

RADIOCARBON DATES CONSTRAIN THE TIMING OF ENVIRONMENTAL AND CULTURAL SHIFTS IN THE HOLOCENE STRATA OF WONDERWERK CAVE, SOUTH AFRICA

Michaela Ecker^{1,2*} • James Brink^{3,4} • Michael Chazan^{2,5} • Liora Kolska Horwitz⁶ • Julia A Lee-Thorp¹

¹Research Laboratory for Archaeology and the History of Art, University of Oxford, Oxford, United Kingdom.

²Department of Anthropology, University of Toronto, Toronto, Canada.

³Florisbad Quaternary Research Department, National Museum, Bloemfontein, South Africa.

⁴Centre for Environmental Management, University of the Free State, Bloemfontein, South Africa.

⁵Evolutionary Studies Institute, University of the Witwatersrand, Johannesburg, South Africa.

⁶National Natural History Collections, Faculty of Life Sciences, The Hebrew University, Jerusalem, Israel.

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 (¹⁴C) 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.

KEYWORDS: AMS dating, Bayesian modeling, Later Stone Age, radiocarbon, southern African archaeology.

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, 1984b; 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 Sampson 1974, 2010; Humphrey and Thackeray 1983; Deacon 1984b; Wadley 1987, 1992, 2000; Parsons 2006). 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 (Humphrey and Thackeray 1983; Beaumont 1990). 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 yr 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 subcontinent.

Although a large number of radiocarbon (¹⁴C) dates exist for Wonderwerk Cave (e.g. Butzer 1979a; Humphreys and Thackeray 1983; Vogel et al. 1986; Beaumont 1990; 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

*Corresponding author. Email: michaela.ecker@utoronto.ca.

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 and Vogel (1984) identified a moist phase in Strata 4b–d and placed this at ca. 10,500–5500 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 1984; Brown and Verhagen 1985; Plug and Engela 1992), but none of these specimens is directly dated. Direct dating of the 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 toward a more open 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 ¹⁴C 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 20 m into the cave entrance (Figure 2 and 3) (Thackeray 1981, 1984; Humphreys and Thackeray 1983; Beaumont 1990, 2004; Beaumont and Vogel 2006).

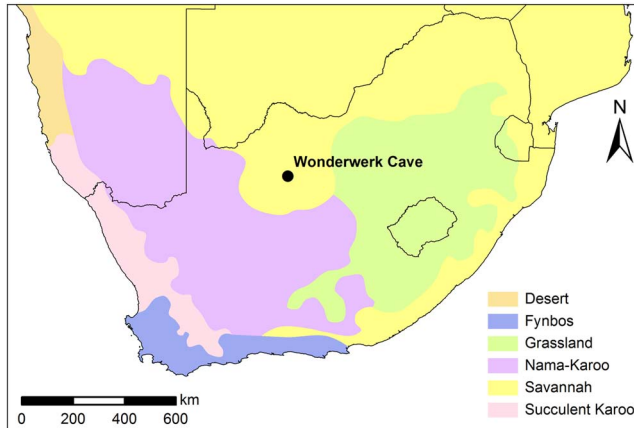


Figure 1 Map of southern Africa, showing biome types (based on Rutherford 1997), as well as the location of Wonderwerk Cave within the savanna biome.

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 1900s), indicating that these layers are anthropogenic disturbances. No ^{14}C 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 artifacts 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 artifacts (Thackeray 1981, 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 artifacts, segments and scrapers, as well as points, borers, notched artifacts, and adzes. Shifts in both artifact types and dominant raw material occur within the Wilton techno-complex. 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

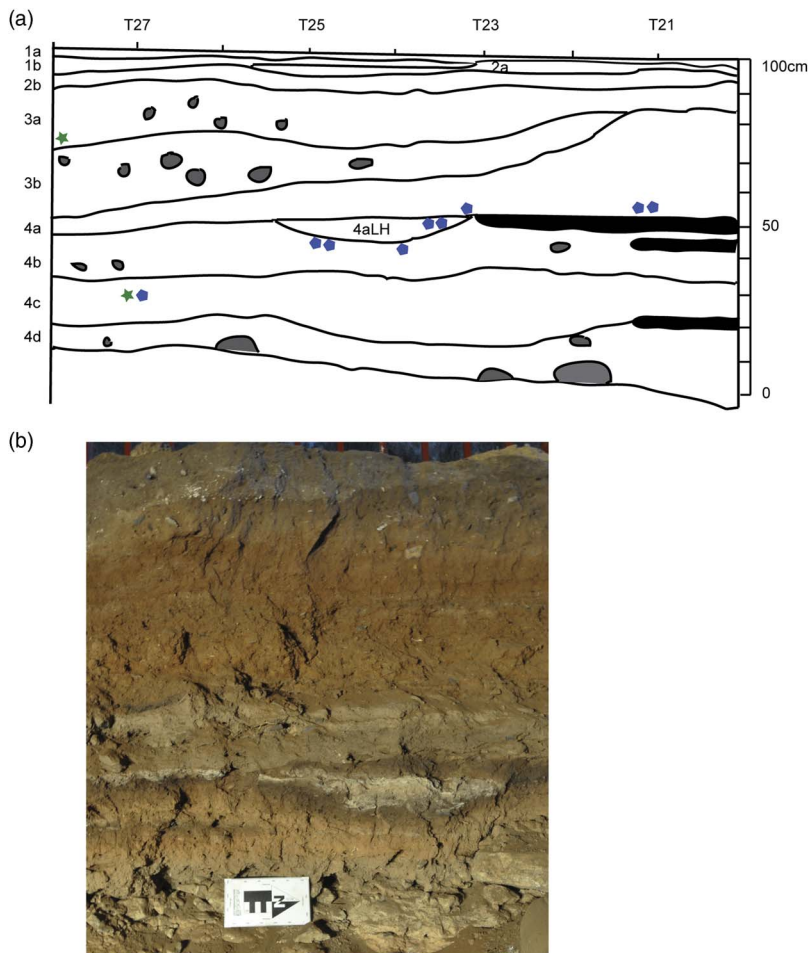


Figure 2 (a) Location of new ^{14}C samples, projected on the schematic section drawing of the T-line after Thackeray (1981). Blue polygons are charcoal samples, and green star shapes are (from lower to higher levels) the *Antidorcas bondi* specimen and the *Damaliscus pygargus phillipsi* specimen, respectively. 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.

dominant (Thackeray 1981; Humphrey and Thackeray 1983; Beaumont 1990; Beaumont and Vogel 2006). Other finds recovered from the Wilton strata include lumps of ocher and specularite, wood and bone artifacts, 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 hematite 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).

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 artifact form, scraper morphology, raw material use, tool types, and associated non-lithic artifacts (Humphrey and Thackeray 1983). The Kuruman

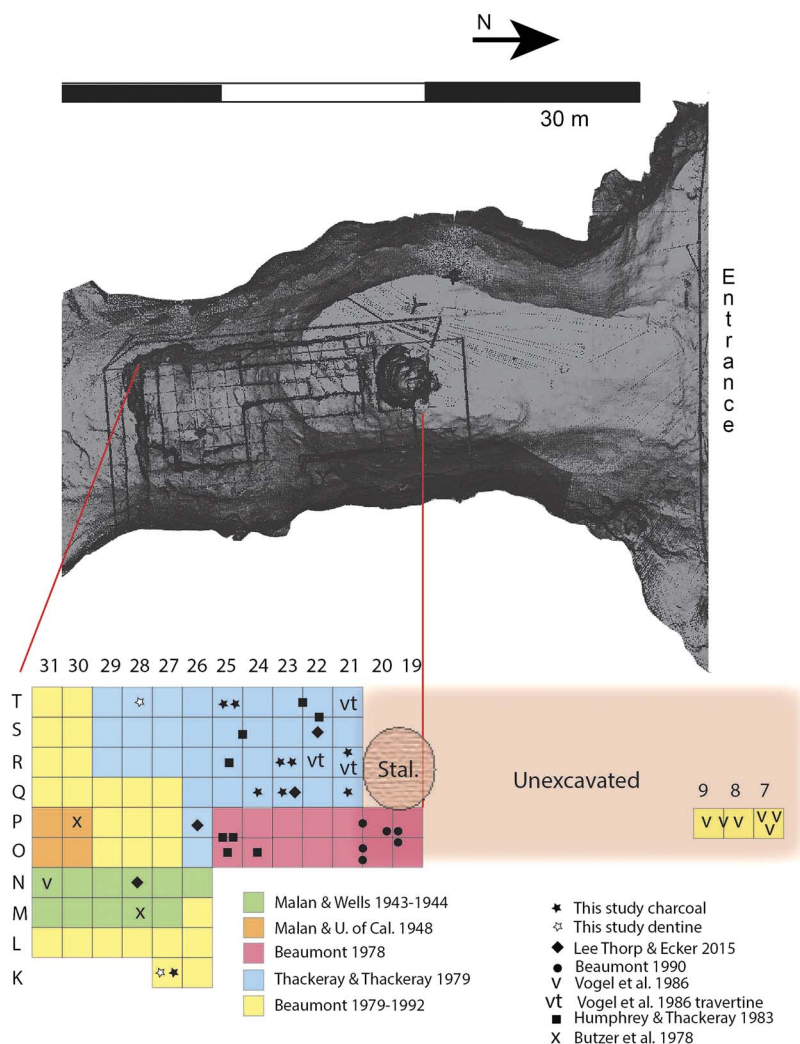


Figure 3 Location of ^{14}C samples in Wonderwerk Cave Excavation 1 and in the entrance trench. Colors indicate the excavator and symbols indicate the radiocarbon sample by referenced publication respectively.

industry is dominated by scrapers with a few blades and retouched adzes and lacks backed artifacts. The dominant raw material is local banded ironstone and dolomite (Thackeray 1981). Engraved dolomite and hematite 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

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 and personal communication) and Thackeray (Thackeray 1981, 1984) excavations are given.

Stratum	Lithic technology (dominant tool type/raw material)	Beaumont spits	Thackeray spits
2b, 3a	Ceramic LSA	3UP, 3MID	2b, 3aI, 3aII
3b	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

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 30 ^{14}C 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, 1979b; 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 that indicate taphonomic factors which may have influenced the depositional record and hence the samples used for dating, as follows:

- Humphreys and Thackeray (1983) note that the sediments comprising Strata 2b–3b were very similar in composition and color such that the interfaces between these strata were 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

Table 2 Raw and modeled ¹⁴C 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 (1) the stratigraphic position in the entrance trench cannot be correlated to the main excavation area, or (2) the samples 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.

Lab code	¹⁴ C measurement		Stratum	Square	Material	Reference	δ ¹³ C (‰)	Modeled date range (cal BP)	Posterior outlier probability (%)
	Date (¹⁴ C yr BP)	Uncertainty (1σ)							
Pta-2779	1210	50	2b	T22/23	Charcoal	Humphrey and 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 and 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 and 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 and 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 and Thackeray 1983	-23.3	8386–8045	4
Pta-2546	9130	90	4dI	O19/22	Charcoal	Beaumont 1990	-23.2	11,800–10,191	80
Pta-2852	9760	120	5a	O24	Charcoal	Humphrey and Thackeray 1983	-23.8	12,190–11,439	30
Pta-2790	10,000	70	4dII	O25	Charcoal	Humphrey and Thackeray 1983	-22.7	11,711–11,270	1
Pta-6884	10,080	100	5a	N28	Charcoal	Lee-Thorp and Ecker 2015	-21.8	12,088–11,461	3
Pta-6872	10,120	120	4dII	P26	Charcoal	Lee-Thorp and Ecker 2015	-23.3	11,774–11,271	2
Pta-6871	10,120	100	4dII	Q23	Charcoal	Lee-Thorp and Ecker 2015	-23.5	11,780–11,288	3
Pta-2786	10,200	90	4dII	O25/P25	Charcoal	Humphrey and Thackeray 1983	-22.6	11,843–11,308	7
Unmodeled dates									
Pta-3426 ¹	2310	60	3a	P7	Charcoal	Vogel et al. 1986	-24.4		
Pta-2139 ²	3060	40	3	P30	OES	Butzer et al. 1978	-8.8		
Pta-3427 ¹	5800	70	3a	P8	Charcoal	Vogel et al. 1986	-22.8		
Pta-2140 ²	5930	50	4c	M28	OES	Butzer et al. 1978	-7.7		
Pta-3425 ¹	6840	80	4cI	P7	Charcoal	Vogel et al. 1986	-24.0		
Pta-3366 ¹	8000	80	4cII	P9	OES	Vogel et al. 1986	-8.0		
Pta-3439 ¹	9030	90	5a	P7/9	OES	Vogel et al. 1986	-8.0		
Pta-2141 ²	12,380	100	5	N31	OES	Vogel et al. 1986	-10.0		
Pta-3441 ¹	12,400	180	5	P7	OES	Vogel et al. 1986	-9.0		

Table 2 (Continued)

Lab code	¹⁴ C measurement		Stratum	Square	Material	Reference	$\delta^{13}\text{C}$ (‰)	Modeled date range (cal BP)	Posterior outlier probability (%)
	Date (¹⁴ C yr BP)	Uncertainty (1 σ)							
Pta-2723 ³	2350	50	Between 3a and 4a	R22	Travertine	Vogel et al. 1986	-0.6		
Pta-2727 ³	2260	50	4a	T21	Travertine	Vogel et al. 1986	0.2		
Pta-2728 ³	3360	60	4c	21	Travertine	Vogel et al. 1986	-1.0		
Pta-2729 ³	2930	60	4d	R21	Travertine	Vogel et al. 1986	-0.9		
New dates (charcoal samples)									
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

stable isotope isotopes, pointing to a high degree of stratigraphic integrity (Horwitz and Chazan 2015).

Hypothetically, Wonderwerk has the densest ^{14}C 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 ^{14}C 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 the following (see also Figure 3):

- Six dates on charcoal from Beaumont's 1978 excavation (Vogel et al. 1986; Beaumont 1990).
- Seven dates from the 1979 excavations of A Thackeray and JF 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 JF 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 Beaumont's 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 ^{14}C 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 (Blaauw 2010) with the latest adjustments for the Southern Hemisphere, in order to locate the pollen sequence. They calculated the average accumulation rate for this sequence as nearly 0.9 cm/100 yr but noted reduced accumulation rates during at least two periods—in Strata 5 and 4dII, ca. 11,000–9000 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 ^{14}C dates were particularly sparse for this phase, the new dating program focused on this period.

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 although they do not occur close to Wonderwerk today, they have the same climate tolerance and could feasibly have grown here in the past (Marion Bamford personal communication 2017).

Figure 2 shows all new ^{14}C samples in stratigraphic context. The selected samples are horizontally close to the majority of former ^{14}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 ^{14}C 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 ^{14}C dates to integrate the ^{14}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* (see supplementary material). 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 (see supplementary material) 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 ^{14}C date ranges are presented at 95.4% probability (approximately equivalent to 2σ uncertainty) and the ages are given in cal BP.

RESULTS

The results of the new ^{14}C 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}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.

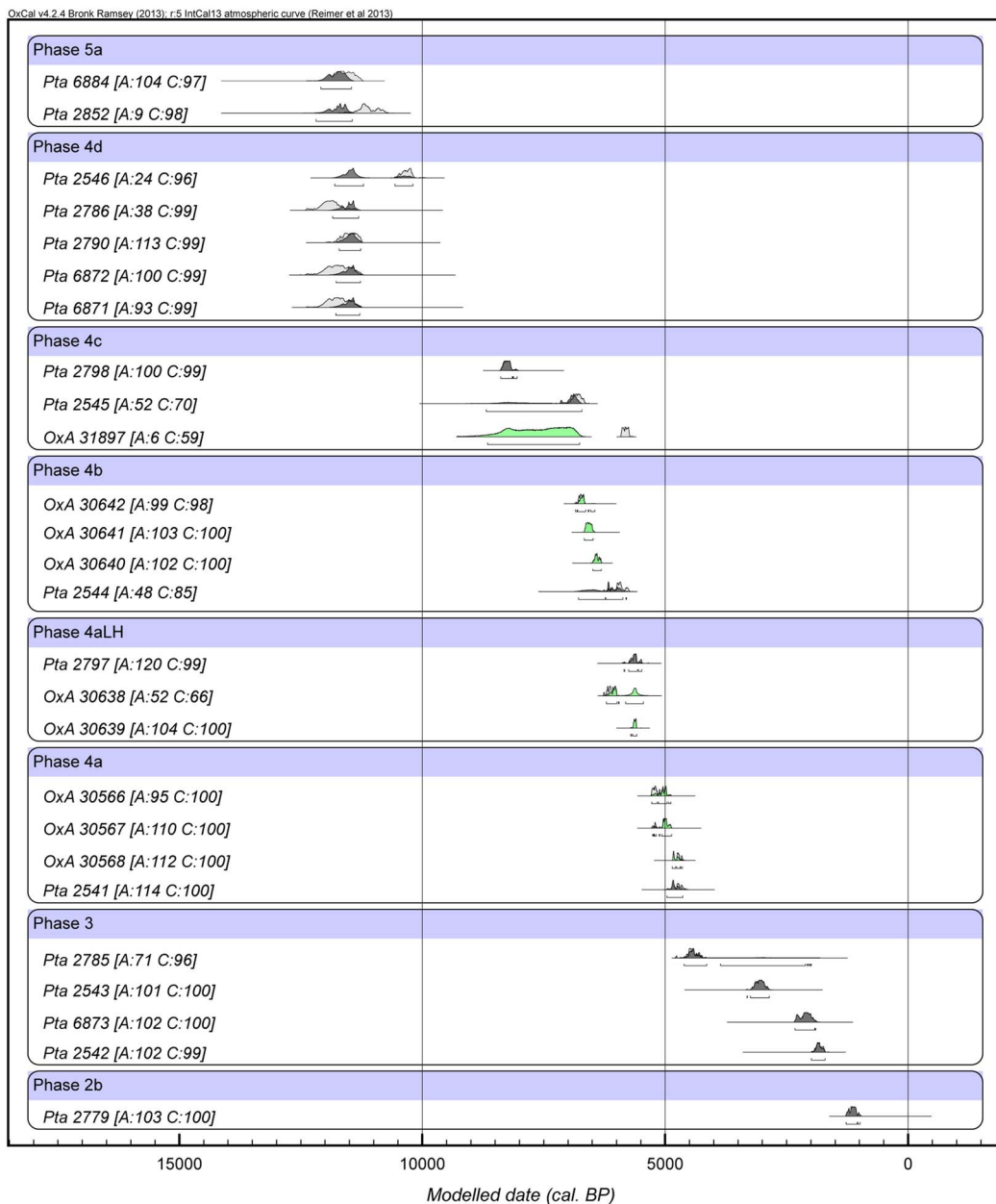


Figure 4 Plot of modeled dates from the OxCal program, ordered from oldest to youngest dates, with the individual agreement indices (A) and the convergence (C) given in brackets next to the sample number. The unmodeled age distributions are indicated in light shading and the modeled range in dark shading.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

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

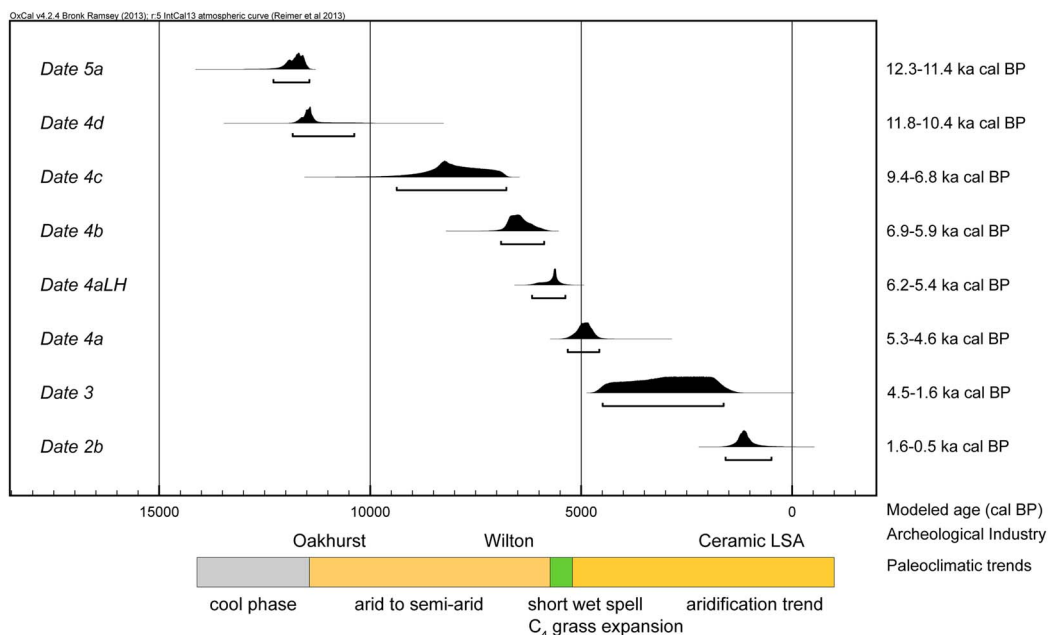


Figure 5 Summary statistics of the strata ages, as a result of the Bayesian model *Date*-function. The rounded age spans are given on the right-hand side of the graph. The figure includes the archaeological industries and general paleoclimatic trends from environmental proxies at Wonderwerk Cave (Avery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

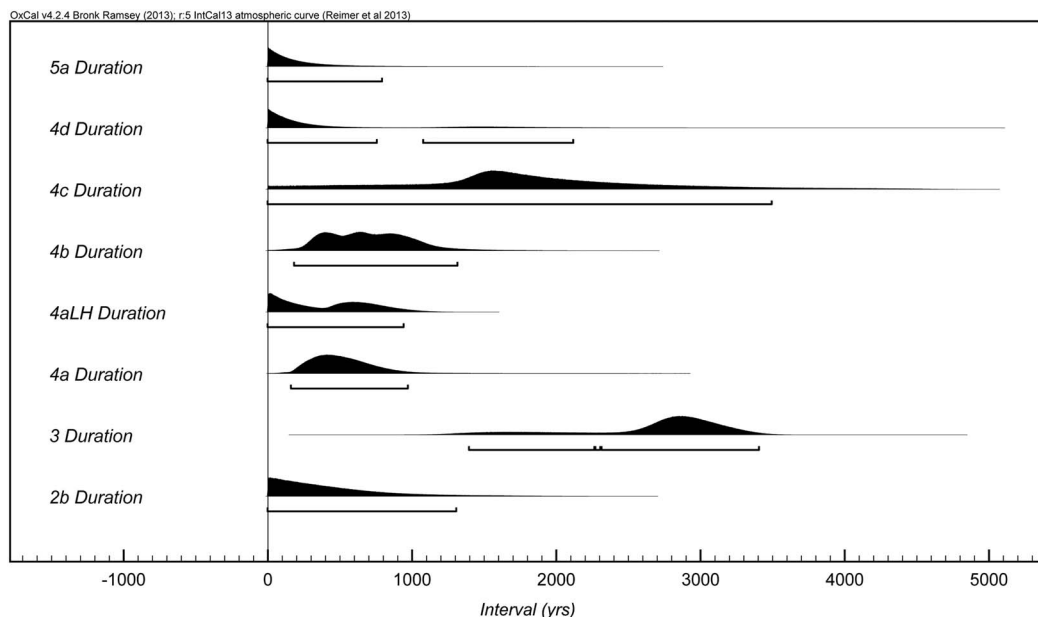


Figure 6 Results of modeled duration of strata in Excavation 1 using the *Difference* function.

short spans of less than 500 yr 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

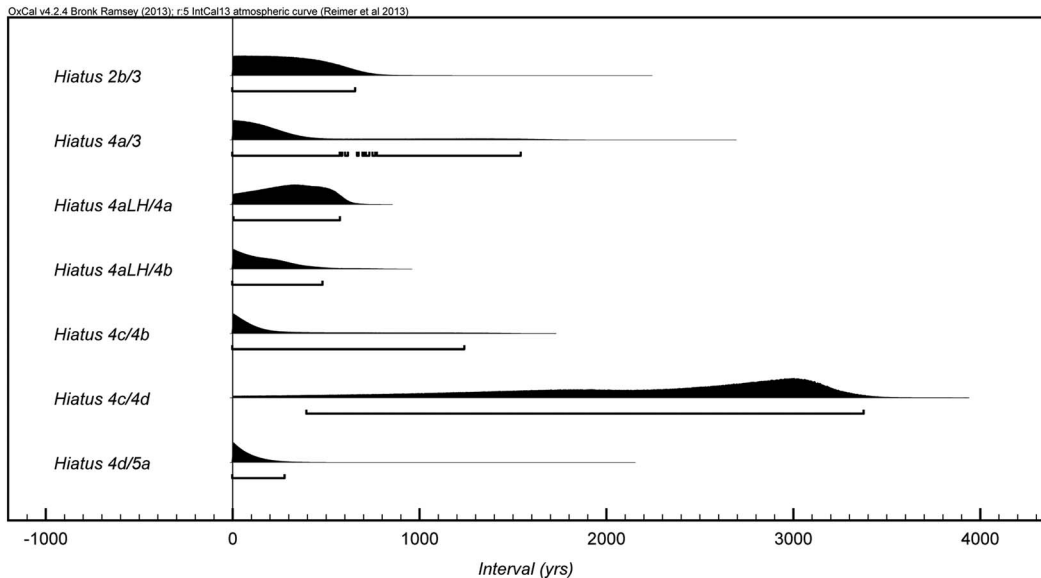


Figure 7 Results of modeled intervals of hiatus length between strata in Excavation 1 using the *Difference* function.

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 yr. Stratum 3, although containing an abundance of archaeological material, shows the longest duration (up to over 3000 yr). 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 yr. 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 yr cal BP to less than 1000 yr cal BP. It allows the construction of a chronological sequence with statistically sound

estimates for all strata compared to calibration of the ^{14}C dates alone. Stratum 4d contains the earliest Holocene industry, the Kuruman, dated to between 11.8 and 10.4 ka 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 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) begin before 9 ka 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 Kuruman 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 (394–3376 yr; 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 5.4 ka and 6.2 ka cal BP. This cultural shift is coincident with a phase of wetter climate and maximum C_4 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 4.5 ka cal BP and uppermost as young as 1.6 ka 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_3 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 10.6 ka cal BP date (Pta-5599; recalibrated 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 10.6–8.5 ka 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), and would seem consistent with a northern origin followed by a subsequent southern dispersion. However, re-analysis of ^{14}C 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 around 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 shards. However, these authors did not distinguish between ^{14}C 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 ± 50) and sample Pta-6873 (2120 ± 80), 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 Sadr and Sampson 2006; Orton et al. 2013; Jerardino et al. 2014).

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 yr 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 ± 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 ± 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 ± 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 ± 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 ^{14}C 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 subcontinent would settle the question of latest appearance with confidence, but adequate preservation of bone collagen remains a challenge in arid regions.

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 ^{14}C dates with stratigraphic information. The updated modeled chronology for Wonderwerk Cave provides more robust age estimates for the technological and paleo-environmental record of the Holocene in Excavation 1. The new ^{14}C 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 yr, between 6.2 ka and 5.4 ka 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 ^{14}C 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 ^{14}C 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.

ACKNOWLEDGMENTS

We are grateful to Professor Marion Bamford (University of Witwatersrand) for identification of the charcoal samples. We thank Fiona Brock, Michael Dee, and Richard Staff for their support and guidance with pretreatment of ^{14}C samples and the use of OxCal. David Morris (McGregor Museum) gave permission for sampling and samples were exported with SAHRA permit CASEID6245. Funding was provided by an ORADS grant (NF/2014/1/14) to JLT and ME. This work is part of a DPhil thesis by ME, for which funding was provided by the German Academic Exchange Service (DAAD). Research at Wonderwerk Cave is funded by grants from

the Canadian Social Science and Humanities Research Council to MC. We thank three anonymous reviewers for comments that greatly improved the manuscript.

This paper is in memory of Peter Beaumont, who passed away in August 2016. Our research at Wonderwerk Cave builds on work undertaken by him at the site.

SUPPLEMENTARY MATERIAL

To view supplementary material for this article, please visit <https://doi.org/10.1017/RDC.2017.55>

REFERENCES

- Avery DM. 1981. Holocene microfaunal faunas from the northern Cape Province, South Africa. *South African Journal of Science* 77:265–73.
- Bamford M. 2015. Charcoal from pre-Holocene stratum 5, Wonderwerk Cave, South Africa. Changing climates, ecosystems and environments within arid Southern Africa and adjoining regions. *Palaeoecology of Africa* 33:153–74.
- Beaumont PB. 1990. Wonderwerk Cave. In: Beaumont PB, Morris D, editors. *Guide to the Archaeological Sites in the Northern Cape*. Kimberley, South Africa: McGregor Museum. p 101–34.
- Beaumont PB. 2004. Wonderwerk Cave. In: Morris D, Beaumont PB, editors. *Archaeology in the Northern Cape: Some Key Sites*. Kimberley: McGregor Museum. p 31–6.
- Beaumont PB, Vogel JC. 2006. On a timescale for the past million years of human history in central South Africa. *South African Journal of Science* 102:217–28.
- Beaumont PB, Vogel JC. 1984. Spatial patterning of the ceramic Later Stone Age in the northern Cape province, South Africa. *Frontiers: Southern African Archaeology Today* 80:95.
- Blaauw M. 2010. Methods and code for “classical” age-modelling of radiocarbon sequences. *Quaternary Geochronology* 5(5):512–8.
- Bousman CB, Mauldin R, Zoppi U, Higham T, Scott L, Brink J. 2016. The quest for evidence of domestic stock at Blydefontein Rock Shelter. *Southern African Humanities* 28:39–60.
- Bradfield J, Thackeray F, Morris D. 2014. An experimental investigation in to the origin of incised lines on a 4000-year-old engraving from Wonderwerk Cave, Northern Cape Province. *South African Archaeological Bulletin* 69(199): 72–9.
- Brink JS, Lee-Thorp J. 1992. The feeding niche of an extinct springbok, *Antidorcas bondi* (Antilopini, Bovidae), and its palaeoenvironmental meaning. *South African Journal of Science* 88 (4):227–9.
- Brock F, Higham T, Ditchfield P, Ramsey CB. 2010. Current pretreatment methods for AMS radiocarbon dating at the Oxford Radiocarbon Accelerator Unit (ORAU). *Radiocarbon* 52(1): 103–12.
- Bronk Ramsey C. 2009a. Bayesian analysis of radiocarbon dates. *Radiocarbon* 51(1):337–60.
- Bronk Ramsey C. 2009b. Dealing with outliers and offsets in radiocarbon dating. *Radiocarbon* 51(3): 1023–45.
- Bronk Ramsey C. 2013. OxCal 4.2. URL: <<http://c14.arch.ox.ac.uk>>.
- Bronk Ramsey C, Higham T, Leach P. 2004. Towards high-precision AMS: progress and limitations. *Radiocarbon* 46(1):17–24.
- Bronk Ramsey C, Dee M, Lee S, Nakagawa T, Staff RA. 2010. Developments in the calibration and modeling of radiocarbon dates. *Radiocarbon* 52(3):953–61.
- Brook GA, Scott L, Railsback LB, Goddard EA. 2010. A 35ka pollen and isotope record of environmental change along the southern margin of the Kalahari from a stalagmite and animal dung deposits in Wonderwerk Cave, South Africa. *Journal of Arid Environments* 74:870–84.
- Brown AJ, Verhagen BT. 1985. Two *Antidorcas bondi* individuals from the Late Stone Age site of Kruger Cave 35/83, Olifantsnek, Rustenburg District, South Africa. *South African Journal of Science* 81(2).
- Butzer KW, Stuckenrath R, Bruzewicz AJ, Helgren DM. 1978. Late Cenozoic paleoclimates of the Ghaap Escarpment, Kalahari margin, South Africa. *Quaternary Research* 10:310–39.
- Butzer KW, Fock GJ, Scott L, Stuckenrath R. 1979a. Dating and context of rock engravings in Southern Africa. *Science* 203:1201–14.
- Butzer KW, Stuckenrath R, Vogel JC. 1979b. The geo-archaeological sequence of Wonderwerk Cave, South Africa. *Society of Africanist Archaeologists Meeting Calgary Abstracts*.
- Chazan M. 2015. Technological trends in the Acheulean of Wonderwerk Cave, South Africa. *African Archaeological Review* 32:701–28.
- Cooke CK. 1979. *Excavations at Diana's Vow Rock Shelter, Makoni District, Zimbabwe, Rhodesia*. National Museums and Monuments.
- Deacon J. 1984a. *The Later Stone Age of Southernmost Africa*. British Archaeological Reports 213. Oxford: Archaeopress.
- Deacon J. 1984b. Later Stone Age people and their descendants in southern Africa. In: Klein RG,

- editor. *Southern African Prehistory and Palaeoenvironments*. Rotterdam: Balkema. p 221–328.
- Dee M, Bronk Ramsey C. 2000. Refinement of graphite target production at ORAU. *Nuclear Instruments and Methods in Physics Research B* 172(1):449–53.
- Ecker M. 2016. Two million years of environmental change: a case study from Wonderwerk Cave, Northern Cape, South Africa [PhD thesis]. Oxford: University of Oxford.
- Faith JT. 2014. Late Pleistocene and Holocene mammal extinctions on continental Africa. *Earth-Science Reviews* 128:105–21.
- Hogg AG, Hua Q, Blackwell PG, Niu M, Buck CE, Guilderson TP, Heaton TJ, Palmer JG, Reimer PJ, Reimer RW, Turney CSM, Zimmerman SRH. 2013. SHCal13 Southern Hemisphere calibration, 0–50,000 years cal. BP. *Radiocarbon* 55(4):1889–903.
- Horwitz LK, Chazan M. 2015. Past and present at Wonderwerk Cave (Northern Cape Province, South Africa). *African Archaeological Review* 32(4):595–612.
- Humphreys AJB, Thackeray AI. 1983. Ghaap and Gariep. Later Stone Age studies in the Northern Cape. *South African Archaeological Society Monograph* 2.
- Inskeep RR. 1987. Nelson Bay Cave, Cape Province, South Africa. The Holocene Levels. *British Archaeological Reports International Series* 357:266–70.
- Jerardino A, Fort J, Isern N, Rondelli B. 2014. Cultural diffusion was the main driving mechanism of the Neolithic transition in southern Africa. *PLoS ONE* 9(12):e113672. DOI:10.1371/journal.pone.0113672.
- Klein RG. 1984. Later Stone Age faunal samples from Heuningneskrans Shelter (Transvaal) and Leopard's Hill Cave (Zambia). *South African Archaeological Bulletin* 39:109–16.
- Levine A, Stanish C. 2014. The importance of multiple ¹⁴C dates from significant archaeological contexts. *Journal of Archaeological Method and Theory* 21:824–36.
- Lee-Thorp JA, Ecker M. 2015. Holocene environmental change at Wonderwerk Cave, South Africa: Insights from stable light isotopes in ostrich egg shell. *African Archaeological Review* 32(4):793–811.
- Loftus E, Sealy J, Lee-Thorp J. 2016. New radiocarbon dates and Bayesian models for Nelson Bay Cave and Byneskranskop 1: implications for the South African Later Stone Age sequence. *Radiocarbon* 58(2):365–81.
- Lombard M, Wadley L, Deacon J, Wurz S, Parsons I, Mohapi M, Swart J, Mitchell P. 2012. South African and Lesotho Stone Age sequence updated (I). *South African Archaeological Bulletin* 67:123–44.
- Macken AC, Staff RA, Reed EH. 2013. Bayesian age-depth modelling of Late Quaternary deposits from Wet and Blanche Caves, Naracoorte, South Australia: a framework for comparative faunal analyses. *Quaternary Geochronology* 17:26–43.
- Mitchell P. 2013. Southern African hunter-gatherers of the last 25,000 Years. In: Mitchell P, Lane PJ, editors. *The Oxford Handbook of African Archaeology*. Oxford: Oxford University Press.
- Mitchell P, Barham LS. 2008. *The First Africans: African Archaeology from the Earliest Toolmakers to Most Recent Foragers*. Cambridge: Cambridge University Press.
- Orlando L, Metcalf JL, Alberdi MT, Orlando L, Metcalf JL, Alberdi MT, Telles-Antunes M, Bonjean D, Otte M, Martin F, Eisenmann V, Mashkour M, Morello F, Prado JL. 2009. Revising the recent evolutionary history of equids using ancient DNA. *PNAS* 106(51):21754–9.
- Orton J. 2012. Late Holocene archaeology in Namaqualand, South Africa: hunter-gatherers and herders in a semi-arid environment [DPhil thesis]. Oxford: University of Oxford.
- Orton J, Mitchell P, Klein RG, Steele T, Horsburgh KA. 2013. An early date for cattle from Namaqualand, South Africa: implications for the origins of herding in southern Africa. *Antiquity* 87:108–20.
- Parkington J. 2006. *Shorelines, Strandlopers and Shell Middens*. Cape Town: Krakadouw Trust.
- Parsons I. 2006. Later Stone Age socio-economic variability during the last 2000 years in the Northern Cape, South Africa [PhD thesis]. Cambridge: University of Cambridge.
- Plug I, Engela R. 1992. The macrofaunal remains from recent excavations at Rose Cottage Cave, Orange Free State. *The South African Archaeological Bulletin* 47(155):16–25.
- Rutherford MC. 1997. Categorization of biomes. In: Cowling RM, Richardson DM, editors. *Vegetation of Southern Africa*. Cambridge: Cambridge University Press. p 91–8.
- Sadr K, Sampson CG. 2006. Through thick and thin: early pottery in southern Africa. *Journal of African Archaeology* 4(2):235–52.
- Sampson CG. 1974. *The Stone Age Archaeology of Southern Africa*. New York: Academic Press.
- Sampson G. 2010. Chronology and dynamics of Later Stone Age herders in the upper Seacow River valley, South Africa. *Journal of Arid Environments* 74:842–8.
- Scott L, Lee-Thorp JA. 2004. Holocene climatic trends and rhythms in southern Africa. In: Batterbee R, Gasse F, editors. *Past Climatic Variability through Europe and Africa*. Netherlands: Springer. p 691–9.
- Scott L, Thackeray JF. 2015. Palynology of Holocene deposits in Excavation 1 at Wonderwerk Cave, Northern Cape (South Africa). *African Archaeological Review* 32(4):839–55.
- Thackeray AI. 1981. The Holocene cultural sequence in the northern Cape Province, South Africa [PhD thesis]. New Haven (CT): Yale University.

- Thackeray JF. 1984. Man, animals and extinctions: the analysis of Holocene faunal remains from Wonderwerk Cave, South Africa [PhD thesis]. New Haven (CT): Yale University.
- Thackeray JF. 2013. The principle of “sympathetic magic” in the context of hunting, trance and Southern African rock art. *The Digging Stick* 30(1):1–4.
- Thackeray JF. 2015. Faunal remains from Holocene deposits, Excavation 1, Wonderwerk Cave, South Africa. *African Archaeological Review* 32(4):729–50.
- Thackeray JF, Lee-Thorp JA. 1992. Isotopic analysis of equid teeth from Wonderwerk Cave, northern Cape Province, South Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology* 99:141–50.
- Thackeray AI, Thackeray JF, Beaumont PB, Vogel JC. 1981. Dated rock engravings from Wonderwerk Cave, South Africa. *Science* 214:64–7.
- van Zinderen Bakker EM. 1982. Pollen analytical studies of the Wonderwerk Cave, South Africa. *Pollen et Spores* 24:235–50.
- Vogel JC, Fuls A, Visser E. 1986. Pretoria radiocarbon dates III. *Radiocarbon* 28(3): 1133–72.
- Wadley L. 1987. Later Stone Age hunters and gatherers of the southern Transvaal: social and ecological interpretation. *British Archaeological Reports* 25.
- Wadley L. 1992. Rose Cottage Cave: the Later Stone Age levels with European and Iron Age artifacts. *The South African Archaeological Bulletin*. 8–12.
- Wadley L. 2000. The Wilton and pre-ceramic post-classic Wilton industries at Rose Cottage Cave and their context in the South African sequence. *The South African Archaeological Bulletin*. 90–106.
- Wendt WE. 1976. “Art Mobilier” from the Apollo 11 Cave, South West Africa: Africa’s oldest dated works of art. *The South African Archaeological Bulletin* 31(121/122):5–11.