

# **Radiocarbon dates constrain the timing of environmental and cultural shifts in the Holocene strata of Wonderwerk Cave, South Africa**

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## **Abstract:**

Wonderwerk Cave has yielded one of the longest and most complete Holocene Later Stone Age (LSA) records for the arid interior of South Africa. This paper presents the results of a new radiocarbon dating program for Excavation 1 that is explored within a Bayesian model of all existing Wonderwerk Cave radiocarbon dates for the Holocene. The proposed model, using *Phases* within an OxCal *Sequence* model, provides robust age estimates for changes in the technological and paleoenvironmental record at the site. The more precise dates allow a comparison of the timing of climate shifts across the interior of southern Africa and begin to allow us to identify whether hiatuses in human occupation, or cultural shifts, are synchronous across broader areas of the subcontinent, or not.

## **Introduction**

The Later Stone Age (LSA) of southern Africa has a Holocene sequence of well-defined lithic industries (e.g. Humphreys and Thackeray 1983, Deacon 1984a,b; Mitchell and Barham 2008; Lombard et al. 2012). The majority of research for this period has focused on the coastal areas

(e.g. Deacon 1984a, Inskeep 1987, Parkington 2006, Loftus et al. 2016) with fewer studies on sites located in the arid interior (but see Humphrey and Thackeray 1983, Deacon 1984b, Wadley 1987, 1992, 2000, Parsons 2006, Sampson 1974, Sampson 2010). Wonderwerk Cave (27°50'46"S, 23°33'19"E) is one of a handful of sites in the interior of South Africa that contains a relatively complete cultural record comprising all Holocene LSA techno-complexes (Beaumont 1990, Humphrey and Thackeray 1983). In addition to its extensive lithic record, the LSA strata at the site have yielded engraved dolomite stones that are among the earliest representatives of rock engravings in southern Africa, at ca. 10,000 years BP (Thackeray et al. 1981, Thackeray 2013, Bradfield et al. 2014). The cultural sequence is accompanied by a rich paleoenvironmental record (Avery 1981, Van Zinderen Bakker 1982, Brook et al. 2010, Lee-Thorp and Ecker 2015, Thackeray 2015, Scott and Thackeray 2015, Ecker 2016). Without a secure chronology of the Wonderwerk Holocene sequence, however, the wider implications of the cultural and environmental record are significantly reduced because we are unable to correlate them precisely with other climate and archaeological records across the sub-continent.

Although a large number of radiocarbon dates exist for Wonderwerk Cave (eg. Butzer 1979a, Beaumont 1990, Humphreys and Thackeray 1983, Vogel et al. 1986, Lee-Thorp and Ecker 2015, Scott and Thackeray 2015), the raw dates were found to be too coarsely distributed to provide a fine-grained evaluation of environmental and cultural changes in the Holocene sequence, as shown in a recent calibration and modeling exercise (Lee Thorp and Ecker 2015). Researchers have long recognized a moister period in the interior of southern Africa during the mid-Holocene but the timing has been too poorly constrained to allow comparisons across space or with broader subcontinental or global climate trends (reviewed in Scott and Lee-Thorp 2004). At Wonderwerk, based on pollen and microfaunal data, Beaumont et al. (1984) identified a moist phase in Strata 4b-d and placed this at ca. 10,500 to 5,500 BP. This has been corroborated by more recent research on pollen (Scott and Thackeray 2015) and stable isotope records (Lee-Thorp and Ecker 2015), but the duration (i.e. whether a short spell or a period lasting perhaps a thousand years) has remained unclear despite efforts to improve the precision of the chronological record using calibration and Bayesian modeling (Lee-Thorp and Ecker 2015, Scott and Thackeray 2015). The latter exercises also pointed to possible hiatuses in the LSA sequence, e.g. between the Oakhurst and the Wilton industries. Again, without adequate coverage it is not possible to assess whether these are real occupation hiatuses or, alternatively, slower

sedimentation rates associated perhaps with lower occupation density in environmentally unfavorable periods (Avery 1981, Humphreys and Thackeray 1983, Scott and Thackeray 2015, Thackeray 2015).

A further significant event in the Wonderwerk record is the potential last known appearance of the extinct small grazing springbok *Antidorcas bondi*. This species is a remnant of Pleistocene faunal communities (Brink and Lee-Thorp 1992) and few *A. bondi* individuals survived into the Holocene (Klein 1984a, Brown and Verhagen 1985, Plug and Engela 1992), but none of these specimens are directly dated. Direct dating of the a Wonderwerk Cave *A. bondi* specimen, recovered from Stratum 4c, would improve understanding of factors influencing its extinction. Another unexpected ungulate appearance in the sequence is the blesbok (*Damaliscus pygargus phillipsi*), which today inhabits the high elevation open grasslands to the east and northeast of the interior (Grassland and Nama Karoo biomes) but not the Savanna biome common around Wonderwerk. Its presence in Stratum 3a may reflect a temporary shift towards a more open local vegetation. Again, however, an age cannot be precisely assigned at present based on the broad chronological range for this stratum.

The aim of this study is to refine the chronology for the Holocene levels in Excavation 1 at Wonderwerk Cave, through the addition of new radiocarbon dates that attempt to illuminate the gaps, and on the understanding that insufficient dates result in uncertainty in constraining archaeological horizons (Levine and Stanish 2014). The new dates are combined with existing ones in a Bayesian model developed to calibrate and constrain the ages for each stratum as *Phases* within a *Sequence* model. This approach has been particularly successful for cave deposits with complex depositional histories (e.g. Macken et al. 2013), although it has rarely been used in South African archaeological sequences so far (but see Loftus et al. 2016). Critically it enables exploration of the timing and tempo of changes in the palaeoenvironmental and cultural record of Wonderwerk Cave in particular, and the LSA in South Africa's interior in general.

## **Background**

Wonderwerk Cave is a ca. 140m long dolomitic cavity, overlain by the banded ironstone formations of the Griqualand West Sequence, located on the eastern flank of the Kuruman hills

in the Northern Cape Province of South Africa (Figure 1). After initial archaeological exploration in the 1930s and 1940s, extensive excavations near the cave's entrance (known as Excavation 1) began in 1978 by Peter Beaumont, then archaeologist for the McGregor Museum, Kimberley. He was joined in 1979 by Anne and J. Francis Thackeray, who were excavating the Holocene cultural, faunal and sedimentary record of Excavation 1, about 20m into the cave entrance (Figure 3) (Thackeray 1981, Thackeray 1984, Humphreys and Thackeray 1983, Beaumont 1990, 2004; Beaumont and Vogel 2006).

The Holocene archaeological strata in Excavation 1 comprise ca. 1 m of deposits which are composed of soft brown to reddish sands (Figure 2). The excavated sequence is as follows (based on Beaumont 1990, 2004, Humphreys and Thackeray 1983; Table 1):

*Strata 1 and 2a* represent historic periods of cave use and have yielded finds of metal, glass and European porcelain as well as sheep and cattle dung (probably resulting from when the cave was used as a stock pen in the early 1900's), indicating that these layers are anthropogenic disturbances. No radiocarbon dates exist for these layers.

*Strata 2b and 3a* are characterized by soft, dark-brown sand and are assigned to the Ceramic LSA due to the presence of small plain grit-tempered ceramic body sherds within a Later Stone Age lithic assemblage.

*Strata 3b, 4a-4c*, represent the Wilton industry. Stratum 3b was formed in soft dark-brown sand with pieces of roof spall, while Strata 4a-4c are characterized by red-brown sand. The Wilton lithic industry, marked by the first appearance of segments in the lowermost spit of Stratum 4c, dominates most of the Holocene sequence but is not uniform. The layers richest in Wilton artefacts are Strata 4a to 4b, with the highest density of finds in 4aLH (Thackeray 1981, Humphrey and Thackeray 1983). Stratum 4aLH, at the base of Stratum 4a, appears in profile as a distinct convex feature (Figure 2b) which does not extend throughout all squares. It was associated with an unusually high concentration of charcoal, fauna, heat-fractured stones and artefacts (Thackeray 1981, Thackeray 1984).

More than 80% of the Wilton lithics in Strata 3b and 4a-4c are unretouched, about 4% are retouched tools and 10-15% utilized. Cores are mostly irregular, with bladelet cores most abundant in Strata 3a to 4aLH, where they comprise 25% of the core assemblage. Retouched tools include backed artefacts, segments and scrapers, as well as points, borers, notched artefacts

and adzes. Shifts in both artefact types and dominant raw material occur within the Wilton technocomplex. There is a predominance of chert in Strata 3b, 4a, 4aLH, while banded ironstone predominated in Strata 2b, 3a, 4b, 4c and 4d. There is a marked transition from banded ironstone to chert and to more backed artifacts in Strata 4b to 4aLH/4a by which time they had become dominant (Thackeray 1981, Humphrey and Thackeray 1983, Beaumont 1990, Beaumont and Vogel 2006). Other finds recovered from the Wilton strata include lumps of ochre and specularite, wood and bone artefacts, ostrich eggshell fragments - some decorated, others made into beads, chert pendants, as well as stone rings (Humphreys and Thackeray 1983, Beaumont 1990). Notable finds were several engraved dolomite and haematite stone slabs with incised lines, parallel or in grids, with the most clearly identifiable being the rump of a zebra (Thackeray et al. 1981, Thackeray 2013, 2015, Bradfield et al. 2014).

<i>Stratum</i>	<i>Lithic technology (dominant tool type/raw material)</i>	<i>Beaumont spits</i>	<i>Thackeray spits</i>
2b	Ceramic LSA	3UP, 3MID	2b, 3aI, 3aII
3	Wilton (backed bladelets/chert)	3LR	3b
4a	Wilton (backed bladelets/chert)	4aUP, 4aMID	4aI, 4aII, 4aIII, 4aIV
4aLH	Wilton (backed bladelets/chert)	4aLWR	4aLH
4b	Wilton (scrapers/ ironstone)	4bTUFA5, 4bTUFA6	4bI, 4bII
4c	Wilton (scrapers / ironstone)	4cUP, 4cLR	4cI, 4cII
4d	Oakhurst/Kuruman (ironstone)	4d top, 4d base	4dI, 4dII
5a	Undefined mixed assemblage (ironstone)	5a	5I

Table 1: Archaeological Strata in Excavation 1 showing associated lithic technology (after Humphreys and Thackeray 1983, Chazan 2015). Correlations of the Strata names with the

corresponding spits in both the Beaumont (Beaumont 1990, Beaumont pers. comm.) and Thackeray (Thackeray 1981, Thackeray 1984) excavations are given.

*Stratum 4d* is characterized by red-brown to orange sands containing ash lenses and roof spall. It contains an Oakhurst-like assemblage, locally designated as the Kuruman Industry, which differs from the overlying Wilton in artefact form, scraper morphology, raw material use, tool types and associated non-lithic artefacts (Humphrey and Thackeray 1983). The Kuruman industry is dominated by scrapers with a few blades and retouched adzes and lacks backed artefacts. The dominant raw material is local banded ironstone and dolomite (Thackeray 1981). Engraved dolomite and haematite stones were also discovered in this layer.

*Stratum 5* underlies Stratum 4d and is of uncertain Late Pleistocene age (<12 000 cal. BP; Lee-Thorp and Ecker 2015). The matrix differs from the overlying layers in that it comprises small pebbles, possibly internally derived cave detritus (Humphreys and Thackeray 1983). This stratum contains some irregular cores and flakes of poor-quality chert, and in general many pieces are broken and damaged. Beaumont assigned it to the Robberg industry due to the presence of rare bladelets (Beaumont 1990), but later revised this first impression claiming the presence of older, intrusive material (Beaumont and Vogel 2006). Indeed, more recent analysis has demonstrated that Stratum 5 represents a complex depositional event at the interface of the Early Stone Age (ESA) and directly overlying LSA (Chazan 2015, Horwitz and Chazan 2015). Renewed excavation is needed to refine the stratigraphy of Stratum 5.

More than thirty radiocarbon dates for the Holocene strata of Excavation 1 in Wonderwerk Cave have been obtained independently by different researchers between 1978 and 1995, measured on charcoal, ostrich eggshell (OES) and travertine (Table 2; Butzer et al. 1978, 1979a, b; Humphrey and Thackeray 1983; Vogel et al. 1986, Beaumont 1990; Lee-Thorp and Ecker 2015). All samples for dating were collected from Excavation 1 and measured in the same reputable laboratory (Pretoria). There are some pointers from the Beaumont and Thackeray excavations which indicate taphonomic factors which may have influenced the depositional record and hence the samples used for dating:

- Humphreys and Thackeray (1983) note that the sediments comprising Strata 2b through 3b were very similar in composition and color such that the interface between these Strata was not always distinct which may have led to incorrect attribution of samples. This is

reflected in our treatment of all samples from Strata 3a and 3b as belonging to one Phase in our model (see below).

- Stratum 4LH (at the base of 4a) represents a clear feature (Figure 2) but may not represent a single event.
- In Stratum 4c, in deposits adjacent to the large stalagmite, travertine lenses are interbedded with sand. The travertine was most likely deposited after the sand was laid down. However, we rejected dates on travertine, and only one charcoal date in Stratum 4c is from the area near the stalagmite.
- Due to the excavation methods used by Beaumont and the Thackerays in 1978-1979, we do not have precise spatial information for these samples beyond the square and the spit or depth in which they were found.

Despite some evidence for episodes when the cave, or parts of it, were not occupied by people, for all strata there is a consistent succession in the lithic assemblages as well as the good overall agreement in trends in the data obtained for micro- and macro-fauna, pollen and stable isotope isotopes, pointing to a high degree of stratigraphic integrity (Horwitz and Chazan 2015).

Hypothetically, Wonderwerk has the densest radiocarbon record for the Northern Cape. However, the dating program was uncoordinated with several researchers submitting samples for dates independently or on material not deemed suitable for radiocarbon dating today. The result is a clustering of dates in certain strata and gaps in the chronology in other phases (Lee-Thorp and Ecker 2015). Dates obtained so far include (Figure 3):

- Six dates on charcoal from Beaumont's 1978 excavation (Vogel et al. 1986).
- Seven dates from the 1979 excavations of A. and J.F. Thackeray (Humphreys and Thackeray 1983).
- Three OES samples from Malan and Peabody's 1948 excavation submitted by Butzer in 1977, reported in Vogel et al. (1986).
- Six further samples of charcoal and OES after the 1981/1982 Beaumont excavation of a trench in the cave entrance, reported in Vogel et al. (1986).
- Five dates commissioned by K. Butzer and reported in Butzer (1978) and Butzer et al. (1979a, 1979b). These dates are not considered in this study as their stratigraphic context is unknown and they are on questionable material, e.g. 'carbonaceous soil'.

- Four dates on travertine lenses commissioned by J.F. Thackeray. The lenses crosscut Holocene layers and are of uncertain stratigraphic position. Consequently, they were excluded from our analyses both because of their unclear stratigraphic position and because the reservoir effects for cave carbonates are unknown in this case (Vogel et al. 1986).
- Four charcoal samples collected by Beaumont in 1995 and submitted for dating by Lee-Thorp (Lee-Thorp and Ecker 2015).

Besides the dates on travertine lenses and the dates from Butzer's investigations, we follow our earlier publication (Lee-Thorp and Ecker 2015) in which we excluded the OES samples from the Malan and Peabody 1948 excavations. The stratigraphy of their excavation cannot be matched with the later excavations with confidence (Table 2). Neither is any detailed stratigraphic documentation of Beaumonts' 1981/1982 entrance trench excavation available. Therefore, the correlation of these strata with those in Excavation 1 is questionable and all samples from the entrance trench were excluded (Table 2). Lee-Thorp and Ecker (2015) produced a Bayesian model of the remaining published conventional bulk radiocarbon dates, whose spatial distribution (Figure 3) is close, with few exceptions. The model included *Phases* with blank dates within a *Sequence* Model to act as boundaries for strata where too few dates were available. Using a selected corpus of these dates, Scott and Thackeray (2015) developed a separate age model using the Clam 2.2 program with the latest adjustments for the Southern Hemisphere (Blaauw 2010), in order to locate the pollen sequence. They calculated the average accumulation rate for this sequence as nearly 0.9 cm/100 years but noted reduced accumulation rates during least at two periods – in Strata 5 and 4dII, ca. 11,000 to 9,000 cal. BP, either due to slower accumulation rates or hiatuses in the sequence (Scott and Thackeray 2015). Both of these exercises exposed the significant gaps in the sequence and the results were too coarse to pinpoint the timing of a moister episode evident in several paleoenvironmental proxies around Strata 4aLH and 4bI. Since radiocarbon dates were particularly sparse for this phase, the new dating program focused on this period.



Lab Code	<sup>14</sup> C Measurement		Stratum	Square	Material	Reference	$\delta^{13}\text{C}$ (‰)	Modelled Date Range (cal. BP)	Posterior outlier probability (%)
	Date ( <sup>14</sup> C yrs BP)	Uncertainty (1 $\sigma$ )							
Pta-2779	1210	50	2b	T22/23	charcoal	Humphrey&Thackeray 1983	-24.4	1275-987	2
Pta-2542	1890	50	3a	O19/P20	charcoal	Beaumont 1990	-21.6	1988-1707	4
Pta-6873	2120	80	3a	S22	charcoal	Lee-Thorp&Ecker 2015	-24.6	2330-1900	3
Pta-2543	2910	60	3b	O19/P20	charcoal	Beaumont 1990	-24.9	3319-2858	4
Pta-2785	3990	60	3b	R25	charcoal	Humphrey&Thackeray 1983	-24.0	4624-2001	29
Pta-2541	4240	60	4a	P20/21	charcoal	Beaumont 1990	-23.9	4967-4635	2
Pta-2797	4890	70	4aLH	T22/S22	charcoal	Humphrey&Thackeray 1983	-23.9	5850-5480	1
Pta-2544	5180	70	4b	O19/P20	charcoal	Beaumont 1990	-23.4	6785-5796	41
Pta-2545	5970	70	4cI	O19/21	charcoal	Beaumont 1990	-23.3	8684-6715	40
Pta-2798	7430	60	4cI	S/T24/25	charcoal	Humphrey&Thackeray 1983	-23.3	8386-8045	4

Pta-2546	9130	90	4dI	O19/22	charcoal	Beaumont 1990	-23.2	11800-10191	80
Pta-2852	9760	120	5a	O24	charcoal	Humphrey&Thackeray 1983	-23.8	12190-11439	30
Pta-2790	10000	70	4dII	O25	charcoal	Humphrey&Thackeray 1983	-22.7	11711-11270	1
Pta-6884	10080	100	5a	N28	charcoal	Lee-Thorp&Ecker 2015	-21.8	12088-11461	3
Pta-6872	10120	120	4dII	P26	charcoal	Lee-Thorp&Ecker 2015	-23.3	11774-11271	2
Pta-6871	10120	100	4dII	Q23	charcoal	Lee-Thorp&Ecker 2015	-23.5	11780-11288	3
Pta-2786	10200	90	4dII	O25/P25	charcoal	Humphrey&Thackeray 1983	-22.6	11843-11308	7
<b>Unmodelled dates</b>									
Pta-3426 <sup>1</sup>	2310	60	3a	P7	charcoal	Vogel et al. 1986	-24.4		
Pta-2139 <sup>2</sup>	3060	40	3	P30	OES	Butzer et al. 1978	-8.8		
Pta-3427 <sup>1</sup>	5800	70	3a	P8	charcoal	Vogel et al. 1986	-22.8		
Pta-2140 <sup>2</sup>	5930	50	4c	M28	OES	Butzer et al. 1978	-7.7		
Pta-3425 <sup>1</sup>	6840	80	4cI	P7	charcoal	Vogel et al. 1986	-24.0		
Pta-3366 <sup>1</sup>	8000	80	4cII	P9	OES	Vogel et al. 1986	-8.0		

Pta-3439 <sup>1</sup>	9030	90	5a	P7/9	OES	Vogel et al. 1986	-8.0		
Pta-2141 <sup>2</sup>	12380	100	5	N31	OES	Vogel et al. 1986	-10.0		
Pta-3441 <sup>1</sup>	12400	180	5	P7	OES	Vogel et al. 1986	-9.0		
Pta-2723 <sup>3</sup>	2350	50	Between 3a and 4a	R22	Travertine	Vogel et al. 1986	-0.6		
Pta-2727 <sup>3</sup>	2260	50	4a	T21	Travertine	Vogel et al. 1986	0.2		
Pta-2728 <sup>3</sup>	3360	60	4c	21	Travertine	Vogel et al. 1986	-1.0		
Pta-2729 <sup>3</sup>	2930	60	4d	R21	Travertine	Vogel et al. 1986	-0.9		
<b>New dates (charcoal samples)</b>									
OxA-30568	4207	30	4aII	R21	<i>Vitex mombassae</i>	this study	-27.1	4853-4646	2
OxA-30567	4427	29	4aII	Q21	<i>Searsia lancea</i>	this study	-25.5	5256-4869	1
OxA-30566	4459	30	4aII	Q23	<i>Ochna pulchra</i>	this study	-22.8	5275-4881	2
OxA-30639	4887	33	4aLH	R23	<i>Vitex mombassae</i>	this study	-23.9	5709-5584	1
OxA-31897	5063	30	4c	K27	<i>Searsia lancea</i>	this study	-23.6	8655-6760	100
OxA-30638	5340	33	4aLH	R23	<i>Heteromorpha trifoliata</i>	this study	-23.3	6211-5448	53
OxA-30640	5627	33	4bI	Q24	<i>Searsia lancea</i>	this study	-23.5	6490-6315	3
OxA-30641	5771	34	4bI	T25	<i>Vitex mombassae</i>	this study	-24.8	6663-6482	2
OxA-30642	5915	34	4bI	T25	<i>Searsia lancea</i>	this study	-22.6	6846-6452	6

Table 2. Raw and modeled radiocarbon dates from Wonderwerk Cave. For calibration OxCal version 4.2 (Bronk Ramsey 2013) and the ShCal13 calibration curve for the Southern Hemisphere (Hogg et al. 2013) were used as described in the text; dates are given with 95% probability. The table includes dates used in the Bayesian model and their posterior outlier probability, and those dates excluded from the model because of (1) stratigraphic position in the entrance trench cannot be correlated to the main excavation area, or (2) were excavated by the University of California Expedition in 1948 and whose stratigraphic position is unreliable, or (3) carbonate ages that were thought to be too old as initial carbonate age unknown, as described in the text.

## Material and methods

### *Sample selection*

Charcoal is abundant and well preserved throughout the Holocene record of Wonderwerk Cave and was chosen as the most reliable material for the dating program. Sample selection was based on the distribution of the existing dates in the Holocene sequence and the spatial position of the samples within the excavation grid (Figure 3), as well as the size of the fragments, with larger ones chosen to facilitate identification to plant species. We selected nine large, individual charcoal pieces between 0.16 and 0.91g, that were identified to species by Professor Marion Bamford. This is an improvement on the previous, conventionally measured charcoal samples, which were unidentified bulk samples. It should be noted that the charcoals identified for dating represent only a few out of a wide range of plant species found at the site. Of the species identified, *Searsia lancea* is a widespread tree and is also a very common charcoal. The other species identified are all woodland or bushland trees and though they do not occur close to Wonderwerk today, they have the same climate tolerance and could feasibly have grown here in the past (M. Bamford pers. comm. 2017).

Figure 2 shows all new  $^{14}\text{C}$  samples in stratigraphic context. The selected samples are horizontally close to the majority of former  $^{14}\text{C}$  samples (listed in Table 2). During sorting of the faunal assemblage for suitable teeth for isotopic analysis, we discovered an *Antidorcas bondi* (Bond's springbok) specimen in Stratum 4c as well as a *Damaliscus pygargus phillipsi* (Blesbok) specimen in Stratum 3a. Both teeth were included in the dating program for their significant contribution to understand the changing environment in the region. Problems with collagen preservation were not expected as the dry cave interior has preserved the fauna well and two previous studies on Equid teeth from Wonderwerk extracted collagen successfully (Thackeray and Lee-Thorp 1992, Orlando et al. 2009).

### *Pretreatment and AMS measurement*

Pretreatment followed standard pretreatment protocols for both charcoal and collagen preparation (Brock et al. 2010). As the results were expected to be younger than 8000 cal. BP, Acid Base Acid (or “ABA”) was considered as sufficient pretreatment for the charcoal samples. Sample graphitization followed Dee and Bronk Ramsey (2000). Finished samples were measured on the ORAU HVEE AMS system (Bronk Ramsey et al. 2004).

Pretreatment of the crushed teeth to extract collagen began with dissolution of mineral in HCl. At this stage sample 37276 (*Antidorcas bondi*) dissolved completely leaving no visible residue. The remaining dentine sample 37277 (*Damaliscus pygargus phillipsi*) in the end did not produce enough collagen either and failed the laboratory's standard test. Neither tooth therefore could be dated. Consequently, a further charcoal sample deriving from the same square and spit as the *Antidorcas bondi* tooth was selected for radiocarbon dating (OxA-31897- Table 1).

#### *Calibration and model specifications*

OxCal v4.2 (Bronk Ramsey 2009a, 2013) was used for Bayesian analysis of the Wonderwerk Cave radiocarbon dates to integrate the  $^{14}\text{C}$  data with stratigraphic information. Excluded dates were calibrated using the ShCal13 curve for the Southern Hemisphere (Hogg et al. 2013) but not included in the Bayesian model (Table 2). For the model, we used a *Sequence Model*, with *Boundaries* between the archaeological strata (prior information), and *Phases* within the *Boundaries* (Appendix 1). The fact that the samples came from several old excavations in different parts of Excavation 1 meant that it was most realistic to model the individual dates within a Stratum (*Phase*) as independent but potentially overlapping. A general *Outlier\_model* with prior outlier probability set to 5% (Bronk Ramsey 2009b) was applied. This approach applies a lower weight to dates that are likely outliers in the model output. Dates identified as 100% outliers are excluded automatically by OxCal. This is a statistically more robust solution than excluding dates manually based on how well they fit with other dates alone.

*Difference* functions, which provide a statistical range between events, were used in two ways: to calculate possible hiatus times between the strata, and to estimate the duration of each strata. The model was run on the SHCal13 curve (Hogg et al. 2013) for the Southern Hemisphere. Several versions of the Bayesian model were run, with and without Stratum 5, with and without spits in Stratum 4d, and with and without separation of Stratum 3 into substrata 3a and 3b, in order to test how dates with unclear stratigraphic position or poor agreement behaved. The model presented here (Appendix 1) is only one possible way to model the results. Here we describe what we believe is the best and most parsimonious fit considering the stratigraphy, distribution of dates and the model constraints. The modeled radiocarbon date ranges are presented at 95.4% probability (approximately equivalent to  $2\sigma$  uncertainty) and the ages are given in cal. BP.

## Results

The results of the new radiocarbon dating exercise and the model results are listed in Table 2. In the model, the OxCal internal agreement index (Index A = a measure of agreement between the modeled and unmodeled data) is very low, with  $A_{model} = 11.4\%$  and  $A_{overall} = 16.3\%$ . However, those indices are less robust than the *Outlier\_model* analysis (Bronk Ramsey 2009b). Several dates stood out in the new model (Figure 4) as having poor individual agreement indices and/or high posterior outlier probabilities:

- Pta-2546 (Stratum 4dI) 23.7% agreement, 80% posterior outlier probability in outlier model.
- Pta-2786 (Stratum 4dI) 38.1% agreement, 7% posterior outlier probability in outlier model.
- Pta-2852 (Stratum 5a) 8.8% (59.5% agreement when considered in Stratum 4dII), 30% posterior outlier probability in outlier model.
- Pta-2545 (Stratum 4c) 51.8% agreement, 40% posterior outlier probability in outlier model.
- OxA-31897 (Stratum 4c) 5.5% agreement, 100% posterior outlier probability in outlier model.
- Pta-2544 (Stratum 4b) 47.8% agreement, 41% posterior outlier probability in outlier model.
- OxA-30638 (Stratum 4aLH) 51.7% agreement, 53% posterior outlier probability in outlier model.

All other dates have more than 60% individual agreement. There is no evident common feature (e.g. Stratum, spatial distribution, method or excavator) that might explain these outliers. Bronk Ramsey et al. (2010) propose four possible scenarios: uncertainty in the reservoir  $^{14}\text{C}$  concentration, sample contamination, incorrect measurement, or uncertainties in the chronological model. Although we cannot exclude any of them, the last is the most likely in this case, resulting from our stratigraphic information entered in the priors. Movement of samples in the loose sediment due to bioturbation is a likely explanation for samples with poor agreement.

Although there are two dates labeled Stratum 5a (Pta-2852 and Pta-6884), the first fits best with Stratum 4d. This is consistent with the observations of A. Thackeray (1981) that the Layer 4d /

Layer 5 boundary is not well defined. The modeled durations of the LSA layers (Figure 6) shows short spans of less than 500 years each for Strata 2b, 4aLH, 4d and 5a, respectively. In Strata 2b, 4d and 5a this relatively short period correlates with a lower density of archaeological material and shallower deposits, and it raises questions about whether the cave was irregularly used for short visits. However, Stratum 4aLH is rich in cultural material in spite of the relatively short duration and the result suggests that during this time period the site was rather more regularly occupied. Strata 4a and 4b show longer durations with a mean between 500 and 1000 years. Stratum 3, although containing an abundance of archaeological material, shows the longest duration (up to over 3000 years). The calculated duration for Stratum 4c is extended, which is a corollary of the imprecision of its associated boundaries. The calculation of hiatus length (Figure 7) showed that little time elapsed between strata, and where hiatuses might have occurred (the results show this possibility for Strata 4aLH/4a and Strata 4c/4d), their duration was less than 500 years. The shortest possible hiatus is between Strata 4d and 5, a result that is consistent with our concerns about the definition of this stratigraphic boundary. The only exception is between Strata 4d and 4c, where a hiatus seems likely as also proposed by Scott and Thackeray (2015). The modeled Strata ages from the *Date* function (Figure 5) are within the wider boundaries for each Stratum and in agreement with the *Difference* function results.

When compared to an earlier version of the model (Lee-Thorp and Ecker 2015), it is evident that both versions give similar ages and age boundaries for the uppermost Strata 2b-4a. This increases confidence in interpretation of the model for these sections and the stratigraphic integrity of the samples. The two models do, however, differ in the older Strata. OxA-30638 from Stratum 4aLH is slightly older than the previous two dates for this stratum such that this Stratum should now be considered as older and Stratum 4b as having a longer time span. The duration of Strata 4b, 4aLH and 4a are reduced and well constrained. The three dates from Stratum 4c on the other hand result in an extended time range for this layer.

## **Discussion**

### *Later Stone Age chronology of Wonderwerk Cave*

The model data provides a chronology that extends from over 12,000 years cal. BP to less than 1000 years cal. BP. It allows the construction of a chronological sequence with statistically



sound estimates for all strata compared to calibration of the  $^{14}\text{C}$  dates alone. Stratum 4d contains the earliest Holocene industry, the Oakhurst, dated to between 11.8-10.4ka cal. BP in Wonderwerk. Principal component analyses of micromammal abundances (Avery 1981, Thackeray 1984), pollen (Scott and Thackeray 2015) and stable carbon and oxygen isotopes of large mammal enamel (Ecker 2016) from Stratum 4d together suggest arid conditions with a higher proportion of woody vegetation and lower grass cover than in the following strata. The Wilton Strata (4c through to 3b) begins before 9ka cal. BP (Figure 5), placing the onset of the Wilton industry rather earlier than previously thought, but entirely consistent with recently re-analyzed coastal sites (Loftus et al. 2016). A. Thackeray (1981) argued that the Oakhurst and the Wilton industries were made by different groups based on the differences in lithic technology. Our estimation of a hiatus of possibly several hundred to several thousand years between these strata (394 to 3376 years, Figure 7) is consistent with, and strengthens, her argument.

Interestingly the scrapers in the lower part of Stratum 4c are described as resembling the Stratum 4d scrapers, while the upper ones are more similar to Stratum 4b scrapers (Thackeray 1981). Based on this observation, Thackeray proposed that Stratum 4c has two phases, but no change to the assigned strata boundary was ever made (Thackeray 1981). The suggestion that Stratum 4c may include two phases is consistent with the long timespan of this layer (6772-9370 cal. BP) and the disagreement between the Stratum 4c ages. However, given the probable hiatus between Stratum 4d and 4c, perhaps also attested to by the presence of roof spall in Stratum 4d, a direct cultural link for the resemblance between the Stratum 4d scrapers and those from the bottom of Stratum 4c must be considered with caution. As noted by Humphreys and Thackeray (1983: 71), in terms of scraper dimensions and retouch parameters in banded ironstone and chert, Stratum 4c “generally occupies an intermediate position between results for 4d and those for 4b upwards”. Types of retouched tools also differ between the two strata (Humphreys and Thackeray (1983: Table 4). Furthermore, Beaumont (1990) argues for keeping the boundary of the Wilton at the base of Stratum 4c, since it coincides with the appearance of segments, a tool type he attributed as signifying the start of this industry. Another possibility is that both samples (OxA-31897 and Pta-2545) have moved down from Stratum 4b. This would leave only one date (Pta-2798) for Stratum 4c and in turn would limit the power of hiatus, duration and *Date* calculations. This issue can only be elucidated by future excavation and sampling.

A cultural shift within the Wilton industry occurs between Strata 4bI and 4aII, and coincides with Stratum 4aLH, which is now placed firmly between 5.4ka and 6.2ka cal. BP. This cultural shift is coincident with a phase of wetter climate and maximum C<sub>4</sub> grass expansion with characteristics of savanna grassland, as attested in the pollen record, OES stable isotope values and an increase in the abundance of large grazer species (Figure 5; Avery 1981, Thackeray 1984, 2015, Lee-Thorp and Ecker 2015, Scott and Thackeray 2015). The subsequent Wilton industry phase in Stratum 4aII is marked by higher proportions of backed bladelets, while the final phase occurs in Stratum 3b, where the lowermost boundary is set at 4.5ka cal. BP and uppermost as young as 1.6ka cal. BP. It was not possible to separate Strata 3a and 3b chronologically even using different model versions. For this reason, the model presented here does not distinguish 3a from 3b, and the onset of the Ceramic LSA cannot be more precisely determined. Interestingly, Thackeray and Humphrey (1983) noted that during excavation the distinction between them was problematic. At Wonderwerk, aridity reached its maximum just after this period at around 2ka cal. BP (Lee-Thorp and Ecker 2015), with a dominance of grazers and the slow increase of the C<sub>3</sub> thornveld of today – an environment characterized by a reduction in trees but with some scrub (Avery 1981). A similar trend has been documented for other sites in the interior (Scott and Lee-Thorp 2004).

#### *Implications for the Later Stone Age of South Africa's interior*

Wonderwerk Cave now has one of the most finely dated Holocene sequences in the South African interior and thus may provide an anchor against which to compare other LSA sites in the interior. The Oakhurst industry in Wonderwerk began earlier than at Rose Cottage Cave in the Free State, although the dates in the latter site have not been calibrated and modeled in the same way. Spit 4dI in Wonderwerk overlaps with a 10.6ka cal. BP date (Pta-5599; re-calibrated in OxCal 4.2 with the SHCal13 curve for the Southern Hemisphere) for the earliest dated Oakhurst at Rose Cottage Cave (Wadley 2000) as well as with the date of 10.6-8.5ka cal. BP for the Lockshoek level at Blydefontein (SMU-1823) (Bousman et al. 2016).

It is commonly assumed that the Wilton technology spread from Zimbabwe and Namibia through the interior to the South African coast (Mitchell 2013). The early dates for the Wilton from Wonderwerk Cave are of similar age to those from Apollo 11 in Namibia (Wendt 1976) and Diana's Vow in Zimbabwe (Cooke 1979) but early compared to Rose Cottage Cave (Wadley

2000) and to some coastal sites (Lombard et al. 2012), would seem consistent with a northern origin followed by a subsequent southern dispersion. However, re-analysis of radiocarbon dates from other southern African sites may still re-align the dates for coastal sites (Loftus et al. 2016).

Pottery and domestic animals, either independently or as a ‘package’, are believed to have moved from central Africa southwards by ca. 2000 BP (Orton 2012, Jerardino et al. 2014). The Wonderwerk dates for the Ceramic Wilton were excluded by Sadr and Sampson (2006) in their summary paper, as they claimed that they spanned too wide a range to securely date the sherds. However, these authors did not distinguish between radiocarbon dates from the entrance trench and the excavation area (stratigraphic correlations between the two areas are difficult), or between Strata 3a and 3b in their analysis. Based on the new model, we propose reliable ages for pottery in the cave from two samples in the Ceramic Wilton in Excavation 1 Stratum 3a; sample Pta-2542 ( $1890\pm50$ ) and sample Pta-6873 ( $2120\pm80$ ), the latter was not published until recently (Table 2; Lee-Thorp and Ecker 2015). Both dates have very low posterior outlier probability in our model. Thus, Wonderwerk Cave has yielded early dates for pottery in Stratum 3a of at least 2000 cal. BP (380 BC). At Wonderwerk, remains of domestic sheep/goat and cattle are found in Strata 1-2a, which are disturbed by more recent use of the cave in the last century and so do not provide reliable ages for the appearance of domestic herd animals in the region. It will require more well-dated sites in the interior with pottery and/or domestic stock to determine whether they arrived as a package and which of the dispersal routes were taken, since two options have been proposed; a westerly route along the coast versus one via the central interior of South Africa (see discussion in Jerardino et al. 2014, Orton et al. 2013; Sadr and Sampson 2006).

The new dates and model extend discussion of the age of *art mobilier* in the interior, as incised slabs were recovered from Strata 4d through to 3a (Thackeray et al. 1981, Thackeray 2013, 2015). The current model more precisely constrains the age of the oldest engraved dolomite slab from Stratum 4dI, depicting an unfinished mammal, to at least 10,200 years old (cal. BP). Consequently, Wonderwerk is one of the oldest sites with rock engravings in southern Africa, a region which is otherwise poor in artistic expressions prior to the Wilton complex. Likewise, the other engraved slabs from the cave are now constrained chronologically as follows:

- a broken dolomite slab depicting the hindquarters of a zebra from Stratum 3aIII-3bI, is dated to 1626-4489 cal. BP and not 4159-4569 cal. BP ( $3990 \pm 60$  BP) as previously published;
- a broken dolomite slab with a ladder design from Stratum 4aIV, is dated to 4569-5317 cal. BP and not 5329-5740 cal. BP ( $4890 \pm 70$  BP) as previously published;
- a broken dolomite slab with a grid pattern on both sides from Stratum 4bI, is dated to 5876-6899 cal. BP and not 5663-6174 cal. BP ( $5180 \pm 70$  BP) as previously published;
- a hematite slab with a grid pattern from Stratum 4a cannot be more precisely dated since it cannot be attributed to a specific phase within this layer.

#### *Implications for extinction events*

Although we could not date the ruminant tooth samples directly, the charcoal date from the same square (Square K27) and spit as the *A. bondi* tooth ( $5063 \pm 30$  ka uncalibrated; 8655-6760 cal. BP) provides a rough age estimate for the layer. It should be noted, however, that this sample's date expanded the Stratum's previous boundaries. If A. Thackeray's argument based on the scraper assemblage is considered, then Stratum 4c might have two phases (Thackeray 1981). This new date might then represent the earlier phase of Stratum 4c. Remains of another extinct animal, *Megalotragus priscus*, come from the same Stratum (Stratum 4cI) (Faith 2014, Thackeray 2015), but their age remains equally unresolved. One potential problem is that the *A. bondi* and charcoal samples are from a square (K27) adjacent to the cave wall (Figure 3), and therefore we cannot exclude thinning of layers or bioturbation in this area. A new stratigraphic analysis and possibly further radiocarbon dates are required for this section in Wonderwerk Cave, to establish the age of the stratum and materials more securely. Of course, directly dated specimens from this site or others across the sub-continent would settle the question of latest appearance with confidence, but adequate preservation of bone collagen remains a challenge in a warm region.

#### **Conclusion**

Bayesian modeling was used to produce a new age model for the Later Stone Age in Wonderwerk Cave. The *Sequence* model in OxCal combined newly determined and previously published radiocarbon dates with stratigraphic information. The updated modeled chronology for Wonderwerk Cave provides more robust age estimates for the technological and

paleoenvironmental record of the Holocene in Excavation 1. The new radiocarbon dating has resulted in improved age certainty for strata 4a, 4b and 4aLH. We can now confidently constrain a moist episode within 4aLH to less than 800 years, between 6.2ka and 5.4ka cal. BP. This episode stands out in otherwise generally arid conditions throughout the record (Lee-Thorp and Ecker 2015, Scott and Thackeray 2015), and coincides with a shift in dominant raw material and tool type. The Wonderwerk radiocarbon chronology shows an early beginning of the Oakhurst as well as the Wilton industry compared to the majority of South African sites further to the east and south. A greater number of radiocarbon dates recovered from forthcoming, new excavations, will further improve our model. Future research should focus on clarifying the boundaries between Strata 3a/3b and for Stratum 4c, and study the possible impact of bioturbation on movement of charcoal in the sediment using micromorphology. Until then, however, the study presented here is the currently most comprehensive age model for the Later Stone Age of Wonderwerk Cave.

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## Figure captions

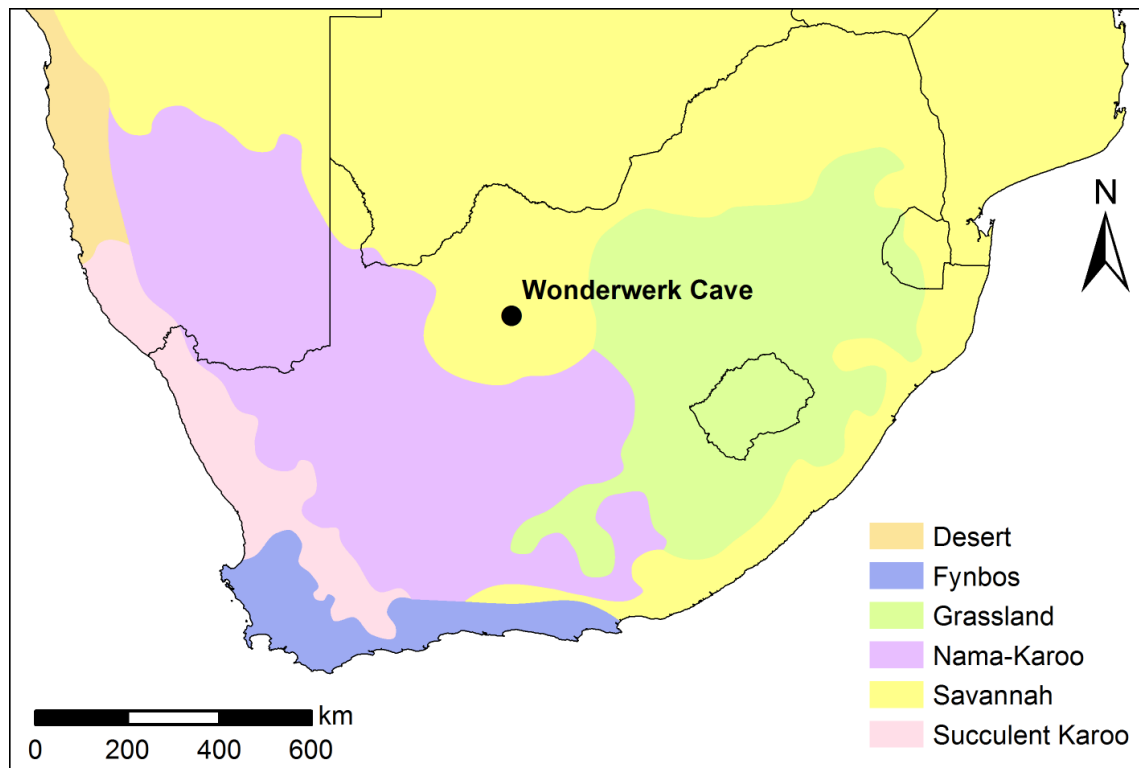


Figure 1: Map of southern Africa, showing biome types (based on Rutherford 1997), as well as the location of Wonderwerk Cave within the Savanna biome.

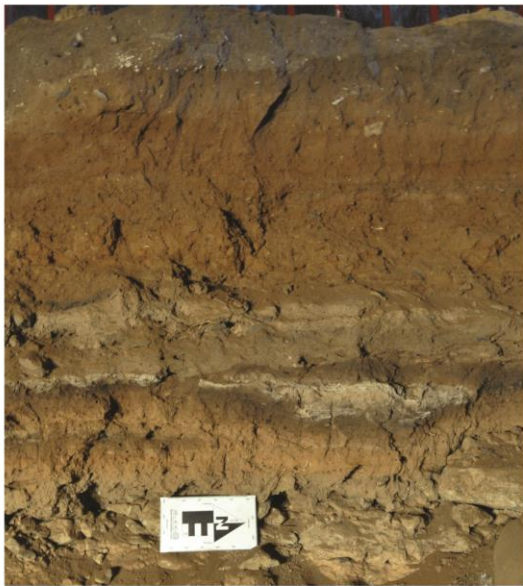
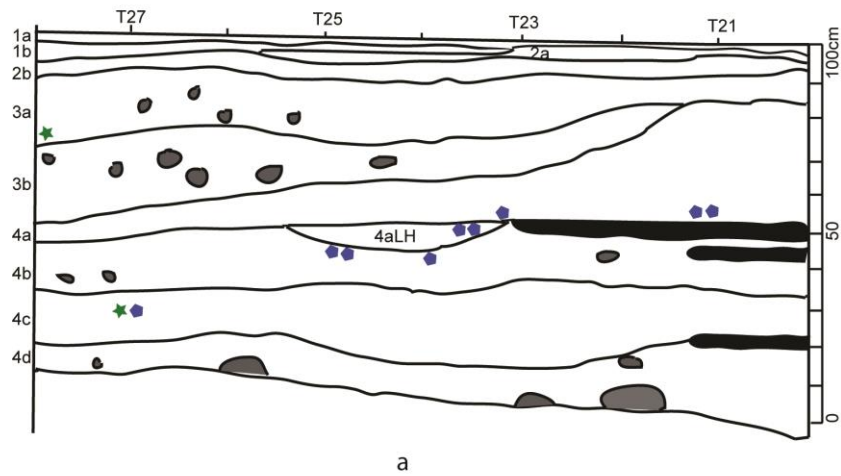


Figure 2: a) Location of new  $^{14}\text{C}$  samples, projected on the schematic section drawing of the T-line after Thackeray (1981). Blue polygons are charcoal samples, and green star shapes are (from lower to higher levels) the *Antidorcas bondi* specimen and the *Damaliscus pygargus phillipsi* specimen, respectively. Black areas indicate flowstones next to the stalagmite. B) Photograph taken of the T-line profile in 2015. Stratum 4aLH is clearly visible as white lens.

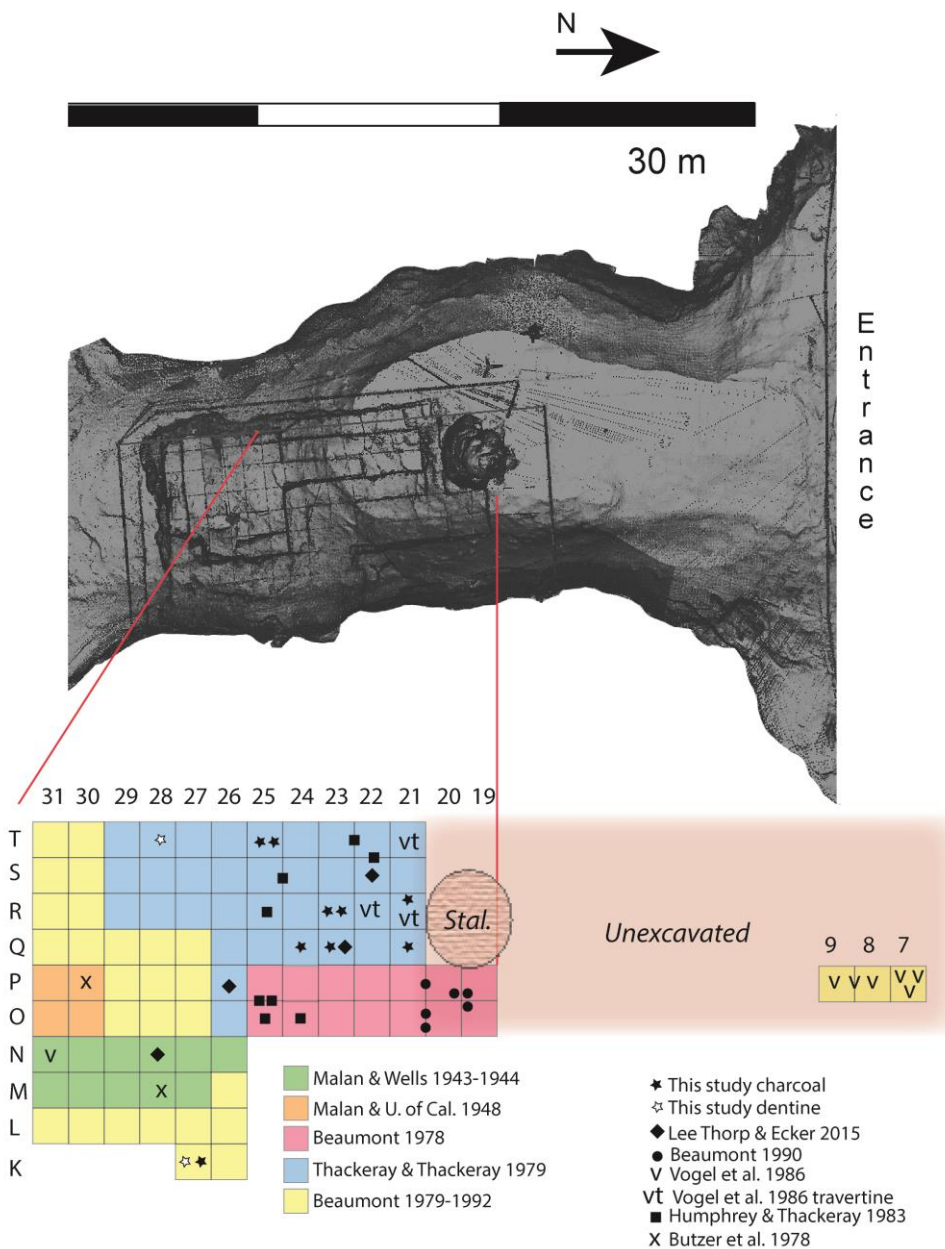


Figure 3: Location of  $^{14}\text{C}$  samples in Wonderwerk Cave Excavation 1 and in the entrance trench. Colors indicate the excavator and symbols indicate the radiocarbon sample by referenced publication respectively.

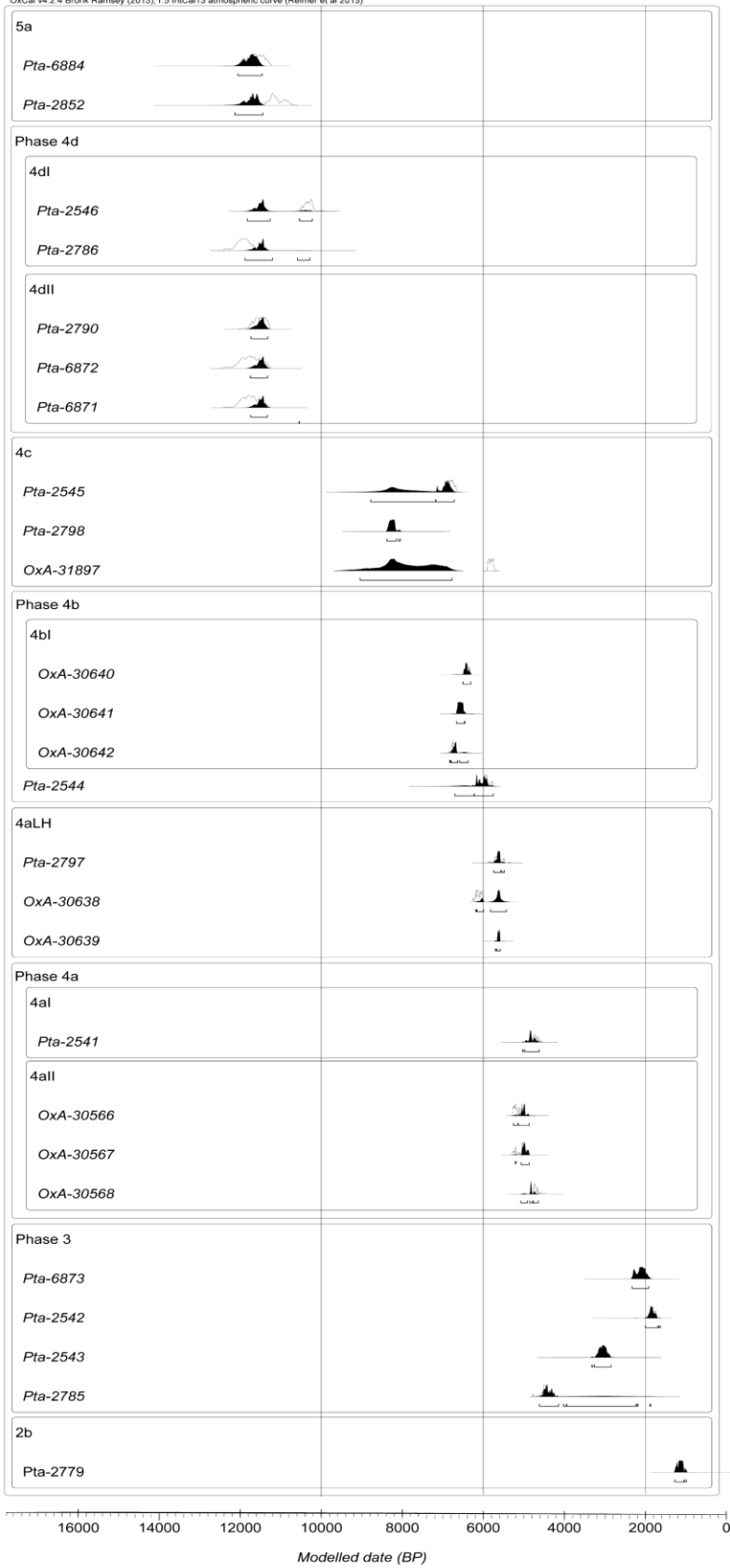


Figure 4: Plot of modeled dates from the OxCal program, ordered from oldest to youngest dates, with the individual agreement indices (A) and the convergence (C) given in brackets next to the sample number. The unmodeled age distributions are indicated in light shading and the modeled range in dark shading. The bracket underneath the dates indicates the posterior 95.4% highest probability density ranges. The new AMS dates are colored green. Not shown in this image are the OxCal Boundaries at the beginning and end of each *Phase*.

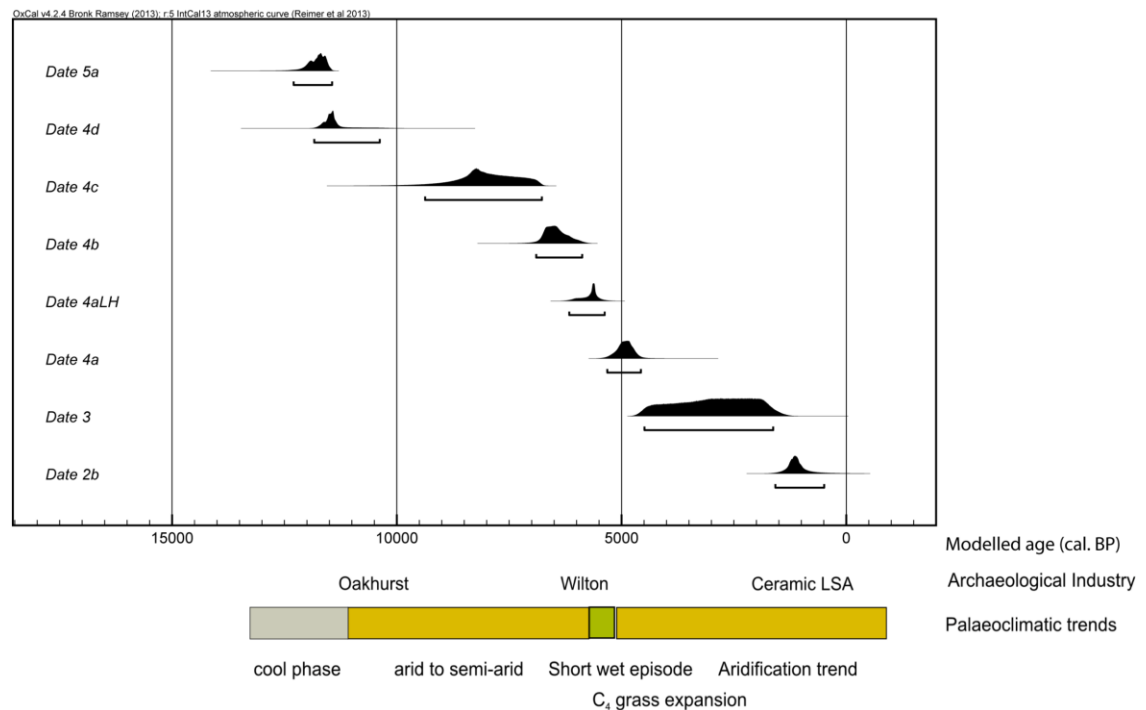


Figure 5: Summary statistics of the strata ages, as a result of the Bayesian model *Date*-function. The rounded age spans are given on the right-hand side of the graph. The figure includes the archaeological industries and general paleoclimatic trends from environmental proxies at Wonderwerk Cave (Avery 1981, Thackeray 1983, Bamford 2015, Lee-Thorp and Ecker 2015, Scott and Thackeray 2015).

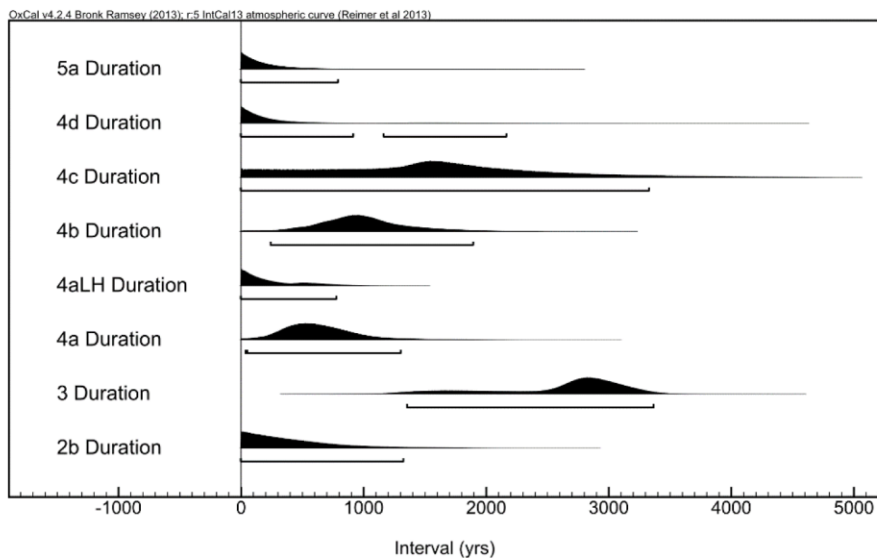


Figure 6: Results of modeled duration of strata in Excavation 1 using the *Difference* function.

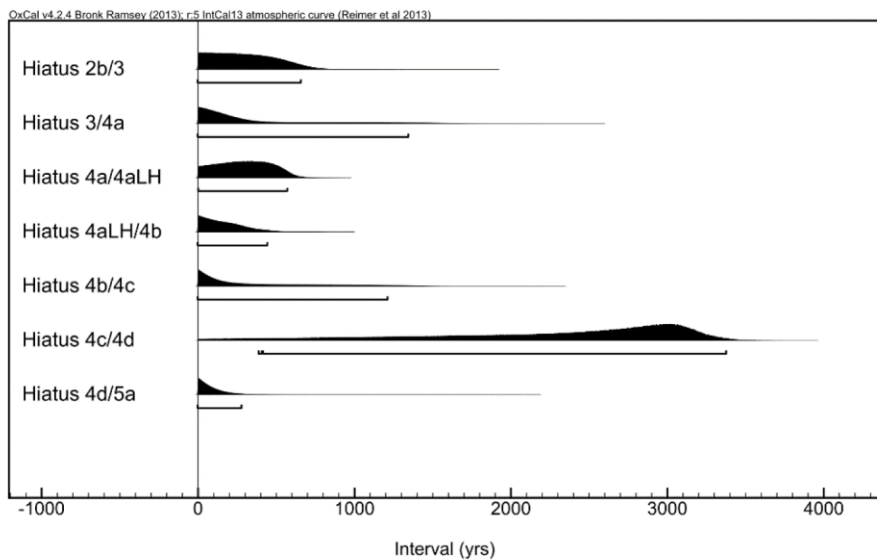


Figure 7: Results of modeled intervals of hiatus length between strata in Excavation 1 using the *Difference* function.



## **Supplementary online information**

SOM 1: OxCal model code.