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Bayesian age-depth modelling of Late Quaternary deposits from Wet and Blanche Caves, Naracoorte, South Australia: a framework for comparative faunal analyses

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ABSTRACT

Bayesian age-depth models were constructed for two Late Quaternary aged fossil-bearing sedimentary sequences from caves in south eastern South Australia. The deposits in Wet and Blanche Caves contain dense assemblages of vertebrate fossils, largely the result of owl pellet accumulation. While individually calibrated radiocarbon determinations from the fossil sequences have provided a chronology for their accumulation, there was limited capacity available with such data to (a) temporally constrain assemblages associated with different depositional units and layers within the two sites, (b) interpret the chronological relationships among successive units and layers and (c) correlate sedimentary units and layers of similar age between the two deposits. Here, Bayesian age-depth models were constructed in OxCal for the Wet and Blanche Cave sequences, incorporating the available radiocarbon data and stratigraphic information collected during their excavation. Despite the low precision of the age-depth models for Wet and Blanche Caves which results in part from there being only single radiocarbon determinations available for a number of units and layers, the models enabled the relationships within and between the two sites to be established. Of particular utility for future faunal analyses is quantification of the temporal relationship between strata from the two sites, where groups of individual layers from Blanche Cave were found to be temporally equivalent with the longer-duration units in Wet Cave. We suggest that the use of `Phase` modelling, as performed here, is useful for cave deposits that have complex depositional histories and even in such instances where, as is common for palaeontological sites, few radiocarbon data are collected relative to the time-spans of tens of millennia that are often represented by them.

Keywords: ^{14}C dating, age-depth modelling, Bayesian statistics, cave sequence, last glacial cycle, Naracoorte Caves

1. Introduction

The utility of radiocarbon (^{14}C) dating to provide chronologies for late Quaternary aged archaeological and palaeontological sites is well demonstrated (e.g., Gillespie, 2002; Vasil'ev et al., 2002; Crowley, 2010). However, sparse radiocarbon data and statistical uncertainty often restrict the resolution and accuracy of site chronologies based on individually calibrated ^{14}C determinations (Parnell et al., 2011). Bayesian chronological methods can overcome

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these limitations and have increasingly been used to develop chronologies for palaeontological and archaeological sites where a high level of dating precision is required (e.g., Petrie and Torrence, 2008; Beramendi-Orosco et al., 2009; Calcagnile et al., 2010; Higham et al., 2010; Zhu et al., 2010). By integrating ^{14}C data (*likelihoods*) and stratigraphic information (*priors*), Bayesian age-depth models produce *posterior* (modelled) site chronologies that not only refine the chronological information available for a given sequence, but also provide quantified uncertainties for such profiles, given the model prior applied (Bronk Ramsey, 2008; Parnell et al., 2011). As demonstrated by Blaauw et al. (2007), Bayesian age-depth models can also be used to temporally correlate the proxy records from contemporaneous sequences. While correlation of depositional sequences commonly utilises stratigraphic, sedimentary and chronological data (e.g., Birkland et al., 1971; Magee et al., 1995; Frumkin et al., 2001), these past approaches have rarely taken account of the underlying chronological uncertainties both within and between records.

Cave sites are particularly important in Quaternary palaeontological studies as they contain deep, well stratified sedimentary sequences often spanning multiple millennia (e.g., Cuenca-Bescos et al., 2009). Caves also provide stable conditions for the long term preservation of skeletal remains of a diverse range of vertebrates, which may have been collected through pitfall entrapment, cave inhabitant death and/or carnivore accumulation (Nielsen-Marsh, 2000). In some cases, vertebrate deposits in caves are associated with a range of other palaeoecological materials such as charcoal, calcium carbonate cave formations (speleothems) and pollen, which may be correlated with fossil faunal assemblages to provide a more accurate interpretation of past environmental conditions (e.g., Burney et al., 2001; Carrión et al., 2003; Auler et al., 2006). The application of Bayesian age-depth models to cave sequences has been valuable where the complex and sometimes random nature of accumulation processes in caves can limit the resolution and accuracy of chronologies for these sites (e.g., Jacobi and Higham, 2009; Blockey and Pinhasi, 2011; Pinhasi et al., 2011).

In south eastern South Australia, 26 caves within the Naracoorte Caves complex contain 100 known vertebrate fossil deposits ranging from early Pleistocene to Holocene age (Reed and Bourne, 2000; Prideaux et al., 2007; Macken et al., 2013; Fig. 1). Within this cave complex, deposits in two of these caves, Wet and Blanche, are broadly contemporaneous, spanning the late Pleistocene from *ca.* 45 ka, to the Holocene period (Darrénougué et al., 2009; St. Pierre et al., 2012; Macken et al., 2013). Fine stratigraphic laminations contained within broader sedimentary units in these cave sequences, in combination with the high density of bone material identified from these deposits (McDowell, 2001; Laslett, 2006; Macken and Reed, 2013) makes them suitable for the analysis of faunal patterns through the last glacial cycle at a range of temporal scales, incorporating both long and short term phases of accumulation. As these sites are of similar age, they also provide an opportunity to quantify inter-site variability within the palaeocommunity through similarity tests of contemporaneous, replicate fossil samples from the one locality, an approach endorsed by Bennington and Bombach (1996).

Data on the calibrated age, duration and temporal continuity of depositional units and layers of the fossil bearing sedimentary profiles of Wet and Blanche Caves are required to temporally constrain the faunal assemblages and to enable an evaluation of faunal change through time, both within and between the two sites. To facilitate such analyses, greater chronological resolution is required than has been previously published. In the case of Wet Cave, only a small number of ^{14}C determinations are available (Macken et al., 2013; Table 1). In Blanche Cave, although more ^{14}C determinations are available for the sequence (St Pierre

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et al., 2012; Table 2), overlap in the calibrated radiocarbon ages of successive layers limits the resolution at which faunal analyses may be conducted.

Here, we use Bayesian age-depth models to assess the chronological histories of Wet and Blanche Cave and the temporal relationships between strata from the two sites. As fossil-bearing deposits, understanding these relationships is critical for robust and informed comparative faunal analyses. More specifically we use Bayesian age-depth modelling to (a) construct probabilistic site chronologies that provide modelled ages for the lower and upper boundaries (reflecting the start and end) of depositional episodes (stratigraphic units and finer sedimentary layers) within the two sequences, (b) determine the temporal duration (resolution) of these depositional episodes and potential hiatuses between them, and (c) identify contemporaneous depositional episodes between the two sites. We discuss the challenges and opportunities presented by such models for the study of complex cave sequences and explore the implications of these models for future study of the fossil assemblages specifically associated with Wet and Blanche Caves.

2. Regional Setting and Study Sites

2.1 Geological setting of the Naracoorte Caves

Wet and Blanche Caves are located within the Naracoorte Caves World Heritage Area, 12 km south-east of Naracoorte in south eastern South Australia (Fig. 1). The caves lie in an uplifted portion of the Oligocene to Miocene aged Gambier Limestone, which originated from fossiliferous marine sediments. Phreatic dissolution of this limestone and structural processes along joints contributed to cave formation (Wells et al., 1984; White, 2005). The oldest sedimentary deposits in the Naracoorte Caves have been dated to 528±41 ka using optically stimulated luminescence dating (Prideaux et al. 2007), suggesting that the caves first opened to the surface during the early to middle Pleistocene. Overlying the Gambier Limestone is a series of stranded Pleistocene beach dune facies known as the Bridgewater Formation. The oldest of these is the East Naracoorte Ridge, dated by whole-rock amino acid racemisation to 935±178 ka (Murray-Wallace et al. 2001) and overlies the Naracoorte Caves. All known caves in the region are registered with the Australian Karst Index (Matthews, 1985) and are identified by unique cave numbers (e.g., 5U10, 11). Here, the '5' refers to the state of South Australia, 'U' to the Upper south east, and '10' and '11' are the numbers allocated to the entrances associated with Wet Cave.

2.2 Wet Cave (5U10, 11)

Wet Cave is composed of three chambers. An upper and lower chamber are accessed via entrance 5U10, located on the southern edge of the main road into the Naracoorte Caves National Park. A third chamber is open to the surface through entrance 5U11, approximately 130 m south of entrance 5U10. The excavated sedimentary sequence was located on the south eastern edge of the sediment cone in the upper chamber associated with entrance 5U10. The sequence was excavated across two 1 m^2 pits (1, lower and 2, upper) in 1998 and 1999 to a total depth of 350 cm. Sedimentary layers through the sequence were excavated separately and their depths measured from a datum established at the top of Pit 2 (Macken et al. 2013; NB. The Wet Cave stratigraphy is represented in Figure 5, Section 4.3).

Following severe storms in December 2010, the excavated section of Wet Cave was filled with flood sediments, limiting further assessment of the site. Prior to this event, the excavated

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section of Wet Cave was composed of six depositional units; Units A (lower) to F (upper; Macken et al., 2013). While stratigraphic and sedimentary observation of the units suggests that the majority were deposited in chronological order, Unit D appears to have incorporated reworked sediments from an older depositional episode (Macken et al., 2013). These stratigraphic relationships were formalised into the Bayesian model framework for Wet Cave, as detailed in section 3.1.2.

Dating of charcoal samples from Wet Cave occurred in two stages. Initial AMS ^{14}C determinations were made on charcoal collected from the exposed stratigraphic profile in the late 1990s with 14 ages published by Pate et al. (2002; 2006). An additional six AMS ^{14}C determinations have since been reported by Macken et al. (2013), measured from charcoal samples sorted from wet-screened material during the original excavation and stored in vials in the fossil laboratory since 1998. The specific depths of these samples are unknown as they were labelled only with the source layer code (Table 1).

2.3 Blanche Cave (5U4, 5, 6)

The structure of Blanche Cave and the sedimentary character, stratigraphic division and chronology of a sediment core from the excavation site has been described by Darrénougué et al. (2009). The Blanche Cave fossil excavation is located in the 3rd chamber associated with entrance 5U6, approximately 400 m north west of Wet Cave entrance 5U10. Fossil excavation in the 3rd chamber occurred between 2006 and 2007. The first excavation was conducted by Laslett (2006) who excavated four 1 m^2 grid squares (A1, B1, A2 and B2) in 5 cm layers to a maximum depth of 1.1 m; however, three of the grid squares were obstructed by the presence of a large limestone boulder. A second excavation was conducted by EHR in 2006/2007 from two grid squares (A3 and B3), both excavated to a depth of 1 m. Excavation of these grid squares followed the stratigraphy such that 27 individual sedimentary layers were excavated as discrete bands, ranging from 1 to 6 cm thick (the Blanche Cave stratigraphy is represented in Figure 5, Section 4.3). The Bayesian model developed here integrates the stratigraphic information associated with the 27 sedimentary layers described from grid squares A3 and B3, rather than the earlier, depth-standardised spit data from Laslett (2006).

Five units (1, lower to 5, upper) have been described from the top 100 cm of the Blanche Cave stratigraphic sequence (Darrénougué et al., 2009), corresponding to the 27 individual sedimentary layers; however, precise depth information relating to the units is not integrated into the Blanche age-depth model. This is because the ^{14}C determinations are stratigraphically constrained at a finer resolution by the 27 layers noted from grid squares A3 and B3. A total of 40 AMS ^{14}C determinations are available from across the 27 layers (Darrénougué et al., 2009; St Pierre et al., 2012; Table 2).

3. Materials and Methods

3.1 Bayesian age-depth models

Bayesian age-depth models were developed in OxCal ver. 4.1 (Bronk Ramsey, 2008; 2009a), applying the IntCal09 calibration curve (Reimer et al., 2009), but allowing for an offset from this for calibration in the Southern Hemisphere (SH) of 56±24 years. This offset is the same as that applied to the earliest 500 years of the SHCal04 calibration curve (McCormac et al., 2004). Although the SH calibration curve is only recommended back to 11,000 cal yr BP, we

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applied the average offset value for the earliest 500 years of the modelled SH dataset across the entire time period sampled in Wet and Blanche Caves. We acknowledge that the accuracy of this offset may decline through the pre-Holocene period (ca. 11,000 to 50,000 cal yr BP) due to a potentially more variable inter-hemispheric offset resulting from changes in ocean circulation and carbon cycling processes under full Glacial conditions. However, no current calibration curve is available for the SH into the Pleistocene, necessitating the compromise approach adopted here. Leaving the oldest ages uncalibrated, as was the approach used by Crowly (2010) would limit the reliability with which the two sites could be correlated. Alternatively, calibrating the pre-Holocene ages to IntCal09 (without an allowance for an inter-hemispheric offset) would affect the reliability of any future comparison of the Wet and Blanche Cave sequences with Northern Hemisphere data. As we apply the same calibration offset to both sites here, the choice of calibration curve (or offset) does not affect the correlation of the two cave sequences. Furthermore, given the resolution of the chronological data, the offset applied does not strongly alter the modelled chronologies for the sequences when compared with models calibrated without an offset.

Both sites were constructed as `Phases` within a `Sequence` deposition model (Bronk Ramsey, 2008), incorporating prior information about the order of events, as determined from the stratigraphy. `Sequence` and `Phase` models are suitable for sites such as caves where the rate or continuity of deposition is unknown, contrasting with lacustrine or marine sediment profiles that might exhibit more regular depositional phases (Bronk Ramsey, 1995; 2008). In both the Wet and Blanche Cave sequences, few assumptions about deposition could be made from the available stratigraphic data. For example, a possible depositional hiatus during accumulation of the Wet Cave sequence is indicated by the presence of bat guano derived materials at depth below datum (D/D) -39 to -52 cm, representing the bottom 13 cm of Unit F; however, the duration of this event is unknown (Macken et al., 2013).

`Boundaries` were applied to the top and bottom of each sequence constraining the maximum age of the models to 60,000 cal yr BP (conservatively earlier than the 50,000 cal yr BP limit of the IntCal09 calibration curve; Reimer et al., 2009) and the minimum age to -50 cal yr BP (i.e., AD 2000). All modelled data are reported at the 68.2 and 95.4% highest probability density (hpd) ranges (approximately equivalent to 1 and 2σ uncertainty, respectively).

3.1.1 Wet Cave

A schematic of the OxCal model for the Wet Cave sequence is presented in Fig. 2a. Separate `Phases` were assigned to each depositional unit identified in the Wet Cave sequence (Macken et al., 2013). These were constrained to be in chronological order (from Unit A, oldest, to Unit F, youngest), except for the potentially re-worked Unit D. In order to utilise the extra chronological data nevertheless available from Unit D (i.e., adding extra potential *terminus post quem* data for the commencement of the overlying Unit, E), this `Phase` was constrained to lie anywhere between the start of the deposition sequence (i.e., the 'Wet Cave bottom' `Boundary`) and the bottom of Unit E (Fig. 2a). In OxCal, this was achieved by nesting the `Sequence` of Units A, B and C, and the independent `Phase` of Unit D, within a broader `Phase` for Units A, B, C and D.

From stratigraphic observation it was deemed that each of the depositional units (except Unit E) were internally heterogeneous such that no assumption of relative chronological ordering could be made of the sediment within each of these units. Unit E, however, demonstrated

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reliable sub-structure, and therefore additional sub-Phases, themselves constrained to lie in stratigraphic order, were nested within Unit E, representing six lenses (2:6/4, oldest, 2:6/3, 2:6/2, 2:6/1, 2:5/2, and 2:5/1, youngest).

All of the ^{14}C data for the Wet Cave samples were inserted within this model framework as R_Dates, except WeC12 and WeC16, which were inserted with the R_F14C function. R_F14C uses the raw $F^{14}C$ measurement, rather than the calculated conventional radiocarbon age, to account for the fact that these samples provided 'infinite' ('greater than') radiocarbon dates (Table 1). Outlier analysis was applied using the 'general' outlier_model described by Bronk Ramsey (2009b). An equal prior Outlier probability of 5% was applied to the majority of ^{14}C determinations (R_Dates and R_F14C). However, based on the threshold identified by Pate et al. (2006), ^{14}C determinations from samples with extracted carbon values of ≤100 μg C were deemed more likely to be questionable and were given an increased prior Outlier probability of 10% (i.e., samples WeC33, WeC23, WeC12). While Pate et al. (2006) argued that sample WeC30 had a low extracted carbon value when compared with the other samples, its mass of 200 μg exceeds the threshold criterion originally identified by the same authors and was assigned a prior probability of 5% here.

3.1.2 Blanche Cave

A schematic of the Blanche Cave OxCal model is presented in Fig. 2b. The model was constructed in a similar manner to that for Wet Cave, with separate Phases assigned to each sedimentary layer. However, stratigraphic observations and sedimentary data could not reliably differentiate whether Layers 23–21, 18–15, 13–10 and 9–4 represented single, sequential depositional phases, or sediments of mixed age within broader depositional episodes. For these sections, overlapping sub-phases (representing each individual layer) were nested within broader Phases for the combined layer sections (Layers 23, 22 and 21; Layers 18, 17, 16 and 15; Layers 13, 12, 11 and 10; and Layers 09, 08, 07, 06, 05 and 04) such that no relative ordering of the sub-Phases was presumed, *a priori*, within these four broader Phases (Fig. 2b). The remaining layers, as well as the four broad Phases, were then constrained to be in stratigraphic order in the overall model Sequence (from Layer 27, oldest, to Layer 1, youngest), except for the potentially re-worked Layer 14 ('special event layer' identified by Darrénougué et al., 2009). As with Unit D in Wet Cave, the Phase for Layer 14 was constrained to lie anywhere between the start of the deposition sequence (i.e., the 'Blanche Cave bottom' Boundary) and the bottom of the overlying Phase (Layer 13), thus providing additional potential *terminus post quem* data for the overlying strata.

The ^{14}C data were inserted within this model framework. Outlier analysis was again applied using the 'general' Outlier_model (Bronk Ramsey, 2009b), with a prior Outlier probability of 5% applied to all of the ^{14}C determinations. For this site, there was no *a priori* reason to believe that any of the samples were more likely to be erroneous than others. However, six samples, 5U6B3-L8BW, 5U6B3-L8BW repeat, 5U6A3-L7BW, 5U6A3-L7BW repeat, 5U6B3-L4BW and 5U6B3-L4BW repeat, were so outlying that their inclusion prevented the model from running. The prior Outlier probabilities of these samples were necessarily increased to 100% to allow the model to run.

3.1.3 Temporal Duration of Phases and Potential Hiatuses between Phases

The modelled duration of Phases representing depositional units in Wet Cave and layers or groups of layers in Blanche Cave were obtained using the Difference query function in

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OxCal. Assessment of the presence and duration of potential temporal hiatuses between successive `Phases` within each sequence were also modelled using the `Difference` function. `Difference` provides the range in calendar years between two events and can be used to test a null hypothesis (H_0) that the two events are contiguous (i.e., that, given the dating evidence available, there is no temporal hiatus/missing sediment between the end of the first event and the start of the next). If the calculated hpd range (for the `Difference` query) does not contain 0 at a given confidence level (typically the 95.4% confidence), H_0 is rejected and there is some evidence to suggest that, at the dating resolution available, there is missing material or a temporal gap detected between the two events. If the null is not rejected, it is possible that the ages of the two events could overlap. Specific cases where sedimentary observations suggest that such overlap is possible (as a result of depositional or post-depositional mixing of materials of different age) have been incorporated into the model priors (Wet Cave Unit D; Blanche Cave Layer 14). All other `Phases` have been assumed, based on sedimentary observations, to be successive and in stratigraphic superposition based on age (with the exception of the individual layers within Blanche Cave Layers 9–4, 10–13, 15–18 and 23–21), and the model priors constructed accordingly.

3.2 Correlation of Wet and Blanche Cave `Phases`

The OxCal queries `Order` and `Difference` were used to examine the temporal relationship between the Wet Cave depositional units and Blanche Cave layers. These functions were queried for all pairwise comparisons of the posterior probability distributions for the Wet and Blanche Cave `Boundaries`, which had been saved as `Priors` from the output data from the two individual site models.

`Order` finds the probability that one event (i.e., t_1) is older than another (t_2). Therefore, the function simply provides the 'most likely' relative ordering of events between the two `Sequences` (i.e., providing a probability threshold of 50%). Application of the `Difference` function provides a more rigorous, quantified probability distribution of these relationships. As with the intra-site queries described above, a `Difference` function with a 95.4% hpd range including 0 prevents rejection of the null hypothesis and implies that, given the available data, synchrony of the two events cannot be excluded.

4. Results

4.1 Wet and Blanche Cave Bayesian Models

Modelled ages for the upper and lower `Boundaries` of Wet Cave `Phases` are presented in Table 3 and Figure 3. Modelled ages for the `R_Dates`/`R_F14Cs` and associated posterior `outlier` probabilities for these data are also presented in Table 3. Samples 5U6-6 and 5U6-1 were both found to be 100% outliers by the model; all other `R_Dates/R_F14Cs` had posterior `outlier` probabilities of ≤11%. The modelled ages for the lower and upper `Boundaries` of Units A and F, respectively, constrain the age of the Wet Cave sequence from 56,032–46,523 to 680– -43 cal yr BP (95.4% hpd range), ostensibly influenced by the prior maximum and minimum age constraints applied to the model.

Modelled ages for the upper and lower `Boundaries` of `Phases`, `R_Dates` and associated posterior `outlier` probabilities for the Blanche Cave sequence are presented in Table 4. Hpd ranges of the modelled `Boundaries` are presented in Fig. 4. While the majority of `R_Dates` fitted the applied model construction well (i.e., posterior `outlier` probability ≤

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the prior of 5%), R_Dates 5U6B3-22 and 5U6A3-L21BW returned posterior outlier probabilities of 95 and 92%, respectively. Nine samples, representing R_Dates from Layers 23, 19, 18, 16, 10, 8 and 1, had posterior outlier probability values >5%, ranging between 8 and 38%.

The modelled ages for the upper and lower-most Boundaries of the Blanche Cave sequence (Layer 27 bottom and Layer 1 top) place the modelled Sequence between a maximum of 59,997–46,259 cal yr BP and 14814– -50 cal yr BP, again heavily constrained by the maximum and minimum prior ages assigned to the model.

4.2 Phase Durations and Potential Hiatuses

68.2% and 95.4% hpd confidence ranges for the Phase durations of units and potential hiatuses between Wet Cave units and Unit E lenses are presented in Table 5. Table 6 presents these data for the Blanche Cave layers. The duration ranges for Wet Cave Units C, D and F and all Unit E lenses contain 0. In contrast, the duration of Unit A ranges from 18,343 to 30,429 years. The 95.4% hpd ranges for Units B and E also point to rejection of the null hypothesis, with upper values of 7,492, and 7,712 years respectively. All Difference functions between successive units and Unit E lenses contain 0 at the 95.4% confidence level. As a result, there is insufficient evidence to reject H_0 (for contiguous deposition) given the radiocarbon data available. The model prior for Unit D was such that it could overlap in age with units A, B or C. The single ^{14}C measurement from Unit D is insufficient to provide refined information (compared to the unmodelled data) to constrain this unit more precisely. For the same reason, there is insufficient information to reject the null hypothesis that Units C and D are contiguous.

Only the duration of the Phase for Layers 18–15 of Blanche Cave does not contain 0 at the 95.4% confidence level, suggesting that, at the dating resolution available, instantaneous deposition of each of the remaining Phases cannot be excluded. Similarly, the null hypothesis of contiguous deposition of successive layers was not rejected at the 95.4% confidence level for all successive layer Boundaries.

4.3 Correlation of Wet and Blanche Cave Phases

Table A.1 (Appendix A) presents the likely chronological order of Wet and Blanche Cave Boundaries based on a 50% probability threshold. Ranges for the difference in ages between Wet and Blanche Cave Boundaries for which the null hypothesis is not rejected are presented in Table A.2. Figure 5 presents the most likely relationships between the Wet and Blanche Cave units and layers.

Wet Cave Units A, B and C demonstrate a statistically significant relationship with groups of layers from Blanche Cave: Layers 27–21 together are temporally equivalent to Unit A; Layers 19 and 20 with Unit B; Layers 18–15 and 13–10 with Unit C (Fig. 5; Tables A.1 and A.2). The relationship of Layers 9 to 4 with Wet Cave units/lenses is less clear. The bottom Boundary of Layer 8 has a similar modelled age range (at 95.4% probability) to the bottom Boundary of Unit C while the lowest Boundary that Layers 9, 7, 6, 5 and 4 overlap with is the top of Unit C. Layers 1, 2 and 3 correspond to Unit E, but cannot be constrained to specific lenses from Unit E because there are only single ^{14}C determinations available for each Phase, limiting the model resolution.

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5. Discussion

5.1 Wet and Blanche Cave Bayesian age-depth model priors

The aggraded sedimentary sequences in Wet and Blanche Caves reflect multiple modes of accumulation and source materials through the late Pleistocene to Holocene period, incorporating the last glacial cycle. Sedimentary characteristics range from aeolian and water transported red-brown sandy clays in Units A and Layers 27 to 21, to aeolian derived pale brown to yellow sands, intersected by likely water transported narrow lenses of darker, silty sands through Units B to E and Layers 20 to 2 (Macken et al., 2013). While the sequence of sediment types in Wet and Blanche Caves is similar, the depth profiles of analogous layers between the sites vary. The thicker depositional strata of Wet Cave contrast with the narrower and more discrete layers of Blanche Cave. As discussed in Macken et al. (2013) these differences in the depth profiles of the two deposits likely result from local accumulation and post-depositional processes associated with each cave and depositional site, despite their geographic proximity (ca. 400 m).

As discussed by Bronk Ramsey (2008), depositional processes that should be considered when developing priors for Bayesian age models include (i) the mechanisms underlying deposition, (ii) random events and (iii) abrupt changes in deposition mode. Deposition of sediments into caves is controlled by a range of interacting factors including cave entrance type, prevailing climatic conditions, proximal vegetation cover and local sediments and their transport (e.g., Farrand, 2001; Hearty et al., 2004; White, 2007). These factors are expected to have affected the mechanisms of sediment deposition into Wet and Blanche Caves, primarily aeolian (dust) and water transportation (Darrénougué et al. 2009; Macken et al. 2013). Random events such as sedimentary slumping and transport of flood-sediments also shape stratigraphic sequences in caves (e.g., Kos, 2001) and have been observed in the Naracoorte Caves in modern times (e.g., filling of Wet Cave with flood sediments and surficial sediment washes and pooling water in Blanche Cave, following severe storms in December 2010). Stratigraphic features such as cut and fills, lenses and flame structures indicate that these random processes have influenced the two cave sequences during their accumulation through the last ca. 60,000 cal yrs. Abrupt changes in deposition are reflected by well-defined sedimentary transitions in both cave sequences (e.g., Unit A to B in Wet Cave), contrasting with other interfaces that are less clear and may reflect more gradual changes in sediment source and/or depositional mode (e.g., Layers 9 to 4 in Blanche Cave).

We suggest that the `Sequence` depositional model in OxCal, incorporating `Phases` of uniform prior duration (see section 5.2) is of particular utility when working with complex depositional environments, such as caves, as they are based on fewer assumptions about the rate and process of deposition when compared with other OxCal deposition models (e.g., `P_Sequence`) and that they are also suitable when modelling sequences for which there are few radiocarbon determinations relative to the timespan covered by the study site. By constructing the Wet and Blanche Cave Bayesian age-depth models within a `Sequence` framework, the order of the ^{14}C data within depositional units/layers could be integrated *a priori* based on an inference of stratigraphic superposition, such that deeper sediments were deposited earlier than those higher in the profile. The finest stratigraphic resolution that could be applied to the Wet Cave model was the depositional units, with the exception of Unit E for which the six lenses were well defined (Fig. 5). In contrast, the potential temporal resolution available in Blanche Cave was much finer, with 27 individual sedimentary layers that could be integrated as prior stratigraphic divisions within the model.

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In two cases (Wet Cave Unit D and Blanche Cave Layer 14) the assumption of stratigraphic superposition was challenged by sedimentary data and/or observations, resulting in more complex model constructions but, nonetheless, could be accounted for using a series of nested `Phases`. The OxCal `Phase` function also allowed us to differentiate prior information for which we had varying levels of certainty, as was the case for the depositional and temporal relationships of groups of individual layers in Blanche Cave (e.g., Layers 9 to 4), particularly where sedimentary transitions were less clear. We note that these layer groupings in the Blanche Cave model contrast with the depositional units defined for Blanche Cave by Darrénougué et al. (2009). These differences arise because the priors for the Blanche Cave model were informed by observations directly from the exposed, excavated section from which the radiocarbon samples were collected. In addition, not all layers were evident in the stratigraphic core from which the units were defined (St Pierre et al., 2012).

5.2 Outliers

Wet Cave `R_Dates` 5U10-1 and 5U10-6 were identified as 100% outliers and were thus excluded by OxCal in the model output. As noted by Bronk Ramsey et al. (2010), there are four main circumstances under which ^{14}C data may conflict with each other or with model priors. These are: (i) uncertainty in the reservoir ^{14}C concentration, (ii) sample contamination, (iii) incorrect ^{14}C measurement and (iv) uncertainties in the chronological models applied. In applying an offset to the calibration for the SH, we have tried to account for systematic uncertainties associated with scenario (i). While the offset we have applied might not be wholly accurate for the entire calibration range, at the chronological resolution available for Wet and Blanche Caves, the impact of this is expected to be negligible. Scenarios (ii) and (iii) may be sample-specific and result in individual or consistent offsets and biases among the ^{14}C measurements. These scenarios would be indistinguishable from each other based on the ^{14}C data alone. Scenario (iv) accounts for circumstances where sample(s) may be residual (older than context) or intrusive (younger than context) (Bronk Ramsey et al., 2010). Uncertainties may also arise when parameters of a deposition model are not clearly defined (e.g., k, the number of accumulation events per unit depth for use in `P_Sequence` models). Such a scenario is not expected to apply to the less rigid `Sequence` models applied to Wet and Blanche Caves, unless the assignment of sequential `Phases` or overlapping sub-`Phases` is incorrect.

Sample 5U10-1 may be an outlier because of measurement issues (scenario iii); however, it is not possible to confirm which of the circumstances identified above most likely accounts for its far outlying ^{14}C determination in comparison to the other samples from Unit A. Sample 5U10-1 was previously noted as being wrongly associated with Unit A (Macken et al., 2013), consistent with scenario (iv) above. However, rather than representing re-worked material as a result of post-depositional mixing of younger sediments with the Pleistocene sediments of Unit A, it was hypothesised that the charcoal sample was disturbed by human activity, most likely during excavation when the deeper sections of the profile were exposed. The consistent character of the sediments from Unit A and Pleistocene ages for all other samples supports this hypothesis and argues against contamination of this section of the sequence with younger material, an important consideration for subsequence analysis of the fauna preserved in Unit A (Macken et al., 2013).

The rejection of sample 5U10-6 points to OxCal accepting the young Holocene age for Unit F given the model prior. The age constraint for the Wet Cave upper `Boundary` of AD 2000

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strongly influences the modelled age for the upper `Boundary` of Unit F and likely contributes to the rejection of 5U10-6 which does not conform to this `Boundary` and is older than some samples from Unit E. In contrast to Unit A, for which little contamination is evident, it is more difficult to determine the extent of potential mixing of Pleistocene aged material into Unit F. The presence of European artifacts (glass and ceramic shards) in Unit F informed the assumption that materials, including charcoal, may have been deposited into Wet Cave in more modern times and also suggests that anthropogenic disturbance of the upper sections of the Wet Cave profile may have occurred (Macken et al., 2013). Based on these assumptions, sample 5U10-6 is expected to reflect contamination of Unit F with Pleistocene aged sediments, possibly by transport and mixing of sediments of different ages at the top of the sequence by human activity. In this case, rejection of sample 5U10-6 by OxCal is assumed to be consistent with scenario (iv) and points to post-depositional mixing of material of different ages in Unit F.

Blanche Cave samples 5U6A3-L21BW and 5U6B3-L22 were identified as outliers by OxCal and were heavily down-weighted in the model. The identification of these samples as outliers seemed somewhat unexpected compared to our prior expectation of the data (based upon casual 'eyeballing'). As a sensitivity test of the whole model, an alternative Blanche Cave model was run with `R_Dates` from Layers 23 to 21 grouped together into a single `Phase` but without allocating them to individual sub-`Phases`. In this latter case, samples 5U6A3-L21BW and 5U6B3-L22 were no longer identified as outliers.

Unless otherwise specified in the model prior, a uniform `Phase` prior is assumed in OxCal. Within this prior, there is no bias towards longer or shorter `Phases` and it is assumed that all of the events within the group are equally likely to occur anywhere between the start and end of the `Phase`; that is, there is no internal sorting (Bronk Ramsey, 2009a). Of the three `R_Dates` from Layer 22, the unmodelled, calibrated age of sample 5U6B3-L22 is ca. 7,000 cal yr younger than the other two samples. Under the uniform phase prior, if the true duration of the Layer 22 sub-`Phase` was represented by the `R_Dates`, then the ^{14}C determinations would be expected to be more evenly spread out (i.e., it would be extremely unlikely, though not impossible, to have two closely temporally spaced dates, with a third dating so much younger). On this basis the model found 5U6B3-L22 to be an outlier. Of the scenarios previously discussed, the reason for such an outlier could be because of either (ii), (iii) or (iv). As noted, in the alternative model in which all of the ^{14}C determinations from Layers 23 to 21 are assessed together under a uniform phase prior (rather than constrained within individual sub-`Phases`), sample 5U6B3-L22 is not found to be an outlier because it is supported by the similarity in age with sample 5U6A3-L21. Despite this, we did not use the alternative model as it provided no capacity to gain additional precision or resolution available from the individual layers within the broader `Phases`, if they were found to be chronologically independent within the model. However, as samples 5U6A3-L21BW and 5U6B3-L22 were found to be outliers within the more complex final model adopted, no greater resolution was gained by assessing these layers individually. We suggest that the most likely reason for this is that the samples are intrusive (i.e., younger than the context), limiting the resolution at which the layers within the broader `Phase` of Layer 23–21 can be evaluated.

Posterior outlier probabilities of 18 to 38% for samples from Layers 8, 10, 18 and 19 suggests that the likelihoods do not fit the model prior particularly well. That said, despite the elevated outlier probabilities of these samples compared to the initial 5% prior probabilities applied, there is still a greater probability of the samples not being, rather than of their being, outliers

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as all posterior probabilities are < 50%. Using the `Outlier_Model`, OxCal downweights the impact of these samples on the model output.

In contrast, ^{14}C determinations for samples 5U6B3-L17 and 5U6B3-L18BW were discarded by Darrénougué et al. (2009) who considered that they had infiltrated the stratigraphic section, presumably during sample collection. However, the posterior outlier probabilities for these samples in the model do not support this assertion. If the model prior for Blanche Cave had been set such that Layer 19 is older than (>) Layer 18 > Layer 17 > Layer 16, then it is highly likely that samples 5U6B3-L17 and 5U6B3-L18BW would have been identified as outliers. However, the model prior grouped Layers 18 to 15 within a single `Phase` highlighting that whether or not samples are identified as outliers clearly depends on the specifics of the model prior applied.

Holocene ^{14}C determinations from Blanche Cave Layers 4, 7 and 8 were excluded from the model as, even with the `Outlier_Model` applied, the model would not run with these samples included. Despite their exclusion from the model, the Holocene aged samples are expected to represent post-depositional reworking of younger material through the sedimentary section (St Pierre et al., 2012). This inference is supported by a U-series age of 4.72±0.21 ka from a soda straw stalactite collected from nearby grid square A1 at a depth of 20–25 cm, corresponding to Layers 3 and 4 in grid squares A3 and B3 (St Pierre et al., 2012; Fig. 5). Further, it is less likely that the Holocene ^{14}C determinations are incorrect due to measurement error or disturbance during collection as in each of Layers 4, 7 and 8, two samples provide very similar ages that are younger than the ^{14}C determinations of adjacent samples.

Additional Holocene aged soda straw stalactites were measured from depths 0–5 cm, 5–10 cm and 55–60 cm from grid squares A1 and B2, corresponding to Layers 1, and 17 and 18 in grid squares A3 and B3 respectively (St Pierre et al., 2012). As noted by St Pierre et al. (2012), reworking may have occurred during or following deposition as a result of material worked down through cracks in the sediment during dry phases or worked down as a result of trampling by animals or humans. However, it is more difficult to explain why many of the ^{14}C and soda straw U-series ages are relatively well ordered such that age increases with depth (St Pierre et al., 2012). The sedimentary layers described from grid squares A3 and B3 are moderately intact; flame structures present in Layers 4 and 8 and a laterally constrained channel fill from Layer 1 through to Layer 7 in grid square B3 provide some evidence of physical disturbance (Fig. 5). However, given the limited lateral extent of these structures, it is unlikely that these features represent significant, broad scale turnover or reworking of sedimentary material through the profile. Despite this, as multiple and varied chronological samples returned Holocene ages for the upper section of the deposit through Layer 8, we caution interpretations of the vertebrate fossil material from these sections which, being small, may have moved through the sedimentary layers in a similar way to the charcoal and soda straws. In contrast, we suggest that the Holocene-aged straw measured from grid square A1 at 55–60 cm depth may not reflect contamination of Layers 17 and 18 in grid squares A3 and B3; the ^{14}C data from these layers accord well with the adjacent samples within the combined `Phase` of Layers 18–15 with none rejected as outliers.

5.3 `Phase` durations, hiatuses and chronological interpretation

As a result of the relatively small number of ^{14}C data available relative to the long temporal coverage of the two sites, the precision of the unit and layer `Boundaries` is on the order of

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100s to 1000s of years. If there were more radiocarbon data, the modelled `Boundaries` would be expected to be more precise and, in turn, allow for more precise estimates of the durations of individual units and layers and potential hiatuses between them. This would also allow for a more robust comparison of the temporal correlation of the two sites. However, despite the overall low precision of the modelled `Boundary` ages, statistical estimates of the minimum and maximum age of individual depositional `Phases` would otherwise have been unavailable from the unmodelled ^{14}C determinations.

The modelled `Phase` durations for Wet Cave reveal slow and rapid phases of accumulation through the depositional sequence. Unit A represents the longest phase between both Wet and Blanche Caves, followed by Units E and B. In the case of Units C, D and F, the null hypothesis of instantaneous accumulation (or, at least, deposition from <1 calendar year) cannot be rejected on the basis of the dating evidence available. For Unit C, this results from having only a single radiocarbon measurement from this Unit. The same is true for Unit F, where the identification of sample 5U10-6 as an outlier (100% posterior `Outlier` probability) gave only a single 'reliable' radiocarbon determination. It is expected that, were additional radiocarbon (or other chronological) data available, these units would not, in reality, represent instantaneous deposition. The presence of silty laminations through the sands of Unit C supports this assumption, as such banding or horizonation is rarely associated with sediments that have slumped or been deposited during a single event, as observed in the homogenous sands of nearby Robertson Cave (Forbes et al., 2007). Sandy laminations observed in Unit F also argue against instantaneous deposition for the upper-most section of Wet Cave.

Having only a single radiocarbon measurement for Unit D accounts for the inability of the model to discount the null hypothesis of instantaneous deposition for this `Phase`, as noted for Units C and E. However, the mottled orange and brown, poorly sorted sandy clays of Unit D do not contain internal structuring as observed in the former two units. The sedimentary character of Unit D and presence of megafaunal bone material suggests that it contains sediments of similar type, origin and age as Unit A (Macken et al., 2013). An hypothesis for the presence of Unit D at the top of Pit 1, stratigraphically above Unit C, is that it represents late Pleistocene aged materials from another part of the cave, transported and slumped down the sedimentary cone during accumulation of the Wet Cave sequence. If this were the case, then it may represent an anomalous, single 'instantaneous' event that re-worked sedimentary and fossil material of mixed origin and age.

In Blanche Cave, only a single `Phase` (Layers 18–15) returned a modelled duration statistically indistinguishable from 0 years at the 95.4% confidence level. Limited rejection of the null hypothesis for the majority of Blanche Cave `Phases` again results from the small number of radiocarbon measurements for many layers. However, the sedimentary and stratigraphic character of some layers suggests that they may represent single, 'instantaneous' depositional episodes associated with surficial water movement of sediments during single flood events (e.g., Layers 7, 9 and 20). For these layers, rejection of the null is in accord with the inference of rapid deposition based on sedimentary observations.

The coarse resolution of the modelled `Boundaries` for both the Wet and Blanche Cave sequences similarly limits the capacity of the model to detect temporal gaps in accumulation between successive phases and/or where there may be missing material between the end of one phase and the start of the next. In all cases, the null hypothesis for contiguous deposition was not able to be rejected at the 95.4% confidence level. A hiatus of 1,485 to 5,269 cal yrs

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between Units B and C and of 379 to 2,013 cal years between layers 25 and 24 was measured at the 68.2% confidence level. As these hiatuses are not supported at the higher confidence level, there is little that can be concluded from these values; however, as both Wet and Blanche Caves have large open-roof window entrances, it is unlikely that prolonged hiatuses in deposition into the caves occurred due to the constant movement and flux of dust across the landscape. The potential for post-depositional erosion of sediments from these sites is more difficult to ascertain.

In contrast, breaks in deposition have been argued for two late Pleistocene cave sequences from south eastern Australia; the inner chamber of Robertson Cave located ca. 6 km south of Wet Cave and McEachern's Deathtrap Cave, ca. 100 km south of the Naracoorte Caves World Heritage Area. The sedimentary sequences from both of these caves reflect hiatuses in deposition over the peak of the last glacial cycle, the Last Glacial Maximum (LGM; Kos, 2001; Forbes et al., 2007). McEachern's Deathtrap Cave has a narrow-pipe entrance that became blocked with sands during the LGM, contrasting with the larger roof-window entrances of Wet and Blanche Caves that are not expected to become blocked in this way. Although Robertson Cave has a roof-window style entrance, the inner chamber is expected to have blocked as a result of high sediment loads in the entrance chamber, which restricted movement through narrower caverns in the cave system connecting the two chambers. In McEachern's Deathtrap Cave there is also evidence for the post-depositional erosion of sediments as a result of groundwater fluctuations, resulting in a gap in the record.

A potential hiatus in deposition between Units E and F of Wet Cave was indicated by the presence of bat guano derived materials at the transition between these units, reflecting minimal sediment input prior to the deposition of the dark brown silty sands of Unit F (Forbes and Bestland, 2006; Macken et al., 2013). The presence of a flowstone at the transitional boundary of Units E and F was also noted in the original excavation notes for Wet Cave; however, it is unknown if the flowstone was attached to the cave wall or free floating, limiting the extent to which it confirms a hiatus in sediment deposition at the end of the Pleistocene in Wet Cave. There is no other sedimentary or stratigraphic evidence to indicate temporal breaks and/or the loss of sediments through erosion in Wet Cave, nor in Blanche Cave. However, we suggest that the lack of statistically significant evidence for depositional breaks detected through the sequences is more likely a consequence of the dating resolution, rather than implicit evidence for continuous deposition into Wet and Blanche Caves during the last glacial cycle. Ultimately, more ^{14}C determinations or other dating evidence is required to improve the resolution of the modelled `Boundaries` and hence, detection of potential hiatuses that may be of shorter duration than the resolution of the current chronology.

5.4 Correlation of Wet and Blanche Cave `Phases`

As discussed by Blaauw et al. (2007), demonstrating synchronicity of events is dependent upon the assumed duration of the events of interest. In the case of Wet and Blanche Caves, the events are depositional episodes that are expected to represent, through sedimentary and stratigraphic characteristics, prevailing climatic conditions. Thus, transitions between events represented by stratigraphic boundaries are assumed to ultimately reflect changes in a range of interacting and complex climatic and depositional parameters operating at both a local and regional scale (Forbes and Bestland, 2007; Forbes et al., 2007; Macken et al., 2013). In most cases, the Blanche Cave layers were expected to be of shorter duration than the Wet Cave units as the latter represent individual phases that together may be consolidated into longer

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depositional periods (units) characterised by (a) similar sediment type and depositional mode and (2) relatively constant prevailing climatic conditions during their deposition. Relationships between the Wet and Blanche Cave `Phases` support this assumption as each Wet Cave unit is temporally equivalent to multiple Blanche Cave layers (Fig. 5).

On the balance of probabilities, Blanche Cave Layers 27 to 21 together overlap in age with Wet Cave Unit A as reflected in the order of the associated `Boundaries` and the statistically indistinguishable posterior calibrated hpd ranges of Unit A top and Layer 21 bottom. Layers 27 to 21 in Blanche Cave therefore represent sub-divisions of the pre-LGM period which may be used to assess the fossil assemblage at a finer resolution, contrasting with the longer time-averaged fauna (i.e., the number of years an assemblage took to accumulate; Hadly, 1999) represented in Unit A as a whole and combined Layers 27 to 21.

Blanche Cave Layers 19 and 20, 18–15 and 13–10 similarly provide a reliable, finer resolution for the LGM period represented in Wet Cave Units B and C, respectively. Modelled ages for the start and end of deposition of Layers 19 and 20 are both statistically indistinguishable from the start and end of the deposition of Unit B; however, given the relative stratigraphic positions of Layers 19 and 20, they are expected to provide successive sub-divisions of the first LGM period. A similar pattern is noted for the modelled ages of the start and end of the deposition of combined Layers 18–15 and 13–10 with Unit C but nonetheless, provide two sub-divisions of the second LGM period represented in the deposits. The statistical correlation of multiple `Boundaries` between Wet and Blanche Cave arises as a result of the resolution of the model, limiting its ability to temporally differentiate the upper and lower `Boundaries` of `Phases`, similar to the impacts noted for the durations and hiatuses.

For Layers 9–4, there is insufficient information to reject the possibility that they temporally overlap both Units B and/or C of Wet Cave. As these layers contain Holocene aged material, the temporal relationship of Layers 9–4 with Wet Cave is not meaningful. In addition, these layers are considered to be unsuitable for inclusion in the analyses of the small mammal faunas unless it can be shown that no fossil material has intruded into this section of the Blanche Cave stratigraphy.

The relationships between Blanche Cave Layers 1 to 3 with Wet Cave are not well differentiated at the available resolution of the modelled `Sequences`. `Order` suggests that Layer 3 is temporally constrained between the bottom `Boundary` of Unit E and the bottom `Boundary` of Lens 2:5/2. The upper `Boundary` of Layer 1 is statistically indistinguishable from all Wet Cave `Boundaries` from 2:6/3 top to Unit F top, a consequence of the insufficient resolution of the modelled data to identify a more precise relationship. As noted in section 4.2, the modelled age for the upper `Boundary` of Layer 1 is strongly influenced by the prior applied for the top of the Blanche Cave sequence of AD 2000. While this model prior was appropriate for constraining the minimum age of the sequence (based on disturbance through human access to the site in modern times and the presence of *Pinus* pollen indicating European settlement; Darrénougué et al., 2009), it is unlikely to be the true minimum age for fossil material contained within Layer 1. As there was only one radiocarbon determination available for Layer 1, the true age of this `Phase` is not well represented by the model. While the correlation is consistent with the output of the model, knowledge of the two sites suggests that Layer 1 is more likely to be temporally equivalent to Lenses 2:6/4 to 2:6/2 and cautions inferences that may be drawn from the fossil material of Layer 1 when compared with Wet Cave.

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6. Conclusion

Bayesian age-depth models were developed for the fossil-bearing sedimentary sequences of Wet and Blanche Caves in south eastern South Australia, utilising available ^{14}C determinations and stratigraphic information. At the dating resolution available from these data, the modelled ages for the start and end of successive units and layers within the two sites show that deposition was contiguous and characterised by phases of slower and more rapid accumulation, as is common for many cave deposits. Statistically supported temporal correlation of depositional phases between Wet and Blanche Caves provides a robust basis for comparative analysis of the fossil assemblages contained within them, and builds upon previous stratigraphic correlations that were based only on sparse, individually calibrated radiocarbon data and sedimentary descriptions.

In contrast to other age-depth models available in OxCal, `Sequence` was applied for modelling Wet and Blanche Caves where only the relative order of events within the two sites could be incorporated as a model prior. By incorporating the depositional events as `Phases` within the model, we were also able to incorporate uncertainties associated with the internal continuity of individual layers and units. `Phases` also offered flexibility in the model where there was more uncertainty associated with both (a) the stratigraphic relationships of individual layers in Blanche Cave and (b) known reworked layers which nevertheless provided extra *terminus post quem data* for overlying layers.

Despite the rigour applied to the chronologies of Wet and Blanche Caves, the resolution of the models is limited by the few ^{14}C determinations relative to the late Pleistocene to Holocene time-span covered by the sites. However, while we acknowledge that the resolution of the model would be improved if more ^{14}C determination were available, we also recognise the practical limitations in obtaining large numbers of radiocarbon data in palaeontological studies. These include the availability of research funds and samples suitable for dating, as well as limitations presented by the time resolution captured in study sites. In light of these challenges, we recommend that, where possible more than one sample is obtained from each stratigraphic layer. Nonetheless, analysis of radiocarbon data within a Bayesian framework provides a means of critically evaluating site chronologies, regardless of the number of ^{14}C determinations available, and provides a means of quantifying the uncertainties associated with the start and end of different accumulation phases.

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Table 1

^{14}C determinations for the Wet Cave stratigraphic sequence. 'WeC' samples are from Pate et al. (2002, 2006); '5U10' samples are from Macken et al. (in press). Reporting of ^{14}C data follows standard protocol outlined in Stuiver and Polach (1977). All samples were charred material.

Sample ID	AMS laboratory ID	C mass (μg)	C yield (%)	$\delta^{13}C$ (‰)	Conventional ^{14}C age BP	1σ	Unit	Unit depth (cm)
5U10-6	BETA-298177	4600	66	-24.9	11,260	60	F	0 to -52
WeC36	OZE 539	2570	62.7	-24.2	740	40		
5U10-5	BETA-298176	2000	51	-24.6	9,180	40	E	-52 to -110
WeC1	OZD 284	1770	63.2	-23.7	9,590	100		
5U10-4	BETA-298175	4000	59	-25.3	12,310	50		
5U10-3	BETA-298174	2200	67	-25.6	13,470	50		
WeC4	OZD 504	1320	47.1	-28.7	13,920	130	D	-110 to -150
WeC33[1,2]	OZE 541	12	1.8	-25	14,150	350	C	-150 to -187
5U10-2	BETA-298173	2000	70	-24.6	20,750	90	B	-187 to -220
WeC32[2]	OZE 536	122	0.2	-26.4	19,400	300		
WeC10[1]	OZD 292	100	50	-25	23,850	1020	A	-220 to -350
WeC25	OZD 714	1380	43.1	-24.2	30,500	400		
WeC21[1]	OZD 715	350	58.3	-25	33,400	650		
WeC23[1,2]	OZD 721	290	1.8	-25	23,400	1600		
WeC27	OZD 717	1950	54.2	-25.9	40,900	850		
WeC12[1,3,4]	OZD 291	70	17.5	-25	>29,000			
WeC35	OZE 538	1360	35.8	-24.8	45,200	1800		
5U10-1	BETA-298172	2200	76	-24.2	9,140	40		
WeC30[1,2]	OZD 724	200	0.7	-25	32,600	900		
WeC16[5]	OZD 506	1640	54.7	-26.4	>45,000			

[1]Assumed $\delta^{13}C$ value of -25o was used as no measured $\delta^{13}C$ was available due to small sample size.

[2]Pretreated sample contained some sand/sediment. Estimated C yield may not be reliable.

[3]AMS laboratory code reported by Pate et al. (2006) as OZE. ANSTO reports indicate that code was OZD (Q. Hua, pers. comm.)

[4]$F^{14}C$ measurement 0.0098±0.0099 (D. Pate, pers. comm.)

[5]$F^{14}C$ measurement 0.0031±0.001 (D. Pate, pers. comm.)

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Table 2

^{14}C determinations for Blanche Cave 3rd chamber stratigraphic sequence, from Darrénougué et al. (2009) and St Pierre et al. (2012), the former marked with an asterisk. A3 and B3 in the sample code refer to the grid square from which the sample was sourced and 'L' refers to the depositional layer. Samples with BW in the code were exposed to bore water to isolate charcoal from sediment matrix. Layer depths measured as depth from sediment surface at boundary of grid squares A3 and B3 (refer Figure 4). NB. No samples for radiocarbon analysis were collected from Layers 9 and 12. Reporting of ^{14}C data follows standard protocol outlined in Stuiver and Polach (1977). All samples were charred material.

Sample ID	AMS laboratory ID (SSAMS ANU #)	C mass (µg)	C yield (%)	δ^{13}C (‰)	±1σ	Conventional ^{14}C age BP	1σ	Layer	Layer depth (cm)
5U6A3-L1*	2805	1230	59	-20.8	1.9	12470	60	1	-5.5 to -11.5
5U6A3-L2BW*	3137	860	54	-30.2	5.8	12700	80	2	-11.5 to -14.5
5U6B3-L3*	2806	1110	61	-24.9	4.8	13200	80	3	-14.5 to -18.5
5U6B3-L4*	2807	950	56	-30.8	3.5	13230	70	4	-18.5 to -23
5U6B3-L4 repeat*	3323	920	59	-10.2	2.1	13410	100		
5U6B3-L4BW	2809	1040	59	-22.1	4.5	1310	45		
5U6B3-L4BW repeat	3324	900	55	-23.4	3.4	1370	50		
5U6B3-L5BW*	2810	1060	63	-29.4	1.3	13300	70	5	-23 to -25
5U6B3-L6*	2811	900	61	-33.2	3.9	13420	80	6	-25 to -29
5U6A3-L7BW	2812	1080	62	-28.2	3.5	9550	60	7	-29 to -31.5
5U6A3-L7BW repeat	3325	970	58	-23.6	2.6	9420	60		
5U6B3-L8	2813	900	60	-28.8	1.7	14160	70	8	-31.5 to -34
5U6B3-L8 repeat	3326	1110	53	-11.7	3.8	14270	90		
5U6B3-L8BW	2814	1360	63	-26.0	2.1	3895	35		
5U6B3-L8BW repeat	3327	930	54	-13.6	5.9	4060	70		
5U6A3-L10*	2816	1050	68	-33.0	3.8	13890	80	10	-35.5 to -40
5U6A3-L10BW	3135	860	59	-22.7	9.0	14630	110		
5U6A3-L11	2817	1030	59	-29.3	2.8	13840	70	11	-40 to -42.5

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5U6B3-L13BW*	2818	1080	59	-35.3	5.3	14180	90	13	-42.5 to -46.5
5U6A3-L14*	3136	750	48	-31.0	2.2	20010	110	14	-46.5 to -49
5U6A3-L15*	2819	960	51	-34.6	6.9	15860	100	15	-49 to -51
5U6A3-L15BW	2820	1000	63	-25.8	3.5	16760	100		
5U6A3-L16*	2821	1030	48	-32.7	2.5	16430	90	16	-51 to -54
5U6B3-L16BW	2823	1050	56	-25.5	2.7	17160	100		
5U6B3-L17*	3328	930	52	-21.5	1.7	15390	90	17	-54 to -58.5
5U6B3-L18BW*	2825	990	58	-23.8	5.5	15200	90	18	-58.5 to -63
5U6B3-L18BW repeat*	3329	990	56	-14.2	5.8	14330	100		
5U6B3-L19*	2826	950	57	-32.9	4.1	18550	110	19	-63 to -69
5U6B3-L19BW*	2827	810	57	-24.3	2.6	20000	120		
5U6A3-L20BW*	2829	1100	53	-23.3	2.1	20590	130	20	-69 to -70
5U6A3-L21BW*	2830	790	61	-25.2	3.5	20710	130	21	-70 to -73.5
5U6B3-L22*	2831	830	57	-31.7	2.9	20670	130	22	-73.5 to -77
5U6B3-L22BW	2832	980	59	-21.7	1.5	27680	280		
5U6B3-L22BW repeat	3330	900	58	-28.5	7.8	27570	300		
5U6B3-L23BW*	2833	900	60	-14.8	5.3	25120	220	23	-77 to -80
5U6B3-L24BW*	3138	940	52	-29.3	2.2	28070	230	24	-80 to -84.5
5U6B3-L24BW repeat*	3139	910	51	-32.0	3.6	27820	240		
5U6A3-L25BW	2835	840	57	-27.6	1.6	30060	380	25	-84.5 to -89
5U6B3-L26BW*	2836	950	58	-21.2	3.6	36290	790	26	-89 to -95
5U6A3-L27BW	2837	880	58	-21.2	1.2	43260	1840	27	-95 to -99.5

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Table 3

Modelled ages of unit Boundaries and radiocarbon determinations (R_Dates and R_F14C functions) for the Wet Cave stratigraphic sequence. All data are given as both the 68.2 and 95.4% highest probability density ranges. Modelled ages calibrated using the IntCal09 calibration curve (Reimer et al., 2009) with a Southern Hemisphere offset of 56±24 years applied (McCormac et al., 2004).

Boundary	R_Date /R_F14C	Modelled calibrated age (cal yr BP)				R_Date/R_F14C posterior Outlier probability
		68.2%		95.4%		
		from	to	from	to	
Wet Cave top		-49	-50	-49	-50	
Unit F top		677	190	680	-43	
	5U10-6	9,519	294	9,729	227	100
	WeC36	722	662	744	565	2
Unit F bottom		10,287	664	10,313	662	
Unit E top		10,403	10,016	10,491	9,204	
	5U10-5	10,390	10,253	10,488	10,240	2
Lens 2:5/1 bottom		10,583	10,291	10,870	10,252	
Lens 2:5/2 top		11,004	10,594	11,151	10,410	
	WeC1	11,142	10,824	11,217	10,677	2
Lens 2:5/2 bottom		11,471	10,806	12,416	10,671	
Lens 2:6/1 top		12,697	11,210	13,604	10,948	
Lens 2:6/1 bottom		13,974	12,441	14,291	11,536	
Lens 2:6/2 top		14,441	13,629	14,810	12,646	
	5U10-4	14,473	14,041	14,879	13,966	3
Lens 2:6/2 bottom		14,779	14,113	15,520	14,019	
Lens 2:6/3 top		15,586	14,489	16,183	14,202	
Lens 2:6/3 bottom		16,381	15,271	16,611	14,624	
Lens 2:6/4 top		16,720	16,096	16,816	15,213	
	5U10-3	16,757	16,420	16,879	15,516	8
Unit E bottom		16,868	16,469	17,130	15,601	
Unit D top		17,132	16,632	18,659	15,680	
	WeC4	17,386	16,846	19,751	16,690	11
Unit D bottom		31,921	16,785	59,998	16,775	
Unit C top		17,502	16,698	18,406	16,197	
	WeC33	17,851	17,049	18,601	16,712	9
Unit C bottom		19,360	17,078	21,928	16,885	
Unit B top		23,577	21,111	24,138	18,599	
	5U10-2	24,884	24,521	25,170	23,293	6
	WeC32	23,727	22,706	24,294	22,371	5
Unit B bottom		26,091	24,591	28,383	24,348	
Unit A top		28,596	25,952	29,889	24,954	
	WeC10	30,237	28,092	31,506	26,671	10
	WeC25	36,124	34,640	36,413	34,476	5
	WeC21	38,874	37,126	40,157	36,593	5
	WeC23	30,833	27,719	33,549	26,074	10
	WeC27	45,367	44,047	46,172	43,193	5
	WeC12	47,259	37,550	50,002	34,457	10
	WeC35	48,919	46,311	50,002	45,669	5
	5U10-1	37,060	26,716	47,698	25,982	100
	WeC30	38,586	36,441	39,946	35,137	5
	WeC16	49,243	46,498	50,003	45,659	5
Unit A bottom		51,815	47,780	56,032	46,523	
Wet Cave bottom		60,001	60,000	60,001	60,000	

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Table 4

Modelled ages of layer `Boundaries` and `R_Dates` for the Blanche Cave stratigraphic sequence. All data are given as both 68.2% and 95.4% highest probability density ranges. Modelled ages calibrated using the IntCal09 calibration curve (Reimer et al., 2009) with a Southern Hemisphere offset of 56±24 years applied (McCormac et al., 2004). Samples 5U6B3-L8BW, 5U6B3-L8BW repeat, 5U6A3-L7BW, 5U6A3-L7BW repeat, 5U6B3-L4BW and 5U6B3-L4BW repeat were excluded from the model as they were so outlying that their inclusion prevented the model from running.

`Boundary`	`R_Date`	**Modelled calibrated age (cal yr BP)**				**`R_Date` Posterior `Outlier` probability**
		68.2%		**95.4%**		
		from	**to**	**from**	**to**	
Blanche Cave top		-49	-50	-49	-50	
Layer 01 top		14,791	-51	14,814	-51	
	5U6A3-L1	14,701	14,156	15,076	7,481	21
Layer 01 bottom		14,978	14,308	15,450	9,858	
Layer 02 top		15,172	14,647	15,594	13,401	
	5U6A3-L2BW	15,227	14,887	15,530	14,639	1
Layer 02 bottom		15,526	14,986	15,919	14,736	
Layer 03 top		16,066	15,405	16,318	15,118	
	5U6B3-L3	16,204	15,648	16,421	15,391	1
Layer 03 bottom		16,405	15,872	16,540	15,544	
Layers 04 to 09 top		16,576	16,246	16,667	15,926	
Layer 04 top		16,628	16,379	16,732	16,148	
	5U6B3-L4	16,660	16,436	16,781	16,264	1
	5U6B3-L4 repeat	16,681	16,452	16,804	16,300	1
Layer 04 bottom		16,765	16,466	17,018	16,331	
Layer 05 top		16,645	16,374	16,769	16,134	
	5U6B3-L5BW	16,684	16,441	16,817	16,273	1
Layer 05 bottom		16,811	16,461	17,080	16,320	
Layer 06 top		16,675	16,403	16,803	16,188	
	5U6B3-L6	16,735	16,487	16,848	16,352	1
Layer 06 bottom		16,859	16,498	17,091	16,370	
Layer 07 top		16,721	16,351	16,980	16,112	
Layer 07 bottom		16,978	16,486	17,174	16,332	
Layer 08 top		17,068	16,445	17,165	16,311	
	5U6B3-L8	17,111	16,492	17,226	16,341	35
	5U6B3-L8 repeat	17,112	16,488	17,238	16,339	38
Layer 08 bottom		17,148	16,503	17,284	16,372	
Layer 09 top		16,721	16,351	16,978	16,112	
Layer 09 bottom		16,979	16,487	17,175	16,332	
Layers 04 to 09 bottom		17,186	16,535	17,342	16,439	
Layers 10 to 13 top		17,336	16,865	17,419	16,657	
Layer 10 top		17,353	16,919	17,447	16,811	
	5U6A3-L10	17,227	16,948	17,449	16,885	3
	5U6A3-L10BW	17,375	16,975	17,533	16,846	33
Layer 10 bottom		17,399	16,995	17,617	16,868	
Layer 11 top		17,209	16,898	17,441	16,787	
	5U6A3-L11	17,211	16,933	17,449	16,851	5
Layer 11 bottom		17,387	16,965	17,491	16,881	
Layer 12 top		17,362	16,932	17,467	16,790	
Layer 12 bottom		17,398	16,991	17,586	16,862	
Layer 13 top		17,352	16,942	17,451	16,849	
	5U6B3-L13BW	17,375	16,982	17,465	16,915	1
Layer 13 bottom		17,396	17,003	17,539	16,905	
Layers 10 to 13 bottom		17,426	17,036	17,802	16,908	
Layer 14 top		23,963	19,917	24,036	17,576	
	5U6A3-L14	24,151	23,726	24,338	23,470	2
Layer 14 bottom		37,098	23,623	55,164	23,528	
Layers 15 to 18 top,		17,751	17,147	18,381	17,075	
Layer 15 top		19,249	18,394	19,369	17,588	
	5U6A3-L15	19,375	18,911	19,413	18,806	3

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	5U6A3-L15BW	20,015	19,570	20,241	19,477	4
Layer 15 bottom		20,386	19,662	21,156	19,543	
Layer 16 top		19,800	18,842	19,994	17,734	
	5U6A3-L16	19,815	19,440	20,036	19,404	2
	5U6B3-L16BW	20,455	20,127	20,814	19,382	9
Layer 16 bottom		20,772	20,160	21,165	19,520	
Layer 17 top		18,696	18,077	18,781	17,491	
	5U6B3-L17	18,716	18,559	18,863	18,496	1
Layer 17 bottom		19,560	18,572	20,767	18,526	
Layer 18 top		18,554	17,312	18,595	17,235	
	5U6B3-L18BW	18,618	18,114	18,681	18,014	2
	5U6B3-L18BW repeat	18,645	17,440	19,151	17,289	37
Layer 18 bottom		19,252	18,149	20,535	18,053	
Layers 15 to 18 bottom		21,237	20,337	21,894	19,935	
Layer 19 top		22,252	21,299	23,855	20,405	
	5U6B3-L19	22,388	22,051	24,001	21,533	8
	5U6B3-L19BW	24,046	23,473	24,303	21,664	18
Layer 19 bottom		24,431	23,676	24,768	22,052	
Layer 20 top		24,753	24,113	25,016	23,009	
	5U6A3-L20BW	24,878	24,441	25,094	24,098	4
Layer 20 bottom		26,105	24,326	28,838	24,114	
Layers 21 to 23 top		30,168	24,440	31,742	24,249	
Layer 21 top		31,617	24,696	31,925	24,406	
	5U6A3-L21BW	31,706	24,838	32,042	24,538	92
Layer 21 bottom		31,954	30,063	32,348	24,744	
Layer 22 top		31,771	31,013	32,059	24,345	
	5U6B3-L22	31,840	31,275	32,191	24,537	95
	5U6B3-L22BW	31,727	31,401	32,020	31,262	3
	5U6B3-L22BW repeat	31,716	31,381	32,000	31,236	3
Layer 22 bottom		31,889	31,485	32,231	31,356	
Layer 23 top		30,309	29,090	31,913	27,098	
	5U6B3-L23BW	30,305	29,705	31,803	29,449	10
Layer 23 bottom		31,644	29,868	31,931	29,663	
Layers 21 to 23 bottom		32,151	31,624	32,502	31,456	
Layer 24 top		32,488	31,900	32,751	31,660	
	5U6B3-L24BW	32,703	32,108	32,941	31,824	1
	5U6B3-L24BW repeat	32,675	32,085	32,899	31,801	2
Layer 24 bottom		32,982	32,187	33,656	31,843	
Layer 25 top		34,797	33,354	35,130	32,402	
	5U6A3-L25BW	35,087	34,491	36,167	33,625	3
Layer 25 bottom		37,165	34,511	40,131	33,988	
Layer 26 top		41,741	38,632	42,244	35,836	
	5U6B3-L26BW	42,021	40,661	42,700	39,507	3
Layer 26 bottom		43,696	40,898	46,473	39,896	
Layer 27 top		47,523	43,331	49,295	41,700	
	5U6A3-L27BW	49,089	45,832	50,003	44,803	4
Layer 27 bottom		59,997	46,406	59,997	46,259	
Blanche Cave bottom		60,001	60,000	60,001	60,000	

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Table 5

Modelled, posterior duration of `Phases` (sedimentary units and lenses from Unit E) and suggested hiatuses between them for the Wet Cave stratigraphic sequence. All data are given as both the 68.2% and 95.4% highest probability density ranges. Modelled ages calibrated using the IntCal09 calibration curve (Reimer et al., 2009) with a Southern Hemisphere offset of 56±24 years applied (McCormac et al., 2004).

Unit /Lens `Phase`	Modelled posterior Phase duration (cal yr)				Modelled posterior hiatus (cal yr)				Modelled posterior hiatus (cal yr)			
	68.2%		95.4%		68.2%		95.4%		68.2%		95.4%	
	from	to	from	to	from	to	from	to	from	to	from	to
									Units C–E			
F	0	9,916	0	9,956								
					0	9,644	-1	9,655				
E	6,046	6,871	4,896	7,712								
					0	446	-4	2,213				
D	-4	15,470	-4	42,829					1	17, 681	0	17,743
					-16,424	1,001	-42,428	1,083				
C	0	1,859	-2	4,456								
					1,485	5,269	2	5,775				
B	1,434	4,944	365	7,492								
					1	2,127	-1	4,042				
A	20,448	25,781	18,343	30,429								
2:5/1	-4	4	-4	188								
					-4	4	-4	187				
2:5/2	-4	4	-4	219								
					-4	4	-4	289				
2:6/1	-4	4	-4	369								
					-4	4	-4	453				
2:6/2	-4	4	-4	263								
					-4	5	-4	184				
2:6/3	-4	5	-4	236								
					-4	5	-4	291				
2:6/4	-4	6	-4	180								

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Table 6

Modelled, posterior duration of `Phases` (sedimentary layers) and suggested hiatuses between them for the Blanche Cave stratigraphic sequence. All data are given as both the 68.2% and 95.4% highest probability density ranges. Modelled ages calibrated using the IntCal09 calibration curve (Reimer et al., 2009) with a Southern Hemisphere offset of 56±24 years applied (McCormac et al., 2004). The duration of Layer 14 and potential hiatuses between Layer 15 and 14, and Layer 14 and 13 were not modelled as Layer 14 is reworked (see Section 3.1.2 for details).

Layer / Phase	Modelled posterior Phase duration (cal yr)				Modelled posterior hiatus duration (cal yr)			
	68.2%		95.4%		68.2%		95.4%	
	from	to	from	to	from	to	from	to
1	-2	14,720	-2	14,776				
					-1	488	-4	3,808
2	0	526	-4	1,726				
					1	565	-1	1,076
3	0	442	-2	931				
					0	381	-2	797
4–9	1	956	-1	1,220				
					-1	207	-4	461
10–13	-1	196	-4	699				
					0	389	-4	988
15–18	2,759	3,954	2,064	4,589				
					3	1,150	-1	1,899
19	3	3,108	0	3,425				
					0	559	-4	1,746
20	-1	1,535	-4	4,425				
					-4	1,463	-4	4,703
21–23	1,689	7,670	0	8,080				
					-4	341	-4	7,289
24	0	536	-4	1,401				
					379	2,013	0	2,571
25	1	2,899	-2	6,006				
					3	5,352	1	6,426
26	1	4,014	-2	7,820				
					1	3,529	-1	6,431
27	1	8,745	-1	14,800				

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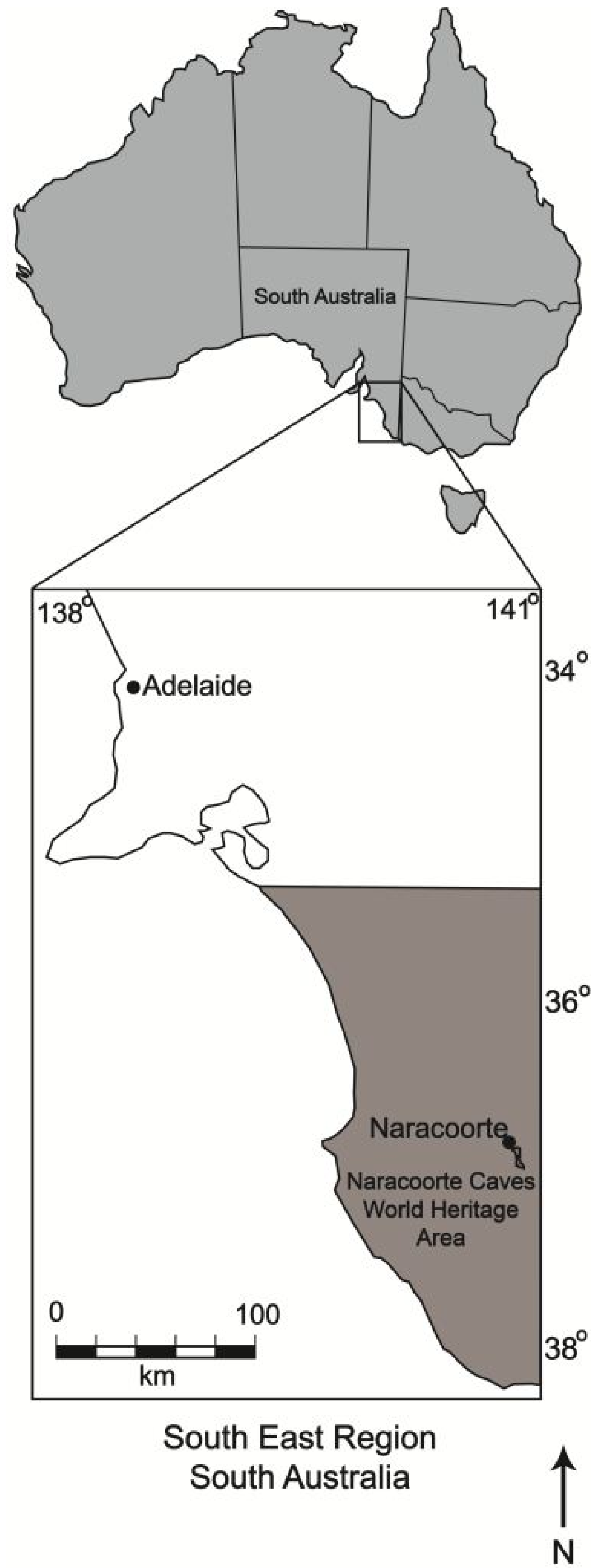

Fig. 1 Location of the Naracoorte Caves World Heritage Area in south eastern South Australia, Australia.

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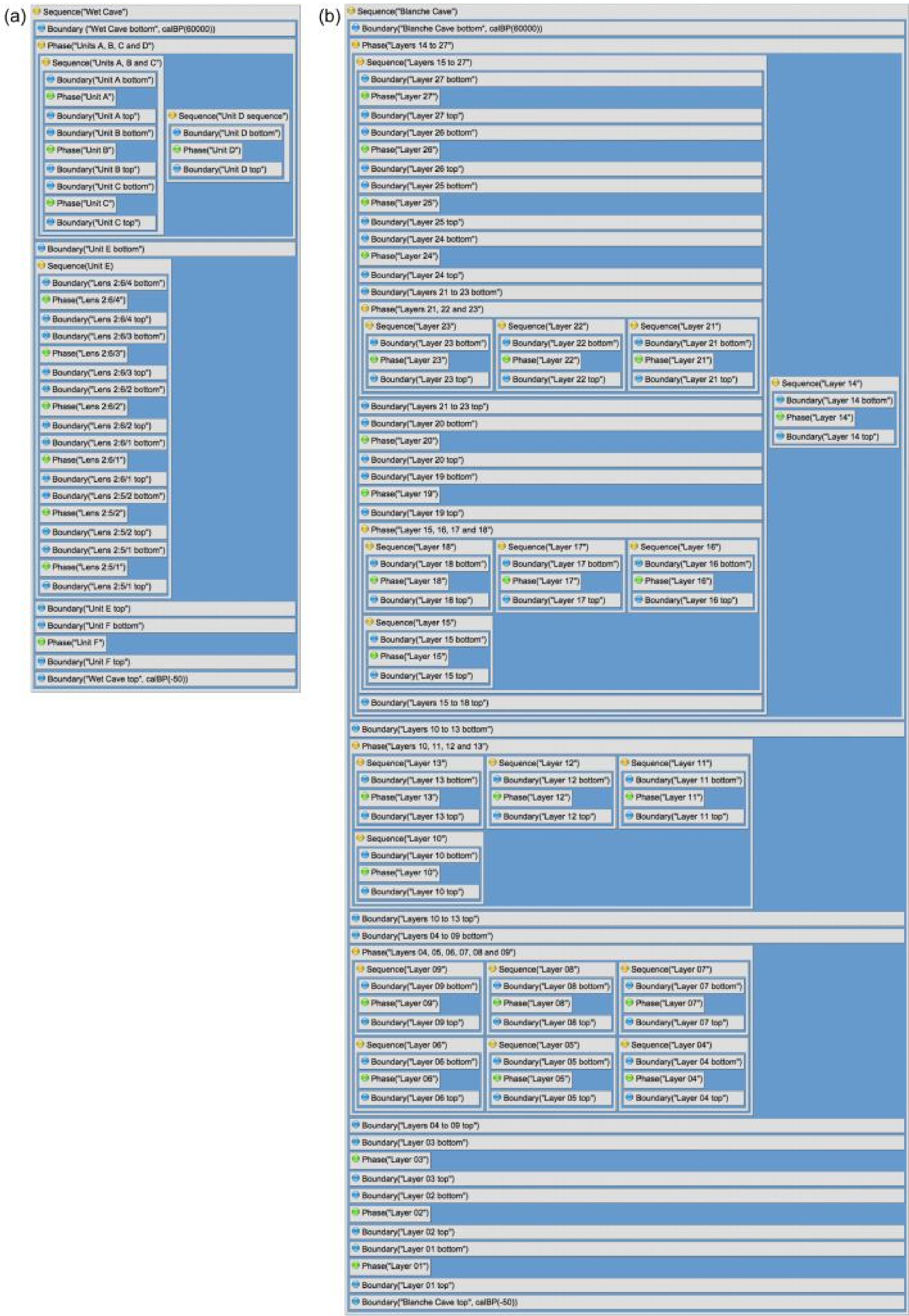

Fig. 2 Bayesian model frameworks run in OxCal for (a) Wet Cave and (b) Blanche Cave. `Phases` and nested sub-`Phases` were constructed within `Sequence` models, based upon stratigraphic and sedimentary observations of the two sites.

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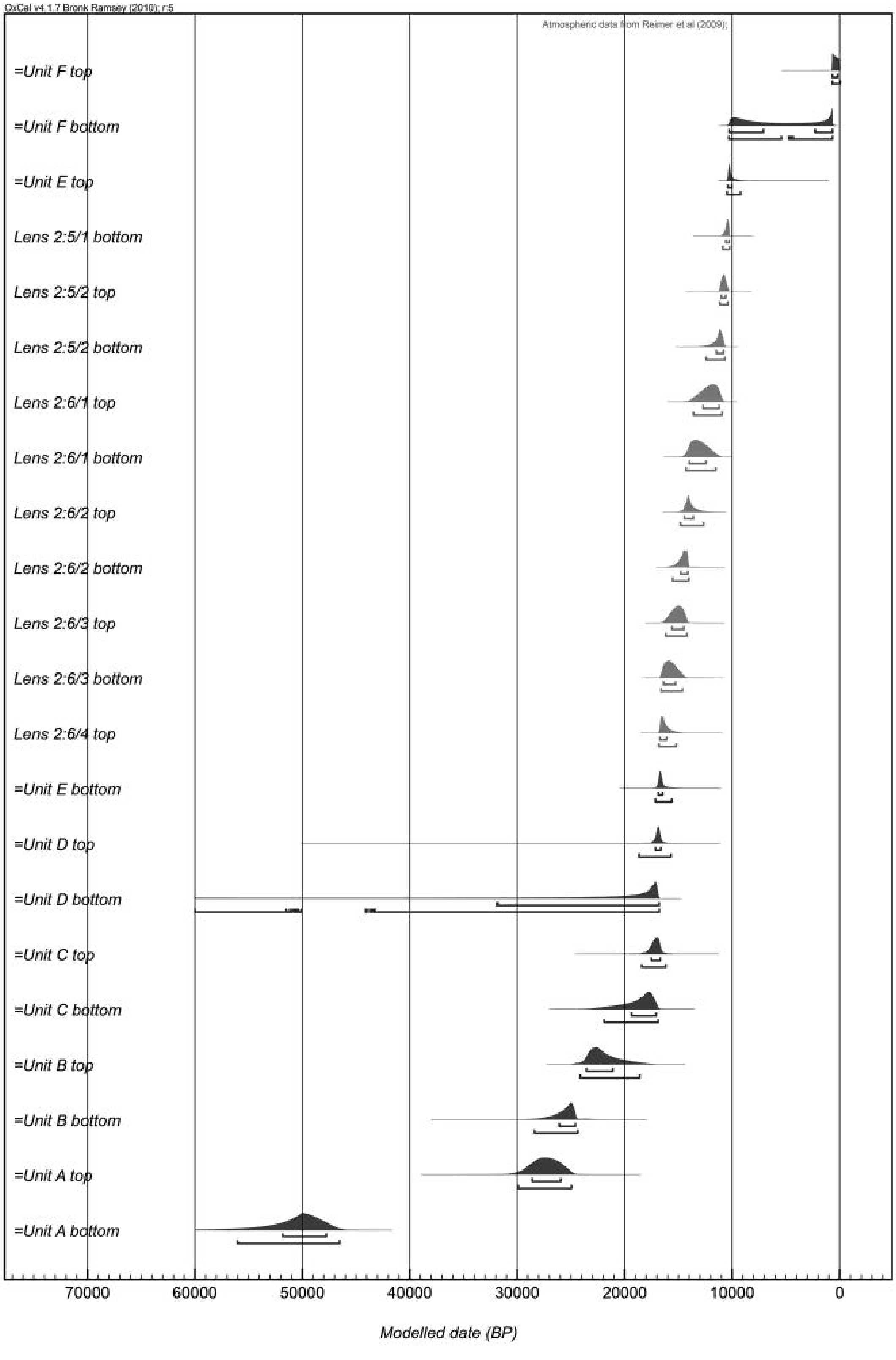

Fig. 3 Modelled ages for unit `Boundaries` of the Wet Cave stratigraphic sequence. `Boundaries` for lenses of Unit E also indicated. Horizontal bars underneath each function represent the posterior 68.2% and 95.4% highest probability density ranges. Model generated using OxCal 4.1 (Bronk Ramsey, 2010), calibrated with IntCal09 and Southern Hemisphere offset of 56±24 years (McCormac et al., 2004; Reimer et al., 2009).

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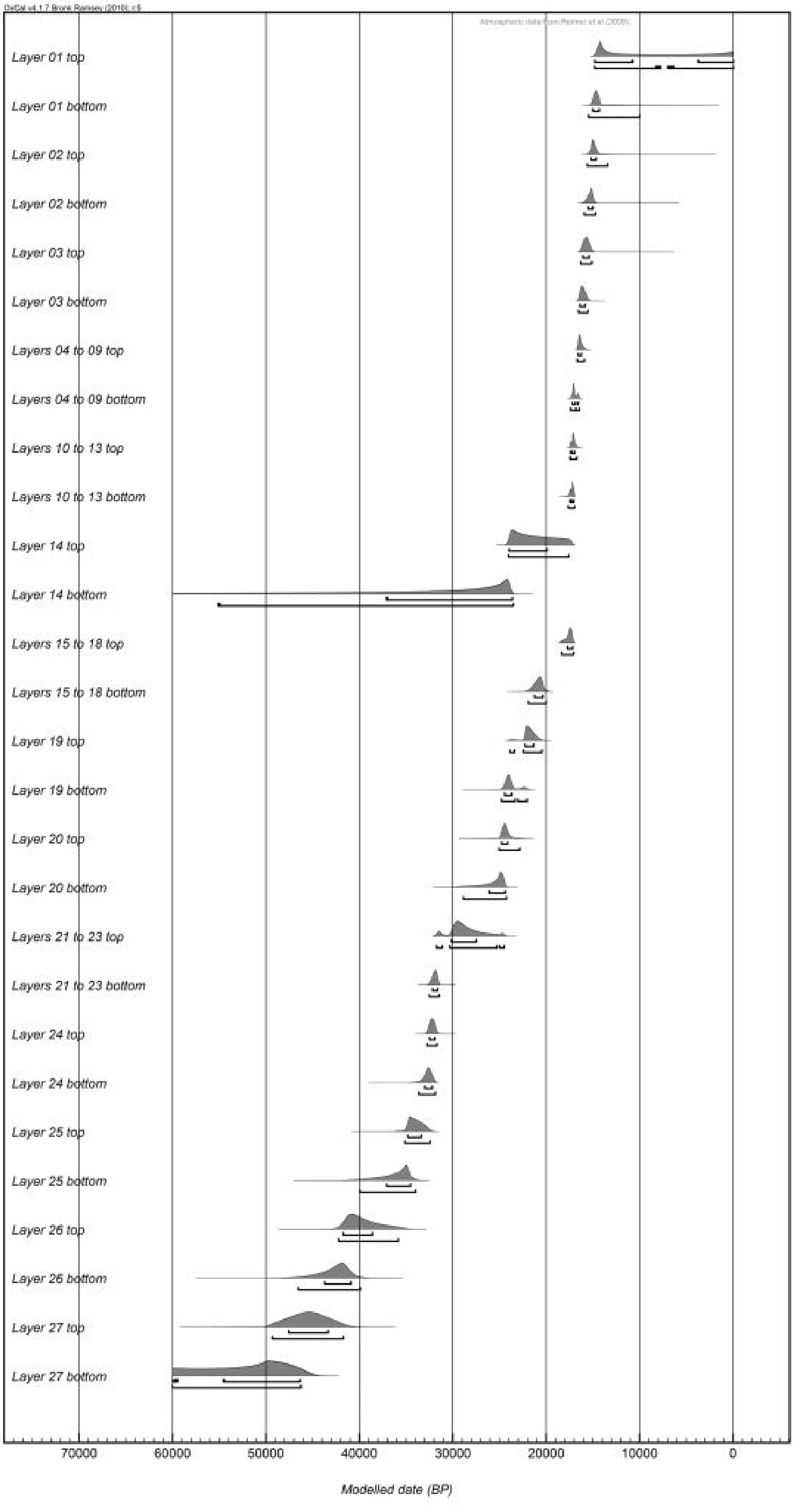

Fig. 4 Modelled ages for layer `Boundaries` of the Blanche Cave stratigraphic sequence. Horizontal bars underneath each function represent the posterior 68.2% and 95.4% highest probability density ranges. Model generated using OxCal 4.1 (Bronk Ramsey, 2010), calibrated with IntCal09 and Southern Hemisphere offset of 56±24 years (McCormac et al., 2004; Reimer et al., 2009).

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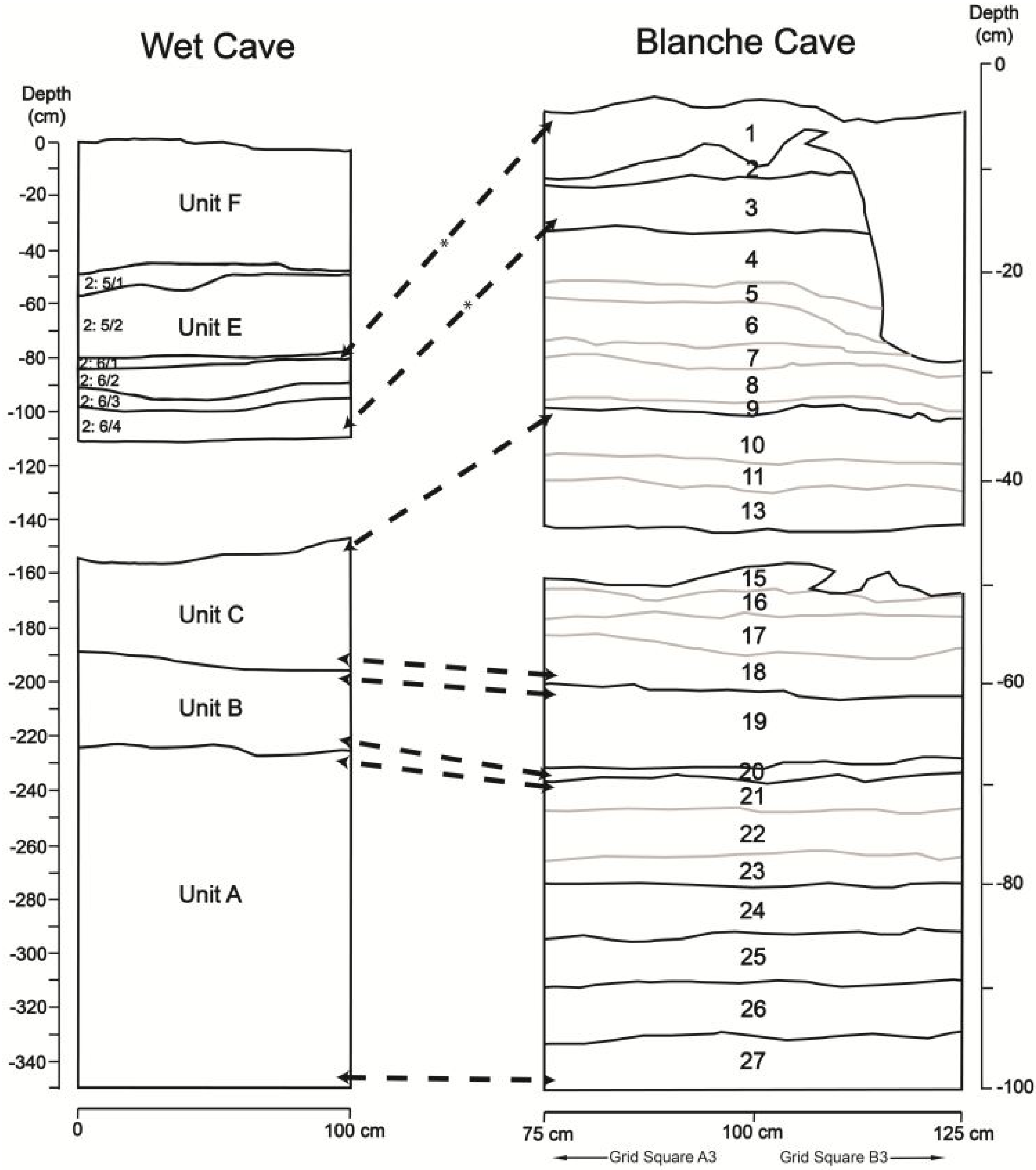

Fig. 5 Correlation of Wet Cave units and Blanche Cave layers based on 50% probability threshold for relative order of `Boundaries` and null `Difference` distributions (i.e., where there is no difference in the modelled age of `Boundaries` between the two sites). Black dotted lines indicate relationship between Wet Cave units with groups of Blanche Cave layers. * represents an inferred correlation between Layers 1, 2 and 3 with Wet Cave lenses, based on the balance of probabilities, stratigraphic information and un-modelled ^{14}C determinations. Gaps in the stratigraphic sequences indicate position of Unit D (Wet Cave) and Layer 14 (Blanche Cave), both of which contain material of mixed age and origin. Groups of layers in Blanche Cave that were modelled as single `Phases` are indicated by the grey lines between stratigraphic layers.

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