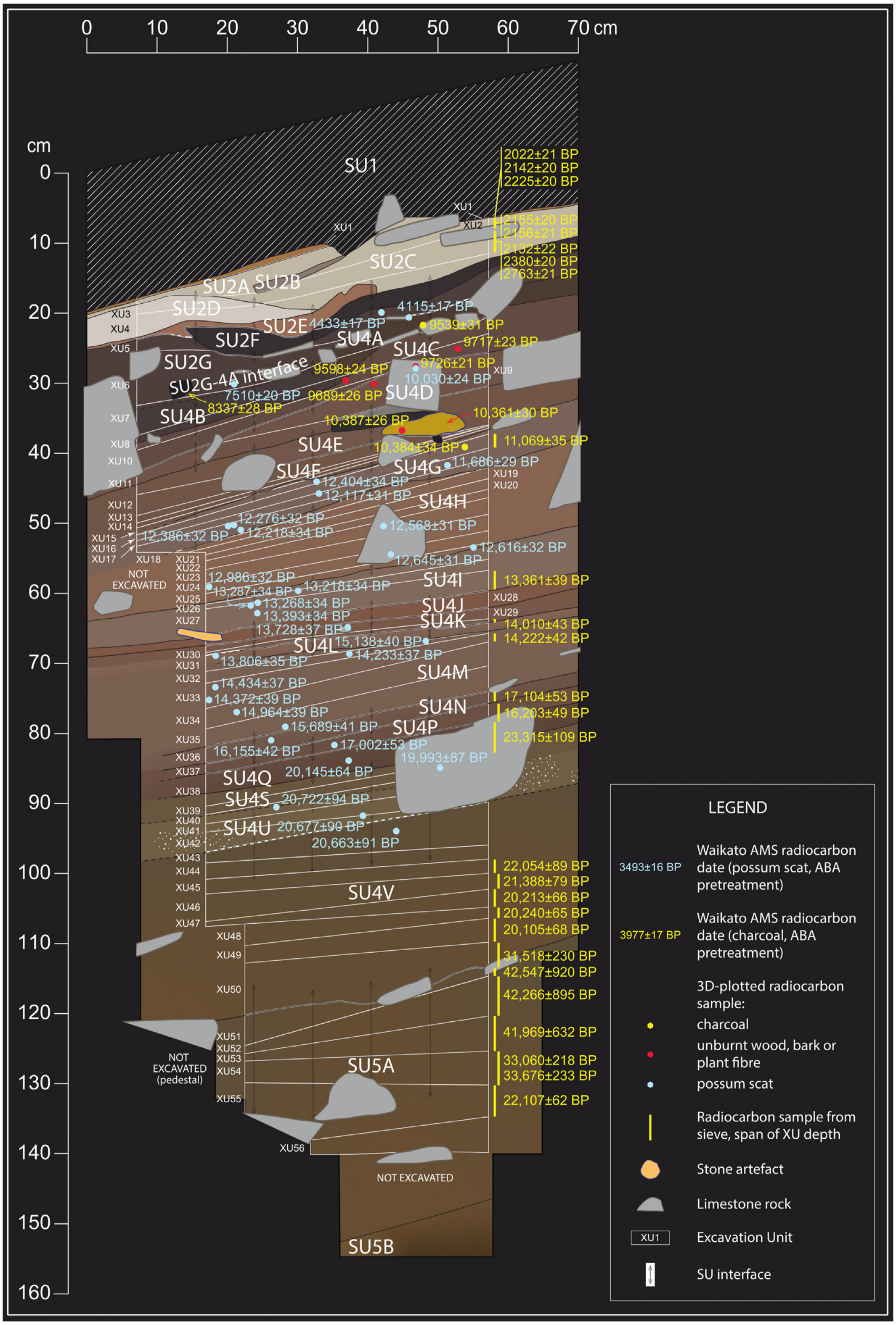

Fig. 4. Section drawing of southwestern wall of Square R31 (as drawn from the northeast wall of the exposed 1971–1972 pit). SU4O, SU4R and SU4T do not appear on the southwestern wall of R31, shown in this figure, as they are localised layers found in other parts of the square. The uncalibrated ^{14}C ages are shown with their 1σ uncertainties.

determined from *in situ* gamma spectrometry, using the windows method (Arnold et al., 2012b; Duval and Arnold, 2013). Cosmic-ray dose rate contributions have been calculated after taking into consideration site altitude, geomagnetic latitude, and density, thickness and geometry of sediment/bedrock overburden (Prescott and Hutton, 1994). A small, assumed internal (alpha plus beta) dose rate of 0.03 ± 0.01 Gy/ka has been included in the final dose rate calculations based on published ^{238}U and ^{232}Th measurements for

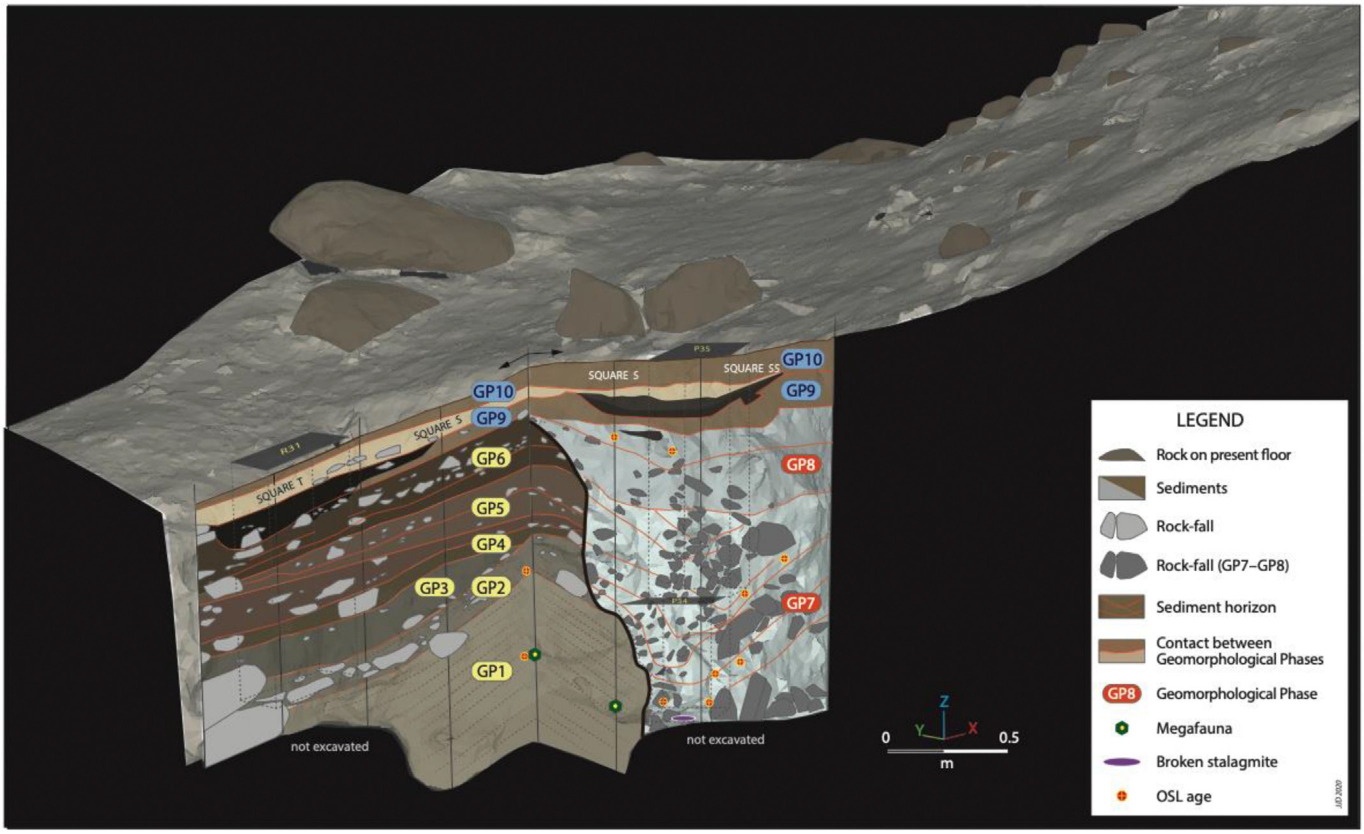

Fig. 5. Isometric view of the northeast and southeast walls of the 1971–1972 pit incorporating the details of the 2019–2020 excavations, as precisely spatially calibrated to a 3D laser scan of the open pit and adjacent slope. The Geomorphological Phases (GPs) represent sets of stratigraphic layers (SUs, see Fig. 4): GP1 = SU5B; GP2 = SU5A; GP3–GP6 = SU4; GP7–GP8 = SU3; GP9 = SU2; GP10 = SU1 (Delannoy et al., 2020).

etched quartz grains from a range of locations (Bowler et al., 2003; Jacobs et al., 2006b; Lewis et al., 2020; Mejdahl, 1987; Pawley et al., 2008) and an alpha efficiency factor (*a*-value) of 0.04 ± 0.01 (Rees-Jones, 1995; Rees-Jones and Tite, 1997).

Radionuclide concentrations and specific activities have been converted to dose rates using previously published conversion factors (Guérin et al., 2011), making allowance for beta-dose attenuation (Brennan, 2003; Mejdahl, 1979) and long-term sediment water contents (Aitken, 1985; Readhead, 1987). The present-day sediment water contents of the Cloggs Cave OSL samples range between 13% and 25% of dry sediment weight and are considered to be representative of moisture conditions prevailing throughout the burial period because: 1) the cave environment remains sufficiently well-protected from major variations in external atmospheric conditions; and 2) newly exposed faces were targeted for sampling. A relative uncertainty of 10% has been assigned to the long-term moisture estimates to accommodate any minor variations in hydrologic conditions during burial.

2.1.3. Bayesian modelling of the ^{14}C and OSL age sequence

To provide a temporal outline for Cloggs Cave and refine the chronology of the layer in which the youngest megafauna remains were found, we constructed and ran a Bayesian Markov chain Monte Carlo sequence analysis, whereby the modelled ^{14}C and OSL ages were constrained within stratigraphic phases and ordered by the sequential position of the SUs to which they belonged (Bronk Ramsey, 2009). The Bayesian sequence model takes into account not only the individual ^{14}C and OSL ages from the northeast wall of the 1971–1972 excavation pit (which preserves the most complete stratigraphic sequence at the site), but also the stratigraphic details that further constrain the relative age of each SU and that help identify potentially intrusive samples. The ages were grouped into multiple phases based on sequence and age, with either contiguous or sequential boundaries depending on the age difference between superimposed layers (see Supplementary Information 3). The internal consistency of the calibrated ages was assessed using a formal outlier analysis, which provides a probabilistic measure of the degree to which samples conform to the constructed model, and then calculates an offset relative to the context within which it is found (Bronk Ramsey, 2010). A general t-type outlier model was assigned to all ages with a prior outlier probability of 0.05.

3. Results

3.1. Radiocarbon ages

The suite of 69 AMS ^{14}C ages from Square R31 is of most significance for evaluating the stratigraphic integrity and antiquity of the megafauna layer at Cloggs Cave, as it relates to the most complete sediment sequence preserved at the site (Table 2, Fig. 4). Preservation was remarkable throughout the deposit, including ‘intact’ Late Pleistocene wooden artefacts, pieces of bark, leaves, mammal scats and other organics, and high %C contents in the dated well-preserved charcoal. Multiple AMS ^{14}C ages were obtained from individual XUs to test the comparability of results from a range of dated materials, with the ages from comparable depths repeatedly returning consistent results (see the multiple results from XU4, XU8, XU11, XU27, XU30, XU33 and XU37 in Table 2).

Table 1
Dose rate data, single-grain equivalent doses and quartz OSL ages for the Cloggs Cave samples.

Sample name	Unit	Grain size (μm)	Water content[a]	Environmental dose rate (Gy/ka)				Equivalent dose (D_e) data				OSL age (ka)[f,l]
				Beta dose rate[b,c]	Gamma dose rate[c,d]	Cosmic dose rate[e]	Total dose rate[c,f,g]	No. of grains[h]	Over-dispersion (%)[i]	Age model[j,k]	D_e (Gy)[f]	
CLO19-2	SU2	212–250	13 ± 1	1.12 ± 0.06	0.36 ± 0.01	0.01 ± 0.01	1.53 ± 0.07	152/800	88 ± 6	MAM-3	6.2 ± 0.2	4.04 ± 0.27
CLO19-3	SU3A	212–250	16 ± 2	1.13 ± 0.06	0.45 ± 0.02	0.01 ± 0.01	1.63 ± 0.08	212/1000	112 ± 6	MAM-4	9.1 ± 0.6	5.58 ± 0.47
CLO19-7	SU3C	212–250	18 ± 2	1.05 ± 0.05	0.39 ± 0.02	0.01 ± 0.01	1.48 ± 0.07	208/1100	96 ± 5	MAM-4	12.8 ± 0.7	8.63 ± 0.66
CLO19-1	SU3D	212–250	19 ± 2	1.00 ± 0.05	0.47 ± 0.02	0.01 ± 0.01	1.51 ± 0.07	202/1000	95 ± 5	MAM-3	13.9 ± 0.6	9.22 ± 0.62
CLO19-4	SU3D	212–250	20 ± 2	0.89 ± 0.05	0.39 ± 0.02	0.01 ± 0.01	1.33 ± 0.07	182/1000	99 ± 6	MAM-3	12.7 ± 0.5	9.50 ± 0.64
CLO19-9	SU3E	212–250	21 ± 2	1.12 ± 0.05	0.47 ± 0.02	0.01 ± 0.01	1.63 ± 0.08	154/1000	95 ± 6	MAM-4	15.1 ± 1.1	9.27 ± 0.80
CLO19-10	SU3E	212–250	25 ± 3	0.96 ± 0.05	0.39 ± 0.02	0.01 ± 0.01	1.39 ± 0.07	205/1000	92 ± 5	MAM-4	12.8 ± 0.4	9.22 ± 0.58
CLO19-8	SU3G	212–250	24 ± 2	1.02 ± 0.05	0.50 ± 0.02	0.01 ± 0.01	1.57 ± 0.08	188/900	96 ± 5	MAM-4	13.4 ± 0.4	8.51 ± 0.53
CLO19-6	SU5A	212–250	18 ± 2	0.64 ± 0.03	0.39 ± 0.02	0.01 ± 0.01	1.07 ± 0.05	201/1000	37 ± 2	MAM-3	50.3 ± 3.6	46.93 ± 4.15
CLO19-5	SU5B	212–250	21 ± 2	0.57 ± 0.03	0.32 ± 0.01	0.01 ± 0.01	0.93 ± 0.05	142/700	45 ± 3	MAM-3	48.4 ± 4.4	51.83 ± 5.51

[a] Long-term water content, expressed as % of dry mass of mineral fraction, with an assigned relative uncertainty of ±10%. Long-term water contents are calculated as being equivalent to the present-day water contents for all samples.
[b] Beta dose rates were calculated on dried and powdered sediment samples using a Risø GM-25-5 low-level beta counter, after making allowance for beta dose attenuation due to grain-size effects and HF etching (Brennan, 2003).
[c] Specific activities and radionuclide concentrations have been converted to dose rates using conversion factors (Guérin et al., 2011), making allowance for beta-dose attenuation (Guérin et al., 2011; Mejdahl, 1979).
[d] Gamma dose rates were calculated from *in situ* measurements made at each sample position with a NaI:Tl detector, using the 'energy windows' approach (Arnold et al., 2012b).
[e] Cosmic-ray dose rates were calculated (Prescott and Hutton, 1994) and assigned a relative uncertainty of ±10%.
[f] Mean ± total uncertainty (68% confidence interval), calculated as the quadratic sum of the random and systematic uncertainties.
[g] Includes an internal dose rate of 0.03 Gy/ka with an assigned relative uncertainty of ±30%, based on intrinsic ^{238}U and ^{232}Th contents (Bowler et al., 2003; Jacobs et al., 2006b; Lewis et al., 2020; Mejdahl, 1987; Pawley et al., 2008) and an a-value of 0.04 ± 0.01 (Rees-Jones, 1995; Rees-Jones and Tite, 1997).
[h] Number of D_e measurements that passed the SAR rejection criteria and were used for D_e determination/total number of grains analysed.
[i] The relative spread in the D_e dataset beyond that associated with the measurement uncertainties of individual D_e values, calculated using the central age model (CAM) (Galbraith et al., 1999).
[j] Age model used to calculate the sample-averaged D_e value for each sample. MAM-3 = 3-parameter minimum age model; MAM-4 = 4-parameter minimum age model. MAM-3 and MAM-4 D_e estimates have been calculated after adding, in quadrature, a relative error of 20% to each individual D_e measurement error to approximate the underlying dose overdispersion observed in 'ideal' (well-bleached and unmixed) sedimentary samples (e.g. global overdispersion dataset mean value of 20 ± 1% (Arnold and Roberts, 2009) and the minimum estimate of intrinsic (experimental) overdispersion determined from the single-grain dose-recovery tests for samples CLO19-1 and CLO19-7.
[k] Age model selection: The choice of whether to use the MAM-3 or MAM-4 for each sample has been made on statistical grounds using the maximum log likelihood score (L_{max}) criterion (Arnold et al., 2009).
[l] Total uncertainty includes a systematic component of ±2% associated with laboratory beta-source calibration.

Additionally, the oldest samples produced ages consistent with the OSL ages from the same unit (Table 2).

3.2. OSL ages

All ten OSL samples exhibit scattered single-grain equivalent dose (D_e) distributions that are consistent with syn-depositional mixing with pre-existing cave deposits prior to burial (see Supplementary Information 2: D_e results and ages). The final OSL ages have therefore been derived using the minimum age model (Galbraith et al., 1999) in order to isolate burial dose estimates from the well-bleached portion of grains that were derived directly from the cave exterior prior to burial (Arnold et al., 2009, 2019; Bailey and Arnold, 2006). The resultant OSL ages are stratigraphically consistent at ±2σ (Table 1), and in statistical agreement with the surrounding ^{14}C ages for the broader SU1–SU5 sequence, underscoring the suitability of both independent dating methods at this site.

The deepest and oldest OSL age was located in SU5B adjacent to the find-spot of the uppermost *Simosthenurus* bone. The second-oldest OSL age came from 45 cm higher, at the base of SU5A (in a part of SU5A devoid of roof-fall). The results for these two samples indicate that the youngest megafauna remains at Cloggs Cave are 51,830 ± 5510 years old (OSL sample CLO19-5). The base of SU5A, the sediment layer above that overlies and seals that of the megafauna remains (SU5B), has an OSL age of 46,930 ± 4150 years (OSL sample CLO19-6) (see below for the Bayesian model of combined ^{14}C and OSL ages).

3.3. Bayesian modelling

The Bayesian modelling results are summarised in Fig. 6, Supplementary Fig. 3 and Supplementary Table 3. Our model identifies five minor outliers with posterior outlier probabilities of 0.05–0.30: Wk-51056 (15%) in SU4M, Wk-50963 (8%) in the SU2G–SU4A interface, Wk-51129 (6%) in SU4M, Wk-51138 (13%) in SU4H, and Wk-51190 (28%) in the SU4V–SU5A interface. There are two major outliers: Wk-51369 (35%) in SU2A–SU2D, and Wk-51193 (51%) in the SU4V–SU5A interface. One hundred percent outliers were identified in the SU4L–SU4M interface (Wk-51052) and SU4Q–SU4R–SU4S (Wk-51132), and Wk-51142 in SU4V. Two samples in SU4V (Wk-51140, Wk-51141 and Wk-51142) were also considered major outliers during 99% of the simulations. The impact of these outliers on the model can be assessed by the convergence values generated (see Supplementary Table 3). These should be >95%, with lower values indicating many different incompatible solutions to the model at these points. Low convergence values are identified for boundary SU2D (0.5%), which is affected by the major outlier Wk-51369, boundary SU2G–SU4A interface end (92.7%), boundary SU4M–SU4N interface end (84.5%), boundary SU4V start (67.2%) and SU4V–SU5A interface end (0.8%), both affected by the high numbers of outliers in SU4V and the SU4V–SU5A interface, and the start boundary of the sequence (71.8%). The latter also partially reflects the limited number of

Table 2
AMS ^{14}C ages on single pieces from Square R31, Cloggs Cave. * Collected from the wall of the cleaned exposed 1971–1972 pit (and plotted on the Square R31 section drawing) prior to commencement of excavation (i.e. this sample does not have an XU attribution). †Dated sample comes from the sieves, from a level that includes rocky SU4V–SU5A sediments mixed from roof-fall.

SU	XU	Material Dated	Wk- Laboratory Code	δ^{13}C (‰)	^{14}C Age (BP)	%C
2A-2C	1	charcoal	51363	−27.0 ± 0.7	2022 ± 21	55
2A-2C	1	charcoal	51364	n/a	2142 ± 20	55
2A-2C	1	charcoal	51365	−24.1 ± 0.7	2225 ± 20	67
2A-2C	2	charcoal	51366	−23.4 ± 0.7	2155 ± 20	51
2A-2C	2	charcoal	51367	−26.5 ± 0.7	2156 ± 21	56
2C-2D	3	charcoal	51368	−24.9 ± 0.7	2132 ± 22	50
2C-2D	3	charcoal	51370	−24.5 ± 0.7	2380 ± 20	63
2C-2D	3	charcoal	51369	−25.8 ± 0.7	2763 ± 21	54
2F-2G interface	4	possum scat	50961	n/a	4433 ± 17	n/a
2F-2G interface	4	possum scat	50962	n/a	4115 ± 17	n/a
2G-4A interface	6	possum scat	50963	n/a	7510 ± 20	n/a
2G-4A interface	*	charcoal	50276	−24.1 ± 0.5	8337 ± 28	46
4A-4C interface	7	charcoal	50964	−24.1 ± 0.4	9539 ± 31	65
4C	8	bark	50965	−22.4 ± 0.4	9717 ± 23	n/a
4C	8	softwood plant fibre	50966	−24.7 ± 0.4	9598 ± 24	n/a
4C	8	twig	50967	−20.9 ± 0.9	9689 ± 26	n/a
4C	9	softwood artefact	50968	−21.6 ± 0.9	9726 ± 21	n/a
4C-4D interface	9	possum scat	50969	−19.4 ± 0.9	10,030 ± 24	n/a
4E	11	wooden artefact	50278	−24.3 ± 0.1	10,361 ± 30	n/a
4E	11	bark	50970	n/a	10,387 ± 26	n/a
4E-4F interface	12	charcoal	50971	−23.0 ± 0.9	10,384 ± 34	66
4F-4G interface	16	charcoal	51126	−23.5 ± 0.2	11,069 ± 35	75
4F-4G interface	15	possum scat	51036	−27.6 ± 0.4	11,686 ± 29	n/a
4G	16	possum scat	51037	−23.6 ± 0.4	12,404 ± 34	n/a
4G	17	possum scat	51038	−23.4 ± 0.4	12,117 ± 31	n/a
4G	18	possum scat	51039	−24.0 ± 0.4	12,386 ± 32	n/a
4G	19	possum scat	51040	−17.9 ± 0.4	12,276 ± 32	n/a
4G	20	possum scat	51041	n/a	12,218 ± 34	n/a
4H	21	possum scat	51042	−25.9 ± 0.5	12,568 ± 31	n/a
4H	22	possum scat	51043	−21.8 ± 0.5	12,616 ± 32	n/a
4H	23	possum scat	51044	−19.3 ± 0.5	12,645 ± 31	n/a
4H	24	possum scat	51045	−24.7 ± 0.5	12,986 ± 32	n/a
4I	25	possum scat	51046	−27.1 ± 0.5	13,218 ± 34	n/a
4I	26	possum scat	51047	−12.8 ± 0.5	13,268 ± 34	n/a
4I	27	possum scat	51048	−16.4 ± 0.5	13,287 ± 34	n/a
4I	27	charcoal	51127	n/a	13,361 ± 39	74
4I	28	possum scat	51049	−23.3 ± 0.5	13,393 ± 34	n/a
4K	29	possum scat	51050	−21.4 ± 0.5	13,728 ± 37	n/a
4K-4L interface	30	possum scat	51051	−18.9 ± 0.5	13,806 ± 35	n/a
4K-4L interface	30	charcoal	51128	−24.9 ± 0.2	14,010 ± 43	73
4L-4M interface	31	possum scat	51052	−24.4 ± 0.5	15,138 ± 40	n/a
4L-4M interface	32	possum scat	51053	n/a	14,233 ± 37	n/a
4M	33	charcoal	51129	−23.8 ± 0.2	14,222 ± 42	75
4M	33	possum scat	51054	−24.8 ± 0.5	14,434 ± 37	n/a
4M	34	possum scat	51055	−23.0 ± 0.5	14,372 ± 39	n/a
4M	35	possum scat	51056	n/a	14,964 ± 39	n/a
4M-4N interface	36	possum scat	51057	−28.5 ± 0.5	15,689 ± 41	n/a
4N	37	possum scat	51059	n/a	16,155 ± 42	n/a
4N-4P interface	37	charcoal	51131	−23.0 ± 0.2	16,203 ± 49	73
4M-4N-4O-4P interface	36	charcoal	51130	−22.1 ± 0.6	17,104 ± 53	72
4P	37	possum scat	51058	−23.2 ± 0.5	17,002 ± 53	n/a
4Q	38	possum scat	51060	n/a	20,145 ± 64	n/a
4Q	38	charcoal	51132	−21.1 ± 0.6	23,315 ± 109	n/a
4Q-4R-4S interface	39	possum scat	51133	n/a	19,993 ± 87	n/a
4S-4U interface	40	possum scat	51134	−29.2 ± 0.4	20,722 ± 94	n/a
4U	41	possum scat	51135	n/a	20,677 ± 90	n/a
4U	42	possum scat	51136	−19.9 ± 0.4	20,663 ± 91	n/a
4V	45	charcoal	51138	n/a	22,054 ± 89	72
4V	46	charcoal	51139	n/a	21,388 ± 79	68
4V	47	charcoal	51140	n/a	20,213 ± 66	71
4V	48	charcoal	51141	n/a	20,240 ± 65	75
4V	49	charcoal	51142	n/a	20,105 ± 68	68
4V-5A interface	50	charcoal	51143	n/a	31,518 ± 230	72
5A	51	charcoal	51144	n/a	42,547 ± 920	68
5A	52	charcoal	51145	n/a	42,266 ± 895	71
4V-5A interface	53	charcoal	51190	−24.3 ± 0.6	41,969 ± 632†	72
4V-5A interface	54	charcoal	51191	−21.9 ± 0.6	33,060 ± 218†	68
4V-5A interface	54	wood	51192	−23.5 ± 0.6	33,676 ± 233†	n/a
4V-5A interface	55	charcoal	51193	−27.1 ± 0.6	22,107 ± 62†	71

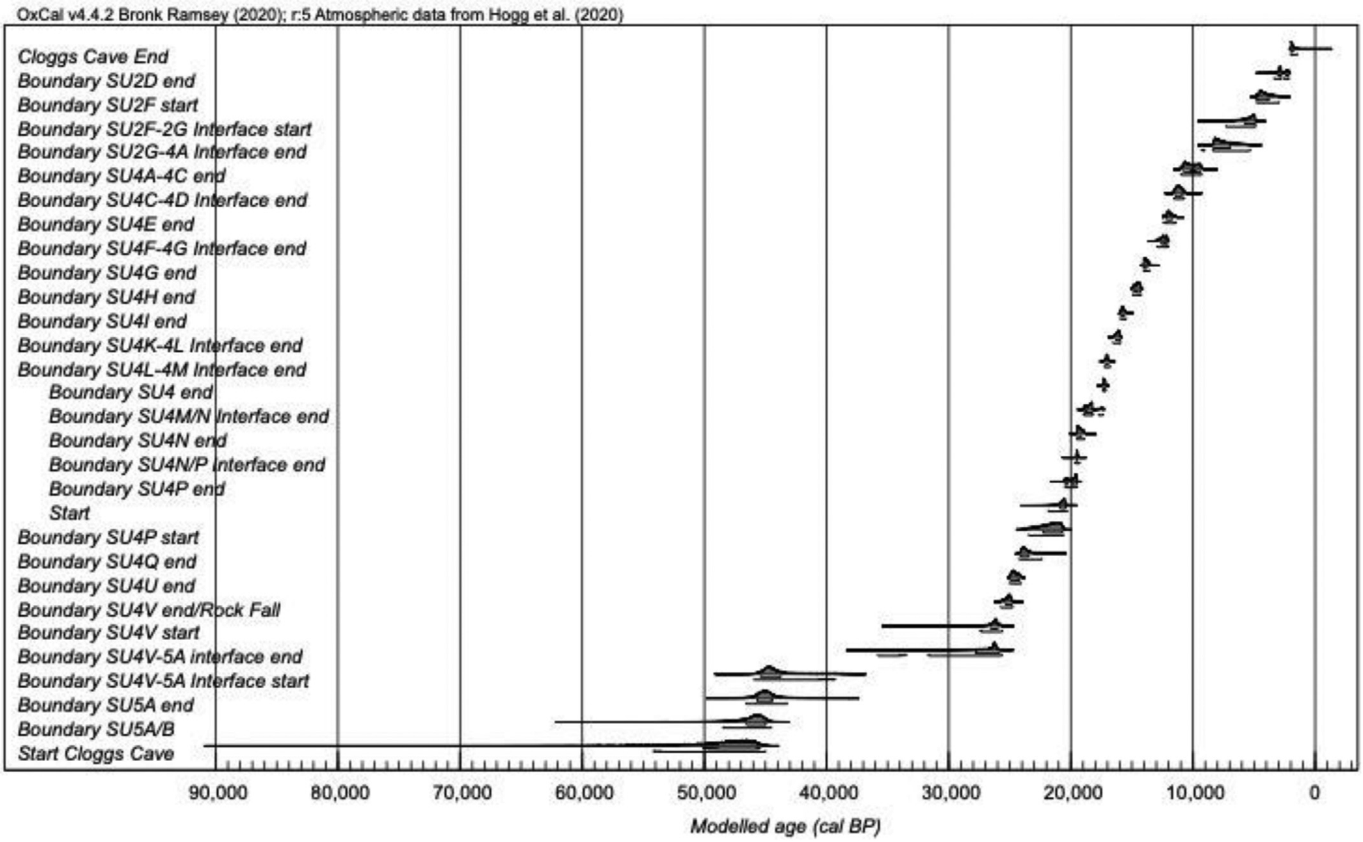

Fig. 6. Modelled boundary ages for the Cloggs Cave sequence, as reported in Supplementary Table 3.

likelihood estimates in the lowermost units (SU5A = 3 age estimates; SU5B = 1 age estimate) and potentially the larger standard error of the OSL age for SU5B (relative to the associated ^{14}C ages), which constrains the boundary age for the entire deposit.

Overall, the model indicates that deposition of SU5B ended 44,500 cal BP (Fig. 6). Given that the megafauna found at Cloggs Cave all came from SU5B, they must be older than this boundary age. The maximum modelled OSL age (OSL-2) for the find-spot of the uppermost megafauna remains is 51,700 cal BP. However, the modelled uncertainty range for the age of this find-spot is relatively imprecisely constrained because it is right at the base of the model. Given the limited number of age estimates available for this part of the model, and the relative size of the standard error associated with the lowermost OSL sample, we can conservatively conclude that the youngest megafauna dates to after 54,160 cal BP and before 44,500 cal BP.

The Bayesian model reveals a near-continuous sequence up to the Late Holocene (the uppermost layer, SU1, remains undated in this part of the site, as it had been removed by excavation in 1971–1972) (Fig. 6). Only four main ‘gaps’ are evident in the sequence. One occurs at the end of SU5A (43,230–46,580 cal BP) and another between the SU4V–SU5A interface and the start of SU4V (25,600–27,390 cal BP), separated by a short period c. 38,000 cal BP. A third gap occurs between the end of SU4Q and the start of SU4P (22,370–24,210 cal BP and 20,590–23,450 cal BP, respectively). A temporal gap also occurs between the end of the combined SU2G–SU4A interface and SU2F–SU2G interface (5310–9300 cal BP and 4860–7290 cal BP, respectively) where SU3, a layer representing a Mid-Holocene catastrophic subsidence and rapid infilling event, is found in Squares P34 and P35. The edge of the subsidence crater would have been a few tens of centimetres to the south of Square R31 when it formed, surrounding surface sediments rapidly cascading into the crater (see Delannoy et al., 2020). As the subsidence crater filled with redeposited sediments, Square R31 would have been located less than 1 m from its northeastern edge, which was then marked by a 30–40 cm-thick depression (subsequently fully infilled by SU3A–SU3B sediments).

Mixing of sediments in the SU4V–SU5A interface is due to rockfall onto the upper parts of SU5A; 50 cm to the southeast of Square R31, SU5A is free of such rockfall, whereas immediately to the northwest of Square R31 it has been impacted by major rockfall. This observation, revealed by the sediments, is reflected also by the reversal of ^{14}C ages in the SU4V–SU5A interface.

Some mixing of sediments in SU4U and SU4V is also likely related to rock fall, possibly multiple collapses based on small and medium-sized limestone rocks in those layers, with one block in Square R31 surrounded by sediment from SU4U. Such mixing is also evident in the slight reversals of the ^{14}C ages and the low convergence values of the modelled ages from SU4V. This appears to have occurred before 27,390 cal BP.

The oldest stone artefact recovered so far (analysis of the stone assemblage is ongoing and may thus be updated when completed) came from XU37 in SU4P and is bracketed by modelled boundary ages of 19,480–20,500 cal BP above and 20,590–23,450 cal BP immediately below.

4. Discussion: late megafaunal extinctions in Sahul?

Over the past 40 years, the timing and cause(s) of Sahul's megafaunal extinctions have been fiercely debated by factions with strongly opposing views, despite analyses of common datasets. Disagreements have revolved around sites whose original dating has been presented without critical examination of potential methodological complications (e.g. Wroe and Field, 2007). Relatively few new dated sites have been presented and excavated in detail over the past few decades (e.g. Hamm et al., 2016; Hocknull et al., 2020), but none of these dated sites provide evidence of survivals significantly later than c. 40,000 years ago.

The most significant relatively recent data for the debate on the antiquity of Sahul's megafaunal extinctions have come from the systematic dating of 28 relatively 'young' (Late Pleistocene) megafauna sites (Roberts et al., 2001), although by today's standards the stratigraphic provenance of each dating sample was relatively vague. U-series dating of flowstones found above and below megafauna deposits (e.g. Moriarty et al., 2000) and multiple grain or multiple aliquot optical dating of sediments that contained megafauna bones (from excavation profiles or sediments held in museum collections) were used to establish burial ages. Where possible, ages were acquired for deposits that contained articulated megafauna bones. Skeletal articulation suggests that the bones were found in their primary depositional contexts for at least 19 of the study sites (Hamilton and Krus, 2018; Roberts et al., 2001). An age model privileging the dated samples associated with articulated bones suggests that the youngest remains were deposited 39,800–51,200 years ago (at 95% probability). This dating study was significant in its consideration of multiple sites and derivation of a regional extinction chronology.

Following these results, two studies assessed the chronometric hygiene of the ages used by researchers to establish the antiquity of the megafauna and fossil deposits (Gillespie et al., 2006; Rodríguez-Rey et al., 2015). Gillespie et al.'s (2006) detailed review rejected every ^{14}C age cited to support the late survival of megafauna, on the basis that they were: 1) analysed prior to the use of modern pretreatment chemistry; 2) lacking adequate stratigraphic descriptions; and/or 3) tenuously stratigraphically associated with megafauna bones. Rodríguez-Rey et al.'s (2015) study used similar criteria to assess and rank the relative reliability of ages for Middle Pleistocene–Holocene fossils. They found that a selection of 'late survival' papers had used a total of 164 age determinations to support their conclusions, of which only 11% were assessed as reliable. Those advocating a short megafauna-human overlap (i.e. an earlier timing for extinctions) used 802 ages, 76% of which were found to be reliable. We note, however, that (Rodríguez-Rey et al. (2015)) do not categorise any ABA pre-treated ^{14}C samples as fully reliable (all are ranked as 'B' rating results under their system), despite the many forms of ABA pre-treatment. Date quality has many more parameters than outlined in that paper.

The most likely place in Australia to have fostered late surviving megafauna is Tasmania, today separated from the Australian mainland by the 199 km-wide Bass Strait. Eight species of megafauna (all marsupials) have been found in Tasmania, as well as *Megalibgwilia ramsayi*, a 1 m-long giant echidna with an estimated body mass of 30 kg (Table 3). These species were also present in mainland Australia. As noted in Section 1, the difficulty in establishing the timing and cause of the extinction of Australia's megafauna species has been exacerbated by the variable quality of age determinations. In an attempt to address this latter problem, the FosSahul 2.0 database provides a three-tier quality rating for age measurements associated with Australian megafauna (Peters et al., 2019). Five dating techniques have been used to generate 117 age measurements in determining the antiquity of Tasmania's megafauna fossils. Of the ages generated, 29 (24.8%) are considered reliable by FosSahul 2.0 (including the Mt Cripps ages [see Gillespie et al., 2012], which had mistakenly been given a 'B' rating, now corrected to 'A' rating). Six species of megafauna from Scotchtown Cave (Table 3) are associated with OSL ages (with 1σ uncertainty ranges) of 56,000 ± 4000 years ago (Turney et al., 2008) and a *Thylacoleo carnifex* incisor from Titan Shelter has been directly dated to 53,000 ± 4000 years ago (1σ uncertainty) using a combination of U-series and electron spin resonance (ESR) methods (Cosgrove et al., 2010). Additionally, a cave at Mt Cripps has yielded a *Simosthenurus occidentalis* specimen that has been directly AMS ^{14}C-dated at 46,000–49,840 cal BP, and another site in the same cave has yielded seven *Protemnodon anak* specimens, the youngest of which has been AMS ^{14}C-dated to 39,700–41,590 cal BP (Gillespie et al., 2012; Turney et al., 2008). The earliest archaeological evidence for people in Tasmania is dated by ^{14}C to 37,360–39,870 cal BP (33,850 ± 450 BP, Beta-68158 CAMS-10270) and 39,020–41,090 cal BP (34,790 ± 510 BP, Beta-42122B ETH-7665B) at Parmerpar Meethaner and Warreen respectively (Allen, 1996; Cosgrove, 1999). An age of 42,340–44,740 cal BP (39,970 ± 950 BP, Beta-68160 CAMS-10272) for charcoal in underlying culturally sterile deposits at Parmerpar Meethaner suggests that people had not yet arrived in this north-central Tasmanian site by then. These ages were obtained before modern pretreatment methods were developed, and so must be considered minimum ages until shown otherwise. Even taking this into account, the accepted ages on megafauna (Cosgrove et al., 2010; Gillespie et al., 2006; Turney et al., 2008) indicate that megafauna and people potentially overlapped in Tasmania. However, clear archaeological evidence of co-existence, such as bones with butchery marks, has not yet been found.

The youngest megafauna remains from Tasmania are among the most recent known from all of Sahul. Cloggs Cave is located in southern Victoria close to Bass Strait and is, therefore, well situated to address the question of the last appearance of Australian megafauna during the Late Pleistocene. During the Last Glacial Maximum, when sea levels receded, the continental shelf was exposed. Bass Strait became the Bassian Plain, connecting what is now southern Victoria with Tasmania. The formation of the Bassian Plain c. 43,000 years ago (Lambeck and Chappell, 2001) provided people with a land bridge into Tasmania. Its formation also coincides with the rapid demise of Tasmania's megafauna. This rapid demise of megafauna in Tasmania after the formation of the Bassian land bridge and also at about the same time that people first inhabited Tasmania signals: 1) the impact of people (e.g. through landscape transformations) on Tasmanian megafaunal extinctions; and 2) the inability of megafauna to repopulate Tasmania from southern Victoria in the north, where they had also become extinct.

An important focus of the extinction debate has been the chronology and chronostratigraphic integrity of sites thought to preserve late surviving megafauna. These have focused on four key contentious sites to the north and west of Tasmania, including Cloggs Cave. Each of these sites has megafauna-bearing strata associated with controversial (mostly ^{14}C) ages younger than 39,000 years (see below). At the ephemeral lake site of Cuddie Springs in southeast Australia, megafauna bones were found next to stone artefacts in strata dating to c. 35,000 years ago (Field, 2006; Field and Dodson, 1999; Field et al., 2001; Fillios et al., 2010; Gillespie and Brook, 2006; Trueman et al., 2005). However, recent OSL and combined ESR/U-series dating indicates that the strata were not intact, and that most of the megafauna bones were significantly older than their host sediments (Field et al., 2001; Grün et al., 2010; Roberts et al., 2001). At the Seton rock shelter on Kangaroo Island (South Australia), four sthenurine kangaroo tooth fragments were found in strata dating to c. 20,570–20,960 cal BP (17,276 ± 70 BP, NZA-25833) (McDowell et al., 2015; see also Hope et al., 1977; Lampert, 1981). All bone from the site is highly fragmented, and while the skeletal remains of extant fauna could be directly ^{14}C-dated, those of the megafauna could not (McDowell et al., 2015). Nombe rock shelter in the New Guinea highlands has *Protemnodon* and diprotodontid bones in the same strata as

Table 3
Species and locations that have yielded megafauna in Tasmania (Gill and Banks, 1956; Goede and Murray, 1977; Peters et al., 2019; Squires, 2012; Turney et al., 2008). ? = uncertain species (indeterminate).

	Beginner's Luck Cave	Montagu Main Cave	Mowbray Swamp	Mt Cripps	Pleisto Scene Cave	Pulbeena limeworks	Scotchtown Cave	Titan Shelter	Emu Cave	Un-named Cave
Phascolonus gigas			X							
Thylacoleo carnifex	X	X			X		X	X		X
Macropus giganteus titan								X		
Protemnodon anak		X		X	X		X	X		
Simosthenurus occidentalis	X	X		X	X		X	X	?	X
Metasthenurus newtonae							X			
Palorchestes azael		X	X		?	X	X			
Zygomaturus trilobus		X	X		?		X	?		

stone artefacts (Flannery et al., 1983; Gillieson and Mountain, 1983; Mountain, 1991). The site's stratigraphy is complex and has been shown to have been reworked, with ^{14}C ages acquired for the strata containing the megafauna remains ranging widely from c. 4900 cal BP to c. 25,000 cal BP (Denham and Mountain, 2016). As concluded above, the so-called late survival sites of Cuddie Springs, Seton rock shelter and Nombe each have significant unresolved chronologies and/or taphonomic problems and are thus best omitted from extinction models until the antiquity and depositional contexts of the megafaunal remains are more reliably determined.

The present chronostratigraphic re-evaluation of Cloggs Cave, which combines multiple dating techniques, high-resolution sampling strategies and appropriate methodological considerations of technique-specific biases (see Supplementary Information 2), reveals that the youngest megafauna bones found at this site were deposited in sediments that date to 44,500–54,160 cal BP. Our broader examination of the site's infilling history (David et al., in press; Delannoy et al., 2020) confirms that the original ^{14}C chronology established in the 1970s was inaccurate by more than 10,000 years, serving as a stark reminder of the interpretative problems that can arise from taking methodologically outdated chronologies of contentious sites at face value. The dismissal of Cloggs Cave's original dating now puts to rest the antiquity of the youngest megafauna remains at this purportedly significant late survivor site.

The absence of late surviving megafauna at Cloggs Cave, and the unreliability of the chronostratigraphy and/or depositional contexts of megafauna remains at Cuddie Springs, Seton and Nombe rock shelters, leaves a total absence of dated megafauna significantly younger than c. 40,000 years ago across the whole of Sahul, Tasmania included. Whether one accepts Madjedbebe's early ages of c. 65,000 years ('65.0 ± 5.7 kyr': 59,300–72,700 years) for the onset of human occupation of Sahul (Clarkson et al., 2017) or an age closer to 50,000 years (O'Connell et al., 2018) for more widespread human settlement across Sahul north of Tasmania (Bowler et al., 2003; David et al., 2019; Maloney et al., 2018; Summerhayes et al., 2010; Turney et al., 2001; Veth et al., 2017), this represents a minimum of c. 10,000–20,000 years of coexistence between people and megafauna relative to site SW9 at South Walker Creek, northeast Australia, the youngest dated fossil megafauna site on the Australian mainland. Hocknull et al. (2020) derived a combined age range of 40,100 ± 1700-year-old (at 1σ) for the SW9 fossiliferous megafauna layer based on all available (finite) numerical dating results awarded an A or A* quality rating according to the Rodríguez-Rey et al. (2015) scheme (11 single-grain OSL ages of 38,900 ± 3000 years [1σ] from the Griffith University OSL laboratory, eight single-grain OSL ages of 43,300 ± 1800 years [1σ] from the University of Adelaide OSL laboratory, and five U-series/ESR ages yielding an average of 35,200 ± 2500 years [2σ]; note that the latter was incorrectly written as 32,500 ± 2500 years in Table 2 of Hocknull et al., 2020). This c. 10,000–20,000 years of coexistence is too long a timeframe for rapid overkill.

The new Cloggs Cave results also indicate that Australia's Late Pleistocene megafauna became extinct well before the peak of the LGM, indicating that the LGM is now irrelevant to the extinction debate.

The final Late Pleistocene megafaunal extinctions took place on the Australian mainland 1) a minimum of c. 10,000–20,000 years after the arrival of people in the far north; 2) c. 40,000 years ago, at a time when archaeological sites (i.e. evidence of people) became more frequent across the continent (Williams, 2013), but without clear-cut palaeoecological evidence that human-induced landscape burning caused significant landscape modification (Johnson, 2016; Kemp et al., 2019); and 3) during a period of widespread landscape aridification (Cohen et al., 2015; Hocknull et al., 2020; Kemp et al., 2019) of a kind that many of the megafauna, being arid-adapted, had previously survived (Prideaux et al., 2007). Together these factors indicate that extinction was not solely due to deliberate hunting (as people had already been on the continent for a long time), nor to major human-induced landscape modification, nor to climate change. Rather, the conditions for, and timing of, their demise can best be explained by a combination of these factors, creating a 'perfect extinction storm'. Only in Tasmania was megafaunal extinction closely associated with the arrival of people (Turney et al., 2008).

Author statement

We confirm that all authors have made substantial contributions to the submission and have approved the paper for publication. We have not submitted this paper elsewhere for publication.

Author contributions

B.D., L.J.A., J.-J.D., J.F., C.U., F.P., M.C.M., R.M., J.M., R.W., J.C., V.N.L.W., H.G. co-wrote the paper; the GunaiKurnai Land and Waters Aboriginal Corporation initiated and oversaw the research and are the Traditional Owners of Cloggs Cave; B.D. coordinated the scientific aspects of the project; B.D., L.J.A., J.-J.D., J.F., C.U., R.M., J.C., J.B., H.G. conducted fieldwork and collected samples at the site; L.J.A. conducted OLS dating on sediments from the site; J.-J.D. undertook geomorphological research and cartography at the site; F.P. conducted ^{14}C dating of samples from the site and constructed the Bayesian chronological model; M.C.M. identified the animal bones excavated from the site; J.M. undertook laboratory analyses of archaeological materials and produced technological data on the site's stone artefacts; R.W. conducted ^{14}C dating of charcoal samples from the site; J.B. undertook LiDAR 3D mapping of the site; V.N.L.W. conducted geochemical analyses on excavated soil samples; H.G. and J.H. dated speleothem samples from the site.

Significance Statement

During the Late Pleistocene, a number of large-bodied species collectively known as 'megafauna' became extinct across Australia. When, and why, this happened remains one of the most debated questions in Australian Quaternary science. Critical to these debates are 'late survivors', megafauna that survived long after the arrival of people. Our research at Cloggs Cave (southeast Australia), previously considered a late survivor site, now shows that here the youngest megafauna remains accumulated more than 10,000 years earlier than previously thought. The diversity of ages associated with all other well-dated megafauna sites in Australia, implies that rather than a single cause, a combination of factors (people and environmental change) created a 'perfect extinction storm'. In Tasmania, megafaunal extinction was closely associated with the arrival of people.

Declaration of competing interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.quascirev.2020.106781.

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