**Holocene environmental change at Wonderwerk Cave, South Africa: Insights from
stable light isotopes in ostrich egg shell**

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Running head: Postglacial environmental shifts at Wonderwerk Cave

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Country and region: Northern Cape, South Africa

1 Abstract

2 Sparse records and discontinuous and/or poor chronologically resolved data hinder
3 construction of reliable palaeoenvironmental sequences for the interior of South Africa.
4 Wonderwerk Cave occupies a central position in the interior where the Kalahari
5 Thornveld/dry woodland vegetation and generally arid conditions are expected to be sensitive
6 to subtle past climate perturbations, and evidence from this site has been key to forming views
7 on environmental change in the interior. A compilation of existing data including principal
8 components analysis of pollen suggested broad trends ranging from variably arid and open in
9 the early Holocene to moister conditions from about 7500 to 5000 years, followed by aridity
10 thereafter. In an effort to better establish the nature and timing of shifts from the late
11 Pleistocene sequence onwards we analyse carbon and oxygen isotope ratios in a robust sample
12 of ostrich eggshell from Wonderwerk Cave. The resulting data are then placed within a
13 temporal framework established by Bayesian modeling of existing radiocarbon dates, and
14 compared against shifts in the Wonderwerk cultural sequence. Several shifts and trends in
15 aridity include an arid to moist shift in Layer 4b near 6000 years coincident with a cultural
16 shift within the Wilton assemblage, and thereafter an aridification trend culminating at about
17 2000 years with the appearance of the Ceramic LSA.

18 Keywords: Aridity, radiocarbon dates, Bayesian model, C₃ vegetation, C₄ grasses

19 Résumé

20 Des données isolées, discontinues, voire mal datées, gênent l'élaboration d'une séquence
21 environnementale fiable pour le centre de l'Afrique du Sud. La grotte de Wonderwerk est
22 située au centre du pays, là où le paysage boisé et sec du Kalahari Thornveld et ses conditions
23 généralement arides, sont susceptibles de réagir aux faibles fluctuations climatiques du passé.
24 Cette grotte est donc un site clé pour la compréhension des changements environnementaux
25 du centre de l'Afrique du Sud. Une compilation de données existantes comprenant l'analyse

1 en composantes principales de pollen suggère des changements allant d'une aridité variable
2 dans un paysage ouvert durant l'Holocène ancien à des conditions plus humides de 7500 à
3 5000 ans, suivit de conditions à nouveau plus arides. Afin d'établir la nature et la chronologie
4 des variations environnementales dès le Pléistocène supérieur, nous avons analysé les
5 variations isotopiques de l'oxygène et du carbone à partir d'un ensemble de coquilles d'œufs
6 d'autruches échantillonnées dans la grotte de Wonderwerk. Les données obtenues ont ensuite
7 été placées dans un cadre temporel établi par modélisation bayésienne de datations au carbone
8 14 existantes, et comparées aux variations observées dans la séquence culturelle de
9 Wonderwerk. Plusieurs changements climatiques ont été observés, parmi lesquels un
10 changement aride-humide au sein de la strate 4b datant d'il y a environ 6000 ans, qui
11 correspond à un changement au sein de l'assemblage datant du Wilton. Ce changement est
12 suivi d'un retour vers des conditions arides qui culminent il y a environ 2000 ans, à
13 l'apparition du Néolithique à céramique.

1 Introduction

One of the major challenges in reconstructing past climates and environments is the synthesis of localised records of change into coherent, regional signals of climate and vegetation. This is particularly the case in arid and semi-arid regions where problems lie in the scarcity of sites often due to the poor preservation occurring in arid environments, frequently poor temporal and spatial resolution of the records themselves, as well as in the identification of relevant, environmentally sensitive proxies. This is certainly the case for the interior of southern Africa where records are mostly too sparse and poorly temporally constrained to fully understand the underlying dynamics, even in the Holocene. Hence the amplitude and drivers of changes in southern Africa are not well understood. For instance, global events such as the Younger Dryas or the Holocene Climatic Optimum may well be reflected in the southern African record but the interpretation of temporal shifts remains uncertain (Burrough and Thomas 2013; Chase et al. 2010; Scott et al. 1995; Scott and Lee-Thorp 2004). The problems associated with identification and interpretation of multiple proxies, coupled with poor temporal control, likewise means that the environmental context of cultural shifts can be difficult to establish, or to interpret.

A compilation of pollen records and their Principal Component Analysis (PCA) indices for moisture availability and temperature shows disparate curves across the central interior regions of southern Africa (Scott et al. 2012). According to these authors, at least some of the contradictions may be due to localised differences in trapping environments and the pervasive problem of low temporal resolution, as well as high proportions of undiagnostic local wetland pollen and non-uniform interpretation and presentation of pollen data (Scott et al. 2012). An earlier compilation based on a broader range of proxies (pollen, microfauna, isotopes from fauna) suggested broad trends from variable aridity in the late Pleistocene/early Holocene, a moister period somewhere between 7.5 and 5Ka, and general aridification thereafter (Scott and Lee-Thorp, 2004). These studies are consistent in recognising that tropical C₄ grasses were present throughout, showing that a summer rainfall regime dominated throughout the Holocene. However, a recent review of geo- and bio-proxy records for central southern Africa, including lakes and pans, suggests greater hydrological variability in the early- to mid-Holocene compared to greater stability in the last few millennia (Burrough and Thomas 2013).

Stable isotope data form a pillar of many palaeoclimate and palaeoenvironmental sequences, but published records in the region are few. Isotopic records from speleothems in the southern

1 African interior (eg. Brook et al. 2010; Holmgren et al. 2003; Lee-Thorp et al. 2001) have the
2 most secure chronologies and can indicate high resolution variability in hydrology and floral
3 composition, but they are nevertheless rare, their interpretation is debated, and they rarely
4 have secure associations with cultural records. Biominerals (bones, tooth enamel and shells)
5 from archaeological sites are an abundant resource for stable isotope analyses, but excepting
6 for the Cradle of Humankind and Makapansgat hominin sites, this avenue has been explored
7 for just a few interior sites (eg. Bousman 2005; Johnson et al. 1997; Lee-Thorp and Beaumont
8 1995; Smith et al. 2002; Thackeray and Lee-Thorp 1992). Notwithstanding their scarcity,
9 available isotopic records based on faunal bone collagen or tooth enamel have suggested
10 significant fluctuations in hydrology and in the proportions of C₃ and C₄ plants, most notably
11 in the late Pleistocene. In addition to an existing stable isotope record of a limited number of
12 grazers from Wonderwerk (Thackeray and Lee-Thorp 1992), two isotope proxy records exist
13 for nearby Equus Cave, based on faunal enamel (Lee-Thorp and Beaumont 1995), and ostrich
14 eggshell (hereafter OES) (Johnson et al. (1997) respectively. Marked variability in moisture
15 availability from the Late Pleistocene through the Holocene was inferred from ¹⁵N/¹⁴N
16 fluctuations in the organic fraction in Equus Cave OES (Johnson et al. 1997). Since
17 radiocarbon calibrated Isoleucine (Ile) epimerization ages for the OES at Equus Cave show
18 strong evidence for vertical movement of ostrich eggshell fragments (Johnson et al. (1997),
19 ages of the OES fragments were established by means of the Ile data rather than according to
20 stratigraphy, with the result that data is sparsely spread compared to the potential in a
21 stratigraphically controlled site. In general, isotope studies based on OES are few, with the
22 exception of the aforementioned Equus Cave data (Johnson et al. 1997) and a shorter
23 Blydefontein Rock Shelter sequence (Bousman 2005) in the interior, and on the west coast, a
24 sequence for Elands Bay Cave (Lee-Thorp and Talma 2000).

25 The upper strata of the deep Wonderwerk Cave sequence provide a well-dated Holocene
26 record in Excavation Area 1, in which abundant cultural, faunal and ostrich eggshell material
27 accumulated. So far, isotope determinations on the large herbivore grazing fauna at
28 Wonderwerk suggested that C₄ grass dominated throughout the Holocene, consistent with the
29 new interpretations of the pollen data (Scott and Thackeray, this volume). A nitrogen isotope-
30 derived mean annual rainfall index was interpreted as suggesting lower moisture in the mid-
31 Holocene (Thackeray and Lee-Thorp 1992), which is inconsistent with the interpretations of
32 Scott and Thackeray (this volume), who posit a moister episode around 5000 years cal. BP.
33 However the equid sample numbers were very small and very sparsely spread across the
34 entire sequence.

1 In this study we examined a dense record of carbon and oxygen isotopes in OES from the late
2 Glacial period at the end of the Pleistocene and through the Holocene sequence, spanning
3 about 12 000 to the last few hundred years in the site. We recalibrated the available
4 radiocarbon dates for this timespan, including 4 previously unreported dates, using Bayesian
5 models (Bronk Ramsey 2009). The isotopic environmental results are assessed within this
6 chronological framework to provide higher resolution palaeoclimate and vegetation context
7 for the region, and for cultural shifts within the site. In particular we aim to identify whether
8 shifts in stone tool technology at Wonderwerk Cave were coincident with changes in
9 environmental conditions.

10 **Background**

11 Wonderwerk Cave and its environmental context

12 Wonderwerk Cave falls in the general savanna biome as defined by Rutherford and Westphal
13 (1986), where the vegetation is described as dry woodland or Kalahari Thornveld (Acocks
14 1953). Today this region is semi-arid to arid with mean annual rainfall of ca. 480 mm/a and
15 high inter-annual variability (standard deviation 120 mm/a, coefficient of variation 0.25)
16 (South Africa Rain Atlas). Most rainfall occurs in summer. As elsewhere in the savanna
17 biome, most grasses use the C₄ photosynthetic pathway (Vogel et al, 1978), while the tree,
18 shrub and herbaceous cover – of varying density - use C₃ photosynthesis. C₃ plants
19 discriminate more strongly against ¹³C than do C₄ plants, which first concentrate CO₂, so that
20 their δ¹³C values are distinct (Smith and Epstein 1971). Plants following a third pathway,
21 Crassulacean Acid Metabolism (CAM, consist mainly of succulents whose δ¹³C values
22 overlap with both the major groups depending on conditions and whether they are obligate or
23 non-obligate CAM (Mooney et al. 1977), but they are rare in this region.

24 Models have suggested that rainfall seasonality shifted in the past in concert with alternating
25 wet and dry episodes (Cockcroft et al, 1987). They have their roots in van Zinderen Bakker's
26 suggestion that climate zones shifted equatorwards in glacial or cold periods (van Zinderen
27 Bakker 1967, 1982). Cockcroft et al. (1987) observed that meteorological records for wet and
28 dry episodes in the summer rainfall interior are associated with shifts in zonal circulation.
29 During moister episodes, the limb of the African Walker cell lies over tropical Africa, the
30 Intertropical Convergence Zone (ITCZ) strengthens and storm tracks shift polewards, while in
31 drier episodes the reverse occurs - the ITCZ weakens and storm tracks move north. In the
32 latter situation the summer rainfall region is drier but with greater penetration of winter

1 storms (Tyson 1986; Cockcroft et al. 1987). Expanding from this situation to deeper time
2 periods, the model predicts that in areas such as the Northern Cape dry, cool conditions
3 should be accompanied by proportionally more rain occurring in winter. Thus fluctuations in
4 aridity might be accompanied by shifts in the proportions of C₃ and C₄ plants. So far,
5 however, existing records have yielded little evidence for such a combination during the
6 Holocene in the Northern Cape.

7 Wonderwerk is one of a handful of sites in the central interior that have produced multiple
8 lines of environmental evidence, mainly pollen and microfauna in association with a cultural
9 sequence. A Later Stone Age (largely Holocene) sequence near the cave's entrance
10 (Excavation area 1) was excavated by Anne and J. Francis Thackeray in 1979 (A.I. Thackeray
11 1981; J.F. Thackeray 1983). The cultural sequence describes the Oakhurst as the first early
12 Holocene lithic industry (Wonderwerk stratum 4d), developing from a late Glacial mixed
13 industry in stratum 5. The Oakhurst assemblage lacks backed artefacts, and is dominated by
14 scrapers with a few retouched adzes and tools, and the dominant raw material is local banded
15 ironstone and dolomite (Thackeray 1981). The following Wilton industry spans most parts of
16 the Holocene (Wonderwerk strata 4c-3b), beginning after 9000 calibrated years BP. It
17 includes backed artefacts, segments and scrapers, with points, borers, notched artefacts and
18 adzes. Shifts in both dominant raw material and artefact types occurred, with the transition
19 occurring at the top of Stratum 4b. Ceramic LSA appears in Strata 3a and 2b around 2000
20 years BP. Strata 1 and 2a were disturbed (Thackeray 1981, Beaumont 1990, Beaumont and
21 Vogel 2006).

22 Environmental proxies established from the Holocene part of the Wonderwerk sequence so
23 far comprise micromammal abundances (Avery 1981; Thackeray, this issue), pollen analysis
24 (Scott and Thackeray, this issue; van Zinderen Bakker 1982), stable isotopes in equid teeth
25 (Thackeray and Lee-Thorp 1992), and the isotope record and pollen from a stalagmite in the
26 cave entrance (Brook et al. 2010). Pollen is not abundant in the sediments, but Poaceae
27 dominate the assemblage for most of the sequence (Scott and Thackeray, this issue). Pollen
28 and microfaunal abundances together suggest a cool and dry start of the Holocene (compared
29 to present conditions), followed by warmer and wetter conditions until about 5000 years ago.
30 A change in raw material and tool production in the Wilton complex is thought to be
31 associated with a later phase of relatively cooler and drier conditions and short grass and
32 shrub vegetation (Thackeray 1981). Fluctuating wet and dry phases when the Ceramic LSA
33 appears around 2000 years ago were suggested by Beaumont et al. (1984). The stable carbon

1 and nitrogen isotope ratios from a small number of equid teeth in strata 2a-4d point to a
2 predominance of C₄ grasses throughout and hint at lower moisture in 4b (Thackeray and Lee-
3 Thorp 1992). The growth pattern, pollen and isotope data from a stalagmite at the Cave
4 entrance, just in front of excavation area 1, provide a discontinuous sequence back to 35ka,
5 but there is a long hiatus from 13 to 4ka, thus no data are available for the early to mid-
6 Holocene. The depositional hiatus is interpreted as indicating drier conditions during the
7 hiatus prior to 4ka, and wetter conditions thereafter (Brook et al. 2010), an interpretation
8 which appears to be at odds with most of the other proxies.

9 Thus a picture emerges of largely arid but fluctuating conditions with a likely humid episode
10 in the mid-Holocene. Broad trends are visible but they lack detail and thus are difficult to
11 associate with the archaeological records. Furthermore, the various lines of evidence are in
12 some cases inconsistent with each other, and due to low chronological resolution, they are not
13 easily matched with other records from the southern Africa interior.

14 Stable isotopes in ostrich eggshell

15 The ostrich, *Struthio camelus australis*, has formed a component of African vertebrate fauna
16 since the Pliocene. Their eggs were clearly valued by hunter-gatherers as well as by hyenas,
17 as eggshell fragments are abundant in many archaeological and palaeontological sites,
18 including Wonderwerk. Ostriches are mixed-feeders; they are one of the few animals known
19 to consume C₃, C₄ and CAM plants, although they show no particular preferences (Brown
20 1982; Williams et al. 1993) as it seems that plant tenderness is *the* over-riding factor (Milton
21 et al. 1994). Ostriches are particularly well-adapted to arid conditions. They are non-obligate
22 drinkers and have limited water excretion; in general, they can remain without drinking for
23 days if there is enough green food available. Their main water intake is from plant water
24 rather than environmental water sources, and they recycle metabolic water (Williams et al.
25 1993).

26 The breeding season occurs at the onset of the rainy season, but it can be variable (Sauer and
27 Sauer 1966; Williams et al. 1993). Ostrich eggs form quickly, within 3-5 days, thus the
28 isotopic composition reflects a limited period. Therefore, each eggshell, and thus each
29 fragment in a site, reflects a much shorter glimpse of time compared to that reflected in teeth
30 or bone. Over 95% of an ostrich eggshell is inorganic calcite (CaCO₃), which is formed from
31 blood bicarbonate. The apparent fractionation between the plant diet and eggshell CaCO₃
32 ($\epsilon^*_{\text{plant-CaCO}_3}$) is about 1.015 for $\delta^{13}\text{C}$ (ie. a difference of about 15‰) (von Schirnding et al.

1982; Johnson et al. 1997, 1998; Ségalen 2003). Given that ostriches eat all plants, blood bicarbonate, and hence eggshell CaCO_3 isotopic composition, cannot provide a measure of the proportions of C_4 (or CAM) plants in the total local plant biomass, but rather a reflection of the proportions of C_3 , C_4 and CAM that the ostrich finds palatable.

Oxygen isotope fractionation between bodywater and CaCO_3 is about 30‰ (following the standard fractionation from H_2O to CaCO_3 ; Sharp 2007). Ostriches' bodywater pool is strongly influenced by ^{18}O -enrichment in plants due to evapotranspiration, which is a response to moisture deficit that is enhanced under high temperatures (Föstel 1978). The net result is that eggshell $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{CaCO}_3}$) strongly reflect the influence of low humidity or relative humidity (RH) conditions, over and above the regional controls exerted by meteoric water $\delta^{18}\text{O}$ values ($\delta^{18}\text{O}_{\text{mw}}$). Modern studies suggest that OES $\delta^{18}\text{O}_{\text{CaCO}_3}$ is highly correlated with mean annual relative humidity (MARH) and with mean annual precipitation (MAP) via their influence on evapotranspiration in plants (Johnson et al. 1998; Ségalen 2003; Lee-Thorp and Ségalen in prep). Thus in an archaeological site, a preponderance of ^{18}O -enriched OES fragments reflects a phase of enhanced aridity (also expressed as lower MAP), while ^{18}O -depleted OES reflects greater humidity (higher MAP). We follow this rationale for interpreting our data.

Ratite (struthionid or aepyornithid) eggshells occur in many palaeontological and archaeological sites. Although it was at one time feared that ostriches' habit of swallowing stones including limestone fragments might impart a radiocarbon reservoir effect, or shift $^{13}\text{C}/^{12}\text{C}$ ratios, no such effects have been observed and ^{14}C determinations show that shell carbonate remains a closed system (eg. Long et al., 1983). Their stable light isotope ratios have been used to indicate vegetation and hydrological changes from the Miocene, Pliocene, Pleistocene and Holocene periods (eg. Stern et al., 1994; Ségalen et al., 2006; Kingston, 2011; Johnson et al., 1997). In archaeological sites, the most important taphonomic constraint is burning or heating of fragments, as it occurs for OES in contact with heated sediments near hearths. It has been shown, however, that colour and, surprisingly, smell, is a good guide as to whether fragments have been heated or not (Crisp, 2013, Chapter 6).

As a result of the short interval represented by eggshell formation during egg-laying, the building of nests over several weeks, the contribution of more than one female to the clutch (Sauer and Sauer 1966; von Schirnding 1982) and the marked intra- and inter-seasonal variability in moisture conditions that typically pertains in arid zones, OES isotopic values can be highly variable even at one time and place (eg. Johnson et al. 1997). Fragments in any

one stratum in an archaeological site represent periods of unknown duration, spanning perhaps just several years to centuries. Therefore, we analysed at least 7, and preferably more, OES more samples per stratum at Wonderwerk Cave. A larger number of samples provide a more robust view of overall conditions related to moisture and the proportions of C₄ grasses or CAM plants in ostrich diets, for each stratum.

Materials and Methods

Stable light isotope analyses:

The samples analysed in this study are all from Excavation Area 1. The square and spit of all samples is known and the stratigraphy follows Anne Thackeray's division of the Holocene strata into Stratum 1-5 (Thackeray 1981). Correlation of the strata numbering with the strata and spits in both Beaumont's (Beaumont 1990, Beaumont pers. comm.) and the Thackerays' (Thackeray 1981, Thackeray 1983) excavations are given in Table 1. The number of samples per stratum varies between 7 and 24 samples.

Samples were analysed in the Godwin Laboratory, University of Cambridge. Fragments were inspected for evidence of heating at temperatures high enough (>100°C) to cause colour changes or a distinctive odour produced on heating (Crisp 2013, Chapter 6), which might alter isotopic composition, but there were none. A small corner of each fragment (ca. 2mm x 2mm) was cleaned by mechanical abrasion, then removed and finely crushed in an agate mortar and pestle, producing about 2mg of powder. The powder was heated at 425°C under vacuum, for 2 hours, in order to eliminate organic matter. CO₂ was produced by hydrolysis in 100% phosphoric acid in a common acid bath, and the resultant dry CO₂ introduced to a VG PRISM II dual inlet mass spectrometer for measurement of ¹³C/¹²C and ¹⁸O/¹⁶O ratios. The reference gas was calibrated against NBS19, and an inter-laboratory carbonate standard, CarraraZ, was interspersed in all runs. A correction was made for the contribution of ¹⁷O. The results for both isotopes are expressed as per mil (‰) in the delta (δ) notation versus the international VPDB standard, as follows.

$$\delta^{13}\text{C}_{\text{VPDB}} = (\text{R}_{\text{sample}} - \text{R}_{\text{ref}}) / \text{R}_{\text{ref}} \times 1000 \text{ where } \text{R} = ^{13}\text{C}/^{12}\text{C}$$

$$\delta^{18}\text{O}_{\text{VPDB}} = (\text{R}_{\text{sample}} - \text{R}_{\text{ref}}) / \text{R}_{\text{ref}} \times 1000, \text{ where } \text{R} = ^{18}\text{O}/^{16}\text{O}$$

Analytical precision, as determined from replicates of CarraraZ and OES samples, was better than 0.1 and 0.2‰ for δ¹³C and δ¹⁸O, respectively.

1 We tested for statistical significant differences between all layers using one-way ANOVA
2 with Tukey's HSD *post-hoc* test in R (R Core Team 2013) with $p < 0.05$ regarded as
3 significant. Before doing this, we tested for homogeneity of variance with a Levene test in R,
4 which confirmed the null hypothesis that all strata variances are equal.

5 Calibration of radiocarbon dates:

6 A number of radiocarbon dates for the Holocene strata of Wonderwerk Cave were obtained
7 independently by several researchers in the 1970s and 1980s, on charcoal and ostrich eggshell
8 (Beaumont 1990; Butzer et al. 1978, 1979a, b; Humphrey and Thackeray 1983; Vogel et al.
9 1986). Beaumont (1990) compiled a list of almost all of these dates. We report a further 4
10 previously unpublished Pretoria Radiocarbon Laboratory (Pta) dates obtained in 1995. The
11 dates used here belong to Excavation area 1 only, and although the various excavators used
12 different stratigraphic terms, all can be assigned to strata (Table 1). Those with unknown
13 stratigraphic position, or on unknown material, and from areas other than Excavation area 1
14 (e.g. an entrance trench) were excluded from our calibration and modeling exercise. This left
15 17 radiocarbon dates on charcoal, all measured in the Pretoria Radiocarbon Laboratory. Since
16 the 1980's, when most of these radiocarbon determinations were made, new radiocarbon
17 calibration curves have been developed, and the application of Bayesian models has become
18 standard for reducing uncertainty. Thus radiocarbon ages from the Late Glacial/Holocene
19 strata were entered into OxCal version 4.2 to build a Bayesian sequential model (Bronk
20 Ramsey 2009, Bronk Ramsey et al. 2013). The dates for the strata were constructed as Phases
21 within the Sequence model. The model was run on the ShCal13 calibration curve (Hogg et al.
22 2013) for the Southern Hemisphere. In order to obtain better time constraints on the spits in
23 each stratum, phases with blank dates were built into the model; these act as boundaries for
24 the known radiocarbon dates (Fig. 1). Greater accuracy was obtained by employing an outlier
25 model with 5% outlier probabilities, whose purpose is to identify and reduce the impact of
26 inconsistent results on the outputs of the model (Dee et al., 2009). The model was run several
27 times, with and without the outlier model, with very similar results. This gave us confidence
28 in our modeled time ranges. The modeled radiocarbon dates are presented in the 95.4%
29 probability range and the ages are given in calibrated years before present (cal BP).

30 **Results**

31 Radiocarbon chronology

1 The 95.4% calibrated age ranges are shown in Table 2, and modeled strata boundaries are
2 shown in Figure 1 using the standard format provided in OxCal (v4.2.2 Bronk Ramsey
3 (2013); r:5). The model data provides a chronology that extends from over 12 000 years cal
4 BP to less than 1000 years cal BP. Thus calibration and Bayesian modeling indicates a rather
5 longer sequence than radiocarbon years alone, and greater resolution for the cultural phases. It
6 allows the construction of a chronological sequence with estimates for all strata and the spits
7 within a stratum, even where the radiocarbon date sampling is incomplete. The start and end
8 boundaries for the strata overlap, suggesting that there are no large time gaps in the
9 Wonderwerk Excavation area 1 sequence. Dates that were excluded from the model because
10 of unclear stratigraphic positions are appended in Table 2. All dates were calibrated
11 individually using the ShCal13 curve for the southern hemisphere (Bronk Ramsey 2009,
12 Hogg et al. 2013).

13 The assemblage of stratum 5 is not well defined culturally but seems from the published
14 radiocarbon dates to have a late Pleistocene age. We found only two reliable dates reported as
15 from stratum 5 (Pta-2852, Pta-6884), but the Bayesian model identified them as outliers with
16 poor agreement. The stratigraphic boundary between 4dII and 5 seems to be problematic, as
17 noted by Thackeray (1981) and Chazan (pers. comm.). Both of the “anomalous” dates fit well
18 into the age range for 4dII (Table 2), thus the age of stratum 5 remains uncertain with a
19 minimum age of 12500 years cal BP (Table 2). The Oakhurst (stratum 4d) is therefore the first
20 Holocene industry in Wonderwerk Cave. Two phases are visible; the older 4dII has an age
21 range (at 95.4% confidence level) from 10.5 to 12.2 ka cal BP, and the younger from 8.6-11.6
22 ka cal BP. The Wilton strata (4c through to 3b) begin before 9ka cal BP – the boundaries for
23 4cII at 95.4% confidence fall between 8.1 and 9.8 ka BP - so that they follow closely on the
24 final Oakhurst phase. This places the early Wilton at the site rather earlier than previously
25 thought, by perhaps 1000 years. A cultural shift within the Wilton industry is marked by the
26 “feature” stratum 4aLH, with boundaries between 4.9ka and 5.8 ka cal BP, between strata 4bI
27 and 4aII. The more recent Wilton phase, marked by higher proportions of backed bladelets
28 now occurs within the stratum boundaries of 4.3 to 5.4 ka cal BP. The last phase of the Wilton
29 occurs in stratum 3b, with rather broad boundaries from 2.06 to 4.8 ka cal BP. The Ceramic
30 LSA appears in stratum 3a, where two dates, when modeled, suggest that this phase may have
31 begun as early as 2.3 ka cal BP. This is perhaps earlier than the chronology suggested by
32 Beaumont and Vogel (2006).

33 Stable isotope composition

1 Basic statistics are given for the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data (means, standard deviations, minima and
2 maxima, and number of samples analysed per stratum) in Table 3, and the full data-set is
3 given in SI, Table 1. The overall mean for $\delta^{13}\text{C}$ is $-8.6 \pm 1.2\text{‰}$, and individual values range
4 between -11.8 and -4.1‰ , spanning a dietary range from C_3 to large amounts (ca. 50%) of C_4
5 plants. The mean for all $\delta^{18}\text{O}$ values is $7.8 \pm 3.2\text{‰}$, but the variation of individual values across
6 all strata is extremely high, from -1.5‰ to $+18.8\text{‰}$. These data suggest highly variable but
7 mostly arid conditions throughout the sequence.

8 In Figure 2, the $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ data are plotted as box and whisker plots according to each
9 stratigraphic level. The sequential information shows that the two isotope ratios largely follow
10 independent trends, with one or two exceptions. This is not entirely surprising as they reflect
11 different environmental variables. However, both $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ values are markedly lower in
12 upper stratum 5I, in the pre-Oakhurst terminal Pleistocene period, and there is a shift in both
13 towards higher values in stratum 4d. Stratum 5I shows the most significant differences in
14 carbon and oxygen isotope values compared to any other layers (SI Table 2), suggesting the
15 end of the Pleistocene to be remarkably different in the isotopic composition of vegetation
16 eaten by ostriches, compared to the Holocene. A modest shift from higher to lower $\delta^{13}\text{C}$
17 values is visible *within* Stratum 4d, suggesting a shift to vegetation with higher proportions of
18 C_3 plants (and less C_4) in ostrich diets after 10.5 ka cal BP. Mean $\delta^{13}\text{C}$ values do not fluctuate
19 much in the Wilton or Ceramic LSA strata (4c-2b) although they remain moderately variable
20 (Fig 2).

21 The $\delta^{18}\text{O}$ record shows largely high values after upper stratum 5, suggesting mostly dry
22 conditions throughout the Holocene. Those fragments with very high $\delta^{18}\text{O}$ values denote
23 extremely arid conditions, akin to values obtained for modern OES in the Central Namib
24 (Lee-Thorp and Segalen, in prep). Within the broad trend there are several shifts, the most
25 marked of which is within 4b and into 4aLH, also marking the boundary between the two
26 Wilton phases. Upper 4b and 4aLH show a modest decrease in mean $\delta^{18}\text{O}$, but both have
27 ranges that incorporate some very low $\delta^{18}\text{O}$ values compared to other Holocene strata.
28 Thereafter the trend is again one of increasing mean $\delta^{18}\text{O}$ values until 3a and 3b. The latter
29 marks the Ceramic LSA, at or before 2000 years cal BP. Mean values for the disturbed strata
30 1 and 2a are similar to modern values obtained by Johnson et al (1998) for Kimberley.

31 Discussion

A combination of stable isotope data and calibration of radiocarbon dates into strata and sub-strata of the Later Stone Age sequence has allowed us to build an environmental and climate record at higher temporal resolution than has been previously achievable. As indicated by the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data, the general, overall picture for the sequence remains one of mostly arid conditions and the near-continuous presence in ostrich diets of minor proportions of ^{13}C -enriched plants. As Scott and Thackeray (this issue) show, Poaceae (grass) pollen dominate the sequence, thus the ^{13}C -enriched component of the ostrich's diet must have been C_4 grass rather than CAM plants, while the more dominant C_3 portion may have been herbs that are poorly represented in the pollen record. The base of the sequence, stratum 5I, shows significantly lower $\delta^{13}\text{C}$ values indicating dominance of C_3 plants in ostrich diets. Shifts in mean $\delta^{13}\text{C}$ values occur from stratum 5 to 4dII, and then again a smaller shift to 4dI, suggesting minor fluctuations in available palatable C_4 grasses at these times. The extended chronology helps to interpret the shifts, since these strata can be shown to reflect early post-Glacial conditions, which elsewhere have been shown to be highly variable (eg. Scott et al. 1995; Smith et al. 2002, Truc et al. 2013, Burrough and Thomas 2013). Thus the period represented by stratum 5 is one with fluctuating vegetation composition, as is, to a lesser extent, stratum 4d containing an Oakhurst lithic assemblage. In the following strata (4c, 4b, 4aLH, 4a, 3b) the generally richer cultural deposits, containing Wilton lithics, includes also much larger amounts of ostrich eggshell. Mean OES $\delta^{13}\text{C}$ values in these strata indicate a minor but consistent presence of ^{13}C -enriched plants in ostrich diets.

The $\delta^{18}\text{O}$ record is perhaps more informative for comparison against the cultural record, as it suggests a sequence of mostly arid, but highly variable, conditions through the sequence. Considerable variability is observed *within* most of the strata especially from stratum 4bI upwards (Table 3 and Fig 2), an observation consistent with the high coefficient of variation (CV) for mean annual precipitation in this area today. The lowest $\delta^{18}\text{O}$ values, suggesting lowest evaporation and highest humidity or precipitation, occur near the base of the sequence in upper stratum 5I, and then again, but more marked, in the middle Holocene. Stratum 5 most likely reflects conditions during the terminal Pleistocene, thus lower temperatures may have been a contributing factor to reducing plant water loss (following Johnson et al. 1998), in addition to, or instead of, higher humidity or precipitation.

An episode with lower mean $\delta^{18}\text{O}$ values, including the lowest individual values in the sequence, occurs squarely in the mid-Holocene in strata 4bI and 4aLH, when it is implausible to consider significantly lower temperatures as an implicating factor. Here low $\delta^{18}\text{O}$ values

1 can be interpreted more confidently as indicating higher humidity and precipitation. Since
2 4bII is apparently drier (with higher $\delta^{18}\text{O}$), a dry to moist shift occurs *within* 4b. The timing of
3 this moist episode is, we suggest, constrained by the 95.4% age ranges for 4bI and 4aLH, at
4 5.5-6.2, and 4.9-5.9 ka cal BP respectively. However, the age model suggests little difference
5 in age between 4bII and 4bI, and the boundaries for 4aLH are just a little younger, therefore
6 the shift must have occurred quite rapidly. Hence we deduce that the period with moister
7 conditions occurred between 6.1 and 5.3 ka cal BP. This finding is consistent with the
8 conclusions reached by Scott and Thackeray (this issue), based on pollen types and a slightly
9 different age model.

10 The transition to 4aLH and 4aII marks a cultural shift identified by a change in raw material
11 preference and tool types that Thackeray (1981) earlier suggested may have been associated
12 with a shift to cooler and drier conditions. Pollen and microfaunal evidence from
13 Wonderwerk and elsewhere have been interpreted as indicating generally moister conditions
14 from ca 7.5 to 5.1 ka, followed by a shift to more arid, and perhaps cooler conditions (Avery
15 1981; van Zinderen Bakker 1982; Scott et al. 2012). If this moister episode is constrained to
16 6.1 - 5.3 ka years cal BP, it suggests a narrower age range of less than 1000 years, more or
17 less consistent with Scott and Thackeray's (this issue) suggestions. The $\delta^{18}\text{O}$ data in
18 subsequent strata suggests gradual aridification consistent with inferences based on PCA of
19 several proxies (Thackeray, this volume). The trend continues until 3a, the onset of the
20 Ceramic LSA, with a slight decline thereafter. The protracted period of increasing aridity until
21 just over 2000 years ago is broadly consistent with the pollen PCA data (Scott et al. 2012; van
22 Zinderen Bakker 1982) rather than with interpretations for increased moisture after 4000
23 years based on stalagmite growth (Brook et al 2010).

24 The closest comparison for the Wonderwerk OES sequence reported here is the sequence
25 established by means of Isoleucine (Ile) epimerisation ratios for individual fragments, and
26 based on $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ and $\delta^{18}\text{O}$ values for OES samples from Equus Cave, in the Ghaap
27 Escarpment (Johnson et al. 1997). In that record, the $\delta^{13}\text{C}$ values change little in the
28 Holocene, and the most notable $\delta^{15}\text{N}$ shift (on which interpretations of aridity were based)
29 occurs between the late Glacial and the Holocene. Although interpreted as indicating shifts in
30 temperature, high $\delta^{18}\text{O}$ variability occurs within the Holocene. Based on the Ile ratios, data
31 are sparse in the early Holocene, but the grouped $\delta^{18}\text{O}$ data after about 6000 years suggest
32 lower values near 4000 years and higher values at ca. 1-2ka. The Wonderwerk OES $\delta^{18}\text{O}$ data

are consistent with the Equus Cave data for 1-2ka, thus both records indicate aridity in the last two millennia.

There are few other isotope-based OES records with which to compare the Wonderwerk OES sequence. The shorter Blydefontein Rock Shelter $\delta^{13}\text{C}$ record for OES suggests a shift incorporating more C_4 plants after 2000 years BP in the Karoo to the south (Bousman 2005). Turning to broader regional comparisons and other substrates, Burrough and Thomas (2013) observe dune stabilisation between 5 and 6ka in northern Botswana, based on a large suite of Optically Stimulated Luminescence (OSL) dates, suggesting more vegetation growth and moister conditions. A detailed $\delta^{15}\text{N}$ record in hyrax dung from the summer precipitation zone in the Central Namib (Spitzkoppe, Namibia), suggests moister conditions around 4-5000 BP and the most arid Holocene conditions around 2000 BP (Chase et al. 2010). These results are broadly comparable to the OES isotope sequence at Wonderwerk.

Conclusion

The $\delta^{18}\text{O}$ record from OES at Wonderwerk suggests mostly arid but highly variable hydrological conditions through the Holocene, while $\delta^{13}\text{C}$ suggests that the proportions of C_3 and C_4 plants in ostrich diets remained broadly similar from about 12000 years cal BP. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ sequences do not shift in concert, a result that does not lend support to notions that increases in proportions of C_4 grasses necessarily denote increased aridity. The OES data are also inconsistent with the possibility for significantly increased penetration of winter rainfall during arid episodes (following Cockcroft et al. 1987). The moist episode in the mid-Holocene is broadly consistent with pollen evidence from the site, and with broader evidence from the region; it can be temporally constrained to between ca. 5.3 and 6.1 ka cal BP. The end of this period coincides with a shift both towards more arid conditions, and a change in lithic technology suggesting marked subsistence changes. The Holocene after ca 5.0 ka cal BP is mostly dry but still variable, suggesting unpredictable climate conditions up until recently.

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Figure and Table captions

Tables:

Table 1. Archaeological strata in Excavation area 1 showing associated stone tool technology. Correlations of the strata names with the corresponding spits in both the Beaumont (Beaumont 1990, Beaumont pers. comm.) and the Thackerays' (Thackeray 1981, Thackeray 1983) excavations are given. The modeled age boundaries at 95.4% confidence for each of the strata is also shown (based on the details provided in Table 2, and as shown in Fig 1)

Table 2. Raw and calibrated radiocarbon dates from Wonderwerk Cave using OxCal version 4.2 (Bronk Ramsey 2013) and the ShCal13 calibration curve for the southern hemisphere (Hogg et al. 2013) as described in the text. The table includes dates used in the Bayesian model, as well as those excluded because (1) the stratigraphic position in the entrance trench cannot be reliably established, (2) samples derived from excavations by the University of California Expedition in 1948, in which the stratigraphic position cannot be determined.

Table 3. Basic statistics for carbon and oxygen isotope ratios in ostrich eggshell at Wonderwerk, by stratum, and showing means, standard deviations, minima and maxima and number of samples per stratum.

Figures:

Figure 1. Bayesian model of strata boundaries in the Wonderwerk Excavation 1 area, modeled on 17 radiocarbon dates (Table 2) (Bronk Ramsey et al. 2013, Hogg et al. 2013). Each modeled age range (x-axis) is shown as the 95.4% confidence range. Modeled stratum boundaries are based on the probability distribution.

Figure 2: Box and whisker plots of the $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data from ostrich eggshell in Wonderwerk Cave, arranged vertically by stratum. Thick black lines show the median, the boxes indicate the 25-75% distribution, and the open circles are outliers.

Supplementary data:

Table 1. Ostrich eggshell carbon and oxygen isotope data from Wonderwerk Cave.

Table 2. Results of one-way ANOVA with Tukey's HSD *post hoc* tests between strata. Significant p-values (<0.05) are marked by **.

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7 October 2014

The Editor
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AARR – S13 – 00037: Revision and response to reviewers' comments

Dear Editor

We herewith submit a revised version of our article for the special Wonderwerk edition "Holocene environmental change at Wonderwerk Cave, South Africa: Insights from stable light isotopes in ostrich egg shell". We have made substantial revisions in response to both of the reviewer's comments, which we outline below. Where we cannot agree we detail the arguments. We hope that we have addressed all concerns.

Thank you for consideration of our manuscript.

Sincerely

A handwritten signature in cursive script that reads 'Julia Lee-Thorp'.

Julia Lee-Thorp
Professor of Archaeological Science

Response to reviewers

Reviewer 1

This reviewer was mainly concerned that we had incorrectly interpreted the carbon isotope results for ostrich diets, and upset that we had misunderstood and/or improperly referenced a study on ostrich eggshell at Equus Cave by Johnson et al (1997). In truth we had dealt with the Equus Cave results rather gingerly, because, in our opinion, mean values on very small samples sizes of OES in a highly variable environment have very limited interpretative value, and moreover the nitrogen isotope method relied upon is unproven for ostriches. However since the issue was raised we have changed and added text. We detail the concerns and the responses below. There were also other points in the review, to which we refer below:

“There are three major flaws with the paper, highlighted below.

(1) The authors misinterpret the carbon isotope results and demonstrate an overall lack of understanding of how isotopes and paleodietary reconstructions work. Using the $\delta^{13}\text{C}$ fractionation factor between eggshell carbonate and diet of 15‰ (established by many and appropriately cited by Lee-Thorp and Ecker on page 8, Lines 23-24), the $\delta^{13}\text{C}$ data of the Wonderwerk eggshell (ranging between -9 and -12‰) reflect a dietary composition of between -24 and -27‰. These values clearly reflect C3-plant dominated diets, as opposed to the C4-dominated diet stated in the text. This is a fatal flaw in the paper, in that the data do not support the discussion. “

We agree that ostriches were never grazers eating consistently large amounts of C₄ grasses. But in fact we did not say that in the manuscript. Data is interpreted as having always, throughout the Holocene, a varying more minor C₄ signal in a C₃ dominated diet. For example, “The overall mean for $\delta^{13}\text{C}$ is $-8.6 \pm 1.2\text{‰}$, and individual values range between -11.8 and -4.1 ‰, spanning a dietary range from C₃ to large amounts (ca. 50%) of C₄ plants.” (P11 L4-6), or “the near-continuous presence in ostrich diets of minor proportions of ¹³C-enriched plants.” (P. 14 L5-6). A larger C₄ contribution is only suggested when looking at the individual OES values (P11 L5-6). The reviewer used means for calculations and in fact the quoted several incorrect means.

However, we accept that we may have over-emphasised the C₄ component and we rewrote parts of the text throughout to ensure that it did not convey the wrong impression.

“(2a) The authors misrepresent the work of one of the only other papers that analyzes stable isotopes in

OES from the area (Johnson et al., 1997). Page 14, lines 32-38. The authors write “However much of the Holocene sequence [at Equus Cave] is composed of single, or at least very few, fragments, which as shown in our study is simply not adequate to cope with the high natural variability.” This first part of this sentence reflects a complete failure of the authors to read and/or understand the eggshell record from Equus Cave. In Johnson et al. (1997), the minimum number of eggshell representing a time period at Equus Cave is 3, not one, as the Lee-Thorp and Ecker state. The second part of this sentence is also false. The authors misrepresent their own work, in that they do not show that fewer than 3 samples is inadequate to cope with the high natural variability.”

We do not agree with the reviewer. The epimerisation method is not at issue here, it is the inherent variability which we are at pains to point out in the introduction and elsewhere. At Equus Cave, where the chronology relies only on Ile epimerisation, there are *often* very few data-points in that material, and the authors consequently grouped the data across what may have been 1000's of years to achieve the greater numbers. That more than 3 data points is required is painfully obvious from the wide range of values for each well-constrained stratum at Wonderwerk. Johnson et al 1997 advise that >5samples per stratum is highly advisable. However, we have rewritten or added more text on the Equus Cave data to clarify what was

done there (P3 L 14-21; , and how or why it differs from our results (P15 L24-32, P16 L 1-2).

“(2b) The authors refuse to tie their results into a paper that is well-cited, well-respected and actually in agreement with their data. Johnson et al. (1997) has been cited in the literature multiple times for the paleoenvironmental data generated from Equus Cave (e.g., Ségalan et al., 2006; Scott et al., 2013; Burrough and Thompson, 2103) and the successful use of radiocarbon calibrated amino acid racemization to date individual OES fragments (Crisp et al., 2013). ...While Johnson et al. (1997) is not without fault, it has yet to be challenged in the literature. Given Lee-Thorp and Ecker do not present a legitimate reason for dismissing the paper, then it cannot and should not be dismissed.”

Again we do not agree. The fact that a paper was cited multiple times does not mean it is correct, or of huge significance for our study. We do not want to “dismiss” it, but on the other hand we didn’t think it provided a very robust comparison, or that the timing corresponds well. The results at Equus do not “agree” with our sequence, or at least they do only around 2Ka. Additionally, it relies on $\delta^{15}\text{N}$ to provide the moisture sequence, and we do not even consider this isotope.

We have provided a little more text to make it clear that the Equus Cave OES inferences are based on $\delta^{15}\text{N}$ (see above), and then, where a comparison *can* be made, we say where they agree or differ (in inference about moisture, and also for $\delta^{13}\text{C}$ /diet) (P15 L24-32, P16 L1-2).

(3) The paper lacks focus. What is the purpose of this work--- to provide isotope-environmental data for the regional assessments of paleoclimate (Scott et al., 2013; Burrough and Thompson, 2013)? To tie cultural shifts into environmental change, or vice versa? The paper accomplishes neither well. The text shifts focus between these potentially important applications of the isotope work without presenting a thorough literature review of either in the introduction or connections to either in the discussion.

A major review of all the isotopic information for the entire region is well beyond the scope of this paper, which is meant to be part of a compilation of work focussed on Wonderwerk Cave and its environs. We tried to ensure that the purpose of the paper was made clear at the end of the Introduction (P6 L1-9).

Other points:

p. 5, Lines 16-17. “Unfortunately the faunal (Lee-Thorp and Beaumont, 1995) and ostrich eggshell (Johnson et al., 1997) records from Equus Cave have poor stratigraphic and temporal control.” While it is true that the stratigraphy (and samples) at Equus Cave have been mixed (Scott et al., 1995), the ostrich.....”

This point essentially repeats 2 above. We have rephrased the text as mentioned.

Page 5. Line 39. Provide basic reference for Bayesian models.

We referenced Bronk Ramsey regularly and appropriately.

Page 5, Line 58. Replace “follow the C3 pathway” with “utilize the C3 photosynthetic pathway”.

This is a matter of personal style but we changed to “use”.

“Page 6. Lines 10-34 and section on changes on seasonality of rainfall. If this is going to tie back into the ^{13}C results, it is necessary to talk about predominant type of vegetation expected during the egg-laying season at Wonderwerk. Additionally, more up-to-date references need to be cited here (c.g., Burrough and Thomas, 2013) and integrated with Scott et al. (2013).”

We added Burrough and Thomas 2013, and also referred several times to Scott and Thackeray in the same AARR issue.

Page 7, Line 30. Replace “data is” with “data are”.
Done

Page 8, Line 27-30. This text sets up the ready to anticipate that C4 plants are going to be important (which biases the reader). Omit “...is not a direct reflection of the proportions of C4 (or CAM) plants in the total local plant biomass...”

Point taken, we have omitted the phrase.

Page 10, line 16. Define “Pta” here, where this abbreviation is first mentioned in the text.
Done, occurs now on P7 L10

Page 11, lines 53-56. The measured $\delta^{13}\text{C}$ values of the Wonderwerk OES are between -8.6 and -11.8 ‰. Using a fractionation factor of 15‰ (as published in multiple papers and cited by Lee-Thorp and Ecker on page 8, line 22-24) the $\delta^{13}\text{C}$ values of the diet ranged between -23.6 and -26.8‰. If the average $\delta^{13}\text{C}$ values of C3 and C4 plants is -27 and -14 ‰, respectively, clearly the diet of these ostriches is dominated by C3 plants, NOT C4 plants. This incorrect interpretation of ostrich diets from Wonderwerk Cave is one of the major fatal flaws in the manuscript.

This statement repeats the complaint voiced in (1) above. As argued above, we did not say that diets are C4 dominated and the reviewer neglects to consider the full range. Additionally the entire ecosystem is more ^{13}C -enriched prior to the fossil fuel effect than he/she states.

Page 11, line 57. How can a range of data be negative (-1.5)? Range = difference between highest and lowest value and will always be a positive number.
Corrected

Page 12, 1st paragraph of discussion. Where are the results of the Mann-Whitney Test? Unit 5I appears to have statistically different isotope compositions from the other units, but all other units do not appear to differ from each other.

Statistics are given and significance now marked in a new Supplementary Table 2.

Page 13, lines 1-4. How does calibration of the radiocarbon dates help explain the shifts?
Response: the explanation is in the text (P14 L12-15).

Page 13, lines 31-33. What is the CV for MAP today?
Response: it was given earlier in the text (P6 L14-16).

“Page 13, lines 40-42. In agreement with Johnson et al., (1997) at Equus Cave.
Page 13, lines 54-56. Also in agreement with results from Equus Cave (Johnson et al., 1987).
Page 14, lines 8-22. Also substantiated by C, N and O isotopes results in OES from Equus Cave (Johnson et al., 1987).”

We cannot detect much of this agreement. At Equus Cave the periods around 17ka and 1-2ka are most important, but we do not have the same temporal overlap; consistency is noted for the 2ka period (P15 L24-32).

Page 14, lines 59-60. Logic is missing. The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ reflect different aspect of ostrich diets (degree of evapotranspiration occurring and relative percent of C3 and C4 plants consumed for O and

C, respectively). These may or may not shift in concert, as Lee-Thorp and Ecker say previously.

Response. The reviewer missed that indeed that IS the point - the two isotopic records from the same material seem to respond to different forcing.

Figure 2 should be plotted against time, not stratigraphic level. This would be much easier to relate to the paleoclimate literature. IF the purpose is to talk about cultural context, then these needs to be fleshed out in some more details.

We cannot produce a continuous age model for an archaeological site. Not every stratum spans a similar amount of time, and the stratum thicknesses vary even within the excavation area. As there are likely overlaps and breaks (as also seen in the radiocarbon calibration), Fig 2 figure follows a temporal scheme but it should not be viewed as a perfectly succeeding sequence. It cannot provide the high temporal resolution as for other palaeoclimate studies of continuously deposited materials (e.g. speleothems), but we can show in this way differences between cultural units, which is one of the aims of this paper.

Reviewer 1

This reviewer had 3 main comments phrased largely as suggestions.

1. It would be good to see a composite figure plotting the various other environmental indicators from Wonderwerk, as described in the fourth paragraph under the heading 'Wonderwerk Cave and its environmental context'.

If this was a stand-alone paper that would indeed be a good suggestion. This article however forms part of a special issue synthesis in AARR of our current understanding of the archaeology, chronology, and environmental and climate contexts of Wonderwerk Cave. So the results requested are provided elsewhere in the special issue. We do think that a collation of all the data will be very useful when the entire project is completed.

2. The authors should add a paragraph or two explaining why they think diagenesis in the ostrich eggshells they have analysed is not a problem. What are the quality controls for $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ measurements in OES?

Although there are no solid *direct* controls on carbon and oxygen isotopes in OES, a good deal of successful work has been done on this material spanning every time period from the Miocene onwards; nobody has detected evidence for diagenesis that would affect the stable light isotope data, nor have comparisons with the sensitive radiocarbon method produced any evidence. We have added a paragraph (P9 L18-28) towards the end of the Introduction section, and a further mention on the topic of burning in the Materials and Methods (P10 L16-19).

3. In Table 2, why are 3 dates on charcoal not included in the Bayesian modelling exercise, as well as a number of dates on OES? Is the different material in the case of the OES dates a problem? Are the 3 dates on charcoal from the entrance trench briefly mentioned in the text? This needs an explanation, to avoid any suspicion that the authors may have modelled only selected dates.

We have revised the Table 2, and its caption, to show these dates as well.

Abstract

Sparse records and discontinuous and/or poor chronologically resolved data hinder construction of reliable palaeoenvironmental sequences for the interior of South Africa. Wonderwerk Cave occupies a central position in the interior where the Kalahari Thornveld/dry woodland vegetation and generally arid conditions are expected to be sensitive to subtle past climate perturbations, and evidence from this site has been key to forming views on environmental change in the interior. A compilation of existing data including principal components analysis of pollen suggested broad trends ranging from variably arid and open in the early Holocene to moister conditions from about 7500 to 5000 years, followed by aridity thereafter. In an effort to better establish the nature and timing of shifts from the late Pleistocene sequence onwards we analyse carbon and oxygen isotope ratios in a robust sample of ostrich eggshell from Wonderwerk Cave. The resulting data are then placed within a temporal framework established by Bayesian modeling of existing radiocarbon dates, and compared against shifts in the Wonderwerk cultural sequence. Several shifts and trends in aridity include an arid to moist shift in Layer 4b near 6000 years coincident with a cultural shift within the Wilton assemblage, and thereafter an aridification trend culminating at about 2000 years with the appearance of the Ceramic LSA.

Keywords: Aridity, radiocarbon dates, Bayesian model, C₃ vegetation, C₄ grasses

Résumé

Des données isolées, discontinues, voire mal datées, gênent l'élaboration d'une séquence environnementale fiable pour le centre de l'Afrique du Sud. La grotte de Wonderwerk est située au centre du pays, là où le paysage boisé et sec du Kalahari Thornveld et ses conditions généralement arides, sont susceptibles de réagir aux faibles fluctuations climatiques du passé. Cette grotte est donc un site clé pour la compréhension des changements environnementaux du centre de l'Afrique du Sud. Afin d'établir la nature et la chronologie des variations

Comment [JL-T1]: added

Comment [JL-T2]: We removed a sentence here

environnementales dès le Pléistocène supérieur, nous avons analysé les variations isotopiques de l'oxygène et du carbone à partir d'un ensemble de coquilles d'œufs d'autruches échantillonnées dans la grotte de Wonderwerk. Les données obtenues ont ensuite été comparées les unes aux autres dans un cadre temporel établi par modélisation bayésienne de datations au carbone 14 existantes. Les résultats donnent de faibles proportions en graminées C₄ dans le régime alimentaire des autruches tout au long de l'Holocène. Plusieurs changements climatiques ont été observés, parmi lesquels un changement aride-humide au sein de la strate 4b datant d'il y a environ 6000 ans, qui correspond à un changement au sein de l'assemblage datant du Wilton. Ce changement est suivi d'un retour vers des conditions arides qui culmine il y a environ 2000 ans, à l'apparition du Néolithique à céramique.

Comment [JL-T3]: This sentence

Figure 1

[Click here to download Figure: Lee-Thorp & Ecker Fig 1.eps](#)

Figure 2
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Table 1
[Click here to download Table: Lee-Thorp and Ecker Table 1.docx](#)

Stratum	Stone tool technology	Boundary age cal. BP	Beaumont spits	Thackeray spits
1-2	modern	Last hundred years	1, 2	1, 2a
2b-3a	Ceramic LSA	190-2700	3UP, 3MID	2b, 3aI, 3aII
3b	Wilton (backed bladelets/chert)	2060-4800	3LR	3b
4aI	Wilton (backed bladelets/chert)	4300-5070	4aUP	4aI, 4aII
4aII	Wilton (backed bladelets/chert)	4500-5400	4aMID	4aIII, 4aIV
4aLH	Wilton (backed bladelets/chert)	4900-5890	4aLWR	4aLH
4bI	Wilton (scrapers/ironstone)	5550-6200	4bTUFA5	4bI
4bII	Wilton (scrapers/ironstone)	5700-6500	4bTUFA6	4bII
4cI-4cII	Wilton (scrapers/ironstone)	5960-9800	4cUP, 4cLR	4cI, 4cII
4dI	Oakhurst	8600-11600	4d	4dI
4dII	Oakhurst	10550-12200	4d	4dII
5I-5II	mixed	<12500	5	5I, 5III, 5IV

Table 2
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Lab Code	Published age BP	one sigma error	Archaeological stratum	Material	Reference	Calibrated BP (95.4%)
Pta-2779	1210	50	Stratum 2b	charcoal	Humphrey&Thackeray 1983	1260-960
Pta-2542	1890	50	Stratum 3a	charcoal	Beaumont 1979	1987-1631
Pta-6873	2120	80	Stratum 3a	charcoal	Lee-Thorp and Beaumont unpubl.	2299-1759
Pta-2543	2910	60	Stratum 3b	charcoal	Beaumont 1979	3230-2795
Pta-2785	3990	60	Stratum 3b	charcoal	Humphrey&Thackeray 1983	4576-2884
Pta-2541	4240	60	Stratum 4a	charcoal	Beaumont 1979	4869-4550
Pta-2797	4890	70	Stratum 4aLH	charcoal	Humphrey&Thackeray 1983	5720-5327
Pta-2544	5180	70	Stratum 4b	charcoal	Beaumont 1979	6176-5726
Pta-2545	5970	70	Stratum 4cl	charcoal	Beaumont 1979	6988-6563
Pta-2798	7430	60	Stratum 4cl	charcoal	Humphrey&Thackeray 1983	8345-8032
Pta-2546	9130	90	Stratum 4dl	charcoal	Beaumont 1979	10556-9937
Pta-2852	9760	120	Stratum 4dll (5a)	charcoal	Humphrey&Thackeray 1983	11700-10885

Pta-2790	10000	70	Stratum 4dII	charcoal	Humphrey&Thackeray 1983	11700-11239
Pta-2786	10200	90	Stratum 4dII	charcoal	Humphrey&Thackeray 1983	11902-11293
Pta-6872	10120	120	Stratum 4dII	charcoal	Lee-Thorp&Beaumont unpubl.	11826-11247
Pta-6871	10120	100	Stratum 4dII	charcoal	Lee-Thorp&Beaumont unpubl.	11816-11261
Pta-6884	10080	100	Stratum 4dII (5a)	charcoal	Lee-Thorp&Beaumont unpubl.	11779-11248
Unmodelled dates						
Pta-3427¹	5800	70	Stratum 3a	charcoal	Vogel et al. 1986	6730-6405
Pta-3426¹	2310	60	Stratum 3a	charcoal	Vogel et al. 1986	2430-2098
Pta-2139²	3060	40	Stratum 3	OES	Butzer et al. 1978	3350-3074
Pta-2140²	5930	50	Stratum 4c	OES	Butzer et al. 1978	6855-6558
Pta-3425¹	6840	80	Stratum 4cl	charcoal	Vogel et al. 1986	7826-7507
Pta-3366¹	8000	80	Stratum 4cII	OES	Vogel et al. 1986	9012-8596
Pta-3439¹	9030	90	Stratum 5a	OES	Vogel et al. 1986	10372-9745
Pta-2141²	12380	100	Stratum 5	OES	Vogel et al. 1986	14920-14020
Pta-3441¹	12400	180	Stratum 5	OES	Vogel et al. 1986	15124-13855

Table 3
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Stratum	n	$\delta^{13}\text{C}$	sd	min	max	$\delta^{18}\text{O}$	sd	min	max
1+2a	24	-8.8	1.0	-10.5	-7.0	7.5	2.8	-1.5	11.2
2b	10	-8.9	0.9	-10.5	-7.2	8.0	2.6	3.8	11.3
3a	18	-8.4	1.5	-10.8	-5.1	9.6	4.9	1.8	18.8
3b	10	-8.2	1.1	-9.2	-5.7	9.8	3.0	5.7	17.1
4aI	19	-8.7	1.4	-11.0	-5.9	8.1	2.6	4.1	12.8
4aII	17	-7.7	1.5	-9.7	-4.1	7.5	2.6	3.5	12.8
4aLH	8	-8.7	1.0	-10.0	-7.2	5.9	4.1	-0.5	10.5
4bI	14	-8.2	0.9	-9.7	-5.7	6.5	3.3	-1.2	10.7
4bII	13	-8.4	1.3	-10.6	-7.0	9.3	3.2	5.7	17.6
4cI	12	-8.7	1.1	-10.5	-7.1	8.1	2.5	3.7	11.8
4cII	11	-8.5	0.9	-9.9	-6.9	7.0	1.6	5.2	9.6
4dI	11	-9.4	1.0	-10.4	-9.5	8.1	1.8	7.3	8.8
4dII	9	-8.1	0.8	-9.9	-7.9	7.8	3.0	6.7	9.3
5I	7	-10.6	0.9	-11.8	-8.8	3.9	1.1	2.8	6.1
5II	13	-9.3	1.0	-10.9	-7.9	7.9	3.2	3.2	13.3
all	196	-8.6	1.2	-11.8	-4.1	7.8	3.2	-1.5	18.8

African Archaeological Review
Holocene environmental change at Wonderwerk Cave, South Africa: Insights from light stable isotopes in ostrich egg shell
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SUPPLEMENTAR TABLE 1

LAB#	ALT#	STRATUM	SQ	$\delta^{18}\text{O}_{\text{PDB}}$	$\delta^{13}\text{C}_{\text{PDB}}$	comments/notes
				(‰)	(‰)	
S/4063	123	STR 1	P6	8.6	-8.0	
S/4064	124	STR 1	P6	5.8	-5.3	
S/4065	127	STR 1	P7	9.3	-7.2	
S/4066	128	STR 1	P7	17.7	-6.3	
S/4067	131	STR 1	P9	5.2	-10.6	
S/4068	132	STR 1	P9	6.5	-9.0	
S/4069	133	STR 1	O20	10.5	-9.4	
S/4070	134	STR 1	O20	7.6	-10.0	
S/4071	136	STR 1	O21	7.6	-9.3	
S/4072	138	STR 1	P20	11.2	-8.3	
S/4073	140	STR 1	P20	5.2	-9.1	
S/4074	143	STR 1a	S21	8.8	-7.8	
S/4075	144	STR 1a	R21	5.6	-8.9	
S/4076	146	STR 1a	R23	10.7	-9.4	
S/4077	148	STR 1a	Q21	-1.5	-9.2	
S/4078	149	STR 1a	T22	8.0	-9.4	
S/4079	151	STR 1a	T23	6.8	-8.8	
S/4080	153	STR 1a	S23	10.6	-7.9	
S/4081	154	STR 2	P7	12.4	-7.3	
S/4082	155	STR 2	P7	9.9	-7.3	
S/4083	156	STR 2	P8	12.5	-8.2	
S/4084	157	STR 2	P8	10.5	-9.3	
S/4085	158	STR 2	P9	10.9	-7.8	
S/4086	159	STR 2	P9	7.0	-8.6	
S/4087	160	STR 2	O19	6.5	-7.2	
S/4088	161	STR 2	O19	4.9	-9.2	
S/4089	162	STR 2	O20	8.0	-9.4	
S/4090	163	STR 2	O20	4.8	-9.7	
S/4091	164	STR 2	P19	11.0	-9.3	

4092	165	STR 2	P2	7.0	-10.0
4093	166	STR 2	P2	9.8	-7.8
4094	167	STR 2a	Q22	9.0	-8.7
4095	168	STR 2a	Q23	9.2	-7.0
4096	169	STR 2a	Q23	9.6	-7.7
4097	170	STR 2a	R21	7.2	-7.8
4098	171	STR 2a	R21	8.6	-7.2
4099	172	STR 2a	S22	5.2	-10.3
4100	173	STR 2a	S22	5.9	-10.5
4141	174	STR 2b/3UP	R23	3.8	-7.3
4142	175	STR 2b/3UP	R23	5.9	-10.5
4143	176	STR 2b/3UP	R23	9.0	-8.3
4144	177	STR 2b/3UP	R22	7.1	-9.1
4145	178	STR 2b/3UP	R22	9.3	-9.3
4146	179	STR 2b/3UP	R22	11.3	-8.9
4147	180	STR 2b/3UP	R21	8.9	-8.8
4148	181	STR 2b/3UP	R21	8.8	-8.9
4149	182	STR 2b/3UP	R21	10.3	-8.0
4150	183	STR 2b/3UP	R21	5.2	-10.3
4151	184	STR 3/3aI	R22	5.2	-9.2
4152	185	STR 3/3aI	R22	10.0	-9.1
4153	186	STR 3/3aI	R22	18.2	-7.7
4154	187	STR 3/3aI	R22	18.8	-7.8
4155	188	STR 3/3aI	Q22	18.8	-7.2
4156	189	STR 3/3aI	Q22	10.7	-7.4
4157	190	STR 3/3aI	Q22	8.9	-5.1
4158	191	STR 3/3aI	Q22	1.8	-9.6
4159	192	STR 3/3aI	R25	8.1	-10.2
4160	193	STR 3/3aI	R25	10.6	-9.1
4161	195	STR 3MID/3aII	Q22	5.0	-9.5
4162	196	STR 3MID/3aII	Q22	11.7	-8.4
4163	197	STR 3MID/3aII	Q22	2.9	-10.8
4164	199	STR 3MID/3aII	R22	6.6	-5.4
4165	200	STR 3MID/3aII	R22	7.5	-8.7
4166	201	STR 3MID/3aII	R22	9.4	-8.3
4167	202	STR 3MID/3aII	R22	10.1	-9.5
4168	203	STR 3MID/3aII	R25	8.8	-8.6
4201	205	STR 3LWR/3b	R24	17.1	-5.7
4202	206	STR 3LWR/3b	R24	8.3	-8.9

4203	207	STR 3LWR/3b	R24	8.4	-8.8
4204	208	STR 3LWR/3b	R24	8.4	-9.2
4205	209	STR 3LWR/3b	Q23	8.8	-8.8
4206	210	STR 3LWR/3b	Q23	9.0	-9.1
4207	211	STR 3LWR/3b	Q23	7.9	-8.8
4208	212	STR 3LWR/3b	Q24	5.7	-7.8
4209	213	STR 3LWR/3b	Q24	13.2	-6.8
4210	214	STR 3LWR/3b	Q24	10.9	-7.8
4211	215	STR 4aUP/4aI	R21	8.8	-8.3
4212	216	STR 4aUP/4aI	R21	7.4	-8.1
4213	217	STR 4aUP/4aI	R21	7.6	-8.0
4214	219	STR 4aUP/4aI	Q22	9.7	-6.2
4215	220	STR 4aUP/4aI	Q22	12.7	-9.1
4216	221	STR 4aUP/4aI	Q22	7.8	-9.6
4217	223	STR 4aUP/4aI	Q21	10.3	-8.0
4218	224	STR 4aUP/4aI	Q21	7.0	-9.8
4219	225	STR 4aUP/4aI	Q21	6.1	-7.1
4220	227	STR 4aUP/4aII	Q21	11.1	-9.8
4221	228	STR 4aUP/4aII	Q21	10.9	-8.6
4222	229	STR 4aUP/4aII	Q21	4.8	-10.3
4223	230	STR 4aUP/4aII	Q21	5.4	-10.0
4224	232	STR 4aUP/4aII	Q22	8.3	-5.9
4225	233	STR 4aUP/4aII	Q22	4.6	-11.0
4226	234	STR 4aUP/4aII	R21	5.0	-9.4
4227	235	STR 4aUP/4aII	R21	6.5	-7.8
4341	236	STR 4aUP/4aII	R21	12.7	-9.9
4342	237	STR 4aUP/4aII	R21	6.3	-8.5
4343	238	STR4aMID/4aIII	R21	9.5	-8.7
4344	239	STR4aMID/4aIII	R21	4.1	-5.2
4345	240	STR4aMID/4aIII	R21	6.3	-9.3
4346	242	STR4aMID/4aIII	Q21	6.9	-7.9
4347	243	STR4aMID/4aIII	Q21	7.9	-6.1
4348	244	STR4aMID/4aIII	Q21	6.5	-8.4
4349	246	STR4aMID/4aIII	Q22	12.8	-4.1
4350	247	STR4aMID/4aIII	Q22	8.4	-7.7
4351	248	STR4aMID/4aIV	Q22	4.8	-7.9
4352	249	STR4aMID/4aIV	R21	4.8	-7.9
4353	250	STR4aMID/4aIV	R21	10.6	-9.7
4354	251	STR4aMID/4aIV	R21	9.7	-6.8

4355	252	STR4aMID/4aIV	R21	3.5	-9.2					
4356	254	STR4aMID/4aIV	Q21	5.1	-7.9					
4357	255	STR4aMID/4aIV	Q21	9.5	-8.2					
4358	256	STR4aMID/4aIV	Q21	9.6	-8.1					
4359	257	STR4aMID/4aIV	Q21	7.3	-8.5					
4361	260	STR4aLWR/4aLH	Q23	9.4	-7.2					
4362	261	STR4aLWR/4aLH	R23	6.6	-7.9					
1296	261	STR4aLWR/4aLH	R23	7.4	-8.2	A	serial sampling of one fragment, mean value used in analysis	mean	sd	n
1297	261	STR4aLWR/4aLH	R23	6.9	-8.0	B	serial sampling of one fragment, mean value used in analysis	$\delta^{13}\text{C}$	-8.11	0.23 5
1298	261	STR4aLWR/4aLH	R23	6.8	-7.8	C	serial sampling of one fragment, mean value used in analysis	$\delta^{18}\text{O}$	7.02	0.21 5
1299	261	STR4aLWR/4aLH	R23	7.1	-8.4	D	serial sampling of one fragment, mean value used in analysis			
1300	261	STR4aLWR/4aLH	R23	7.0	-8.3	E	serial sampling of one fragment, mean value used in analysis			
4363	262	STR4aLWR/4aLH	R23	6.3	-9.7					
4364	263	STR4aLWR/4aLH	R23	7.9	-9.0					
4365	265	STR4aLWR/4aLH	R23	10.5	-8.2					
4366	266	STR4aLWR/4aLH	R23	-0.5	-9.4					
1466	266	STR4aLWR/4aLH	R23	-0.3	-10.1	A	serial sampling of one fragment, mean value used in analysis	mean	sd	n
1467	266	STR4aLWR/4aLH	R23	-0.4	-10.1	B	serial sampling of one fragment, mean value used in analysis	$\delta^{13}\text{C}$	-9.99	0.30 5
1468	266	STR4aLWR/4aLH	R23	-0.2	-10.1	C	serial sampling of one fragment, mean value used in analysis	$\delta^{18}\text{O}$	-0.32	0.08 5
1469	266	STR4aLWR/4aLH	R23	-0.4	-10.2	D	serial sampling of one fragment, mean value used in analysis			
1470	266	STR4aLWR/4aLH	R23	-0.3	-9.5	E	serial sampling of one fragment, mean value used in analysis			
4367	269	STR4bUP/4bTUF5	R22	6.3	-8.4					
4368	270	STR4bUP/4bTUF5	R22	-1.2	-9.7					
4369	271	STR4bUP/4bTUF5	Q23	8.0	-9.3					
4370	272	STR4bUP/4bTUF5	Q23	7.2	-5.7					
4371	273	STR4bUP/4bTUF5	Q22	10.7	-8.4					
4372	274	STR4bUP/4bTUF5	Q22	3.8	-8.2					
4373	275	STR4bMID/4bTUF6	R23	6.2	-10.6					
4374	276	STR4bMID/4bTUF6	R23	8.9	-9.4					
4375	277	STR4bMID/4bTUF6	Q22	11.7	-7.4					
4376	278	STR4bMID/4bTUF6	Q22	9.6	-8.5					
4378	280	STR4bMID/4bTUF6	R22	9.6	-7.0					
4379	281	STR4bMID/4bTUF6	R22	9.9	-7.2					
4380	282	STR4bMID/4bTUF6	R22	7.2	-7.7					
4387	289	STR4bUP/4bI	R24	2.3	-8.0					
4388	290	STR4bUP/4bI	R24	10.3	-8.0					
4389	291	STR4bUP/4bI	R23	9.0	-8.4					
4390	292	STR4bUP/4bI	R23	7.9	-8.5					

4391	293	STR4bUP/4bI	Q23	3.4	-7.9
4392	294	STR4bUP/4bI	Q23	7.2	-8.9
4393	295	STR4bUP/4bI	Q24	9.3	-7.3
4394	296	STR4bUP/4bI	Q24	6.6	-8.0
4395	297	STR4bLWR/4bII	R23	6.1	-10.4
4396	298	STR4bLWR/4bII	R23	5.7	-9.7
4397	299	STR4bLWR/4bII	R24	17.6	-7.1
4398	300	STR4bLWR/4bII	R24	10.7	-9.2
4399	301	STR4bLWR/4bII	Q23	10.6	-7.0
4400	302	STR4bLWR/4bII	Q23	6.7	-8.1
4492	304	STR4cUP	N26	5.4	-10.5
4493	305	STR4cUP	N26	9.3	-8.7
4494	306	STR4cUP	N26	10.3	-8.8
4495	307	STR4cUP	M26	10.5	-9.7
4496	308	STR4cUP	M26	8.9	-8.1
4497	309	STR4cUP	M26	6.3	-8.9
4498	310	STR4cLWR	M26	5.2	-8.9
4499	311	STR4cLWR	M26	6.1	-6.9
4500	312	STR4cLWR	N27	7.7	-8.7
4501	313	STR4cLWR	N27	5.4	-9.9
4502	314	STR4cLWR	N27	5.6	-8.7
4503	315	STR4cLWR	N27	6.4	-8.8
4504	317	STR4cUP/4cI	R23	9.0	-7.5
4505	318	STR4cUP/4cI	R23	6.3	-8.3
4506	319	STR4cUP/4cI	R23	6.3	-10.4
4507	320	STR4cUP/4cI	R25	9.8	-8.4
4508	321	STR4cUP/4cI	R25	11.8	-8.1
4509	322	STR4cUP/4cI	R25	3.7	-7.1
4510	323	STR4cLWR/4cII	S25	8.9	-7.9
4511	324	STR4cLWR/4cII	S25	6.7	-9.5
4512	325	STR4cLWR/4cII	S24	9.6	-7.3
4513	326	STR4cLWR/4cII	S24	6.6	-9.0
4514	327	STR4cLWR/4cII	S24	9.4	-7.4
4515	328	STR4dUP/4dI	R24	8.8	-10.4
4516	329	STR4dUP/4dI	Q23	7.3	-9.5
4517	331	STR4dLWR/4dII	R23	8.8	-7.9
4518	333	STR4dLWR/4dII	Q24	9.1	-8.8
4519	334	STR4dLWR/4dII	Q23	6.7	-9.4
4520	335	STR4dLWR/4dII	Q23	9.3	-9.9

	487	STR 5UP/5I	Q28							
4840	488	STR 5UP/5I	Q28	3.3	-11.0					
4841	489	STR 5UP/5I	Q27	3.2	-11.0					
4842	490	STR 5UP/5I	Q27	4.1	-11.8					
1761	598	STR 5UP/5I	Q27	2.8	-10.4					
1762	599	STR 5UP/5I	Q27	4.1	-10.4					
1763	600	STR 5UP/5I	Q27	4.0	-10.7					
1764	601	STR 5UP/5I	Q27	6.1	-8.8					
4843	491	STR 5UP/5II	P8	9.1	-8.2					
4844	492	STR 5UP/5II	P8	9.2	-8.4					
4845	493	STR 5UP/5II	P9	9.3	-9.0					
4846	494	STR 5UP/5II	P9	10.9	-7.1					
4847	495	STR 5UP/5II	P9	7.8	-9.5					
4848	496	STR 5MID/5III	Q29	5.8	-9.8					
1451	496	STR 5MID/5III	Q29	5.0	-8.9	A	serial sampling of one fragment, mean value used in analysis	mean	sd	n
1452	496	STR 5MID/5III	Q29	5.3	-9.1	B	serial sampling of one fragment, mean value used in analysis	$\delta^{13}\text{C}$	-9.64	0.63 5
1453	496	STR 5MID/5III	Q29	5.7	-10.0	C	serial sampling of one fragment, mean value used in analysis	$\delta^{18}\text{O}$	5.48	0.32 5
1454	496	STR 5MID/5III	Q29	5.6	-10.3	D	serial sampling of one fragment, mean value used in analysis			
1455	496	STR 5MID/5III	Q29	5.8	-10.0	E	serial sampling of one fragment, mean value used in analysis			
4849	497	STR 5MID/5III	N27	3.2	-10.9					
4850	498	STR 5MID/5III	N26	5.6	-7.9					
4851	499	STR 5MID/5III	N26	13.3	-9.3					
1476	499	STR 5MID/5III	N26	10.0	-8.4	A	serial sampling of one fragment, mean value used in analysis	mean	sd	n
1477	499	STR 5MID/5III	N26	10.6	-8.1	B	serial sampling of one fragment, mean value used in analysis	$\delta^{13}\text{C}$	-8.12	0.18 5
1478	499	STR 5MID/5III	N26	10.7	-8.0	C	serial sampling of one fragment, mean value used in analysis	$\delta^{18}\text{O}$	10.52	0.28 5
1479	499	STR 5MID/5III	N26	10.7	-8.0	D	serial sampling of one fragment, mean value used in analysis			
1480	499	STR 5MID/5III	N26	10.6	-8.1	E	serial sampling of one fragment, mean value used in analysis			
1215	602	STR 5MID/5III	P27	9.0	-8.7					
1216	603	STR 5MID/5III	Q26	12.5	-9.1					
1217	604	STR 5MID/5III	Q26	6.7	-8.4					
1218	605	STR 5MID/5III	Q26	3.6	-10.9					
4852	500	STR 5MID/5IV	N28	9.8	-8.6					
4853	501	STR 5MID/5IV	N28	7.9	-9.9					
4854	502	STR 5MID/5IV	N28	8.6	-9.9					
ME 176		4dI	Q24	6.3	-9.4		Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford			
ME 166		4dI	P25	10.2	-7.8		Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford			
ME 190		4dI	R24	10.5	-9.8		Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford			
ME 167		4dI	Q23	5.9	-9.5		Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford			

ME 132	4dI	T28	13.8	-4.7	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 189	4dI	T22	6.8	-9.1	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 135	4dI	S22	10.5	-6.7	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 177	4dII	P25	10.5	-8.2	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 143	4dII	Q23	9.4	-7.4	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 136	4dII	Q25	7.6	-8.5	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 179	4dII	T22	6.5	-7.6	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 25	4dII	R32	5.0	-8.3	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford
ME 23	4dI	P26	5.9	-9.5	Measured by ME using a Gasbench II coupled to a Thermo Finnigan Delta V, University of Bradford

Holocene environmental change at Wonderwerk Cave, South Africa: Insights from light stable isotopes in ostrich egg shell

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Suppl. Table 2

**Significance p<0.05

Strata	p-value ($\delta^{13}\text{C}$)	p-value ($\delta^{18}\text{O}$)
5II-5I	0,6747910	0,2734277
4aLH-5I	0,1512047	0,9957897
4aI-5I	0,0423374**	0,1333973
4aII-5I	0,0000484**	0,3589290
4bI-5I	0,0026042**	0,8791176
4bII-5I	0,0136593**	0,0181670**
4cI-5I	0,0826436	0,1963553
4aII-5I	0,0278848**	0,7119888
4dI-5I	0,0975396	0,1028259
4dII-5I	0,0543954	0,1943132
Modern-5I	0,0577343	0,2655509
3a-5I	0,0083307**	0,0034071**
3b-5I	0,0060633**	0,0105367**
2b-5I	0,2926264	0,3056213
4aLH-5II	0,9966459	0,9801263
4aI-5II	0,9817814	1,0000000
4aII-5II	0,0318568**	1,0000000
4bI-5II	0,4475541	0,9978805
4bII-5II	0,8079248	0,9974647
4cI-5II	0,9922539	1,0000000
4cII-5II	0,9030659	0,9999977
4dI-5II	0,9942250	0,9999994
4dII-5II	0,9451231	1,0000000
Modern-5II	0,9952997	1,0000000
3a-5II	0,7606530	0,9567317
3b-5II	0,5690740	0,9746627
2b-5II	0,9999821	1,0000000
4aI-4aLH	1,0000000	0,9270720
4aII-4aLH	0,8914226	0,9952921
4bI-4aLH	0,9997982	1,0000000
4bII-4aLH	0,9999999	0,4522994
4cI-4aLH	1,0000000	0,9477437
4cII-4aLH	1,0000000	0,9999501
4dI-4aLH	1,0000000	0,8341073
4dII-4aLH	1,0000000	0,9156927
Modern-4aLH	1,0000000	0,9899454
3a-4aLH	1,0000000	0,2000154
3b-4aLH	0,9998487	0,3052475

2b-4aLH	1,0000000	0,9794893
4aII-4aI	0,5195347	0,9999998
4bI-4aI	0,9953244	0,9807306
4bII-4aI	0,9999933	0,9987417
4cI-4aI	1,0000000	1,0000000
4cII-4aI	0,9999997	0,9999097
4dI-4aI	1,0000000	1,0000000
4dII-4aI	0,9999999	1,0000000
Modern-4aI	1,0000000	0,9999998
3a-4aI	0,9999950	0,9624794
3b-4aI	0,9975443	0,9814145
2b-4aI	0,9999999	1,0000000
4bI-4aII	0,9996132	0,9998590
4bII-4aII	0,9777453	0,9612118
4cI-4aII	0,7313186	0,9999997
4cII-4aII	0,9702197	1,0000000
4dI-4aII	0,7601884	0,9998247
4dII-4aII	0,9901124	0,9999783
Modern-4aII	0,2541290	1,0000000
3a-4aII	0,9330701	0,7519575
3b-4aII	0,9999350	0,8596837
2b-4aII	0,4437552	1,0000000
4bII-4bI	1,0000000	0,5446765
4cI-4bI	0,9987818	0,9888998
4cII-4bI	0,9999995	1,0000000
4dI-4bI	0,9989728	0,9277734
4dII-4bI	0,9999999	0,9750729
Modern-4bI	0,9617180	0,9994574
3a-4bI	0,9999993	0,2116292
3b-4bI	1,0000000	0,3738168
2b-4bI	0,9680742	0,9976156
4cI-4bII	0,9999988	0,9998264
4cII-4bII	1,0000000	0,9015243
4dI-4bII	0,9999990	0,9999998
4dII-4bII	1,0000000	0,9999998
Modern-4bII	0,9995914	0,9465115
3a-4bII	1,0000000	1,0000000
3b-4bII	1,0000000	1,0000000
2b-4bII	0,9990663	0,9995464
4cII-4cI	1,0000000	0,9999291
4dI-4cI	1,0000000	1,0000000
4dII-4cI	1,0000000	1,0000000
Modern-4cI	1,0000000	0,9999998
3a-4cI	0,9999994	0,9924213
3b-4cI	0,9992407	0,9950756
2b-4cI	1,0000000	1,0000000
4dI-4cII	1,0000000	0,9971742
4dII-4cII	1,0000000	0,9993460
Modern-4cII	0,9999627	1,0000000
3a-4cII	1,0000000	0,6495910
3b-4cII	0,9999996	0,7608079
2b-4cII	0,9998258	0,9999943
4dII-4dI	1,0000000	1,0000000

Modern-4dl	1,0000000	0,9997874
3a-4dl	0,9999994	0,9998929
3b-4dl	0,9993380	0,9998907
2b-4dl	1,0000000	1,0000000
Modern-4dll	0,9999854	0,9999780
3a-4dll	1,0000000	0,9999294
3b-4dll	0,9999999	0,9999148
2b-4dll	0,9999081	1,0000000
3a-modern	0,9995067	0,6669119
3b-modern	0,9804530	0,8241990
2b-modern	1,0000000	1,0000000
3b-3a	0,9999994	1,0000000
2b-3a	0,9990445	0,9882979
2b-3b	0,9790136	0,9919557